# Urbanisation and renewable energies in ASEAN: multi-disciplinary approaches to analysing past and future trends

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# Abstract

By using multi-dimensional and comprehensive analyses, this thesis aims at providing harmonised targets, which not only follow the global trend of sustainable development but also serve the rapid economic and demographic growths in the developing countries. This thesis consists of four papers dealing with different challenges faced by Asian Emerging and Developing Countries (EMDCs) in the face of fast-approaching climate change and energy transition. The four papers can be divided into two main streams based on the research method applied. The first two essays employ decomposition and correlation methods to investigate long-term energy service demand and renewable energy developments. The last two essays turn to techno-socio-economic models with much attention to solar PV, a promising renewable energy type in most of Asian EMDCs.

The relationship between urbanisation and renewable energy are explored throughout all articles of the thesis. Paper 1 + 2 conclude that urbanisation causes energy consumption increases drastically in Southeast Asian countries, but at the same time creates momentum for renewable energy development, especially in urban areas. Suggestions for combining urban and energy plans in policy design are provided to use urbanisation as a motivation for renewable energy development. Paper 3 estimates a techno-economic potential for rooftop PV and found evidence of a high-concentration of rooftop solar PV potentials in urban areas in Vietnam. Paper 4 conducts a socio-economic assessment to investigate Social Acceptance (SA) and Willingness To Pay (WTP) toward residential PV products in Vietnam. The results show that PV can be considered as a lifestyle product with much greater attention and intention to purchase from the public in urban areas.

To assist policymakers in energy planning, Papers 1 + 2 provide decision support and innovative multi-level comparison tool, called the Impact Matrix. It is used for visualising factors comparison by placing considered factors in four quadrants of the matrix corresponding to four relative priority levels of policy focus requirements. The complex relationships between impact factors and energy demand and renewable energy changes can be explained by following the instruction in Paper 2.

Paper 3 develops a cost-effective, accessible, transferable and scalable method for cost-potential assessment of decentralised solar rooftop PV in developing countries where limited resource availability. Adjusting the module efficiency corresponding to regional and household conditions has been implemented to improve the output accuracy. The simulation for rooftop PV market is made regarding different input assumptions and estimates of the effect of various policy designs, including changing the Feed-In Tariffs (FiTs), grid tariff, and technology development.

In order to explore future rooftop PV adoption, paper 4 conducts empirical research focusing on discovering the differences between Social Acceptance (SA) and Willingness To Pay (WTP). This paper contributes to the literature of customer behaviour toward renewable energy by providing extended moderated mediation models to differentiate the distinctive roles of each influencing variable of SA and WTP. Policy advice is given to translate environmental interest and PV knowledge to higher SA and adopting action.

# List of Publications

This thesis is based on the following papers, which are referred to in the text by their following numerals.

1. Phuong M. Khuong, Russell McKenna, Wolf Fichtner. Multi-level decomposition of ASEAN urbanisation effects on energy. International Journal of Energy Sector Management. DOI: 10.1108/IJESM-12-2018-0002. May 2019

2. Phuong M. Khuong, Russell McKenna, Wolf Fichtner. Analysing drivers of renewable energy development in Southeast Asia countries with Correlation and Decomposition methods. Journal of Cleaner Production · DOI: 10.1016/j.jclepro.2018.12.192. December 2018.

3. Phuong M. Khuong, Russell McKenna, Wolf Fichtner. A Cost-Effective and Transferable Methodology for Rooftop PV Potential Assessment in Developing Countries. Energies. DOI: 10.3390/en13102501. May 2020.

4. Phuong M. Khuong, Fabian Scheller, Russell McKenna, Dogan Keles, Wolf Fichtner. Willingness To Pay for residential PV: reconciling gaps between acceptance and adoption. Working paper series in Production and Energy. KIT. DOI: 10.5445/IR/1000124530. October 2020.

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# Part A: Overview

## 1. Introduction

## 1.1 Background and motivation

Emerging and developing countries (EMDCs) have historically contributed little to greenhouse gas emissions because of their relatively small economic scale. However, most EMDCs require carbon-intensive investments to reduce poverty and create opportunities for growth (Martínez et al., 2019). The emerging industries with an average energy intensity of around 0.14 koe/$2015p[1] are 40% more energy-intensive than the developed industries (Enerdata, 2019). EMDCs like BRICS (Brazil, Russia, India, China and South Africa) are identified as some of the highest overall emitters (Enerdata, 2019). While EMDCs in Sub-Saharan Africa have realised carbon emission reductions but, in turn, have experienced poverty increase, the EMDCs in East & South Asia and the Pacific have achieved poverty reduction in the last ten years, but have increased $CO_2$ emissions by more than 200% (Adam Goldstein, 2015).

Among the East & South Asia and the Pacific economies, the Association of Southeast Asian Nations (ASEAN) had a broadly robust economic growth of 5.5% in 2018 (excluding Singapore), compared to the global growth of 2.5% and to the growth of other EMDCs of 4.1% (ASEAN, 2019; World Bank Group, 2020). The ASEAN economies are driven by strong domestic demands and foreign investments, contributing to worldwide income rising from 1.9% to 3.5% over the last fifteen years (IMF, 2019b). Implementing massive infrastructure projects in these countries is expected to provide substantial support to the region's economy (ASEAN, 2019). However, this development trend threatens the ASEAN’s environment and quality of life. ASEAN identified the urgent situation of air and solid pollution in the region due to uncontrollable rapid development (SOER 5th, 2017).

Fossil fuels have underpinned ASEAN's rise. Total energy demand in the region has grown by more than 80% since 2000, and a doubling in fossil fuel use has met the largest share of this growth. As member countries pursue their economic goals, ASEAN's energy demand is projected to more than double and $CO_2$ emissions to triple by 2040 (ASEAN Energy Outlook, 2017), which would worsen the alarming level of pollution in most of the ASEAN countries due to increasing fossil fuel consumption. ASEAN as a whole is now on the verge of becoming a net importer of fossil fuels for the first time. The region has witnessed a rapid growth in electricity demand, at an average of 6% per year, among

[1] Koe/$2015p: Kilogram oil equivalent per USD at constant exchange rate, price and purchasing power parities of the year 2005

the fastest in the world. Despite the effort of the governments to support renewable energy deployment and the falling costs of renewable energy technologies, renewable energy only meets 15 % of the energy demand and the contribution of solar photovoltaics (PV), and wind remains small (IEA, 2020).

Despite the fact that ASEAN identified energy transitions to renewable energy as a prerequisite to ensure sustainable development (IMF, 2018), renewable energy development faces substantial barriers in the region, including insufficient policy support, high up-front cost, long payback periods, various informational gaps and lack understanding of customer behaviours toward renewable energy (Barroco and Herrera, 2019; Erdiwansyah et al., 2019b).

While ASEAN countries have attempted to lessen the consequences of rapid economic development by promoting energy transition, a new challenge may be arising in the form of rapid urbanisation. The evolution in size and complexity of urban systems, which is proportional to the increase of overall energy consumption in developed countries (Chabrol 2016; Behera and Dash 2017), may worsen ASEAN's energy and environmental issues (Hof et al., 2017). Urbanisation in ASEAN has increased by 3% per year during 1995-2014, higher than the average global rate of 2% per year. Further urban growth is expected in ASEAN, with the projected percentage of urbanites increasing from today's 47% to 56% in 2030 and 67% in 2050, respectively (UN, 2014). ASEAN governments have been confronting challenges to cope with the rapid increases in the urban population, resulting in energy-related severe environmental problems, especially from growing demands for necessary infrastructure (SOER 5th, 2017).

The developing world is having the highest rate of energy demand increase and will become a more significant emitter in the future to ensure public access to energy for life quality and economic development. Therefore, energy transition solutions are urgently required to make sure that the rest of EMDCs will not go down the path of BRICs. Energy assets are long-lived, which means anticipating a future carbon constraint will often be cheaper than risking stranded assets that have to be scrapped early (Samant et al., 2020; Seetharaman et al., 2019). Especially at the early stage of the industrialisation, when the energy transition is not yet complicated, creating industries driven by achieved or imminent competitiveness of low-carbon technologies may set up a quantum leap for low-carbon economies later on in these countries.

This energy transition will require a significant degree of support from both the public and private sectors under a powerful conceptualisation of balancing multi-disciplinary interests and multiple targets. However, the EMDCs have limited capacity in front-loading massive finances and weak multilaterally cross-subsidised public political frameworks for renewable energy. They may not be able to induce complementary private investments as natural market forces. Therefore, a robust policy framework and fiscal response are needed to promote long-term investments to accelerate the energy transition and create a sustainable growth premise. These countries can benefit from renewable development by decarbonising their energy systems early, although the speed of decarbonisation will depend on individual circumstances. With a proper investment plan in renewable energy, energy services can assist these countries in accelerating economic growth and will allow them to leapfrog the previous energy transitions, jump straight from centralised infrastructures towards private businesses with new, more productive technologies, as they have done with mobile telephony (Svobodova et al., 2020; Wang and Wang, 2020).

## 1.2 Objectives and research questions

This thesis is motivated by the apparent needs for research on energy transition in developing countries. Four main research questions are identified:

(1) What measures can be applied to solve problems of long-term energy service demand?
(2) Is urbanisation an obstacle or an engine in the energy transition?
(3) What factors constrain rooftop PV potentials?
(4) How can self-sufficient development of rooftop PV be ensured in developing countries?

To answer these questions in order to support the energy transition in Asian EMDCs, literature gaps are identified. First of all, previous studies on energy transition less considered different challenges present in developing countries, such as high urbanisation (Behera and Dash, 2017; Gollin et al., 2016; Wu et al., 2016), presence of competing for developmental interests (economic growth versus reducing energy consumption) (Adenle, 2020), low level of capabilities (financial, technological and absorptive capacities) (Seetharaman et al., 2019), and weak interaction in local and global dialogue (Andrews-Speed, 2016; Kim, 2019; Miller et al., 2015; Richard, 2016).

Secondly, controversial results appearing along with the research history about the causal link between urban concentration and economic growth need to be elucidated. The missing of multi-level comparison, cross-sectors consideration between different countries, and interaction policies between local and state administrations to deal with these topics in the region are significantly noted (ASEAN, 2019, 2018, 2017). The lack of integrated planning, which considers both centralised and decentralised perspectives for various regions/sectors with different size, administrative, geographical, and cultural settings caused problems of untransferable policies and poor and expensive implementations.

Thirdly, the conflicting interests of sustainable growth in EMDCs are stronger than in other countries (Adam Goldstein, 2015; Fankhauser and Jotzo, 2018). Even though with a low level of capabilities, sub-national governments have chosen the path of becoming leaders of solar development by setting more ambitious targets than their national counterparts (REN21, 2019). In this case, a low-cost potential assessment that supports deployment strategies and aggressive local, state, and national policies to boost and explore renewable energy potential are vital (Castellanos et al., 2017; Choi et al., 2019; Hofierka and Kaňuk, 2009).

Lastly, the lack of bottom-up planning, which works toward setting a plan at the most detailed level of classification, is undeniable (Chang et al., 2019; La Rue Can et al., 2019; Marquardt, 2017a, 2014). For many years, stakeholders and policymakers have faced the deficiency of analyses focusing specifically on specific region/sector considering different inputs (e.g. electricity demand, installed capacity, specific expenses, and customer behaviour) (Qazi et al., 2019; Sovacool, 2014). Now the ever-growing demand for energy resources is putting great pressure on researchers to investigate techno-socio-economic challenges in Asian EMDCs in order to assist these countries accomplishing their energy transition mission.

Based on these motivations and realised literature gaps, the four research questions are divided into two general lines. The first two essays use decomposition and correlation methods to investigate long-term energy service demand and renewable energy developing trends. The last two essays focus on designing techno-socio-economic models with much attention to solar PV, a promising renewable energy type in most of Asian EMDCs.

## 1.3 Overview of this thesis

This book is organised into two parts. Part A presents the background, motivation, methods, and own contributions of this work. Part B includes all articles that are related to this work. After the introduction, chapter 2 of part A presents the context of the energy transition in EMDCs. The main contents of the work are presented in chapters 3 and 4. While chapter 3 presents and discusses the research framework, chapter 4 summarises the main contributions published in these papers in part B. Chapter 5 discusses the possibilities for further research in accelerating the successful energy transition in developing countries.

# 2. Asian EMDCs and the energy transition

## 2.1 Status: Asian EMDCs and energy service demands

### 2.1.1 EMDCs and their socio-economic characteristics

Emerging and developing countries (EMDCs) are in this study the group of countries having the per-capita gross national income (GNI) between $1026 and $3995 and $3996 to $12375, respectively, in 2019 (The World Bank, 2019b). Developing countries have a less developed industrial base than other countries (O'Sullivan and Sheffrin, 2003). They tend to have some common characteristics such as low levels of living standards, high levels of pollution, and generally poor infrastructure (Althor et al., 2016; Korotayev and Zinkina, 2014). Meanwhile, emerging economies are becoming more integrated with global markets. They have increased liquidity in local debt and equity markets, enhanced trade volume, foreign direct investment, and modern financial and regulatory institutions (IMF, 2019a).

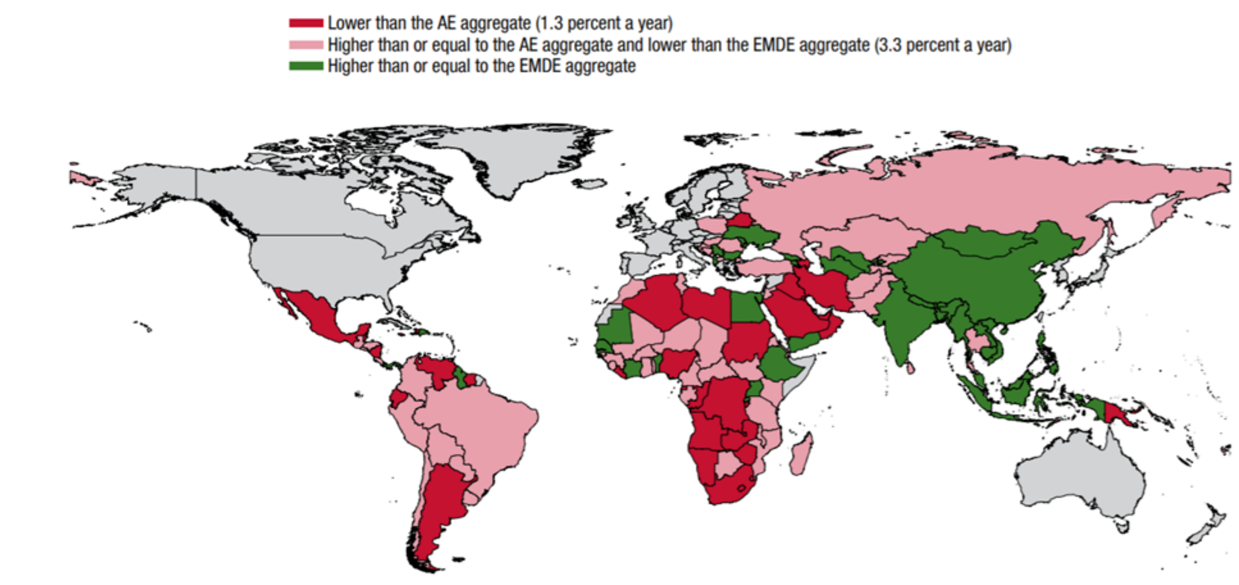



*Figure 1. A comparison of global economic growth rates in 2019. Notes: AE = advanced economy, EMDE = emerging and developing economy (IMF, 2019b)*

Since 2000, EMDCs substantially increased their share in global GDP from 43.2% in 2000 to around 52% in 2018 and is expected to be 62.7% in 2023. Until 2019, Asia EMDCs remain the main engine of the world economy, but growth is gradually softening with China's structural slowdown. While the economic average growth is projected to stabilize at about 4.8% in all EMDCs, in Asian EMDCs, it is expected to remain at about 6% through the forecast horizon (IMF, 2019b).

GDP and energy use are closely coupled (Banday and Aneja, 2019; Saidi et al., 2017; Streimikiene and Kasperowicz, 2016; Topcu et al., 2020; Tzeremes, 2018). The rapid economic growth in Asian EMDCs leads to an immediate increase in energy demand, which is much faster than their GDP increase (IMF, 2019a). The economies will need to produce a tremendous effort to build their infrastructures. Fossil fuel consumption has been increasing most dramatically in the Asian EMDC, where the total consumption increased more than 12-fold over this period from 1965-2015 (IEA, 2019). As a result, in 2015, Asia Pacific was the largest regional energy consumer with 42%, which was about the same as North America, Europe, and Eurasia combined (at 43%). The Middle East, Latin America, and Africa account for around seven, five, and three percent, respectively (Figure 2). Asia is also by far the largest emitter, accounting for 53% of global emissions in 2017. China is, by a significant margin, Asia's and the world's largest emitter, accounted for 58.9% and 27.2% of Asia Pacific and global emissions, respectively, in 2017.

### 2.1.2 Asian EMDCs and their dramatically increased energy demand

During the initial development stages of an EMDC, since the early years of access to and utilisation of more abundant modern energy (i.e., fuels and electricity) includes many energy-intensive activities (Martínez et al., 2019), most EMDCs started with higher levels of energy intensity. On average, their energy intensity is still higher than those in developed nations, but that gap is shrinking until 2019 (IEA, 2019). The energy intensity indicators for less developed regions, including low & middle income, will gradually converge in their domain; yet, they are not expected to reach the level of the economically developed countries by 2040 (Eder and Provornaya, 2018). Only after the development takes hold and industries established, the energy intensity can fall as cost-cutting is employed to "squeeze" more value out of now established markets and manufacturing subsectors (Goldemberg and Siqueira Prado, 2011).

Located in the southeast Asia Pacific, the Association of Southeast Asian Nations (ASEAN) accounts for only around 13% of the total primary energy consumption in the region in 2019 but is among the most emitters in Asia after China and India (Figure 2). Primary energy consumption in ASEAN grows dramatically by around 7 %/year continuously from 1990 until 2019 compared with about 4 %/year and 1 %/year in the Asia Pacific and the world, respectively. This region is one of the most dynamic and fast-growing economic regions in the world. The ASEAN's GDP per capita ranges from about $1,390 in Cambodia, a lower-middle-income developing economy, to $57,713 in Singapore, a high-income advanced economy (The World Bank 2019b). Most other members are middle-income countries, but they are different in terms of size and sustainable development outcomes and poverty rates. Together, ASEAN countries emitted 1.5 billion tonnes $CO_2$ in 2017 (ACE, 2017). The energy mix in the region has historically been dominated by fossil fuels, such as coal in Indonesia, the Philippines and Malaysia, and oil and gas in Vietnam, Thailand, and Singapore (ASEAN, 2017; ERIA, 2019). This domination means that the average $CO_2$ emission intensity in these countries is around 537 kgCO2/$ in 2017[2] (IEA, 2019).

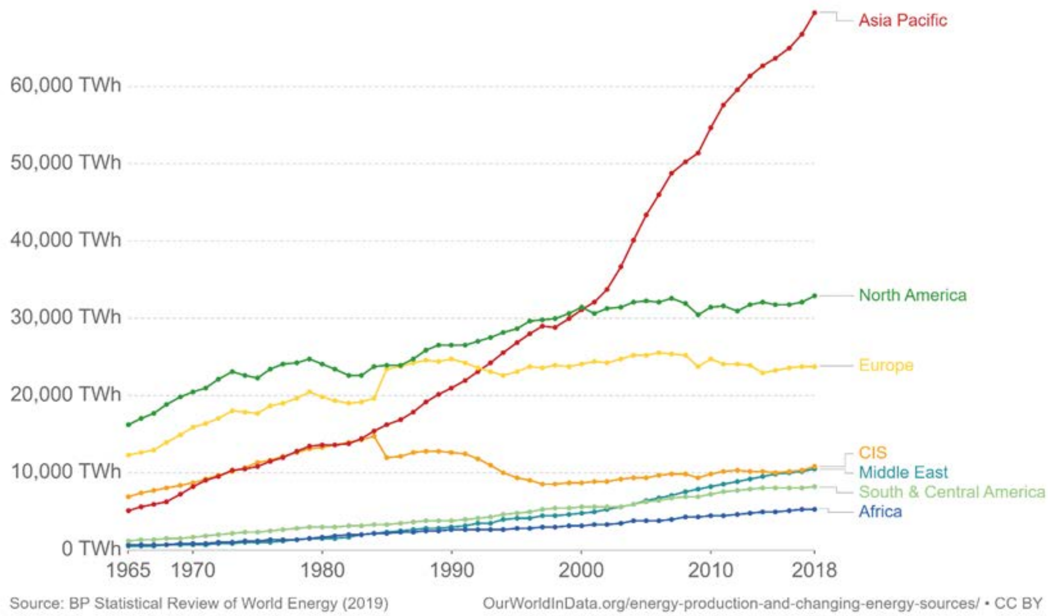



*Figure 2. Primary energy consumption by world region (Source: BP Statistical Review of World Energy. 2019)*

In detail, the high-income (Singapore and Brunei) and the upper-middle-income (Malaysia and Thailand) groups have a $CO_2$ emission intensity higher than most of the countries in the same income groups in the world (Figure 3). Among the lower-middle-income group, Vietnam emerges as an infamous example of using high energy and $CO_2$ intensity technologies to promote a rapid growth rate (Figure 4). Because of the absence of significant decarbonising technologies in the energy mix, energy-related GHG emissions in the ASEAN region will almost double by 2040, reaching 2.3 billion tonnes (IEA, 2017). The increasing emission trend will worsen the currently vulnerable condition to climate change in the region (David Eckstein et al., 2019).

However, ASEAN faces both familiar and different challenges from other EMDCs in pursuing energy transition toward low-carbon technologies (Khosla et al., 2017). Most ASEAN countries (except for Singapore) need to handle multiple sustainable development tasks. Apart from energy transition, they need to reorient their policies to improve the quality of life and to avoid further damaging environment, and to ensure that the benefits are broadly shared across the population (Andrews-Speed, 2016; Hof et al., 2017; Khosla et al., 2017). For the lower-middle-income ASEAN countries, in particular, governments need to balance different sustainable development tasks that are more complex, calling

[2] kgCO2/$: kg CO2 emission per 2017 Purchasing Power Parity (PPP) $ of GDP

for policies to improve health and education outcomes further and address the infrastructure gap (IMF, 2018; Khosla et al., 2017).

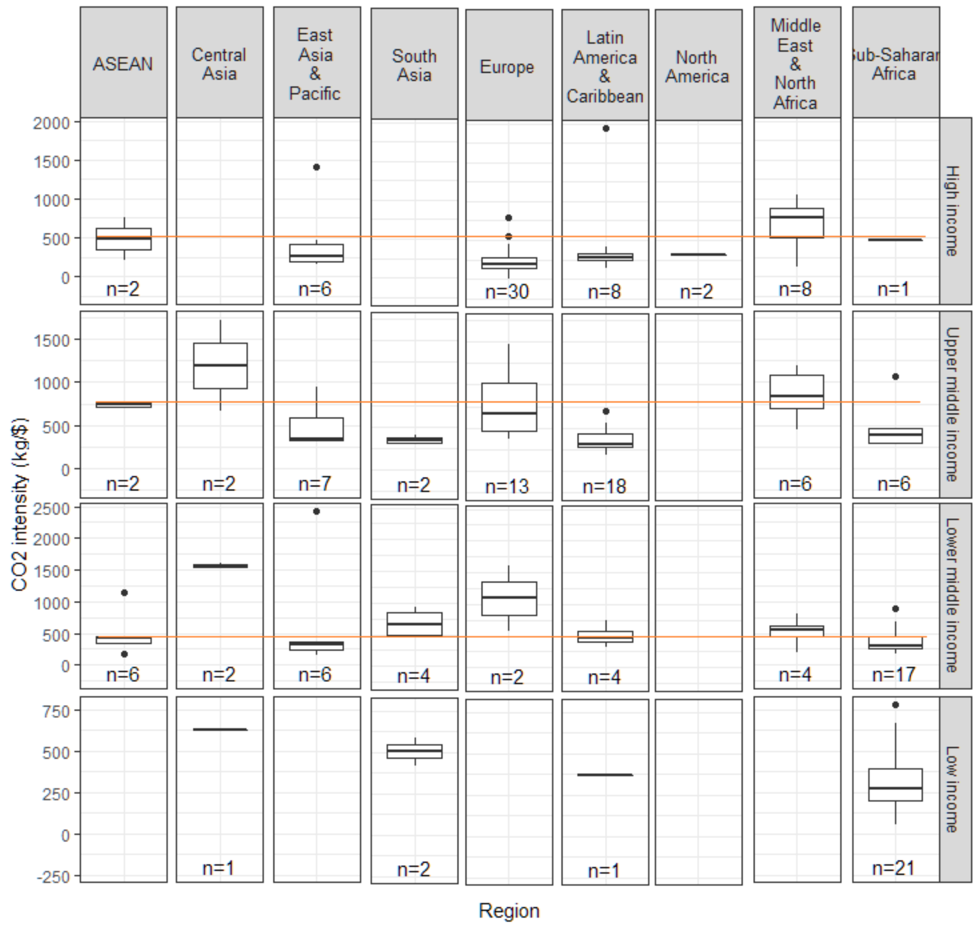



*Figure 3. Comparing CO2 emission intensity (kg/$) between different regions in 2017. Own illustration based on the data source (Our World in Data, 2020)*

Moreover, ASEAN is characterized by rapid urbanisation, industrialisation, and an increasingly important role in the urban service sector. The urban population in the region is expected to grow by around 100 million people, rising from 280 million people in 2018 to 373 million people by 2030 (ASEAN, 2018). ASEAN is recorded as the second-fastest developing region in the world, with an average GDP growth rate of 4.8% in 2016 and 5.1% in 2017 (IMF 2018), and is predicted to grow faster, by an average 6.3% per year over the period 2018-2022 (OECD 2018). The changes have occurred historically in megacities and large cities, and nearly 40 % of ASEAN's GDP growth to 2025 is expected to come from 142 cities with populations between 200,000 and 5 million (The Economist Intelligence Unit 2016). Since highly urbanized countries tend to consume more energy, ASEAN governments are experiencing problems in dealing with local energy shortages (especially power shortages in the Philippines and Vietnam) and GHG emissions from the high-density population (Adam Goldstein, 2015; ASEAN, 2018; Goh and Ang, 2020; Islam and Abdul Ghani, 2018).

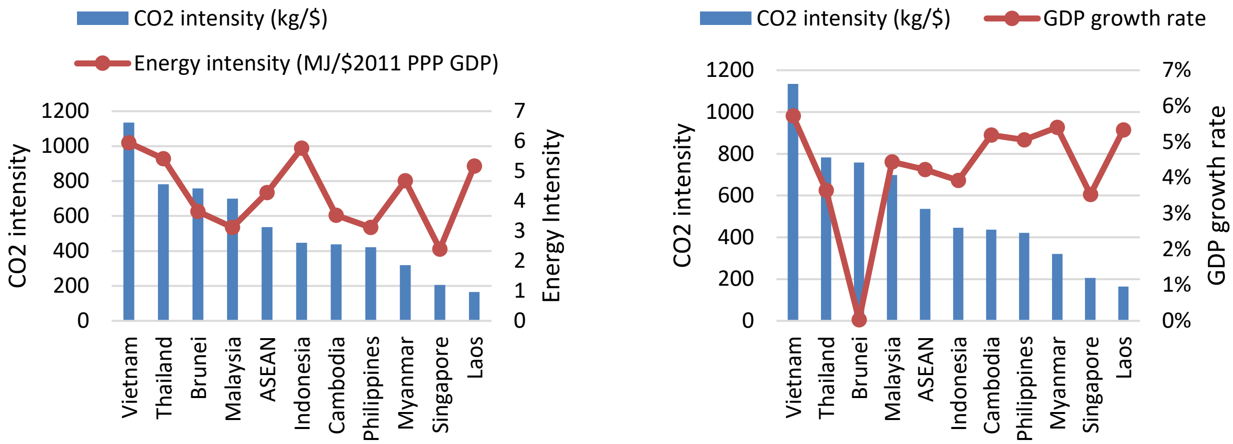



*Figure 4. Comparing CO2 intensity, energy intensity, and GDP growth rate in ASEAN. Own illustration based on (Our World in Data, 2020; The World Bank, 2019a)*

## 2.2 Trend: Renewable energy

As the market for renewable energy and the technology for smart grids continues to grow, more innovations have been given birth to generate electricity through alternative means (Kirchherr and Urban, 2018; Mario Cervantes et al., 2018). New technological advances over the last two decades have driven this increased reliance on renewable energy by reducing costs, and new technological developments promise to augment this solar usage by further decreasing costs and increasing solar panel efficiency (Aramesh et al., 2019; Energy Initiative, 2015). Solar PV systems are viable because of the vast array of system designs, minimal maintenance, cost reduction, and smarter technologies available. Solar technology is becoming increasingly efficient in function (Bambara and Athienitis, 2019; Marucci et al., 2018; Xie et al., 2019), persistent increasing in energy output efficiency (Aramesh et al., 2019; Khosla et al., 2017), and is easily capable of functioning in a variety of locales (Adenle, 2020; Aramesh et al., 2019; Kirchherr and Urban, 2018; Kumar et al., 2019; Reda and Fatima, 2019).

### 2.2.1 Renewable energy potential and developments in ASEAN

ASEAN is richly endowed with diverse renewable energy sources, especially wind and solar, in the region (ACE, 2017). The significant realisable potential of wind energy in Indonesia, Thailand, Vietnam, and the Philippines is approximately 63 TWh, 57 TWh, 45 TWh, and 22 TWh, respectively (IEA, 2010). Due to being located close to the equator, the countries receive high daily insolation of 4-7 kWh/m2. Consequently, the physical potential of solar power is evaluated at 65 GW in Cambodia, 10 GW in Laos, 26 GW in Myanmar, 33 GW in Thailand, and 25 GW in Vietnam (ADB, 2015; IEA, 2010). The rapid growth of renewable energy technology (Ishugah et al., 2014; Terziotti et al., 2012) and a subsequent decline in renewable energy costs (IRENA, 2018; Wei et al., 2014) could lead urban neighbourhoods to move away from traditional energy resources and centralised utility models to decentralised energy supply.

In 2016, renewable energy accounted for 26% of total primary energy supply (TPES) in ASEAN but was dominated by traditional biomass (20%) and hydropower (3%) (Southeast Asia Energy Outlook – OCED 2017). Solar and wind are considered the most promising forms of renewable energy in ASEAN (Ismail et al., 2015; Singh and Banerjee, 2015). Overall, the shares of installed capacity for wind and solar, however, accounted for only 1% and 2%, respectively, of total existing renewable energy capacity by the end of 2016. The remainder, consisting of non-hydro renewable, accounts for a relatively limited percentage in total demand, less than 1% of TPES.

Comparing the installed capacity of all renewable energy types corresponding with their targets in each country shows the significant gaps between the expectation and reality of ASEAN renewable energy development (Table 1). Except for Malaysia, where the total renewable energy installed reaches 65% of its 2020 target (mostly coming from increasing hydro with 91%), the other countries are struggling in promoting renewable energy, especially Cambodia, Laos, and Myanmar.

*Table 1. Progress to renewable energy target of ASEAN countries in 2015. Source: (Khuong et al., 2019a)*

| | **Target year** | **Installed capacity target (MW)** | **Specialisation** | **Installed capacity 2015 (MW)** | **Progress to target 2015** | **Target for solar (MW)** | **Installed solar 2015 (MW)** | **Progress to target 2015** |
|---|---|---|---|---|---|---|---|---|
| **Brunei Darsm** | 2025 | 954 (GWh) | All | 2 GWh | 0.2% | - | 1 | - |
| **Cambodia** | 2020 | 2241 | Hydro | 931 | 41.5% | - | 12 | - |
| **Indonesia** | 2025 | 46307 | Exclude biomass | 6709 | 14.4% | 80 | 9 | 11.25% |
| **Lao PDR** | 2025 | 951 | Exclude large hydro | 31 | 3.2% | 33 | 1 | 3% |
| **Malaysia** | 2020 | 2080 | Solar, biomass, small hydro | 1360 | 65.3% | 4200 | 262 | 6% |
| **Myanmar** | 2030 | 2000 | Exclude hydro | 12 | 0.6% | - | 12 | - |
| **Philippines** | 2030 | 15304 | Geothermal, hydro, wind | 6260 | 40% | 350 | 132 | 37.7% |
| **Singapore** | 2020 | - | - | - | - | 350 | 60 | 17.1% |
| **Thailand** | 2036 | 19684 | Hydropower, biomass, solar, wind | 7432 | 37.7% | 2000* | 1425 | 72.6% |
| **Vietnam** | 2030 | 45800 | Total | 11956 | 26.1% | 6000** | 139** | 2.3% |

*Note: *: a target for 2020. **: target and installed capacity for both wind and solar*

Comparing solar and wind development with other types of renewables between 2015 and 2016 reveals strong growth in ASEAN. While hydropower increased the installed capacity by 939 MW, corresponding to a 3.8% annual growth rate, wind extended by 297 MW, equaling a 37% annual growth rate, and solar PV experienced a sharp increase by 1621 MW, amounting to a 88% annual growth rate. However, the progress towards national solar and wind targets seems to be slow. Except for Thailand, by the end of 2015, the total installed solar capacity arrived at 73% of the expected capacity in the 2020 target (Erdiwansyah et al., 2019a).

## 2.2.2 The effort to establish renewable energy policy in ASEAN

In recent years, ASEAN governments as a whole, as well as individual countries, have created many schemes based on their renewable energy development targets to develop renewable energy in the region. Table 2 provides an overview of renewable energy policy in ASEAN by the end of 2017.

The first five columns in Table 2 summarize the government policy. The national program indicates a promoting program for different renewable energy types, such as solar heat, solar power, wind, geothermal, and biofuel. Among ASEAN countries, Thailand is the only one having a supporting program for solar heat; the other countries instead focus on solar power, wind, and biofuels. With verified high geothermal potentials, Indonesia and the Philippines are the only countries with added programs for developing it.

*Table 2. Overview of renewable energy policy in ASEAN. Source: (Khuong et al., 2019a)*

| | Government policy | | | | | R&D 2013 £Million | Investment status | Integrated Governance Policy |
|---|---|---|---|---|---|---|---|---|
| Country | **National program** | **FiT** | **Subsidy and grants** | **Tax deduction** | **Specialisation** | | | |
| Brunei Darsm | - | - | - | - | - | - | Insignificant | - |
| Cambodia | - | - | X | - | Own PV, Rural, Off-grid | - | Insignificant | - |
| Indonesia | X | X | - | X | - | - | Increasing | - |
| Lao PDR | X | - | X | - | Small hydro | - | Insignificant | - |
| Malaysia | X | X | - | X | Solar, No wind | 28.3 | Increasing | X* |
| Myanmar | - | - | X | - | Off-grid, Rural | - | Insignificant | - |
| Philippines | X | X | X | X | - | 64.5 (ADB) | Decreasing | - |
| Singapore | X | - | X | - | Only solar | 329 | Increasing | - |
| Thailand | X | X | X | - | Bioenergy, Solar heating | 120 | Increasing | X |
| Vietnam | X | X | X | X | Rural | - | Decreasing | - |

*Note: *. The policy is being prepared for implementation.*

As leaders in the region for committed renewable energy, Indonesia has completed guidelines for biomass, biogas, small hydropower, and geothermal at the end of 2016, while Malaysia completed guidelines for small hydropower and solar implementation. The Philippines and Vietnam finalized their solar power guidelines in early 2017 (ACE, 2017; IEA, 2017; IRENA, 2018). Although each country has a different policy from each other, they still collaborate. One such joint effort was the common target and roadmap called Remap Options for a Clean, Sustainable and Prosperous Future, published in 2016 (IRENA and ASEAN Centre for Energy, 2016). This roadmap provided a breakdown of renewable energy potential by sector and source and established guidelines to achieve all targets.

Considering the investment in renewable in the seventh column, ASEAN mostly invests in renewable energy in the power sector (excluding large hydropower) with a minimal amount of over 2.6 billion USD in 2016, which equals to 1% of global and 2% of Asia-Pacific investment (BNEF, 2017). Investment in solar PV increased dramatically in Thailand, with 3.8 USD billion in 2015. Besides, the investment trend has significantly increased in Singapore and Indonesia but has decreased in the

Philippines, Malaysia, and Vietnam (IRENA, 2018). According to the IRENA report about Renewable Energy Market Analysis (IRENA 2018), ASEAN would need around 0.7 billion dollars in the incremental energy system to increase the renewable share from the current of 17% to the target of 23%, which is less expensive than the previous period.

The sixth column in Table 2 summarizes R&D funding in the region. The funding comes from national budgets and international banking budgets such as ADB – Asian Development Bank. Recently, Singapore is leading the R&D that focuses entirely on solar rooftop deployment, followed by Thailand and the Philippines. The last column specifies the integrated policy between government and governance in ASEAN. Thailand is the first country in ASEAN that implemented governance policies below the government one in 2013, following this is Malaysia with a policy pending approval. However, Thailand has struggled to ensure efficient and effective corporate governance and resolve any potential conflicts of authority at the ministerial and regulatory levels.

Combining the progress of renewable energy development in Table 1 and the relevant policy in Table 2 shows that renewable energy extension is closely linked to policy support. There are three different developing situations in the region. The first is the slow development of renewable energy in Brunei, Cambodia, Laos, and Myanmar. Secondly, countries with marginal investment and R&D like Vietnam can reach only 2.3% of their target. Thirdly, those that are more advanced in expanding renewable energy, such as Malaysia, the Philippines, Singapore, and Thailand, pay more attention to R&D and investment, and can, on average, reach the target of around 17% to 37%. The noteworthy progress of Thailand in terms of enhancing solar by fulfilling 72% of its 2020 target by the end of 2015 is shown in the last column of Table 1 and can be explained by Thai renewable energy policies. Thailand is the only country focusing on solar heating and urban areas to integrate government and governance policies.

## 2.3 Challenges: barriers to renewable energy development

In the context of large pressure on energy service demand and climate change concerns, governments and policymakers are increasingly promoting and disseminating renewable energy technologies. However, this effort has faced many technical, economic, institutional, and socio-cultural challenges. Moreover, policy barriers also hamper the fast development of renewable energy, e.g. the untransferable, insufficient government's regulations and policies, making renewable energy more expensive and less accessible. The main challenges are identified, such as the unrealizable governmental targets, the absence of national support policies, bureaucratic burdens, excess regulation, insufficient encouragements, and the lack of standards and certifications.

### 2.3.1 Lacking remedial measures to overcome technical barriers

Technical challenges (e.g. resource availability, technology and skill requirement design and operation and maintenance) have been widely reported as a critical challenge affecting renewable energy diffusion, especially decentralised renewables in Asian EMDCs (Sharvini et al., 2018; Yaqoot et al., 2016). To serve the rapid demand in Asian EMDCs, coal and other fossil fuels play a vital role due to its convenience to scale-up and to connect to the grid. Although decentralised renewable energy is modular and highly scalable, it got into the troubles of complicated land acquisition and insufficient transmission infrastructure (Boie et al., 2014). The integration of non-dispatchable renewables requires substantial changes in operations of the power system, e.g. a high percentage of responsive oil, gas, hydro supplies to the residual load levels, highly developed electricity markets with sophisticated and robust price signals for flexible capabilities and operation. However, these characteristics hardly hold for any developing countries (Raheem et al., 2016; Waseem and Hammad, 2015).

These problems are exacerbated due to the fact that Asian EMDCs (excluding China and India) can only passively access to renewable technologies. The renewable energy industry is now dominated by major Chinese, European, and US producers and therefore create great barriers for expertise in the developing industries to learn and then diffuse the knowledge to the local firms. Consequently, it limits developing countries to acquire and utilize such technologies for transiting their energy systems (Atuahene-Gima, 2012; Gallagher, 2006).

Remedial measures are needed to assist these countries to overcome technical barriers by establishing appropriate institutional set-ups for developing renewable energy and turning the energy market into the diffusion of decentralised renewable energy. Main remedial measures are identified as a more accurate resource assessment (Seetharaman et al., 2019; Yaqoot et al., 2016), diffusion assessment for even spatial development (Thormeyer et al., 2020), diffusion assessment for coordination and technology transfer (Aspeteg and Bergek, 2020).

### 2.3.2 Lacking affirmative actions to overcome economic barriers

Unlike consumers in developed countries, who can afford the upfront costs of decentralised renewable energy, most consumers in Asian EMDCs can hardly afford such an investment. Indeed, the investment for a decentralised renewable system, e.g. solar PV of 2-5 kWp is around 1300-4000 Euro, which is around half or even almost a year income of people in these countries. This financial issue hinders the spread of technology within national borders and constrains government's ability to motivate domestic resources necessary for spreading the technology (Byrnes et al., 2013; Lyu and Shi, 2018). Extra effort to stimulate private and public investments, reinvigorate technology adoptions and innovations and promote a growth-friendly macroeconomic and institutional environment need to be made (Carfora et al., 2019; IMF, 2018; Ito, 2017; World Bank Group, 2020). In effect, all sectors must engage in a low-carbon transition to achieve significant greenhouse gas emissions reductions at the national level (Richard, 2016).

However, literature shows that the dominating renewable energy model tends to focus on economic growth as precedence rather than people's wishes or welfare, and environmental processes and limits (Ahmad et al., 2020; Dagoumas and Koltsaklis, 2019; Deng and Lv, 2020). Some literature supported economic growth coming first in developing countries and concluded that investment in environmental protection should be left to a later stage of development, mostly accepting environmental degradation to meet immediate needs (Deng et al., 2011; Juutinen et al., 2019; Kumar et al., 2020; Zhang et al., 2020). This advice can keep renewable energy in the worst competitive position compared to fossil energy sources in accessing government funds.

In order to break the economic barriers of renewable energy diffusion, economic and financial policies and measures are needed (Sun and Nie, 2015). Shifting the incentive and motivating structure to the private sector is necessary. In this regard, governments can contribute as a problem-solver by using administratively set Feed-in tariffs (FIT) and auctions for renewable energy generators and establish financial institutions and soft loans for renewable energy projects (Zeng et al., 2018; Zhang et al., 2014).

To do these works, reforming the calculation of renewable energy potential and providing strong and realistic targets toward renewable energy development are needed at first. The new measure must be oriented to different country situations (Erdiwansyah et al., 2019a; Hopkins et al., 2020).

### 2.3.3 Insufficient policy framework hinders renewable energy development

Asian EMDCs, in general, and ASEAN, in particular, have too ambitious targets on renewable energy (IMF, 2018). Thus, it is challenging to translate these target into actions (Althor et al., 2016; Höhne et al., 2017; Rogelj et al., 2016). It is a result of lacking scientific support and consultants of clear insight and realistic development (Byrnes et al., 2013; Painuly, 2001; Yaqoot et al., 2016). Asian EMDCs' governments would have to invest a large amount of money to achieve their ambitious emission reductions and renewable energy targets (Hof et al., 2017). However, they have struggled in reality with the availability of funding, which has so far been dramatically insufficient. Most developing countries are vulnerable to the global financial system. While varied, they are generally less resilient and more susceptible to market volatility, often forced to pursue pro-cyclical macroeconomic policies, exacerbating economic instability and undermining long-term growth. As a result, there are fewer financial institutions that are providing loans and financing renewable energy projects (Lyu and Shi, 2018) .

Ambitious target-setting is a result of the dependence on generic rooftop PV assessments. These assessments often have a rather low accuracy, which could direct investors into suboptimal locations and configurations (Hofierka and Kaňuk, 2009; Hong et al., 2017). Consequently, the diffusion of PV power projects is spatially heterogeneous between the different regions in a country (Mansouri Kouhestani et al., 2019; Singh and Banerjee, 2015; Yan et al., 2019). If the development goes in one direction only, this could have a far-reaching impact on both grid and market congestion (Chaianong et al., 2019; Kappagantu and Daniel, 2018; Sweerts et al., 2019; Yan et al., 2019). To avoid this, policymakers urgently need a superior method to provide their market with transparent targets and stable policies so that the market will continue growing without threatening the stability of the national electricity systems.

Moreover, the governments are stuck in the old development paradigm, lack of information, and relevant data availability, limited capacity of policy and decision-makers were identified as reasons for the limited development of renewable energy (Sharvini et al., 2018). The energy industry in most developing countries has a small number of players. It is highly centralised. Such a monopoly system sometimes becomes unreceptive to distribute new technologies such as renewable energies. Modification of existing laws and regulations is needed in the very first place to introduce and promote renewable energy technologies, especially for integrating renewable energy into the power system (Browne et al., 2015; Sun and Nie, 2015). Strong regulatory policies within the energy industry are required to resolve the inconsistency between renewable and non-renewable energy (Zhang et al., 2014). Moreover, the absence of adequate financial incentives, such as FITs, results in high costs for investors that hinder renewable development (Sun and Nie, 2015).

Another major influence on renewable energy development is the lack of a multi-level integration between different disciplines (Geels, 2011). Lack of awareness of national intentions among subnational authorities, together with poor consultation in the process of policy creation among decision-makers both vertically and horizontally, leads to misunderstandings about local circumstances among national policymakers (Marquardt, 2017b). Lack of coordination between different authorities and administrative hurdles lead to an unnecessarily long delay of the project start-up period (Ahlborg and Hammar, 2014). Local authorities and cities are responsible for energy issues such as the provision of licenses and permits, project implementation, and renewable energy development and planning due to the process of rapid decentralisation (Marquardt, 2014). However, without local governments' support, specific renewable energy projects cannot be implemented, especially when it involves public land acquisition (Erdiwansyah et al., 2019b). Thus, at the national level, a multi-disciplinary approach to governance is needed rather than the persisting tendency for different line ministries, departments, and agencies to act without a clear framework for coordination across sectors.

Poor community involvement was noted as a final significant political barrier to achieving sustainable development goals (Byrnes et al., 2013). A top-down approach by centralised authorities often imposes projects and programs on local governments. Moreover, policy-making and implementation do not take into consideration the grassroots needs or involve the lower levels of government (e.g. state, city, or district governments).

Missing integration between government and governance policies is another problem. Because of the intimate relationship between renewable energy development and political support, adjusting renewable energy support mechanisms is crucial to help renewable energy development. Since renewable energy potential is differentiated by geographic location and terrain elevation, local governments with governance policy might play a more critical role in increasing renewables' uptake. They can provide a greater understanding of the current and future potential for different renewable technologies (e.g. heating, cooling, transport biofuels, etc.) based on their own demographic and economic characteristics. Because of the differentiation of socio-economic, cultural, and political situation, local policymakers can invest more wisely and precisely to enhance renewable energy deployment and identify possible benefits for local citizens and businesses (Chimres and Wongwises, 2016; Daniel M. Kammen and Deborah A. Sunter, 2016; Eskew et al., 2018).

Moreover, urban governance policy is either missing or weak in ASEAN as well as in other Asian EMDCs (Marquardt, 2014; Zhang et al., 2014). ASEAN governments released several incentives and policy initiatives at a national level, which mentioned the importance of city governments and governances in working together to support the implementation of renewable energy strategies, policies, and programs. In fact, 8 out of 10 countries in ASEAN have no governance policy, lack of awareness for political intentions among subnational authorities, weak capacity on the local level, and a lack of consultation during policy formulation (Marquardt, 2014). This lack of policy integration means that these types of complicated, interconnected issues cannot be appropriately addressed, and is resulting in ineffective and inefficient policy deployment (Runhaar, Driessen and Soer, 2009).

## 2.4 Extra pressure from demographic challenges?

Urbanisation in developing countries is decoupled from industrialisation, suggesting a different trajectory for increases in carbon emissions (Gollin et al., 2016). ASEAN, for example, has undergone greater levels of urbanisation. It will witness massive urbanisation in the next three decades. Around 70% of the population will be urbanized by 2050, making them the world's largest middle-income emerging markets after China and India, leading to enormous resource scarcity (UN, 2019). The unprecedented urban growth is expected to lead to a rapid rise of more than 200 smaller cities. Such an unprecedented rate of urbanisation poses serious pressure on energy consumption.

The relationship between energy consumption, economic, and demographic has been intensively researched in developed countries, e.g., EU (Kasman and Duman, 2015), United States (Elliott and Clement, 2014; Ewing and Rong, 2008), Canada (Isabelle Larivi`ere, 1999), and in China (Donglan et al., 2010; Jiang and Lin, 2012; Lin and Ouyang, 2014), and India (Ghosh and Kanjilal, 2014), etc. However, the studies proposed controversial results. Some revealed a positive correlation between urbanisation and energy use in developing countries (Jones, 2004, 1989; Parikh and Shukla, 1995; Poumanyvong et al., 2012), and in developed countries (Elliott and Clement, 2014; York, 2007). On the other hand, some studies identified a negative link between urbanisation and energy consumption, e.g., in developing countries (Li et al., 2011; Mishra et al., 2009), and developed countries (Isabelle Larivi`ere, 1999).

From a cursory look at ASEAN, energy consumption seems to increase faster in the country with a lower annual urban growth rate, except for the Philippines (Figure 5). It could mean urbanisation reduces energy consumption and therefore reduces its effects on the environment. Moreover, since urbanisation is the main factor driving renewable energy development in the region (Khuong et al. 2019), it may speed up the energy transition process towards higher shares of renewables in the total energy mix, and therefore help to reduce the effect of increasing energy consumption on the environment.

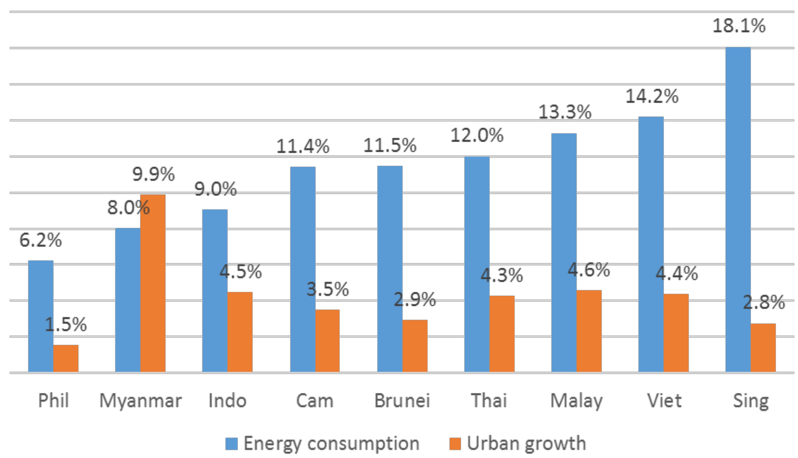



*Figure 5. Average annual energy consumption and urbanisation growths in ASEAN between 1995 & 2014 (own calculation based on the database of World Bank, 2018 and IEA, 2018, last accessed 01.12.2018)*

The two possible and contradictory effects of urbanisation on energy consumption reveal a problem lacking or incomplete knowledge on this issue that could impede ASEAN progress towards achieving their sustainable development goals (Global megatrends, AIMD, 2017). The controversial discussions about the resulting urbanisation effects in different sectoral and regional scales evoke criticism of further investigation for this issue. This requires a multi-disciplinary approach to decompose the aggregated effect of urbanisation into separated effects on sectors and sub-sectors and insight into cross-country variability of aggregated urbanisation growth. The measurements for the energy transition in EMDCs must be suitable in the countries' contexts.

## 2.5 How to deal with energy transition challenges?

The energy transition is critical to reducing greenhouse gas emissions and addressing climate emergencies. Household consumption accounts for approximately one-third of the end-use of electricity (IEA, 2019). Transiting this demand to renewable demand will transform the energy market and accelerate the transition to a clean economy. More demand for decentralised renewable power brings economies of scale and therefore, can make renewable power the cheaper option and a better choice than fossil fuels for the environment and energy service.

The ambition of renewable energy targets in Asian EMDC raises the bar for cooperation between the government and the public on renewable electricity. The government and governance cooperation need to set a transferable public goal to source their electricity consumption from renewable sources with specified support schemes, so the initiative increases corporate demand for – and in turn, supply of – renewable energy. To do so, they need:

- management tools to set target groups, highlight, and address policy and market barriers to corporate sourcing of renewable electricity
- research support to develop transferable, sufficient, and achievable renewable targets unified from state to local administrations. Thereby, the administrations can be enabled to communicate based on a shared vision and then corporate on promoting renewable electricity.
- a tool to measure the effects of changing policies on the renewable electricity market and then communicate the potential compelling business cases for renewables to household customers together with companies, utilities, market operators, policymakers, and other key influencers
- research on Social Acceptance and Willingness To Pay for renewable electricity to identify the motivation of consumer behaviour, highlight market diffusion and barriers to realising the business and economic benefits of renewable electricity.

In order to support governments in promoting renewable electricity, this thesis focuses on dealing with these questions. The research framework for each topic will be discussed in section 3. Detailed methods and results are presented in four articles in part B.

# 3. Research framework

The discussion on the research framework and gaps in this section is summarized from the four papers, which can be found in detail in Part B of this book. The primary objective here is to systematically organize the thesis and provide the framework on understanding factor analysis and techno-socio-economic models, which will be the two main streams of this book. Nonetheless, this section summarised the literature gaps, which consistently suggests that there is an under-investigation in multi-level comparisons, effective and low-cost measurements, as well as empirical customer behaviour research, particularly in ASEAN.

## 3.1 Factors driving long-term energy service demand developments

This section aims to review, summarize, and synthesize the arguments and ideas of previous research that focused on analyzing the relationship between urbanisation and energy consumption (see Table 3). After scrutinizing these studies, the author identified certain research areas that have been given little attention in this area. These areas are highlighted in blue in Table 3 to demonstrate the novelties of paper 1 and 2 of this thesis, and a detailed explanation is given in the following sections. The content

*Table 3. Summary of relevant literature on the relationship between urbanisation and energy consumption. Source: (Khuong et al., 2019b)*

| | **Research scope** | | | | | **Method** | | | **Considered relationships** | | | | | | **Results** | | **Purpose** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Author, year** | M | C | P | S | L | R | O | D | GDP | EC | Em | In | EI | Others | S | L | |
| **Parikh, Shukla 1995** | X | | | | | X | | | X | X | | | | | + | | Sus |
| **Imai 1997** | X | | | | | X | | | X | X | | | | | + | | |
| **York 2007** | X | | | | | X | | | X | X | | | | | + | + | ED |
| **Lenzen et al. 2006** | X | | | | | X | | | X | X | | | | | -/+ | | Sus |
| **Fang et al. 2012** | X | | | | | X | | | X | X | | | | | - | | CC |
| **Liddle, Lung 2014** | X | | | | | X | | | X | X | | | | | - | | Sus |
| **Jones 1989** | X | | | | | X | | | X | X | X | | | | + | | Eco |
| **Poumanyvong, Kaneko 2010** | X | | | | | X | | | X | X | X | | | | | +/- | Sus |
| **Sharif Hossain 2011** | X | | | | | X | | | X | X | X | | | | | + | Eco |
| **Poumanyvong et al. 2012** | X | | | | | X | | | X | X | X | | | | | + | Eco |
| **Al-mulali et al. 2013** | X | | | | | X | | | | X | X | | | | + | | Sus |
| **Sadorsky 2013** | X | | | | | X | | | X | | | X | X | | | -/+ | CC |
| **Li, Lin 2015** | X | | | | | X | | | X | X | X | X | | X | -/+ | | Eco |
| **Asif et al. 2015** | X | | | | | X | X | | X | X | | X | | | | + | Eco |
| **Burney 1995** | X | | | | | | X | | X | X | | | | | + | | Eco |
| **Mishra et al. 2009** | X | | | | | | X | | X | X | | | | | - | + | Eco |
| **Wang 2015** | X | | | | | X | | | | X | X | | | | | + | Sus |
| **Zhang et al. 2017** | X | | | | | X | | | X | X | X | | | X | | | RE |
| **Jones 1991** | | X | | | | X | | | X | | | X | X | | + | | ED |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Lin et al. 2008** | | X | | | | X | | | X | | | | | X | | + | CC |
| **Liu 2009** | | X | | | | X | | X | X | X | | | | X | + | ~ | ED |
| **Ghosh, Kanjilal 2014** | | X | | | | X | | | X | X | | | | | | ~ | Sus |
| **Belloumi, Alshehry 2016** | | X | | | | X | X | | X | | | X | X | | + | + | ED |
| **Wei et al. 2003** | | X | | | | | X | | X | X | | | | X | -/+ | | Eco |
| **Li et al. 2011** | | X | | | | | X | | X | X | | | | X | -/+ | | ED |
| **O'Neill et al. 2012** | | X | | | | | X | | X | X | X | | | | | ~ | ED |
| **Yang et al. 2015** | | X | | | | | | X | X | X | | | | X | | -/+ | RE |
| **Franco 2017** | | X | | | | X | | | | X | X | | X | | | + | Sus |
| **Newman, Kenworthy 1998** | | | X | | | X | | | X | X | | | | | - | | Sus |
| **Wang 2014** | | | X | | | | | X | X | X | | | | X | | -/+ | ED |
| **Kenworthy, Laube 1996** | | | | X | | X | | | X | X | | | | | - | | Sus |
| **Isabelle Larivi'ere 1999** | | | | X | | X | | | X | X | | | | | - | | ED |
| **Jiang, O'Neill 2007** | | | | X | | X | | | X | X | | | | | | | ED |
| **Ewing, Rong 2008** | | | | X | | X | | | X | X | | | | | - | | ED |
| **Adom et al. 2012** | | | | X | | X | | | X | X | | | | | + | | ED |
| **Li, Yao 2009** | | | | X | | X | | | | X | | | | X | | | ED |
| **Sun et al. 2014** | | | | X | | X | | | | X | | | | X | | + | ED |
| **Holtedahl, Joutz 2004** | | | | X | | X | X | | X | X | | | | | + | + | ED |
| **Halicioglu 2007** | | | | X | | X | X | | X | X | | | | X | | + | ED |
| **Shahbaz, Lean 2012** | | | | X | | X | X | | X | X | | X | | X | | + | ED |
| **Shen et al. 2005** | | | | X | | | X | | | X | | | | | + | | Eco |
| **Jiang, Lin 2012** | | | | X | | | X | | | X | | X | | | | + | Eco |
| **Fan et al. 2017** | | | | X | | | | X | X | X | | | X | | | + | ED |
| **Liu et al. 2018** | | | | X | | | | X | X | X | | | | | | + | ED |

*Acronyms:*
*Scope: M: Multi-country, C: Country, P: Province, S: Sector, L: Linking between multi-country and country and sector levels.*
*Method: R: Regression, O: Other methods, D: Decomposition*
*Considered relationship: GDP: gross domestic product, EC: energy consumption, Em: emission, In: industrialisation, EI: energy intensity*
*Results: S: short term, L: long term, +: Positive effect, -: negative effect*
*Purpose: ED: energy demand, Eco: Economic development, Sus: sustainable development, CC: climate change. Blue column: covered by this research*

## 3.1.1 Gaps in long-term factor analysis

Issue 1 – Lacking multi-level comparisons in the research scope

As shown in the first column of Table 3, previous research mostly focused on proving and comparing the effects of urbanisation on energy consumption between countries with similar economic conditions, such as in developed (Parikh, Shukla 1995; Liddle, Lung 2014; York 2007) and developing countries (Jones 1989, 1991; Madlener, Sunak 2011; Mishra et al. 2009; LENZEN et al. 2006). Alternatively, they investigated the relationship in one country within different energy-consuming sectors, such as Larivi'ere (1999) in Canada, Wei et al. (2003) in China, Halicioglu (2007) in Turkey, Ewing & Rong (2008) in the US. Some researchers investigated the effect between different countries for one sector such as transportation, agriculture (Jones 1991; Liddle, Lung 2014; Poumanyvong, Kaneko 2010), building energy consumption (Li, Yao 2009), and national residential energy use (Holtedahl, Joutz 2004; Poumanyvong et al. 2012b).

However, the comparison of relative impacts of urbanisation between sector-sector and sector-country has not been carried out in general, as well as specifically for ASEAN. Energy service demand configuration consists of micro-level radical innovation, the regime and the landscape of the configuration (Iizuka, 2015). The regime is the dominant system, which entails a broader configuration of actors that contribute to stabilizing a certain technological trajectory. The landscape is an exogenous environment, such as global macroeconomic conditions, deep cultural patterns, and macro-political developments whose speed of change is usually slow. The lacking of multi-level comparisons causes insufficient coherence and multidimensional landscape design. The final landscape, therefore, can be orientated by local and group interests.

Issue 2 – Regression limitations in providing a multi-level comparison

The regression analysis with dynamic and statistical models was used in most studies in this field, accounting for 34 out of 45 studies. However, this method can reveal general relationships but not individual factor contributions (Liu 2009). Liu (2009) concluded that using regression showed only unidirectional Granger causality between China's urbanisation and its total energy consumption, but in order to find out the contribution share of urbanisation on energy consumption required a decomposition analysis.

Moreover, regression requires large data sets, which are quite challenging to obtain for developing countries (Zeng Shihong 2017), like ASEAN, where the database has only been developed over the last 15 years or so. Moreover, regression models using cross-sectional data (Jones 1991; York 2007; York et al. 2003) as well as time-series data (Liu 2009; Holtedahl, Joutz 2004), and even panel data (Poumanyvong et al. 2012b) typically overlook the comparison with the base year, i.e., using data with current currency instead of constant currency (purchasing power parity, PPP). Liu (2009), York (2007) and Zeng Shihong (2017) claimed the method runs into difficulties when dealing with unbalanced data (i.e., a panel that has some missing data for at least one year or one period, or for at least one entity), and nonlinear data in explaining the relationship and the changes.

Furthermore, when analyzing individual sectors or whole countries, many approaches overlook the volatility and interactions among types of energy users. The combined resource requirements of energy input in manufacturing and transportation activities, for example, may increase energy consumption but reduce energy utilisation in residential areas. This offsetting impact could eliminate energy consumption fluctuations, i.e., it could erroneously imply unchanged or only slightly changed total energy consumption. If only the total energy consumption is considered, the regression typically overlooks the hidden effect from this phenomenon, such as inefficient energy use and issues relating to the energy system and the economic structure.

Issue 3 - Partly conflicting results

The results for multi-country assessment often present opposing effects (see Table 1). Two-thirds of the reviewed studies revealed a positive correlation between urbanisation and energy consumption in multi-country approaches as well as in sectoral-level research. On the other hand, some studies identified a negative link between urbanisation and energy consumption at the country level.

At the sector level, while some authors mention that urbanisation causes several significant reductions in residential energy use (e.g., Ewing, Rong (2008) researching in the US and Wang (2014) studying China), others (like Holtedahl, Joutz, 2004) conclude that urbanisation is responsible for energy use increasing in this sector. The same contradictory findings were obtained for the transportation sector between Liddle & Lung (2014), who showed a negative effect in 23 OECD countries, and Poumanyvong et al. (2012a), who found a positive influence of urbanisation in 92 countries.

The controversy in earlier literature can be at least partly ascribed to differences in methodologies, data, and economic and/or regional characteristics. Therefore, it is necessary to investigate further the relationship between urbanisation, energy use, and other factors (such as GDP, industrialisation, emissions) by placing it within a region-country-sector context.

Issue 4 – Unclear urbanisation definition

One of the common issues encountered in the research is the different kinds of "urbanisation". Most of the previous studies (Jones 1991, 1989, 2004; Parikh, Shukla 1995) considered the variable "urbanisation" as the number of people living in urban areas. The term "urbanisation growth rate" is used to refer to the growth rate of the urban population in each considered period. Urban areas are categorized by urban morphology such as cities, towns, conurbations, or suburbs.

Other authors (Ewing, Rong, 2008) used several forms of urbanisation when investigating urban effects on energy use, including the percentage of the population living in urban areas, the population density in urban areas, and the average apartment size, which more accurately reflects the specific energy consumption in the residential and commercial sectors (Liddle, Lung 2014; Liu, Xie 2013). In researching the residential sector, Pachauri and Jiang (2008) compared India and China and used the number of households as an urbanisation indicator.

The influence of urbanisation on energy consumption changes based on the urbanisation form considered. Therefore, this thesis used the most common urban indicators in the research field, namely urban population, symbolized as Urban 1, and non-agriculture employee, symbolized as Urban 2, to conduct the investigation.

### 3.1.2 The solution: combining decomposition and correlation analyses

In investigating impact factors on energy consumption, while regression methods pose limitations in multi-tiered analysis, the decomposition method has proved to be an effective and powerful tool to explain the changes and impacts that occur in variables over time and/or space. In particular, decomposition approach analyzes multi-level data and assesses the effect of different factors on different energy users without requiring the equivalent of evaluated factors in different fields (Hoekstra and van den Bergh, 2003; Zhang and Ang, 2001). For example, the diverse factors affecting energy consumption in the industry, such as income, industrial structure, and transportation, for instance, freight and passengers, can be used in decomposition analysis to compare energy intensity in each sector (Lin et al. 2008; Liu 2009).

The decomposition analysis has frequently been utilized in energy-related studies from the late 1970s until the present to analyze the impact of product mix changes on energy consumption (Ang, Zhang 2000; Hoekstra, van den Bergh 2003). It was introduced with two techniques for decomposing indicator changes, structural decomposition analysis (SDA), which analyzes the input-output effect, and the index decomposition approach (IDA), which compares different effect factors. In assessing urbanisation's influence on energy consumption, Liu (2009) suggested the decomposition method as a new approach.

Using SDA, Wang (2014) and Liu et al. (2018) investigate the effects of China's urbanisation on residential energy consumption. Wang (2014) conducted independent research on household usage and product usage by dividing total energy consumption into residential energy consumption (REC) and production energy consumption (PEC). Liu et al. (2018) analyzed the changes in indirect (IEC) and direct (DEC) energy consumption in households. Both studies suggested that urbanisation has a positive effect on household energy consumption. However, the method can hardly be applied in Asian EMDCs due to the insufficient annual input-output data for different sectors.

Approaching with IDA, Yang et al. (2016) and Fan et al. (2017) assess the impact of urbanisation on renewable energy consumption growth and residential energy consumption in China. Yang et al. (2016) focused on the macro analysis to analyze five effects: energy mix, energy intensity, economic structure, GDP, and urbanisation effects. Comparing urban with other effects on total energy consumption and renewable energy consumption was expressed as weighted averages of effect shares and renewable energy change relatives. He concluded that the urbanisation effect is insignificant for renewable energy use. Meanwhile, Fan et al. (2017) focus on household consumers, concluding that urbanisation contributes to about 15.4% of the residential energy consumption. However, the calculation only focuses on the macro view and compared urban effects between the growth of total energy consumption and the growth of renewable energy by adding the energy mix effect, reflecting the changes in the ratio of renewable energy consumption to total energy consumption.

In order to investigate the contribution of urbanisation to energy consumption growth with a multi-disciplinary analysis, decomposition analysis needs improvement to become a sufficient tool, which has stronger comparability to explore the diverging influences from nations to sectors. The improvement idea in this thesis is to combine regression with decomposition analyses.

Few previous studies came up with the idea of combined decomposition and regression analyses in the energy literature such as Zhang and Jiang (2016); Shakouri and Khoshnevis Yazdi (2017); Karimu et al. (2017); Nicholas Apergis and Dan Constantin Danuletiu; Saad and Taleb (2017); Metcalf, (2008); Mulder and de Groot, (2012); Sue Wing, (2008). However, the studies mostly focused on energy efficiency advice. For example, Metcalf (2008) and Sue Wing (2008) only focused on energy intensity determinants and trend analysis, respectively, whereas Mulder and de Groot (2012) focused on trend and energy convergence of similar sectors across countries.

The idea of combining the two techniques allows taking advantage of both decomposition and correlation methods in measuring the impact of different influencing factors on energy consumption and renewable energy developments. It will disentangle the contributions by comparing them in a multi-level, regional-country-sectorial analysis to identify the main driving factors for energy consumption and renewable energy developments. The results can be used to determine key target groups and specific incentives to policymakers.

## 3.2 Techno-Socio-Economic Rooftop PV assessment

The rooftop solar PV system is a PV system in which electricity-generating solar panels are mounted on a residential or commercial building or structure rooftop. With the ever-increasing population and difficulties for large-scale solar power plant installation, interest in rooftop solar is increasing (Choi et al., 2019). The exploitation potential of a renewable energy resource for a site or area needs to be addressed (Anwarzai and Nagasaka, 2017; Bódis et al., 2019). Techno-economic assessment needs to be investigated with considering different technical characteristics of the solar PV system (e.g., module efficiency, inverter capacity, and system design), system technical performance, sustainability criteria if applicable, and costs associated with technical potential. Moreover, Social Acceptance (SA) and Willingness To Pay (WTP) need to be discovered in order to understand public opinions about rooftop PV.

### 3.2.1 Impediments to precise techno-economic methods in EMDCs

Issue 1 – Financial issue for renewable energy R&D in EMDCs.

EMDCs find themselves at a crossroads when it comes to investments in the clean technology sector, which is always combined with capital intensity and new technologies that the countries lack (Donastorg et al., 2017). The six key challenges hindering the success of renewable energy entrepreneurs in the world’s developing regions are inadequate access to institutional finance, the price of renewable energy technologies (RETs), the lack of skilled labour, underdeveloped physical infrastructure and logistics, power/dominance of incumbents, and inadequate government or policy support (Gabriel, 2016).

The financial development, especially the capital market and foreign investment, is the most critical factor in renewable energy development in EMDCS. For example, it contributes to an overall of 42% of the variation of renewable energy growth in China (Ji and Zhang, 2019). Unfavourable financing terms, specifically the high cost of debt in EMDCs, are expected to increase RE costs, for example, by 24-32% in India compared to the US (Nelson and Pierpont, 2013). While the portion of debt ranges around 70–90% in developed economies, renewable energy projects in EMDCs would require higher equity injection (30–40%) due to the inability to raise sufficient debt (UNEP, 2007). This debt creates pressure for policymakers and renewable energy investors in the EMDCs to raise higher equity contributions, and their inability to do so usually leads to the failure of those renewable energy projects to reach financial closure (UNEP, 2005, Glemarec, 2011, Nelson and Pierpont, 2013).

Despite ambitious targets in the EMDCs, especially in ASEAN, their results showcase a significant lack of investment in the renewable energy sector, constraining the region's ability to meet its renewable energy target (discussed in Section 2.1). The financing gap in the EMDCs in Asia is largely due to the lack of economic diversity and the immature capital market (Ng and Tao, 2016). Due to the heterogeneous nature of the EMDCs in Asia, different economies can deal with this difficulty differently. Advanced economies such as Singapore can promote the use of innovative financial instruments such as green bonds. Rising emerging markets such as Indonesia, Thailand, Malaysia, and the Philippines are already introducing various favourable RE policies, need to focus on building fixed financial markets. Lastly, newly emerging economies, such as Cambodia and Vietnam, should reduce financial barriers towards renewable energy projects (Ng and Tao, 2016).

However, one of the biggest challenges for the new financial trend in developing countries is the perceived risk due to the inaccurate and sometimes misleading knowledge regarding the cost and power generation of renewable energy (Donastorg et al., 2017). Leading causes for that are the lack of transparency in the government and the methodology along with the lack of reliable data, resources, and assumptions used to make cost calculations (Barroco and Herrera, 2019; Ohunakin et al., 2014; Painuly, 2001; Seetharaman et al., 2019; Yaqoot et al., 2016). It is crucial to identify, assess, and address renewable energy potential with highly accurate results to strengthen and empower institutions.

Issue 2 - The lack of renewable energy research in EMDCs excluded China and India

Scholars from developed economies currently dominate renewable energy researches (Aleixandre-Tudó et al., 2019; Zhang et al., 2019). Among 12,167 renewable energy papers from 2007 to 2016, mostly focus on wind, solar, and ocean energies, research on developed countries, leading by the United States (2,320 articles), the United Kingdom (1007 articles), Germany (730 articles) and Spain (729 articles) (Aleixandre-Tudó et al., 2019). In the developing world, researches are concentrated in China and India (Aleixandre-Tudó et al., 2019). More studies on renewable energy issues from developing countries' perspectives would help regulators and policymakers align different policy goals and develop well-defined policy objectives. With clear information advantages, scholars from developing countries will be given more chances, and more international collaboration between developing and developed countries are expected (Zhang et al., 2019).

Results show that project finance incidence is higher for baseload, high-capacity utilisation, non-intermittent technologies, non-FiT projects with revenue contracts, and larger projects owned by public companies. Contrary to expectations, project finance was less utilized for FiT-eligible renewable energy and projects owned by private or small investors. Project finance was utilized primarily by well-capitalized investors, and mostly by power and financial companies. The Philippine FiT's tight deadlines and low technology-specific capacity caps increased revenue uncertainty, resulting in a high concentration of project ownership and potential public support erosion (Barroco and Herrera, 2019). Given the intrinsic uncertainty of renewable energy and developing countries, policymakers need to design policies to minimize revenue uncertainty, enable project finance, and broaden the investor base.

Furthermore, despite the advances of PV assessment methods, a lack of information regarding the feasibility of solar power systems among installers and consumers, financial groups that hinder large installations, policymakers who enable the deployment of technology, and even scientists and engineers from other complementary disciplines, has become a formidable barrier to their extensive penetration (Balta-Ozkan et al., 2015; Elshurafa et al., 2018; Seetharaman et al., 2019). Nonetheless, a gap is still present between the solar estimations generated by researchers and their practical use in the PV energy system and policy designs, and management works by engineers, designers, and planners. Consequently, greater efforts are required to minimize this gap by maximizing the applicability and practicality of future modelling and assessment results. All the solar energy potential and economic and environmental aspects are associated with the geospatial context. Therefore, it is necessary to conduct convergence research to develop a couple of geographic, technology, and economic potential analyses with policy design.

Issue 3 – Asian EMDCs depending on the poor quality of the low-budget methodology

The high-resolution PV potential assessments have been the most favourite method to estimate PV potential around the world. It uses advanced and accurate technologies such as 3-D models to calculate geometry, insolation, and shading of buildings (Calcabrini et al., 2019; Desthieux et al., 2018; Ha T. Nguyen and Joshua M. Pearce, 2013; Hong et al., 2017; Redweik et al., 2013). Even though the methods are more precise than the formers, the main barrier to employing them at national and international scales is the associated challenge of an exponentially increasing number of uncertain parameters with increased sample size or studied space. Solving this difficulty requires computationally intensive models and expensive data collection (Mainzer et al., 2014), especially for 3D models (Calcabrini et al., 2019; Desthieux et al., 2018; Redweik et al., 2013) or solar detective models (Mainzer et al., 2017). Therefore, these methods are not currently economically viable for developing countries (Bódis et al., 2019; Castellanos et al., 2017).

National and local governments in EMDCs are dependent on generic rooftop PV assessments. These assessments often have a rather low accuracy, which could direct investors into suboptimal locations and configurations (Hofierka and Kaňuk, 2009; Hong et al., 2017). Low-level resolution assessment is usually top-down methods based on statistical data, e.g., population density as a proxy for building/rooftop area (Freitas et al., 2015; IEA, 2016), which is supposed to be homogeneous throughout the investigated area (Byrne et al., 2015; Castellanos et al., 2017; Polo et al., 2015). It can be employed on a large scale, e.g., many cities all around the world, based on the correlation between solar insolation and population density. As a result, the diffusion of PV power projects is spatially heterogeneous between the different regions in a country (Mansouri Kouhestani et al., 2019; Singh and Banerjee, 2015; Yan et al., 2019).

Due to the uneven distribution of population and buildings between different areas, this type of assessment provides poor quality and inaccurate results due to the general assumptions. If the development goes in one direction only, this could have a far-reaching impact on both grid and market congestion (Chaianong et al., 2019; Kappagantu and Daniel, 2018; Sweerts et al., 2019; Yan et al., 2019). To avoid this, policymakers urgently need a superior method to provide their market with transparent targets and stable policies so that the market will continue growing without threatening the stability of the national electricity systems.

### 3.2.2 The limitations of current medium resolution methods

The medium-level resolution methods include approaches that combine aggregated statistical data with spatial information derived from geographic information system (GIS) and light detection and ranging (LiDAR) methods. A GIS can be utilized for PV potential assessment, produce a database, provide visualisation, and estimate physical potential, and geographic potential. Specifically, the SolarGIS method is based on using statistically aggregated solar and temperature data stored in the database with a time step of 15 min. It provides meteorological and geographical data as inputs to assess power generation from PV systems (Tarigan et al., 2014).

While GIS is useful for database and visualisation, it shows its limitation in other applications, e.g., rooftop extraction, radiation modelling, shading analysis, and spatial analysis tools, due to the unavailable data in many regions (Choi et al., 2019). For example, GIS has been utilized to extract rooftops (i.e., building orientation, shading effect, and other roof uses) from Google Earth satellite imagery using a feature extraction tool of ENVI EX software employing object-based image recognition. Global horizontal irradiance and direct normal irradiance maps can be derived from the Meteosat Indian Ocean Data Coverage satellite imagery based on the Heliosat method (Polo et al., 2015). Subsequently, the solar potential was assessed by performing simple simulations. GIS was used to combine the solar potential with the land availability determined based on the slope conditions and to map the technical solar potential. However, results require further analyses considering solar panel tilt and azimuth angles (Khan and Arsalan, 2016) and detailed sensitivity analyses (Izquierdo et al., 2011).

Light detection and ranging (LIDAR) is a ranging method based on laser technology. These units typically involve a laser with an oscillating mirror that enables the unit to conduct ranging in 2D space. 3D laser scanning can be achieved with a multiaxis unit. It can be performed automatically over specific cities or districts in high accuracy by considering surfaces' topographies, long-term direct and diffuse irradiance measurements, and shadowing influences. However, it fails to apply in larger scales, e.g., regional and national scales (Lingfors et al., 2018; Suomalainen et al., 2017). It also shows the limitation in providing any insights into the production of electrical energy by a specific PV system (Lukač et al., 2014; M. Martín et al., 2015).

Moreover, the computation of shadowing and roof brightness remains an open issue, requiring a completely 3D city model. The error of the results due to the insufficient quality building image extraction is obvious (Bergamasco and Asinari 2011). The building-related datasets, e.g., the total floor area, assumptions on the different types of buildings, and the associated number of floors, are required to estimate the total roof area available. Most data is recorded related to a suitable area in a single building/house for installing PV systems. Non-suitable areas are the distance between the rooftop access-maintenance space and the area covered by equipment such as water tanks, water meters, etc. Building roof availability is usually based on assumptions, e.g., 40% (Defaix et al., 2012) or 50% (Kabir et al., 2010; Khan and Arsalan, 2016) for all types of consumers. It is sometimes distinguished between residential and commercial buildings, at 39% and 60%, respectively (Byrne et al., 2015). Although previous works used annual data and average daily solar radiation data with limited accuracy (Ko et al., 2015) and assumption of building roof availability (Jamal et al., 2014; Kabir et al., 2010), no sensitivity analyses have been carried out.

Medium resolution methodologies that can cover a large number of cities at medium or high resolution are noticeably lacking due to the technical and data barriers (Bódis et al., 2019; Castellanos et al., 2017; Izquierdo et al., 2010). Because they are faced with the uncertainty caused by using a large number of assumptions due to data deficiency (Bódis et al., 2019), their outputs tend to vary widely from 16% to 207% compared to other resolution assessments over the same geographies (Hofierka and Kaňuk, 2009; Hong et al., 2017). Large discrepancies in the estimation of rooftop PV potential occurred when comparing high-level and low-level approaches, irrespective of the number of cities covered. The existing medium resolution rooftop PV assessments may be too inaccurate to be widely used for tailored policy designs (Castellanos et al., 2017).

Current studies focus on a small scale and are difficult to upscale. To conquer the uncertain and applicable issues, studies in this field usually focus on developing high-level assessments on a small scale, e.g., for buildings (Calcabrini et al., 2019; Ha T. Nguyen and Joshua M. Pearce, 2013; Kodysh et al., 2013) or district(s) (Hong et al., 2017) to avoid inaccurate results. At this scale, the scholars can use high-resolution LiDAR data in order to create solar radiation maps and estimate the solar potential of buildings individually. A precise calculation method of PV system yields in complex urban environments can be developed thanks to the advantage of small scales (Calcabrini et al., 2019). Other scholars used advanced and accurate technologies such as 3D models to calculate geometry, insolation, and shading of buildings (Calcabrini et al., 2019; Desthieux et al., 2018; Ha T. Nguyen and Joshua M. Pearce, 2013; Hong et al., 2017; Redweik et al., 2013). In order to inspect the potential of building an integrated PV system for a building, previous studies must combine different models, e.g., a digital surface model (DSM) or digital elevation model (DEM) with GIS or LIDAR to simulate vertical facades of buildings. However, since these methods require high-quality data and technical complications, they are difficult to be scaled up to the national assessment, especially in EMDCs, where unavailable data is the main issue (Calcabrini et al., 2019).

When studying a larger scale, e.g., at city-level or multi-cities level, researchers are limited to estimating only the geographic potential based on different assumptions such as roof area available (Byrne et al., 2015; Defaix et al., 2012; Jamal et al., 2014; Kabir et al., 2010), land use data (Byrne et al., 2015; Singh and Banerjee, 2015), and type of building (Byrne et al., 2015). Some studies investigate the technical potential (Hong et al., 2014; Margolis et al., 2017; National Renewable Energy Laboratory, 2016), but detailed uncertainty analyses to measure the error are not covered. Many literature works investigate rooftop PV potential at a city-level scale using spatial information and solar radiation data (Hong et al., 2017; Khan and Arsalan, 2016; Ko et al., 2015). The sampling-based analysis adopted average solar radiation data over the analyzed district, normalized in monthly values, were used to calculate the total available rooftop area through extrapolation (Khan and Arsalan, 2016). High-granularity land use, solar irradiance, temperature data, and various types of solar PV modules were also used to estimate PV potential (Singh and Banerjee, 2015). The high-resolution digital orthophotos to estimate rooftop areas for solar potential calculation (Bergamasco and Asinari, 2011; Wiginton et al., 2010) can be used, but again it faces cost and data obstacles in EMDCs.

### 3.2.3 Socio-economic potential assessment: Social Acceptance and Willingness To Pay

The use of renewable energy is essential in order to meet future energy-related challenges. To achieve this, awareness of renewable energy technologies is crucial to increase public acceptance of these clean energy resources (Sütterlin and Siegrist, 2017; Tsagarakis et al., 2018). With the increase in public awareness of clean environment (Lucas et al., 2018; Trop and Goricanec, 2016), renewable energy, especially solar and wind, are utilized to replace fossil fuels and combat energy crises (Adenle, 2020; Aramesh et al., 2019; Ludin et al., 2018; Raheem et al., 2016). In order to promote renewable energy use, especially in households, policymakers need to explore public opinion toward renewable energy to create a solid and sustainable development plan for renewable energy due to the crucial influence of public acceptance on policy creation and successful implementation (Bhowmik et al., 2017; Richard, 2016).

While techno-economic research has focused on technical, policy, and financial challenges to renewable energy deployment (Sovacool, 2014), less attention has been paid to its social dimensions, yet public opinion is highly relevant (Schumacher et al., 2019). To boost the acceptance of renewable energy and to avoid the critical problem of global warming (due to the energy provided by fossil fuels), analysis of public opinions towards renewable energy is vital (Kapoor and Dwivedi, 2020; Liebe et al., 2011; Moore, 2014; Schumacher et al., 2019). The public opinion can be recorded and analyzed using survey studies and conjoint analysis techniques in order to determine the present and future intentions of users related to renewable energy and explore new insights (Liu and Zhang, 2012; Qazi et al., 2017).

There are many influences on purchasing behaviour, including social (culture, sub-culture, social class, reference groups, and family), technological, political, economic, and personal factors (motivation, personality, self-image, perception, learning, beliefs, and attitudes). Customer behaviour toward purchasing a good is measured by a two-stage decision process, including "Social Acceptance" (SA) to support the innovation, and the "Amount of Willingness To Pay" (WTP) (see Figure 6) (Liebe et al., 2011). While economists rely on the concept of preferences in order to determine what people value and identify the "Amount of WTP", psychologists and sociologists have a strong affinity to the attitude concept and determine the "Acceptance". The main difference between the two concepts is that preferences pertain to choices between alternatives, whereas attitudes focus on “the desirability of a single action or object” (Liebe et al., 2011).

The residential PV technology is considered as a discontinuous innovation, which is disruptive, forcing a change in business and people's behaviour (Moore, 1999). Therefore, it is necessary to investigate customer behaviour towards this technology to understand the process of developing interested in accepting, selecting, and purchasing such a product (Sovacool, 2014). In this regard, policymakers can explore public opinion towards this product to create a solid and sustainable development plan for residential PV adoption (Bhowmik et al., 2017; Richard, 2016). Yet, although the research field is growing in terms of explorative studies (Axsen and Kurani, 2012; Bashiri and Alizadeh, 2018; Hille et al., 2018; Korcaj et al., 2015; Rai et al., 2016; Scarpa and Willis, 2010; Wolske et al., 2017), its merits for understanding and predicting individual adoption of residential PV is limited, as outlined in the following sections (Geels et al., 2018; Lin and Huang, 2012; Peattie, 2010).

It is important to consider both SA and WTP. SA research focuses on understanding the complex, multi-level, and polycentric process of transforming socio-technical systems, while WTP estimation presents a proxy attitude and focuses on the public trade-off point. Literature confuses these two definitions, such as claiming WTP to be a reflection of Social Acceptance. The confusion needs to be uncovered (Wolsink, 2018). SA is a multi-dimensional conceptual model, which covers social responsibility in government and law. SA informs business and policy through social and commercial marketing. However, WTP does not reflect any acceptance process, such as the recognition of consumers or the engagement of citizens in the process of establishing renewable energy infrastructure. Whereas WTP studies are of limited value for evaluating Social Acceptance, the method can reflect market acceptance in real-life decisions with individual cost-benefit assessments. Considering both social and market acceptance forms the distinguish contrast aspects of acceptance involving different actors. This approach emphasises upon each dimension inter-relates across different segments.

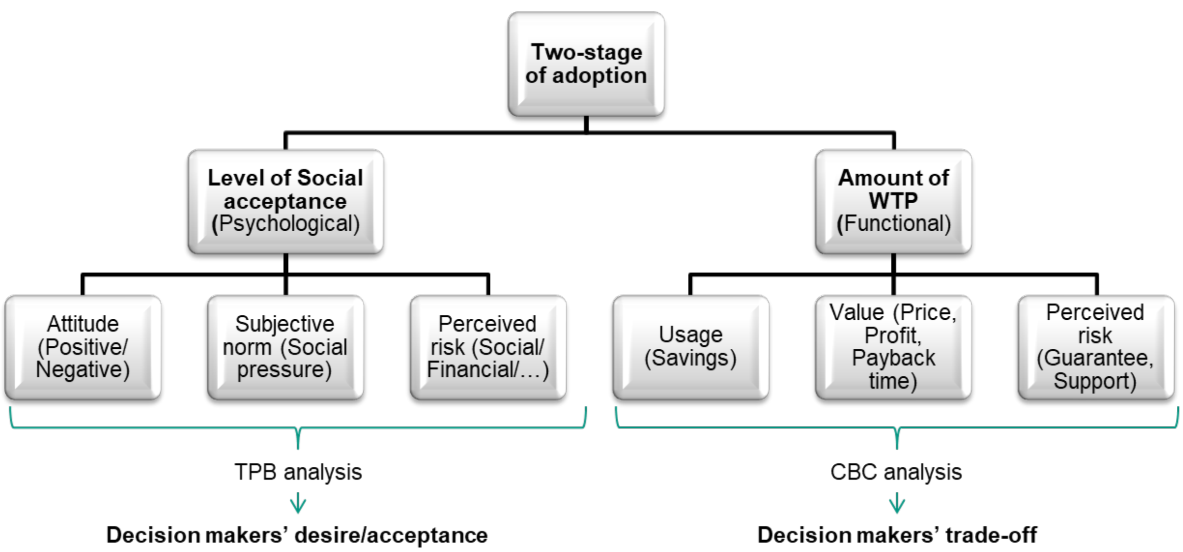



*Figure 6. Two-stages of adoption behaviour (Ajzen, 1991; Ram and Sheth, 1989)*

As outlined in Figure 6, a distinction between SA and WTP concepts needs to be made. SA and WTP are the two stages of the decision process when measuring customer behaviour towards purchasing a good. While economists measure decision marker's trade-off with determinants, such as usage, value and perceived risk, based on monetary measurement, psychologists and sociologists use determinants, such as attitude, subjective norm, and perceived risk, based on customers' satisfaction. SA is a personal intention towards technology, and various factors influence it. A consumer may have a very favourable attitude toward a product, but not towards the act of purchasing it. However, if a person buys the product but does not accept it, it is unlikely that full adoption will occur. In order to cover this situation, a necessary amendment needs to be made when selecting measurement approaches. There are other stages beyond simple WTP, and this is where acceptance plays an important role (Solomon, 2006). In this thesis, a solution is suggested by a common consideration of planned behaviour analysis and conjoint analysis.

### 3.2.4 A need for empirical research on residential solar PV, especially in developing countries

Renewable energy, especially solar and wind, are utilised to replace fossil fuels and combat the energy crises (Adenle, 2020; Aramesh et al., 2019; Ludin et al., 2018; Raheem et al., 2016). Residential PV is particularly crucial to lowering the environmental impact of the residential sector (Shahsavari and Akbari, 2018). However, the broad implementation and extensive use require customer acceptance, adoption, and proper use (Adenle, 2020; Energy Initiative, 2015; Yaqoot et al., 2016). Unfortunately, customers' awareness and acceptance are often considered as one of the biggest barriers in technology spread (Barroco and Herrera, 2019; Byrnes et al., 2013; Ohunakin et al., 2014; Painuly, 2001; Waseem and Hammad, 2015). Paradoxically, it is rarely the central topic in renewable energy research and in designing renewable energy schemes, especially in developing countries (Sovacool, 2014).

Only a very small fraction of empirical research, i.e., 2.2%, is dedicated to understanding end-user behaviour (Sovacool, 2014). Far too little attention has been paid to specific behaviours related to residential solar SA and WTP (Si et al., 2019). Table 4 presents a comprehensive summary of social science research focused particularly on the SA and/or WTP of residential customers toward residential PV. Overall, social research serves many different research objectives (Column 2) and can be done in different ways, either with a direct or an indirect survey (Column 5). However, prior research has been done mostly in developed countries (Column 7).

Most of the relevant papers pertained to the pilot testing conducted among the target population (Table 4, Column 3). There is a lack of a pooled analysis from different subgroups. While the experimental survey sample has different sizes (Column 6), there were significant weaknesses with regard to the conduct and analysis of the studies (Column 8-10). There is hardly any research building an econometric model to explain the relationships between different determinants and independent variables (SA and WTP). The issue of market segment and bias results were also neglected. The lack of concern about the impact of different information portals on consumer's decision is also obvious.

*Table 4. A comprehensive summary of social research on residential PV from 2010 to 2019 ( (Khuong et al., 2020b)*

| Source | Objective | Object | Subject | Direct/ Indirect survey | Sample size | Region | Econometric model | Segment /bias analysis | Considers information channels |
|---|---|---|---|---|---|---|---|---|---|
| **(Alsabbagh, 2019)** | Public perception & policy suggestion | Random | SA & WTP | D/ TPB | 764 valid/825 total | Bahrain | - | - | x |
| **(Hille et al., 2018)** | Factors drivers for PV | Building installed PV | Preference for PV colour & WTP | I/ ACBC | 6104 representative sample; 408 valid | Switzerland | - | - | - |
| **(Sommerfeld et al., 2017)** | Perception | PV owner | SA | D | 22 valid | Queensland, Australia | - | - | x |
| **(Wolske et al., 2017)** | Interest in residential solar panels | Non- adopter homeowner | SA | D/ DOI, TPB, and VBN | 904 valid | US | x/ only direct impact | - | x |
| **(Ida et al., 2014)** | Greenhouse gas emissions reduction | Random household | Preferences & WTP | I/ CBC | 8997 valid; 649 from high- and 694 from low-interest | Japan | - | x | - |
| **(Islam and Meade, 2013)** | Technology attributes & adoption time | Targeted homeowner | Preferences & adoption time | I/ CBC | 298 valid /372 total | Ontario, Canada | - | - | - |
| **(Wissink et al., 2013)** | PV impact on home purchasing | Dwelling buyers | Preferences & WTP | I/ CBC | 227 valid | Eindhoven, Netherlands | - | - | - |
| **(Chen et al., 2013)** | Market analysis | PV owners | Preferences | I/ ML | 22 valid | California, USA | - | x | - |
| **(Scarpa and Willis, 2010)** | Policy suggestion | Targeted household | WTP | I/ CBC | 1241 valid | UK | - | - | - |

*Acronyms: HH: household, I: indirect, D: direct, "-": not implied, "x": implied, DOI: diffusion of innovations theory, TPB: theory of planned behaviour, VBN: value-belief-norm theory, CBC: choice-based conjoint, ML: machine learning*

Given the important role of residential PV in the future environment, SA and WTP toward residential PV should be afforded sufficient attention in the research world.

The hypothetical method proceeds by formulating a hypothesis in a form that can be falsifiable, using a test on observable data where the outcome is not yet known. It is used to research on customer behaviour during the product development process, especially in the new-born market. There are two widely used methods to measure SA and WTP. The theory of planned behaviour uses direct questions to discover people's perception of a product (Ajzen, 1991), while the conjoint analysis uses indirect surveys (Schmidt and Bijmolt, 2019). Measuring SA and WTP with direct or indirect methods could evoke hypothetical bias. The mixed extant evidence feature arguments for comparing the result of both methods.

The Theory of Planned Behaviour (TPB) is a socio-psychological method for explaining individual intention and behaviour. It can well predict the psychological driving factors in the execution of a particular behaviour of SA. Especially in the field of environmental science, from 2008 to 2018, the average annual growth rate of 62% in the number of articles dealing with TPB indicates that it is increasingly being advocated as a key theory for predicting environmental behaviours (Klöckner, 2013; Si et al., 2019). The Theory of Planned Behaviour (TPB) measures the attitude towards the behaviour (the act of buying) rather than merely the attitude towards the object (Ajzen, 1991; Ajzen and Driver, 1992; López-Mosquera et al., 2014; Yang, 2013).

This method has some theoretical drawbacks compared to indirect methods. TPB relies on the researcher's ability to accurately identify and measure all salient attributes that are considered by the consumer if forming their attitude (Solomon, 2006). The reliance on cognition appears to neglect any influence that could result from emotion, spontaneity, habit or as a result of cravings (Dillard and Pfau, 2002). Behaviour in certain circumstances may result not from attitude evaluation, but from the overall affective response in a process called 'affect-referral' (Solomon, 2006).

Among the variety of indirect methods to compute WTP (Lusk and Schroeder 2004), the most prominent is choice-based conjoint (CBC) analysis. Each participant chooses several times among multiple alternative products, including a "no choice" option that indicates the participant does not like any of the offered products. Each product features several product attributes, and each attribute offers various levels. In order to measure WTP, the price must be one of the attributes. From the collected choices, it is possible to compute individual utilities for each presented attribute level and, by interpolation, each intermediate value. Because indirect methods do not prompt participants to state their hypothetical WTP directly, strategic answering may be less likely (Jedidi and Jagpal 2009). However, CBC also has some drawbacks that might influence the hypothetical bias. Indirect methods address this drawback by forcing participants to weigh the costs and benefits of different alternatives.

Generically, direct statements are cognitively challenging, whereas methods that mimic realistic shopping experiences require less cognitive effort (Brown et al. 1996). The ability to interpret of TPB has been improved by extending variables or integrating other theories. However, the research on influencing factors predicted by extending the TPB has shown limitations to varying degrees. Whether the existing predictors can fully represent the influencing factors of a particular behaviour needs further consideration by combining with other models in interdisciplinary fields and considering more related external and demographic factors to obtain better predictions and implications (Si et al., 2019).

# 4. Summary of main contributions

Chapter 2 reveals the need for energy research in Asian EMDCs as they will be the centre of the energy crisis in the future because their economic growth rate is among the fastest in the world and their energy service demand dependents heavily on fossil fuels. In order to assist policymakers, stakeholders and the public in promoting renewable energy use, especially for decentralised solar, detailed analyses of long-term energy service demands and assessments of the costs and potentials of PV technologies are required.

Most of the contributions in this thesis focus on providing sufficient models and multidisciplinary tools for policymakers, especially relating to set up central/local targets and prioritizing and leveraging the region/sector/factor upon to focus in the context of limited resources. Different measures and pricing strategies are provided in order to compare different development scenarios of renewable energies in EMDCs, with specific examples in Southeast Asia and Vietnam.

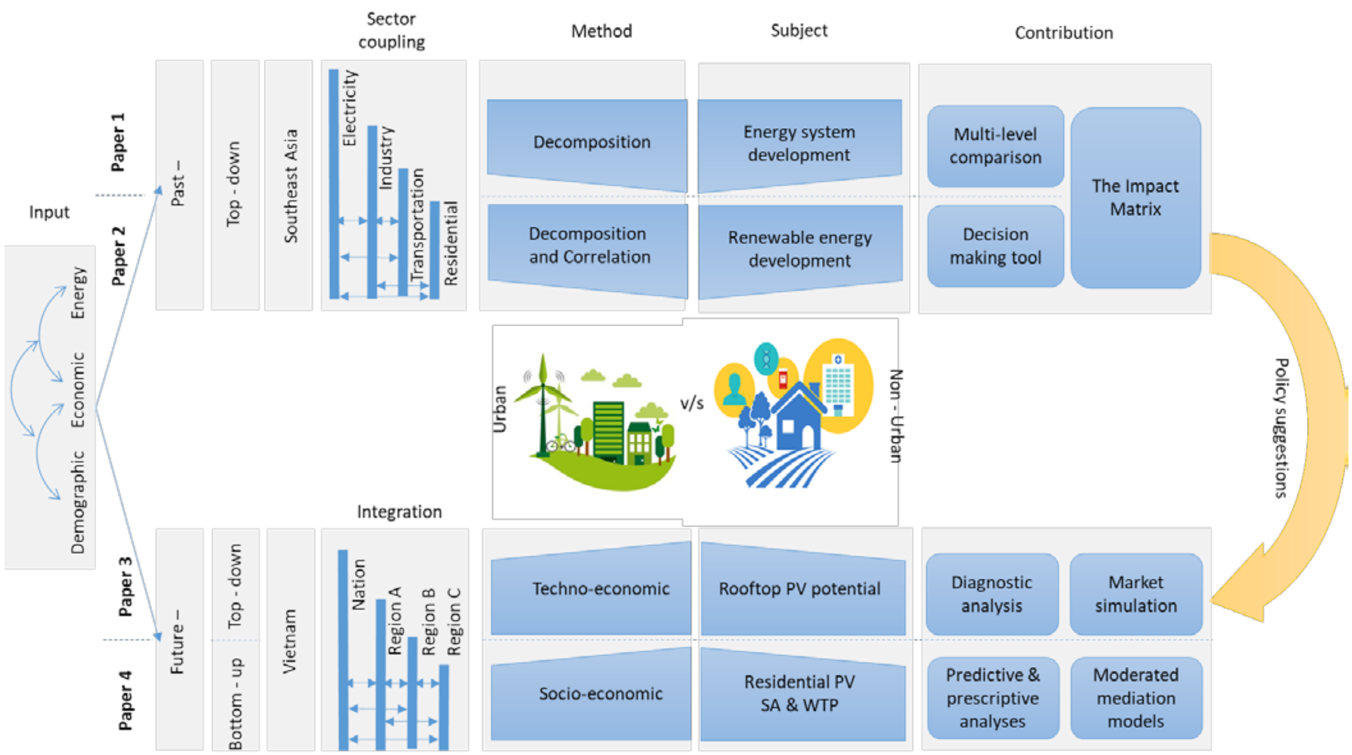



*Figure 7. PhD story and methodology contributions*

Figure 7 describes the whole story with the detailed methods, subjects and main contributions of the four papers of this thesis. With the main theme of the study revolving around the different aspects that influence the development of renewable energy, this thesis exploits the extremes of renewable energy developing potential by using both top-down and bottom-up approaches. The four papers are divided into two general lines with a central focus on the relationship between economic growth, demographic and energy consumption changes in urban and non-urban areas. The first two essays use decomposition and correlation methods to investigate long-term energy service demand and renewable energy developing trends. The last two essays focus on designing techno-socio-economic models with much attention to solar PV.

In the following, Section 4.1 discusses the findings related to urbanisation and renewable energy relationship throughout all papers of the thesis. Section 4.2 presents the contribution of paper 1 and 2, which focus on innovative decision making and a multi-level comparison tool, called the Impact Matrix. Section 4.3 reports the contributions of paper 3 related to developing a cost-effective, transferable and scalable method for cost-potential assessment of decentralised solar in developing countries with limited resource availability. In order to complete the whole picture of future rooftop PV development, this thesis conducts bottom-up research in paper 4 with an empirical study on Willingness To Pay (WTP) and Social Acceptance (SA) of the public toward residential rooftop PV systems (Section 4.4).

## 4.1 Using urbanisation as a motivator for sustainable energy development in developing countries

### 4.1.1 Urbanisation causing energy consumption increase drastically

The essential requirement of restraining energy consumption and promoting energy efficiency is becoming more critical in the context of economic and urban growth. A more in-depth analysis of the disaggregated results of factors driving energy service demand for each sector and country enables a more accurate understanding of the urban impacts on energy consumption. With this purpose, the decomposition method has been implemented in this study for seven ASEAN countries in the period 1995-2013 to assess the effect of urbanisation on energy consumption and compare this effect with other structured effects based on multi-level indicators. This analysis is based on two types of urbanisation, including the general urban indicator of urban population and the urban pull indicator of non-agriculture workers. The results decompose the changes of overall energy consumption into intra- and international effects and isolate the contribution of each component factor, including the energy mix, energy intensity, activity, and urbanisation. To the author’s knowledge, this is a novelty, as previous studies have only shown results across sectors or countries.

While there was some controversy about the effect of urbanisation on total energy consumption as well as sectorial energy consumption, the results of the first paper in this thesis demonstrate the positive effect of urbanisation at national and sectoral levels in the ASEAN region. Although effects are different among the countries, the urbanisation effect on energy consumption is more substantial in lower-income countries. The urbanisation effect is much more significant than the population and other effects, e.g. energy intensity and activity effects in the whole country, as well as in each of the sectors in the region.

The detailed results about urbanisation-related energy consumption changes in Table 5 could serve as a suggestion for the whole ASEAN region in controlling urbanisation and its effects on energy consumption. For comparison across sectors in ASEAN during 1995-2013, the demographic effect of population change influence on commercial energy consumption is weighted at 1. The demographic effect on energy consumption changes is relative to this value of unity. More detail explanation can be found in Paper 1, Section 4 and 5.

*Table 5. Cross country-sector comparison of demographic factors impacts on energy consumption growth in ASEAN in the period 1995-2013 according to two different approaches (% change in energy consumption per 0.1% change in respective demographic factor). Source: (Khuong et al., 2019b)*

| | | **Without economic structure** | | | | **With economic structure** | | |
|---|---|---|---|---|---|---|---|---|
| | | COM | IND | RES | TRA | COM | IND | TRA |
| **Brunei** | Population | 0.39 | 1.28 | 1.70 | 1.01 | 0.37 | 0.69 | 1.03 |
| | Urban 1 | 0.52 | 1.70 | 2.25 | 1.33 | 0.49 | 0.91 | 1.36 |
| | Urban 2 | 0.55 | 1.82 | 2.48 | 1.46 | 0.52 | 1.01 | 1.49 |
| **Cam** | Population | 0.11 | 0.55 | 1.38 | 1.32 | 0.11 | 0.55 | 1.32 |
| | Urban 1 | 0.17 | 0.85 | 2.07 | 2.14 | 0.17 | 0.84 | 2.12 |
| | Urban 2 | 0.37 | 1.89 | 4.84 | 2.62 | 0.37 | 1.88 | 2.72 |
| **Malay** | Population | 0.22 | 0.42 | 0.60 | 0.31 | 0.22 | 0.42 | 0.31 |
| | Urban 1 | 0.40 | 0.76 | 1.09 | 0.57 | 0.40 | 0.76 | 0.57 |
| | Urban 2 | 0.35 | 0.65 | 0.96 | 0.49 | 0.35 | 0.60 | 0.49 |
| **Myan** | Population | 0.19 | 0.31 | 1.57 | 0.62 | 0.19 | 0.31 | 0.62 |
| | Urban 1 | 0.39 | 0.63 | 3.08 | 1.37 | 0.39 | 0.63 | 1.37 |
| | Urban 2 | 0.65 | 1.03 | 5.60 | 2.12 | 0.65 | 1.03 | 2.12 |
| **Phil** | Population | 0.16 | 6.20 | 1.44 | 3.47 | 0.29 | 6.20 | 3.47 |
| | Urban 1 | 0.40 | 5.35 | 1.36 | 2.79 | 0.25 | 5.35 | 2.79 |
| | Urban 2 | 0.78 | 11.48 | 3.19 | 6.13 | 0.57 | 11.45 | 6.13 |
| **Thai** | Population | 0.20 | 0.35 | 0.71 | 0.69 | 0.20 | 0.35 | 0.69 |
| | Urban 1 | 0.56 | 0.88 | 1.53 | 2.03 | 0.56 | 0.88 | 2.03 |
| | Urban 2 | 0.61 | 0.93 | 2.15 | 2.15 | 0.61 | 0.93 | 2.15 |
| **Viet** | Population | 0.16 | 0.22 | 0.46 | 0.16 | 0.16 | 0.22 | 0.16 |
| | Urban 1 | 0.40 | 0.53 | 1.10 | 0.38 | 0.40 | 0.53 | 0.36 |
| | Urban 2 | 0.78 | 1.15 | 2.48 | 0.80 | 0.80 | 1.16 | 0.80 |

*Acronyms: Sector: COM - Commercial, IND - Industrial, RES - Residential, TRA – Transportation. Urban 1 - Urban population, Urban 2 – Non-agriculture workers. Country: Cam - Cambodia, Malay - Malaysia, Myan - Myanmar, Phil - The Philippines, Thai – Thailand, Viet – Vietnam.*

The strong effect of urbanisation on domestic energy consumption poses new questions for policymakers in this field. In particular, they should focus their efforts on finding an optimal solution to decentralised, efficient energy systems for current and future urban cities. Therefore, this study suggests three key recommendations to policy-makers in setting energy policy: (1) urban areas should be considered as one of the core targets for energy policy; (2) the lower-middle-income countries should pay attention to effective policies to manage the rapid change of the non-agriculture workers' effect; and (3) there is an essential need for energy policy at city-levels besides subsector-levels.

### 4.1.2 Urbanisation motivates renewable energy development

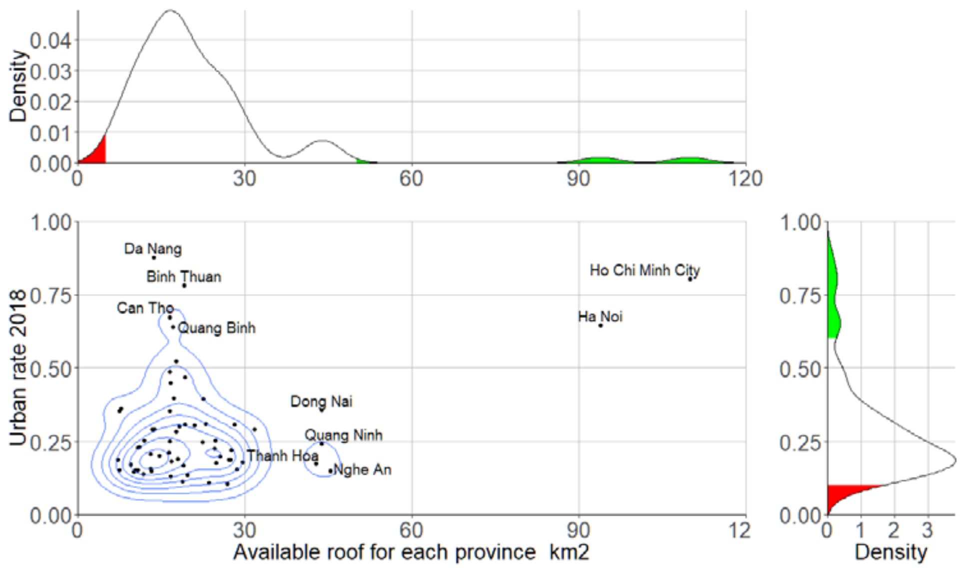
By employing a correlation decomposition approach at regional, country and city levels, the second paper in this thesis investigates the determinants of renewable energy expansion and explores the trend drivers in ASEAN countries from 1995 to 2013. The results suggest that urban areas should also be the focus of renewable energy policy instead of rural areas. The tremendous impact of economic growth creates an excellent impetus for renewable energy development; urbanisation is the second pull for renewable energy extensions. Since the two effects are located in the first quadrant of the Impact Matrix, if strategists affect these factors, they will create the most powerful incentive for renewable energy growth. The result confirms that if the strategic aim is to promote renewable energy market development, it is clear that the target must be focused on the richer and more crowded places. The energy transition policy should not only focus on the electricity sector but also need more supporting mechanisms and schemes in household and commercial sectors to promote smart and green cities.

The main problem in renewable energy policy in the region is the insufficient regulatory framework, lacking clear specific targets at the national level, and no targets at the local levels. The root cause seems to be that governments do not have the tools to make decisions and select target audiences, with confusion in translating national objectives into local targets. Some countries are combining electrification with smart and green city targets in designing renewable energy policy. So local governments do not know what should be the first priority. The apparent selection criteria and assessing policy matrix as proposed in this paper would provide a systematic approach to developing renewable energy policy at national and local levels. The criteria and the Impact Matrix provide a common 'language' for municipal governments and governance in collaborating. They can be used to make policy more transparent and convincing to stakeholders by providing quantitative answers to questions of target setting in a specified period.

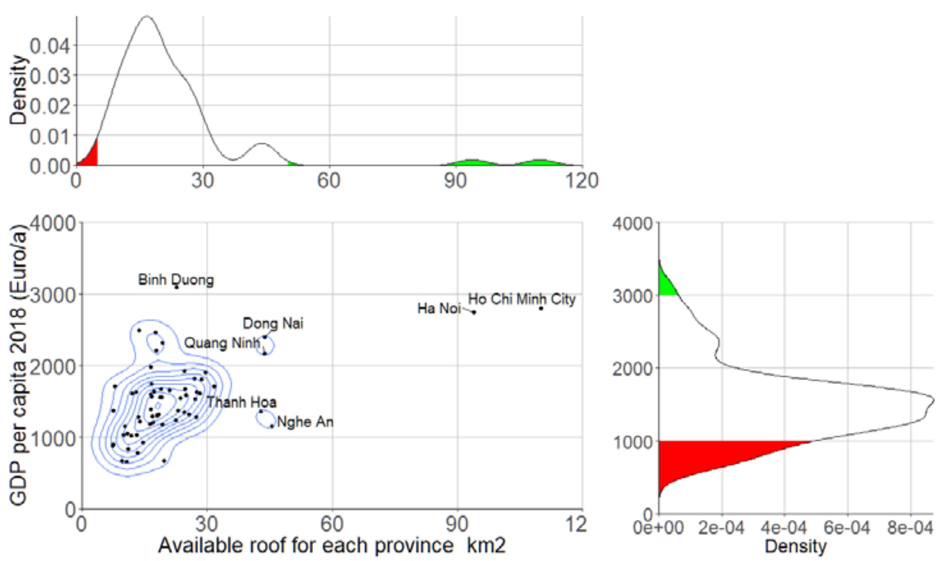
If Southeast Asian countries should redirect their renewable energy supporting schemes to make the urbanisation trend environmentally sustainable, many actors need to work together to come up with solutions. For example, not only the government but also businesses, citizens and governance processes should be involved. Economic growth in urban areas could encourage household investment in renewable energy, especially in solar PV. It also helps to tackle increasing energy consumption in the area. Therefore, renewable energy policy should create supporting mechanisms not only for the supply side but also for the demand side.

### 4.1.3 Rooftop PV is concentrated in urban areas

Paper 3 assesses the techno-economic potential for rooftop PV in Vietnam. Figure 8 shows the available rooftop PV distribution corresponding to the level of urbanisation (left) and the GDP per capita (right) in 2018 in 63 regions in Vietnam. The distributions highlighted in red, which consist of 14 provinces, indicate the minimal potential area, with less than 5 $km^2$ of roof area, 15% of urbanisation, and 1000 Euro/a income. The green distributions illustrate the outstanding potential area, including nine provinces with more than 35 $km^2$ of the available roof, 60% of urbanisation, and 2000 Euro/a income.




(a)




(b)

*Figure 8. Rooftop PV potential distribution corresponding to the level of urbanisation (a) and income per capita (b) (General Statistics Office Of Vietnam) in 63 provinces in Vietnam. Source: (Khuong et al., 2020a)*

Because most of the provinces have a relatively low (15%-60%) urban rate and humble economic development (1000-2000 Euro/a income), the success of the first adopters plays a crucial role in the new market due to their potential impacts on followers. In order to improve rooftop solar development, the role of local and government authorities is equally essential. However, in practice, sub-national or local governments are constrained by limited resources, weak institutional capacity, inadequate mechanisms, and limited availability of information (Byrne et al., 2015; Kabir et al., 2010; Mansouri Kouhestani et al., 2019; Seetharaman et al., 2019). These circumstances, as well as the complication of land ownership, constitute a narrow space for policymakers to encourage rooftop PV development at the local level without significant support from the government. This means that there is an obvious need for selecting target groups that are unified from national to local levels.

Based on the market characteristics, Paper 3 suggests determining target groups based on k-means clustering of the development dynamics of 63 provinces in Vietnam with the criteria, i.e., their techno-economic potentials including the available roof ($km^2$), the production potential (TWh/a), LCOE[3] (Euro cent/kWh), and the level of urbanisation (%) (General Statistics Office Of Vietnam) and GDP (Euro/a) (General Statistics Office Of Vietnam). The results are shown in Table 6 and Figure 9. Because there are more than two dimensions (variables), Table 6 shows the principal component analysis and plots the data points according to the first two principal components (Dim1 and Dim2) that explain the majority of the variance and shows an illustration of the clusters.

*Table 6. Priority groups and their specific characteristics. Source: (Khuong et al., 2020a)*

| **Priority** | **Cluster name** | **Available roof km²** | **Average LCOE (euro cent/kWh)** | **Production potential (TWh/a)** | **GDP per capita (Euro)** | **Urban rate** | **No. province** |
|---|---|---|---|---|---|---|---|
| **1** | 6 | 101.95 | 8.25 | 20.20 | 2260.53 | 65% | 2 |
| **2** | 2 | 17.11 | 8.06 | 3.51 | 1558.96 | 51% | 7 |
| **3** | 1 | 29.04 | 7.59 | 6.59 | 1431.55 | 29% | 9 |
| **4** | 3 | 26.12 | 8.92 | 4.42 | 1307.08 | 22% | 13 |
| **5** | 5 | 17.03 | 7.69 | 3.74 | 1143.27 | 26% | 18 |
| **6** | 4 | 12.57 | 8.96 | 2.07 | 794.10 | 19% | 14 |

Ranked in order of priority for rooftop PV policies, Hanoi and Ho Chi Minh are classified as priority 1, which requires the most policy focus due to their most favourable condition for rooftop PV development, followed by Ba Ria Vung Tau, Binh Duong, Can Tho, and Da Nang.

The results do not only recommend policy priority but also support national policymakers to redirect and balance the PV development between different regions. The growing PV project in a specific location, where LCOE is particularly lower than others, e.g. the group with LCOEs of around 7.59

[3] LCOE: Levelised cost of electricity, is a measure of the average net present cost of electricity generation for a generating plant over its lifetime

Euro cents/kWh, is avoided. The government can provide a favourable policy to the higher LCOE but potentially fast-uptake regions, e.g. cities and provinces of the priority 1 and 2.

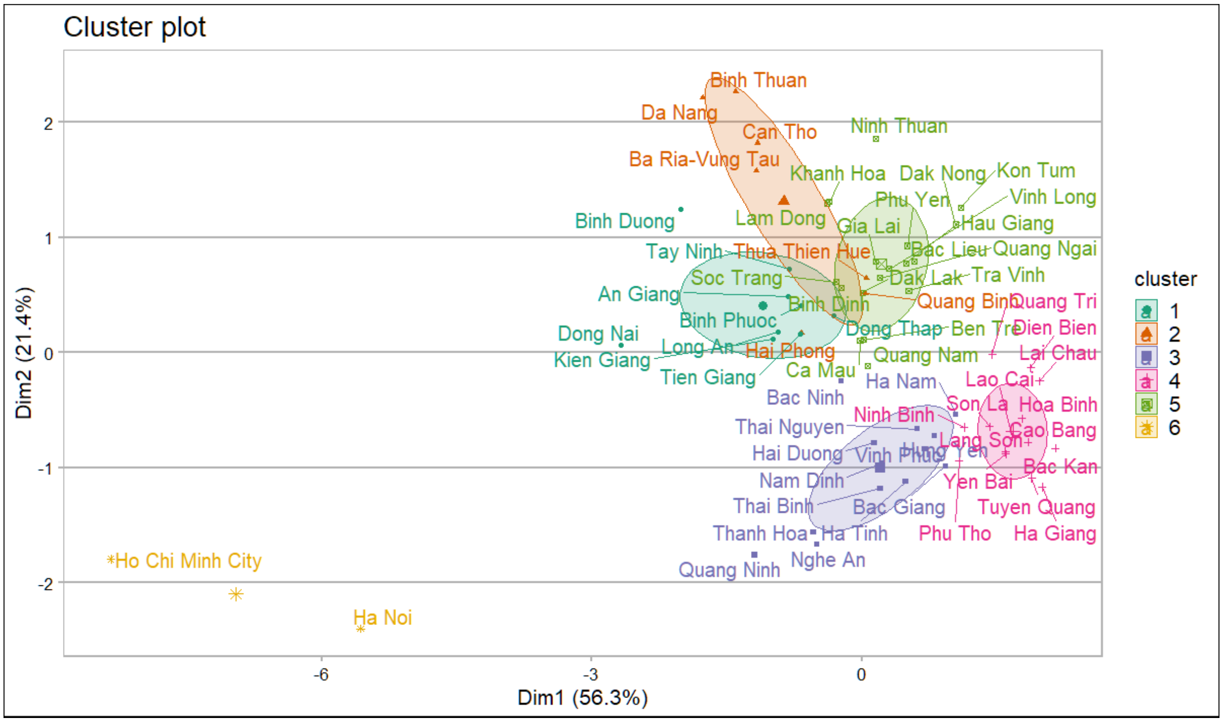



*Figure 9. The results of clustering provinces based on their potentials and characteristics. Source: (Khuong et al., 2020a)*

### 4.1.4 A lifestyle product in urban/suburban/nonurban life

There is growing evidence that the explanatory power of the individual demographics structure or multiple, independent, detached characteristics is limited in the context of heterogeneous actor structures. As counter-proposal, the lifestyle approach offers the possibility to build a differentiated view on possible customer groups employing many socio-demographic, psychographic, and behaviour-oriented features.

Residential PV can be considered as a lifestyle product since SA and WTP reveal the strong relationship with environmental interest concerning different lifestyle groups of urban, suburban and rural areas in Vietnam. The results of interestingly different reaction and motivation of people in different places of residence provide a fundamental base to discover the dynamic markets in different territories in Vietnam. Paper 4 also provides specific evidence related to why different territories react differently to the same product. From that, policymakers and stakeholders can design adequate policies and promote schemes for different areas in order to boost PV use.

The SA and WTP are dominated by financial status and environmental interest delivered through personal attitude. Paper 4 confirms the importance of environmental interest in motivating people using an environmentally friendly product in literature. For example, consumers with a higher income tend to have a greener and more energy-efficient lifestyle, while principally younger, mixed-income lifestyles are more likely to have low environmental awareness (Hierzinger et al. 2011). In terms of residential PV adoption, adopters rank significantly higher on environmental interest than the average (Jager 2006).

## 4.2 Multi-level comparison and decision-making with the Impact Matrix

### 4.2.1 The Impact Matrix – a combination of decomposition and correlation in one decision-making tool.

The Impact Matrix proposed in this thesis evaluates and prioritizes a list of options and is a decision-making tool. Based on the physical force concept, the results of the two techniques, decomposition and correlation, are combined in an Impact Matrix. The Impact Matrix provides the relative positioning for aggregate impact on the vertical axis based on decomposition results, and the relative positioning for the direction of the impact on the horizontal axis based on correlation results. The higher its placement on the vertical axis, the greater the impact the process has on the perception of value.

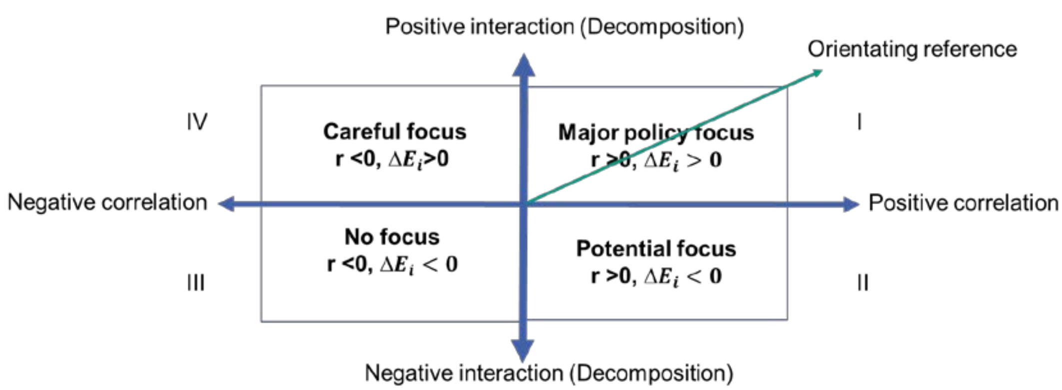



*Figure 10. Proposed Impact Matrix to support policymaking. Source: (Khuong et al., 2019a)*

The impact on renewable energy growth is defined as the rate of increase of the vector, which is the combination of aggregate impact and direction impact (Figure 10). This means that the force, which produces acceleration for renewable energy growth in a given direction, has two components connected by a definite relation. One is the aggregate impact that pulls the renewable energy according to its scale; the other impacts give direction for the growth.

In order to determine the complex impacts and prioritize their effects on the renewable energy growth rate from strongest to weakest, the Impact Matrix is divided into four parts (Figure 10):

- Zone I – where the decomposition result (ΔEi) and the correlation result (r) have positive values.
- Zone II –where the decomposition result (ΔEi) is negative, but the correlation result (r) is positive.
- Zone III –where both the decomposition result (ΔEi) and the correlation result (r) are negative.
- Zone IV –where the decomposition result (ΔEi) is positive, but the correlation result (r) is negative.

### 4.2.2 Policy advice based on the Impact Matrix

The Impact Matrix can be used to make complex decisions, prioritize tasks and solve problems. The Impact Matrix is useful for selecting a problem or an improvement opportunity within the control of the decision-makers with limited financial and human resources. In this case, the issue list must be narrowed down to a manageable number. Typical situations are when one improvement opportunity or problem must be selected to work on or when only one solution or problem-solving approach can be implemented.

Secondly, the matrix demonstrates the cause of renewable energy growth during the considered period. It also visualises the urgent problems and suggests solutions. Thus, it can illustrate the potential effect of a factor in future based on projected data, for example, what factor should be targeted and how strong it will impact renewable energy growth.

Zone I, with positive interaction and positive correlation, illustrates the strongest impact. Consequently, if policy-makers would focus on this area, it could accelerate renewable energy growth rate the most. Zone I is called the Major Policy Focus area.

Zone II, with positive correlation but negative interaction, covers the impacts that have a naturally positive correlation with renewable energy growth rate, however, have insignificant motivation to promote faster growth. This part is called the Potential Focus area, which means that if the policy-makers focus on the influence elements in Zone II, they could move from insignificant impacts to a greater impact in Zone I.

Zone III includes all the factors that have plainly negative impacts on renewable energy growth. It is called the No Focus area. Note that, no focus indicates that it is not a favourable focus to accelerate renewable energy increase for policy-makers.

Zone IV covers the factors that have a negative correlation with the renewable energy growth rate. However, it still shows its positive interaction. If the considered factors are placed in this area, policymakers should be careful in creating more renewable energy supporting schemes, because it does not ensure a positive effect. This zone is called the Careful Focus area.

The most efficient option for policymakers to accelerate a renewable energy development is to keep the driving factor moving along the dissection of the major policy focus quadrant, as can be seen in Figure 10 as the orientating reference.

By extending the matrix with more detail insights, for example in Figure 11, the matrix shows

- the potential effects of one factor on different sectors (e.g. urbanisation impact (ΔEur) is stronger on residential but weaker on transportation),
- the potential effects of different factors on one sector (e.g. in the industrial sector, economic growth (ΔEact) is the strongest effect among other effects)
- that the fast reacted and most effective factor in promoting renewable energy growth is urbanisation factor in the residential sector.
- that potential problems during implementation are the economic structure factors (ΔEstr)
- potential negative consequences: all the factors in the left X-axis.

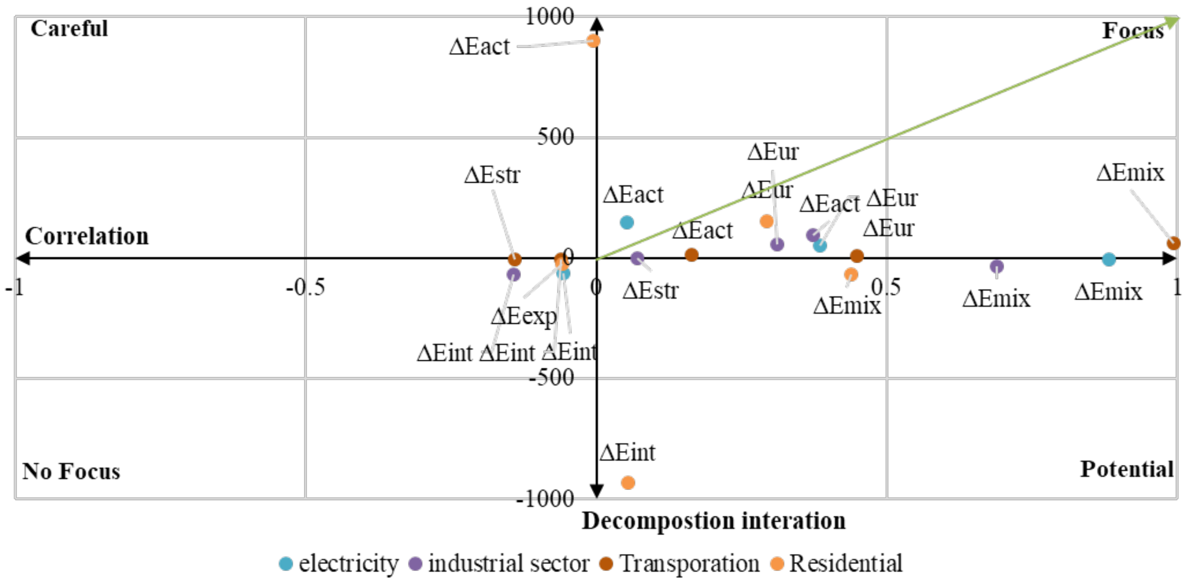



*Figure 11. An extended Impact Matrix to compare different sectors in Vietnam between 2010 and 2013. Source: (Khuong et al., 2019a).*

### 4.2.3 The advantage of the Impact Matrix

By dividing impact factors according to their strength and direction into a certain priority level, the presented method represents a combination of two quantitative approaches. Starting with the decomposition approach, the method aims to calculate numeric values that describe the association of each factor with renewable energy change. Thereafter, a correlational analysis is conducted on variables to measure and demonstrate the presence of the relationship between the impact factors and renewable energy growth. Combining two quantitative results, the Impact Matrix makes relative judgments in order to categorize the importance of the impact, such as “focus”, “potential”, “no focus” and “careful”. The weight-scaled impact score is the combination of the correlation score and decomposition score. Therefore, it can compare different alternatives.

The Impact Matrix has been developed to help to determine how different factors affect renewable energy development. Therefore, it could support policy-makers to decide where to focus attention and reduce the problem of transparency between policy formulation and impacts. Due to this ability of cross comparing between region-country-sector-city, it could help to understand better the complex interactions between renewable energy development and the effects of the energy transition, economic structure change, economic growth, and demographic change. It could, therefore, be useful in generating and analyzing scenarios by using historical data combined with future projections.

It is an ideal solution for debating between a few comparable solutions that each have multiple quantitative criteria. The Impact Matrix process is best used when policymakers and stakeholders need to assess a situation from a logical viewpoint, as it is a logical tool in nature. It provides a comparable picture to make a weighted analysis. The matrix can be used on its own, or in tandem with other decision-making tools and techniques if policymakers and stakeholders are deciding on a solution that has less distinct options. Moreover, the matrix is easy to implement, visually friendly, scalable and can be used for training factors (e.g. forecasting data) with different dataset at different scales.

### 4.2.4 The Impact Matrix implications in ASEAN renewable energy analyses

In ASEAN, economic growth (ΔEact) and urbanisation (ΔEur) are the two factors placed in the major policy focus (Figure 12). It illustrates that renewable energy consumption increases linearly when the urban population increases and economic growth results in more demand. This effect is described by the positive correlation between ΔEact and ΔEur with the change of renewable energy ΔRE in X-axis.

However, economic growth (ΔEact) has a much higher position than urbanisation (ΔEur), but on the left side. It means that while economic growth (ΔEact) has stronger impacts on renewable energy market development, urbanisation (ΔEur) creates a stronger momentum for renewable energy growth. If the urbanisation factor continues to increase in the Y direction and passes the green line, it achieves its best impact range with a steadily pull for renewable energy growth faster.

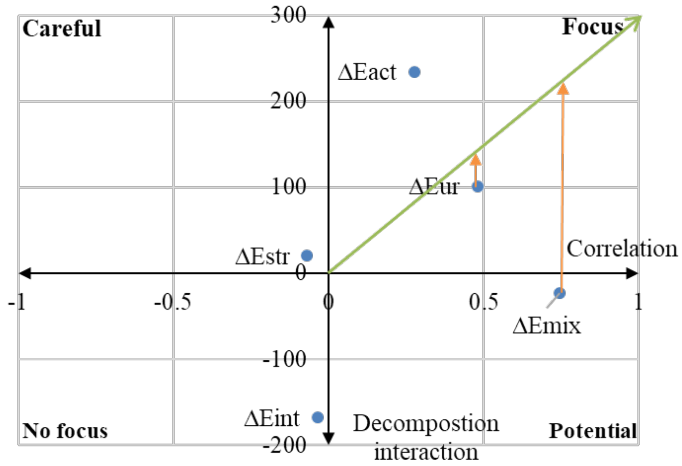



*Figure 12. The Impact Matrix for renewable energy focus in ASEAN between 1995 and 2013. Source: (Khuong et al., 2019a)*

## 4.3 Transferable and cost-effective method for evaluating and exploring PV potential

Rooftop PV is driving the decentralisation of electricity production. It is a great contributor to the sustainable development concept in Asian EMDCs, whereby households become more independent of the electricity grid due to a thorough integration of renewable energy sources. However, it is still often seen as a novelty. Local authorities have difficulties enforcing this specific technology in their detailed development plans, partly because of the lack of expertise and somewhat because of lack of capital. Therefore, it is relevant to address potentials as early as possible when planning for the type of energy source. Since different regions have different climates, geographic and demographic profiles, this thesis provides an affordable, robust and high-resolution potential assessment for rooftop PV. It suggests target groups alongside policy solutions with clear national and local goals, based on the findings. The proposed method considers construction and design constraints, obstacles on the rooftop (e.g. HVAC, chimney, etc.), the proper orientation on the roof, including shading effects, and the slum areas (informal settlements), with the application in Vietnam as an example for other emerging countries. The results can provide an overview plan as well as an integrated strategy for developing rooftop PV between different administrative levels.

### 4.3.1 A transferable, cost-effective and scalable model

The method proposed in this thesis consists of three steps. The first step is determining the geographical potential using ArcGis and geostatistical analysis. The second step is identifying the technical potential, in which the accuracy of the assessment is improved by determining the electricity output of the solar cell regarding the expected operating temperature of the PV module and the corresponding solar cell efficiency for the specific considered region. The last step is economic analysis.

The proposed method considers the temperature and solar radiation, which have significant effects on the performance of photovoltaic (PV) systems, the PV cell temperature, which is related to the ambient temperature, and the solar radiation incident on the PV surface, which depends on the slope and azimuth of the PV panels.

The method can be upscaled from district assessment to national assessment in estimating the PV potential. Detailed field investigations using high-resolution street maps, household data from government statistics, living area and exterior/interior areas, solar irradiation at different azimuths, inclination angles, and horizontal positions regarding different locations were performed.

For a larger research scale, the approach shows the ability to evaluate the shape and orientation of roofs based on the architecture data of the slope of roof surfaces or shading by trees and other objects in the calculation. This thesis uses statistical modelling to extrapolate the representative building typology as the geographical unit of the analysis to give a nationwide estimate of the technical potential. The horizontal irradiance on roofs was derived by using radiation computed based on the geometry of the sun-earth system, land use maps, and building maps. Based on the PV arrangement and model, the technical potential of a roof-integrated PV system is estimated. This method can be used for city-country-level spatial analyses for rooftop PV systems, e.g. the case of Vietnam rooftop solar potential for the whole country, 5 regions and 63 provinces with a sensitivity analysis of factors affecting solar electricity productivity (location, azimuth, slope) was carried out.

The distributed PV potentials, including the specific production potential per total area (GWh/km$^2$) and the LCOE (Euro/kWh) in Vietnam, are discovered. The potential density is significantly high in the two river delta regions, which are the Red River Delta (RRD) and the Mekong River Delta (MRD) in Vietnam. The two largest cities of the country, Hanoi (in the RRD) and Ho Chi Minh (in the MRD) have the highest potential of electricity production of about 12 GWh/km2 and 5 GWh/km2, respectively. These cities are the largest metropolitan and most populous cities with an estimated population of 7.7 million and 8.4 million, corresponding to 8.6% and 9.3% of the national population, and they also have the largest household area in Vietnam (Government statistical reports, 2018). Hanoi has 407 km$^2$ of housing land, of which around 93.9 km$^2$ rooftop available to install solar cells, while Ho Chi Minh City has about 282 km$^2$ housing land but can provide an estimated 110 km$^2$ roof for installing solar. Moreover, since Ho Chi Minh City is in the southern part of Vietnam, it could potentially generate in total 24.8 TWh/a or 23.4 TWh/a with monocrystalline or polycrystalline solar cells, respectively, which is nearly 60% more than the electricity production potential from solar in Hanoi. This makes Ho Chi Minh City, the most significant potential for solar power throughout the country, while Hanoi is ranked second. Currently, Ho Chi Minh City has only installed around 44.56 MWp of its 18 GWp total potential (EVNHCMC, 2019).

## 4.3.2 Diagnostic analysis to identify behaviour patterns of data

This thesis used diagnostic analysis in finding the cause of the insight found in statistical analysis. Hierarchal clustering, in the manner of the Pareto principle, is used to generate the ranking of the uncertainty factors according to their relative contribution to the output variability. The influencers are categorized into different groups, including "strong influencer", "moderate influencer", and "negligible influencer". The goals of the analysis are to provide different references for policymakers and stakeholders to choose an appropriate interaction with the current rooftop PV market status. One goal focuses on quantifying the uncertainty in the output of the model, so it will be used as a control tool for modellers and policymakers in order to ensure the accuracy of the output. The other goal focuses on apportioning output uncertainty to the different sources of uncertainty inputs. The results of this analysis will be used for designing policy and supporting the decision-making of investors in the rooftop PV market.

To verify the correlation of the variation of these variables with the output, this paper uses regression techniques, including curve fitting and linear fitting, to specify the model that provides the best explanation of the relationships between the uncertain parameters and outputs. The considered outputs are the technical potential ($y_1$) and the LCOE ($y_2$). The uncertain parameters are indicated below:

$x_1$ Area added to a ground floor area
$x_2$ Utilisation factor for flat roof
$x_3$ Utilisation factor for slanted roof
$x_4$ Average number of apartments on one floor
$x_5$ Performance ratio
$x_6$ Azimuth of building
$x_7$ Capital cost
$x_8$ O&M cost
$x_9$ Discount rate

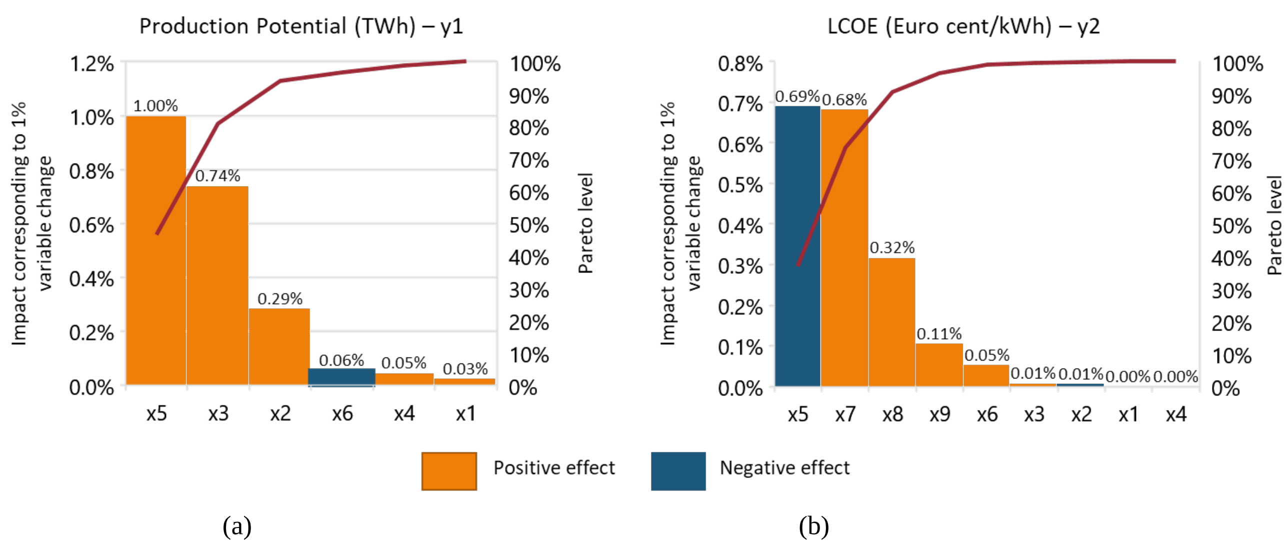



Figure 13. Comparing the influence of the considered parameters on the technical potential (a) and the LCOE (b). Columns in orange: positive value. Columns in blue: negative value. Red lines: Pareto line. Source: (Khuong et al., 2020a)

Figure 13 shows the strong influence of the uncertain parameters on the outputs in descending order. Using the Pareto principle (He et al., 2017; Kramp et al., 2016), which indicates that roughly 80% of the effects come from 20% of the causes, this paper divides them into three groups. The first group is called "strong influencer", which consists of $x_3$, $x_5$, and $x_5$, $x_7$ that are responsible for more than 80% of the impact on the technical and economic outputs, respectively. The second one is the "moderate influencer", which includes $x_2$ for technical output and $x_8$ for economic output, and accounts for the next 15% of the impact on the outputs. The other factors belong to the "negligible influencer" group. By selecting impacts based on their strength, the change of the outputs can be measured based on the different possible alterations of the uncertain parameters, as in Equation (1) and Equation (2).

$$y_1 = 0.2851\, x_2 + 0.7401\, x_3 + x_5 + 0.025 \qquad (1)$$

$$y_2 = -0.6908\, x_5 + 0.6827\, x_7 + 0.3173\, x_8 + 0.3128 x_9^2 + 0.1965 x_9 + 0.364 \qquad (2)$$

The results show how dependent the output is on a particular input value. The performance ratio, $x_5$, has the most significant impact on both outputs of the model, which are the electricity potential, $y_1$, and the LCOE, $y_2$. While the electricity potential is also changed considerably when the utilisation factors change, the LCOE is not be affected by these two variables. It alters when the costs and discount rates vary.

These results can be used to assist policymakers for decision making by predicting the outcome of a decision in case they intend to change inputs using policy incentives/subsidies. It helps in assessing the riskiness of a strategy and in making informed and appropriate decisions.

### 4.3.3 Reducing data uncertainty by using Monte Carlo simulation

Monte Carlo simulation is one of the most popular ways to calculate the effect of unpredictable variables on a specific factor. Monte Carlo simulations are used as a probability model in paper 3 to help predict risk and uncertainty. In order to test a hypothesis or scenario, a Monte Carlo simulation will use random numbers and data to stage a variety of possible outcomes based on any results. Monte Carlo simulation is an incredibly useful tool across a variety of fields, including project management, finance, engineering, logistics, and more. Testing a variety of possibilities will show how random variables could affect the outcome of the proposed model.

The conversion of solar irradiation into a power output for a specific PV technology is associated with several uncertainties. The validation of all the methods and missing sensitivity and uncertainty analyses are claimed in almost all studies' conclusions (Bódis et al., 2019; Byrne et al., 2015; Castellanos et al., 2017; Choi et al., 2019). Considering the performance ratio, the module efficiency and orientation, and differentiating between manufacturers and models seem necessary due to diversity of the PV panels. However, in practice, this is not feasible due to the sheer number of manufacturers and models available, not to mention the lack of data. Hence why a more detailed understanding of how module-specific factors (over and above the ambient and module temperature) contribute to the power behaviour of individual modules is required.

The proposed method carries out resource assessments for rooftop PV in developing countries, as applied to Vietnam. The method is a top-down method that can be employed where detailed, accurate data on buildings, their outlines, and associated infrastructure are lacking. It represents an improvement beyond state of the art and has an absolute error of about 5% compared to detailed bottom-up city models, which is very low for a method at this spatial scale and resolution.

This method utilizes advanced data-driven methods for rooftop character analyses, detailed spatial information and analysis of the solar irradiance. It is suitable for applying in the complex environments of decentralised PV, which require comprehensive analysis for rooftop characteristics and the roof's shape and orientation effects. The thesis proposes using Monte-Carlo simulation to estimate rooftop inclination, shape, and orientation of buildings.

Uncertainties relating to the input data are significant but have been considered in the sensitivity analysis, which should be borne in mind when interpreting the results. Especially the assumptions relating to the building location, size, orientation, and shadings impacts are country-specific and need further research. One promising avenue in this context is the combination of open mapping data with satellite images, in order to automatically identify suitable geometries for rooftop PV (Mainzer et al., 2017). By further validating the top-down results from this study with bottom-up results from 3D models (such as Effigis Geo-Solutions 2018), the method could be improved and applied to other contexts. Finally, this and related studies have tended to focus on the supply side for rooftop PV, but there is a need for future research to analyze the demand side, especially public opinion and Willingness To Pay for PV systems.

In order to improve the accuracy of the assessment, two-step PV performance analyses, including ideal condition and practical condition analyses, are conducted. In the first step, the thesis determines the power output of the solar cell regarding the expected operating temperature of the PV module and the corresponding solar cell efficiency. The effect of the irradiance and temperature changes over a calendar year on the electricity output of a solar cell across the seasons is calculated.

In the second step, the thesis calculates the corrected energy conversion efficiency ($\eta\_cor$) of a solar cell corresponding to the operating temperature $T\_mod$, which is reflected in the latitude and climate of the considered region. In order to assess the PV system performance for a conservative perspective, the daily hours of sunshine on the surface were analyzed at the winter solstice using the Sun Elevation Angle and solar radiation analysis tool in ArcGIS. The number of sunshine hours was found to range from 6 hours/day to 9 hours/day without interference from shadows depending on different regions.

### 4.3.4 A multi-criteria decision-making approach for improving policy application

A comprehensive analysis of PV assessment with a spatial resolution of 100m across Vietnam stands out as the only high-resolution assessment covering the largest area in southeast Asia. The physical potential in the raster maps, which encompasses the maximum amount of solar energy that can be received in a particular area, is broken down into the geographic potential of in total 1407 $km^2$ of the available rooftop by gradually excluding the zones reserved for other uses and restricting the locations where solar energy can be gathered. The technical potential is calculated with the results of roof-mounted solar cells in the whole country being about 228 and 216 GWp or about 278 and 263 TWh/a with monocrystalline and polycrystalline solar cells, respectively. The LCOE is also calculated, ranging from 7.6 to 9.2 Euro cents/kWh at a discount rate of 8% in 63 provinces in Vietnam. However, since the techno-economic potential of PV solar is associated with a certain degree of uncertainty, the thesis measures the error regarding the uncertainty of data assumptions and inputs and the inherently unknowable reaction of the market. Overcoming the unfavourable data conditions, this thesis provides a practical and useful tool for policy-making processes. The thesis suggests dividing the market by target group and priority level based on their PV potentials, demographic, and economic status. Hanoi and Ho Chi Minh City should be classified as the highest priority cities for policy focus based on its high potential and robust internal economic and demographic conditions.

This thesis also provides systematic guidance to help policymakers designing political strategies to support market development. The different possibilities of different metering models concerning LCOEs and grid tariffs are considered. The business model indicates that residential customers can sell generated electricity on the grid to the system operator. The self-consumption model indicates that consumption of PV electricity takes place directly at the house/building—either immediately or delayed through the use of storage systems. For example, only projects with total costs and discount rates lower than 850 Euros/kWh and 8% respectively can be beneficial in the current market. With total costs from 650-850 Euros/kWh, the only attractive investment option is the business model, while total costs lower than 650 Euros/kWh create a choice between the business and the self-consumption models possible for their rooftop PV projects. For self-consumption, there is no clear strategy, except for improving the situation by continuing to increase grid tariffs annually. Consumers must, however, wait until around 2025 when their grid tariff should rise to 8.7 cents/kWh and self-consumption will become attractive, but this date could be sooner if costs for solar technology continue to decrease. By simulating the rooftop PV market in different projected FITs, the government is recommended to consider their tariff strategies carefully. In the case of changing the average FiTs from 8.83 to 9 Euro cents/kWh and establishing regional FITs, they can activate an additional 16% of the total market, equivalent to 56 TWh potential and a possible of 28 million Euro of extra profits. However, if they would reduce the FiTs to 7.79 Euro cents/kWh, it would deactivate 60% of the rooftop PV market and would reduce total market benefits by 900 million Euro.

## 4.4 Willingness To Pay and Social Acceptance of decentralised PV

Analyzing public opinion toward RE is crucial due to the influence it can have on policy creation. The research has suggested an important link between public opinion and public policy. Public opinions that have become a hot field of research are growing intensively through advanced computing technique.

Paper 4 uses interdisciplinary approaches by integrating theoretical ideas from the social psychology of the Theory of Planned Behaviour (TPB) and from the market response of conjoint analyses, which are designed to reveal the self-interest of a respondent, to tackle the questions. The psychological TPB measures personal acceptance, which provides a parsimonious explanation of the informational and motivational influences on individual behaviour (Icek Ajzen 1991). The conjoint analysis, measuring the WTP, is used to determine how people value different attributes (feature, function, benefits) that make up an individual product or service (Ratcliffe 2000). These methods allow for simulating random taste variations, unrestricted substitution patterns, and correlations in unobserved factors over time. Combining both questions of SA and WTP for residential PV in one survey allows us to extend our analysis beyond literature with tracking the gap between a person’s perception toward the product and reaction in the store. In this manner, the main contributions of this thesis in SA and WTP for residential PV are:

- Discover the econometric models explaining the relationship between impact factors of SA and WTP, SA and WTP.
- Identify and compare drivers, mediators and moderators of the two concepts and then to combine them to support each other in order to provide robust policies.
- Identify the gap between a person's perception of the product and his/her behaviour in the marketplace.

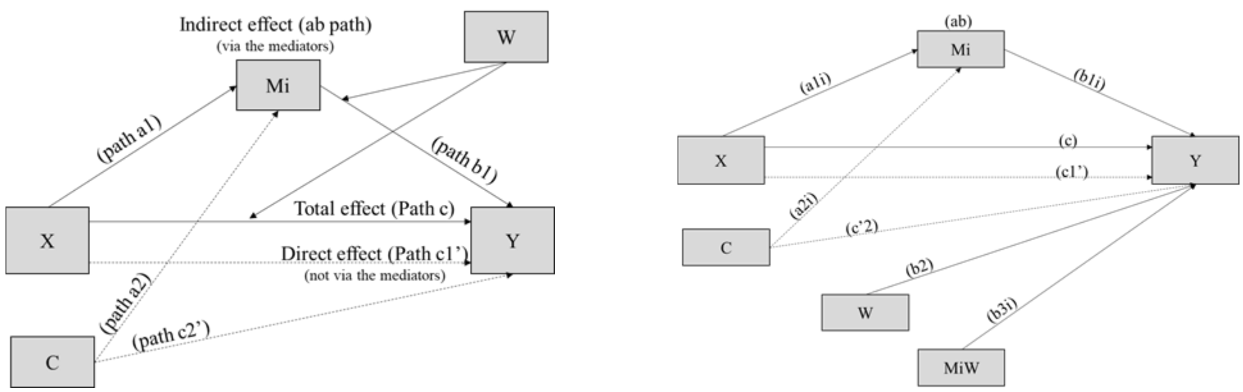
### 4.4.1 Predictive and prescriptive analyses

Predictive analysis is used to predict future outcomes based on current or past data, while prescriptive analysis combines the insights from all previous analysis to determine which action to take in a current problem or decision. One can use data analysis tools and software, which will help to understand, interpret, and derive conclusions based on the research purposes.

Hypothesis testing is used to compare the collected data against hypotheses and assumptions in empirical research. Hypothesis testing assesses if a certain premise is actually true for the collected data set and the population. In data analysis and statistics, the result of a hypothesis test is considered statistically significant if the results could not have happened by random chance.

Logistic regression analyses are conducted to identify the predictors of SA and WTP outcomes with the potential predictors, including demographic variables and extended moderating/mediating variables. Correlation tests are made for each outcome. A hierarchical model building procedure is used to select variables for inclusion in the final set of models. Variables are separated into three conceptual blocks: demographics, moderating factors and determinants of the output. Each block of predictors was regressed separately on each outcome in a logistic regression model. Significant predictors ($p < 0.05$) in any block model are retained in the set of final models used to estimate the simultaneous effects of predictors. This procedure ensures the inclusion of the same set of participants in each outcome and to facilitate interpretability of results. Three interactions are also considered for each outcome to provide an exploration of moderation effects. All variables in an interaction block model with a significant interaction term for a given outcome are included in the final model for that specific outcome.

A regression model with the bootstrapping function of 20000-50000 bootstrap samples is used to perform testing of three main groups of hypotheses, which have PV knowledge, Acceptance and Price elasticity as dependent variables, respectively. Regular, mediator and moderator regression models are run to test the statistical significance and to find the best explanation for the independent variables— the level of confidence for all confidence intervals in output 95%. A heteroscedasticity consistent standard error and covariance matrix estimator are used. The F-test is used to test the statistical significance of the model and the critical values for one-tailed t-tests greater than 2.33 (significance level =1%) was applied for each independent variables.




(a) (b)

*Figure 14. Statistical diagrams for the moderated mediation model: (a) concept used in this paper and (b) the concept interpretation. Illustrated using a directed acyclic graph showing the causal pathways between target variable X and outcome Y, mediators (M_i), moderate (W), and measured covariates (C). (Khuong et al., 2020b)*

The concept of the model with one target variable (X) and one final behavioural output (Y), is illustrated in Figure 14. X has both direct (c1'-path) and indirect (through M with a-path and b-path) effects on Y. The total effect is c-path, which is the summary of c1'-path and ab-path. The effects between mediators are d-path which is not illustrated in Figure 14 to simplify. Covariates (C), characteristics of the participants in an experiment, are included in all models to strengthen the results' validity.

W might moderate the indirect and/or direct effect of X on Y It means the effects of X on Y are conditional, depending on the value of W. There are two locations within the model where W may serve as a moderator: the direct effect of X on Y and the effect of X on M.

### 4.4.2 The moderated mediation of SA and WTP and their driving factors

This study found out that the market is driven by four main factors, including two demographic factors (Income and Age-Family-Children) and two psychological factors (environmental interest and PV knowledge). Rooftop PV has the potential for residential self-sufficiency since all the driving factors are the projected growing indications in Vietnam. These factors are projected to continue increasing in all scenarios without any strong external impacts such as policy and force in the national master plan of Vietnam (Ministry of Planning and Investment Portal 2020).

Literature has shown economic growth motivates renewable energy use in Vietnam (Khuong et al. 2019), and yet more evidence that income growth leads to increasing SA toward PV in society is disclosed from our study. It promises a bright future for residential PV in a developing country with rapid economic growth like Vietnam. As income increases, people seem to be less concerned about price and brand of the product but more concerned about the guarantee.

The demographic factors of Age, Family status, Children has a stronger direct effect on personal acceptance than income on SA, as well as on other variables, especially on the Environmental interest. There is a turning point when a customer changes his/her status from single to married; his/her SA toward residential rooftop increases dramatically.

The price sensitivity is explained by income and place of residence variables through personal attitude and acceptance variables. Since the price sensitivity is a negative value, income increases lead to lower sensitivity. People who live in the urban area seem to be less sensitivity with the price. Environmental interest can significantly strengthen the relationship between income and price sensitivity. Environmental interest increase lessens the price sensitivity directly and indirectly.

All the five considered attributes of a residential PV system, including total investment (price), guarantee, saving and manufacturer (or product origin) show their relative importance to others in a person’s decision in buying a PV system for their home. Meanwhile, the different saving potentials and scheme support are less significant in people’s decision-making process.

The calculated WTP values show that people, in general, would pay about 100 Euro more for a product with a guarantee. However, it does not matter for them if the guarantee is 10 or 15 years. Among all the supplier countries, Japan and Germany are the favourites by the public. Accordingly, consumers are willing to pay around 30 to 60 Euro more for these products than for products from Korea, Taiwan and China, respectively.

### 4.4.3 The differences between SA & WTP

Residential PV generally gets a positive reaction from the random respondents with more than 60% of them finding residential PV a purchasable product. However, the acceptance level seems to be less optimistic, with only around 20% of the population having a SA level at 4/5 and above. A positive signal of WTP toward residential PV with more than 55% of participants willing to pay for the product is recognised. However, along with this, almost 20% of respondents are completely neglecting the product. Most of the higher-approval people are on average 40-49 years old, with the highest level of knowledge about PV system (average of 2.75/5), the highest electricity bill (3.15/5) and the highest income (5/8).

This study also discovers four main results behind the refusal behaviour of the public toward purchasing rooftop PV for their own house.

- Relatively low Environmental interest in society. Despite the decisive role on SA and WTP, Environmental interest level in Vietnam remain relatively low at the average of 2.88/5.
- Lack of knowledge. By comparing between PV owner and people who willing to buy PV product at any price (Unconditional WTP), at a certain price (Conditional WTP) and who will very unlikely buy PV product at all (Unlikely), we see that the PV knowledge of the PV owner is not so much better than the other, around 2.8/5 and 2.3/5, respectively.
- Lack of understanding about customer preference. People do not buy products solely based on price. They do factor in price with around 25% of their decision, but they will buy based on the guarantee and brand, which leads to another issue. It is an access problem. People prefer a product from Germany or Japan. However, they are not available everywhere and also expensive.
- Not yet an essential-product. Consumers will reach out to the product when their electricity bill and Income reach a certain level.

It may be time for the policymakers and stakeholders to evaluate why the market is not working and whether they target the right market with the right policy and message.

### 4.4.4 Environmental interest are game-changers

Environmental interest plays a central role in the whole PV market situation. In case people are more interested in the topic, they tend to have a higher level of SA, but at the same time are more sensitive to price changes. However, with people's increased concern more about environmental problems, they seem to be more confident in making the decision and consider investing in PV as less risky than the other people. PV knowledge does not have a direct impact on WTP, but it is a motivation to raise an environmental interest, and it affects directly on SA towards PV product.

Among all considered variables, Environmental interest plays the most important role as the target variable or significant predictor causing SA and WTP. The results indicate that people's higher interest in protecting the environment will potentially translate into positive SA and increase the likelihood of adoption. This finding is generally in line with the hypotheses and confirm previous research that Environmental interest has a direct and positive effect on WTP (Schwarz, 2007; Claudy et al., 2011) and is the most matters to people's WTP (Maichum et al., 2016; Li et al., 2019). In contrast to previous studies, this study emphasises the importance of the indirect effect of Environmental interest not only on WTP but also on personal SA, Attitude and Perceived behavioural control.

The indirect effect of Environmental interest is almost equally important to the direct effect, as reported coefficient of .073 and .064 on SA. It means the SA level is regulated passively and proactively through individual Environmental interest. However, there is a large deviation between direct and indirect effects of Environmental interest on WTP. The conditional indirect effects of Environmental interest (X) on Price sensitivity (Y) through moderators. It can indicate that with people's increased concern about environmental problems, they seem to be strongly motivated in deciding on investing in PV, even though they may not see the item less risky than the other people do.

Apart from that, PV knowledge does not have a direct or indirect impact on WTP, but a slightly indirect effect on SA. Environmental interest is the original motivation to raise PV knowledge. It means that if the government wants to encourage people to use residential PV, the first thing they should do is to draw people's attention to the environmental matter, which will associate with a higher chance of SA for the PV product.

# 5. Conclusion and outlook

This thesis utilises different approaches to solve the problem of the energy transition in developing countries under resource constraints. With the main theme of the study revolving around the different aspects that influence the development of renewable energy, this thesis exploits the extremes of renewable energy developing potential by using both top-down and bottom-up approaches. The thesis gives insights and recommendations about different multi-perspective approaches and combining different data mining methods in order to determine the most beneficial, cost-effective and immediate impact for renewable energy, especially decentralised PV, in the future.

In the first part of the thesis, a top-down approach is used to perform an extensive multi-level analysis of the relationship between different sectors, regions, areas within the energy transition framework in developing countries, particularly in ASEAN countries during 1995 to 2013. By employing a new combined Correlation and Decomposition approach at country and city levels, this thesis investigates the determinants of energy consumption and renewable energy expansion. An Impact Matrix is developed to position and interpret the relative push (e.g., policy) and pull (e.g., market) impacts on renewable energy development, and to derive policy recommendations for countries and sectors. The factors affecting energy consumption and renewable energy development are identified for each sector and country. The connection between urbanisation, economic growth, and energy consumption in the context of cross-country and cross-sector analyses is investigated to extend the local boundary of the energy transition to the whole ASEAN boundary. The multi-level (across countries and sectors) index decomposition method is employed to analyse urbanisation, energy mix, energy intensity, and activity effects on energy demand.

The appropriate policies are provided based on the multi-level comparison of the urban effect on energy consumption and renewable development. The gap between national policies and local governance in ASEAN is identified, especially in urban areas, which requires attention to ensure future target fulfilment. The strong effect of urbanisation on domestic energy consumption urges policymakers to focus on finding an optimal solution for decentralised and efficient energy systems for urban areas.

In the second part, this thesis focuses on researching rooftop PV potential and how to promote an efficient uptake of rooftop PV. Techno-socio-economic models are used to determine PV potentials, a promising renewable energy type in most of Asian EMDCs, and to investigate customer behaviours toward rooftop PV.

To solve the problem of the existing ineffective framework hindering rooftop PV development, this thesis develops a more accurate, cost-effective, and robust potential assessment method for emerging and developing economies. This techno-economic model can be employed where detailed, accurate data on buildings, their outlines, and associated infrastructure are lacking. It represents an improvement beyond state of the art and has an absolute error of about 5% compared to detailed bottom-up city models, which is very low for a method at this spatial scale and resolution. Uncertainties relating to the input data are significant but have been considered in the sensitivity analysis, which should be borne in mind when interpreting the results. The rooftop PV market changes are simulated regarding different input changes and estimates of the effect of various policy designs, including changing the Feed-in tariffs, grid tariffs, and technology development. However, in a resource-constrained environment with high short-term costs and uncertain economic benefits, the government needs to make smart investments and introduce supporting mechanisms in solar technologies by using target defining tools based on economic-technological-demographical potential prioritization instead of the current single perspective prioritization.

To solve the problem of the lack of understanding customer behaviour toward renewable energy in ASEAN, this thesis analyses Social Acceptance and Willingness To Pay for rooftop PV in Vietnam as a case study. The psychological Theory of Planned Behaviour is used to measure Social Acceptance, which provides a parsimonious explanation of the informational and motivational influences on individual behaviour. For measuring the Willingness To Pay, a conjoint survey is used to determine how people value different attributes (feature, function, benefits) that make up an individual product or service. This thesis contributes to the literature of customer behaviour toward renewable energy by incorporating explanatory variables referring to attitudinal and psychological traits as sources of heterogeneity. In particular, in applied economics, different attitudinal and psychological theories have been used: for example, the implementations of Ajzen's Theory of Planned Behaviour to rationalize differences in stated choice behaviour and how this correlates with real choice. The present contribution demonstrates, yet again, the advantages of bringing into applied economics theories derived from other disciplines to enrich the explanatory power of more conventional approaches by means of theoretically meaningful constructs. Based on the moderated mediation models, this study identifies the factors that boost customers intention to accept and adopt residential PV and suggests policymakers and stakeholders act accordingly to promote residential PV development in developing countries. Policymakers should mostly focus on promoting environmental interest among society by providing environment-friendly awareness and promotion activities. This education can be directly translated to higher Social Acceptance and Willingness To Pay as well as indirectly to more positive attitudes and perceived behavioural control, which can also lead to higher Social Acceptance and Willingness To Pay. Stakeholders should divide the market into different segments and then develop a different strategy for each segment separately. Moreover, they should establish a market in urban and suburban areas instead of focusing on rural areas in developing countries.

In general, urbanisation is concluded as the main cause of energy consumption increase in ASEAN, but at the same time, it creates momentum for renewable energy development, especially in urban areas. Suggestions are provided to use urbanisation as the main motivation for renewable energy development in ASEAN. The evidence of a high-concentration of rooftop solar PV potentials as well as a high acceptance of people toward residential rooftop PV in urban areas in Vietnam is discovered. Residential PV is not yet considered as an essential good for a living but a lifestyle product with much greater attention and intention to purchase from the public in urban areas.

Future work will be the further development of PV potential assessment and customer behaviour investigation. For PV potential assessment, the accuracy of the assumptions relating to the building location, size, orientation, and shadings impacts are country-specific and need further research to be employed elsewhere. One promising avenue in this context is the combination of open mapping data with satellite images, in order to automatically identify suitable geometries for rooftop PV (Mainzer et al., 2017). By further validating the top-down results from this study with bottom-up results from 3D models (such as Effigis Geo-Solutions 2018), the method could be improved and applied to other contexts. For further customer behaviour investigation, based on encompassing the adoption process within different social groups and analyzing the demographic and cause of resistance of different adoption groups, future work can build the diffusion curve and introduce a method to identify inertia-diffusion between the early adopters and more widespread use. The evidence of the existence of different segments of the population can be further analysed. The next study will aim to cluster the determined segments into the five market groups of Innovators, Early Adopters, Early Majority, Late Majority, and Laggards.

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# Part B: Publications

1. **Phuong M. Khuong, Russell McKenna, Wolf Fichtner. Multi-level decomposition of ASEAN urbanisation effects on energy. International Journal of Energy Sector Management. DOI 10.1108/IJESM-12-2018-0002. May 2019**

2. **Phuong M. Khuong, Russell McKenna, Wolf Fichtner. Analysing drivers of renewable energy development in Southeast Asia countries with Correlation and Decomposition methods. Journal of Cleaner Production · DOI: 10.1016/j.jclepro.2018.12.192. December 2018.**

3. **Phuong M. Khuong, Russell McKenna, Wolf Fichtner. A Cost-Effective and Transferable Methodology for Rooftop PV Potential Assessment in Developing Countries. Energies. DOI: 10.3390/en13102501. May 2020.**

4. **Phuong M. Khuong, Fabian Scheller, Russell McKenna, Dogan Keles, Wolf Fichtner. Willingness To Pay for residential PV: reconciling gaps between acceptance and adoption. Working paper series in Production and Energy. KIT. DOI: 10.5445/IR/1000124530. October 2020.**

# Multi-level decomposition of ASEAN urbanization effects on energy



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## Abstract

**Purpose** – The connection between urbanization and energy consumption in the context of cross-country and cross-sector analyses is poorly understood, especially in the Association of South East Asian (ASEAN). This paper aims to present the first extensive multi-level analysis of the relationship between urbanization and energy consumption in ASEAN countries from 1995 to 2013.

**Design/methodology/approach** – The multi-level (across country and sector) index decomposition method is used to analyze urbanization, energy mix, energy intensity and activity effects on energy demand. Urbanization is measured by two representative factors, name the urban population and the number of non-agriculture workers.

**Findings** – Despite the decreasing rate of urbanization, its effect on energy consumption has played the most important role since 2000. Since then, the effect has continued to increase at the national and sectoral levels across the whole region. The strongest urbanization impacts are encountered in the residential sector, followed by transportation and industrial sectors with much weaker effects in the commercial sector. The way in which urbanization impacts energy consumption depends strongly on the income level of the country studied.

**Practical implications** – The results provide quantitative relationships between urbanization and energy demand. For example, if the urban population and the non-agriculture workers decreased by 0.1 per cent per year, this would reduce energy demand by 1.4 per cent and 2.6 per cent per year respectively.

**Originality/value** – This contribution provides detailed quantitative insights into the relationships between urbanization and energy demand at sectoral, national and international levels, which are invaluable for policymakers in the region.

**Keywords** Decision-making, Energy sector, ASEAN, Urbanization, End-use models, Decomposition, Energy conversion, Energy balance

**Paper type** Research paper

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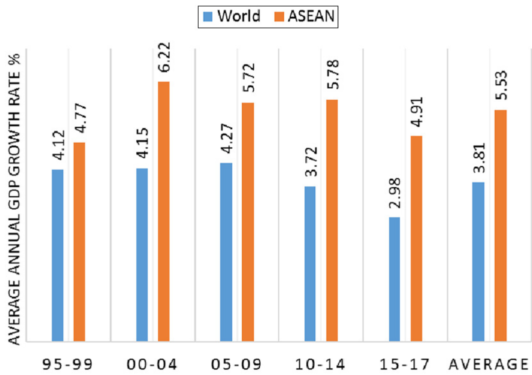
## 1. Introduction

The relationship between energy consumption, economic and demographic changes has been intensively researched, especially for emerging economies such as India and China. Much of this research addresses the challenge of ensuring sustainable development, in the context of resource shortages and reduced environmental quality, while maintaining economic growth (Wang *et al.*, 2013, Wang, 2014, Pachauri and Jiang, 2008, etc.).

These issues also burden many other developing countries such as ASEAN (the Association of South East Asian Nations), whose economy has been growing rapidly since the mid-1980s and has become a growth engine of the global economy[1] (see Figure 1). ASEANs' GDP growth rate is projected to continue to increase at on average 5.2 per cent over the period 2019-2023 (Economic Outlook, 2019). In its 5th State of the Environment Report (SOER 5th, 2017) ASEAN identified the urgent situation of air and solid polution in the region as a result of uncontrolled rapid development. As member countries pursue their economic goals, ASEANs' energy demand is projected to more than double and $CO_2$ emissions to triple by 2040 (ASEAN Energy Outlook, 2017), which would worsen the alarming level of pollution in most of the ASEAN countries due to increasing fossil fuel consumption (Global megatrends, AIMD, 2017).

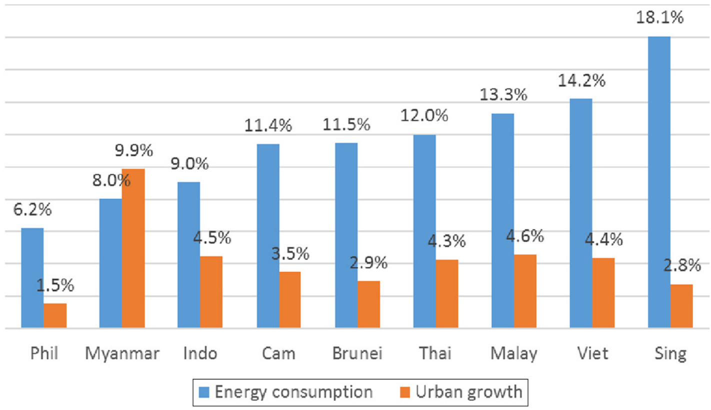
While ASEAN countries have attempted to lessen these problems, a new challenge may be arising in the form of naturally rapid urbanization. Recently, urbanization (refer to section 2 for a detailed definition) in ASEAN has been considerably increasing by 3 per cent per year during the period 1995-2014, higher than the average global rate of 2 per cent per year. Futher urban growth is expected in ASEAN, with the projected percentage of urbanites increasing from today's 47 per cent to 56 per cent in 2030 and 67 per cent in 2050 respectively (UN, 2014). ASEAN governments are finding it difficult to cope with the rapid increases in the urban population, resulting in serious energy-related environmental problems, especially in the pressure of growing demands for constructing basic infrastructure (SOER 5th, 2017).

However, a superficial look shows that energy consumption seems to increase faster in the country with the lower annual urban growth rate in ASEAN, except for the Philippines (see Figure 2). It could mean urbanization reduces energy consumption, and therefore reduces its effects on the environment. Moreover, as urbanization is the main




**Source:** Own calculation based on the database of World Bank, last accessed (3 December 2018)

**Figure 1.** Average annual GDP growth rate over the World and ASEAN from 1995-2017




**Source:** Own calculation based on database of World Bank (2018) and IEA (2018) last accessed (1 December 2018)

**Figure 2.** Average annual energy consumption and urbanization growths in ASEAN between 1995 and 2014

factor driving renewable energy development in the region (Khuong *et al.*, 2019), it may speed up the energy transition process towards higher shares of renewables in the total energy mix, and therefore help to reduce the effect of increasing energy consumption on the environment.

The two possible and contradictory effects of urbanization on energy consumption reveal a problem of lacking or incomplete knowledge on this issue that could impede ASEANs progress towards achieving their sustainable development goals (Global megatrends, AIMD, 2017). Moreover, as ASEAN has deepened cooperation in sustainable development (ASEAN Community Vision 2025), it is necessary to extend the investigation of the effects on energy consumption not only in national sectoral interactions but also international interactions. The literature review in Section 2 illustrates the research gap in comparing the differential impact of urbanization on energy consumption across countries and sectors, as well as discussing the decomposition method over the regression method for investigating the problem. Answering this and related questions is of primary importance for academics and ASEAN policy makers to make a horizontal and vertical scan of the effect on international-national-sectoral scales.

With this purpose, this paper proposes the multi-level Index Decomposition Analysis (IDA) capable of cross-country-sector comparison to investigate the issues related to the relationship between energy consumption, economic growth and urbanization. The paper aims to:

- estimate the urbanization effect and the other contributing effects (population, economic development etc.) on energy consumption changes;
- compare the effects at multi-levels between ASEAN countries; and
- propose some suggestions for policy makers in the context of economic development and urbanization.

The remainder of the paper is structured as follows. Section 2 presents a literature review and thus demonstrates the gaps filled by this study. Section 3 introduces components of the dataset and explains the methodology for assessing the urbanization effect. Section 4 provides the results from multi-level analyses. Section 5 discusses the effects of demographic factors on energy consumption and critically reflects on the methodology used in this paper. Finally, section 6 gives a conclusion and outlook, including some suggestions for policymakers about urbanization-energy issues and further research requirements.

## 2. Literature review

This section aims to review, summarize, and synthesize the arguments and ideas of previous research that focused on analyzing the relationship between urbanization and energy consumption (see Figure 3). After scrutinizing these studies, we identified certain research areas that have been given little attention in this area. These areas are highlighted in blue in Figure 3 to demonstrate this paper's novelties, and a detailed explanation is given in the following sections.

### *2.1 Issue 1 – lacking multi-level comparisons in research scope*

As shown in the first column of Figure 3, previous research mostly focused on proving and comparing the effects of urbanization on energy consumption between countries with similar economic conditions, such as in developed countries (Parikh and Shukla, 1995; Liddle and Lung, 2014; York, 2007), and developing countries (Jones, 1989, 1991; Madlener and Sunak, 2011; Mishra *et al.*, 2009; LENZEN *et al.*, 2006). Or they investigated the relationship in one country within different energy consuming sectors such as Larivìere and Lafrance (1999) in Canada, Wang *et al.* (2013) in China, Halicioglu (2007) in Turkey, Ewing and Rong (2008) in the USA.

Some researchers investigated the effect between different countries for one sector such as transportation, agriculture (Jones, 1991; Liddle and Lung, 2014; Poumanyvong and Kaneko, 2010), building energy consumption (Li and Yao, 2009) and national residential energy use (Holtedahl and Joutz, 2004; Poumanyvong *et al.*, 2012b).

However *the comparison of relative impacts of urbanization between sector-sector and sector-country has not been carried out in general, as well as specifically for ASEAN.*

### *2.2 Issue 2 – limited results due to the method*

*2.2.1 Revealing general relationships but not individual factor contributions.* The regression analysis with dynamic and statistical models was used in most studies in this field, accounting for 34/45 studies. However, this method can reveal general relationships but not individual factor contributions (Liu, 2009). Liu (2009) concluded that using regression showed only unidirectional Granger causality between China's urbanization and its total energy consumption, but to find out the contribution share of urbanization on energy consumption required a decomposition analysis.

*2.2.2 Obstacles in data processing and analysis.* Regression requires large data sets, which are quite challenging to obtain for developing countries (Zeng *et al.*, 2017), such as ASEAN, where the database has only been developed over the past 15 years or so. Moreover, regression models using cross-sectional data (Jones, 1991; York, 2007; York *et al.*, 2003) as well as time-series data (Liu, 2009; Holtedahl and Joutz, 2004), and even panel data (Poumanyvong *et al.*, 2012b) typically overlook the comparison with the base year, i.e. using data with current currency instead of constant currency [purchasing power parity (PPP)]. Liu (2009), York (2007) and Zeng *et al.* (2017) claimed the method runs into difficulties when dealing with unbalanced data (i.e. a panel that has some missing data for at least one year or one period, or for at least one entity), and nonlinear data in explaining the relationship and the changes.

| | Research scope | | | | | Method | | | Considered relationships | | | | | | Results | | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Author, year** | **M** | **C** | **P** | **S** | L | **R** | **O** | D | **GDP** | **EC** | **Em** | In | EI | Others | **S** | **L** | |
| **Parikh, Shukla 1995** | X | | | | | X | | | X | X | | | | | + | | Sus |
| **Imai 1997** | X | | | | | X | | | X | X | | | | | + | | |
| **York 2007** | X | | | | | X | | | X | X | | | | | + | + | ED |
| **Lenzen *et al.* 2006** | X | | | | | X | | | X | X | | | | | -/+ | | Sus |
| **Fang *et al.* 2012** | X | | | | | X | | | X | X | | | | | - | | CC |
| **Liddle, Lung 2014** | X | | | | | X | | | X | X | | | | | - | | Sus |
| **Jones 1989** | X | | | | | X | | | X | X | X | | | | + | | Eco |
| **Poumanyvong, Kaneko 2010** | X | | | | | X | | | X | X | X | | | | | +/- | Sus |
| **Sharif Hossain 2011** | X | | | | | X | | | X | X | X | | | | | + | Eco |
| **Poumanyvong *et al.* 2012** | X | | | | | X | | | X | X | X | | | | | + | Eco |
| **Al-mulali *et al.* 2013** | X | | | | | X | | | | X | X | | | | + | | Sus |
| **Sadorsky 2013** | X | | | | | X | | | X | | | X | X | | | -/+ | CC |
| **Li, Lin 2015** | X | | | | | X | | | X | X | X | X | | X | -/+ | | Eco |
| **Asif *et al.* 2015** | X | | | | | X | X | | X | X | | X | | | | + | Eco |
| **Burney 1995** | X | | | | | | X | | X | X | | | | | + | | Eco |
| **Mishra *et al.* 2009** | X | | | | | | X | | X | X | | | | | - | + | Eco |
| **Wang 2015** | X | | | | | X | | | | X | X | | | | | + | Sus |
| **Zhang *et al.* 2017** | X | | | | | X | | | X | X | X | | | X | | | RE |
| **Jones 1991** | | X | | | | X | | | X | | | X | X | | + | | ED |
| **Lin *et al.* 2008** | | X | | | | X | | | X | | | | | X | | + | CC |
| **Liu 2009** | | X | | | | X | | X | X | X | | | | X | + | ~ | ED |
| **Ghosh, Kanjilal 2014** | | X | | | | X | | | X | X | | | | | | ~ | Sus |
| **Belloumi, Alshehry 2016** | | X | | | | X | X | | X | | | X | X | | + | + | ED |
| **Wei *et al* 2003** | | X | | | | | X | | X | X | | | | X | -/+ | | Eco |
| **Li *et al.* 2011** | | X | | | | | X | | X | X | | | | X | -/+ | | ED |
| **O'Neill *et al.* 2012** | | X | | | | | X | | X | X | X | | | | | ~ | ED |
| **Yang *et al.* 2015** | | X | | | | | | X | X | X | | | | X | | -/+ | RE |
| **Franco 2017** | | X | | | | X | | | | X | X | | X | | | + | Sus |
| **Newman, Kenworthy 1998** | | | X | | | X | | | X | X | | | | | - | | Sus |
| **Wang 2014** | | | X | | | | | X | X | X | | | | X | | -/+ | ED |
| **Kenworthy, Laube 1996** | | | | X | | X | | | X | X | | | | | - | | Sus |
| **Isabelle Larivi`ere 1999** | | | | X | | X | | | X | X | | | | | - | | ED |
| **Jiang, O'Neill 2007** | | | | X | | X | | | X | X | | | | | | | ED |
| **Ewing, Rong 2008** | | | | X | | X | | | X | X | | | | | - | | ED |
| **Adom *et al.* 2012** | | | | X | | X | | | X | X | | | | | + | | ED |
| **Li, Yao 2009** | | | | X | | X | | | | X | | | | X | | | ED |
| **Sun *et al.* 2014** | | | | X | | X | | | | X | | | | X | | + | ED |
| **Holtedahl, Joutz 2004** | | | | X | | X | X | | X | X | | | | | + | + | ED |
| **Halicioglu 2007** | | | | X | | X | X | | X | X | | | | X | | + | ED |
| **Shahbaz, Lean 2012** | | | | X | | X | X | | X | X | | X | | X | | + | ED |
| **Shen *et al.* 2005** | | | | X | | | X | | | X | | | | | + | | Eco |
| **Jiang, Lin 2012** | | | | X | | | X | | | X | | X | | | | + | Eco |
| **Fan *et al.* 2017** | | | | X | | | | X | X | X | | | X | | | + | ED |
| **Liu *et al.* 2018** | | | | X | | | | X | X | X | | | | | | + | ED |

**Notes:** Acronyms – Scope: M: Multi-country, C: Country, P: Province, S: Sector, L: Linking between multi-country and country and sector levels. Method: R: Regression, O: Other methods, D: Decomposition. Considered relationship: GDP: gross domestic product, EC: energy consumption, Em: emission, In: industrialization, EI: energy intensity. Results: S: short term, L: long term, +: Positive effect, -: negative effect. Purpose: ED: energy demand, Eco: Economic development, Sus: sustainable development, CC: climate change. Blue column: covered by this research

**Figure 3.** Summary of relevant literature on the relationship between urbanization and energy consumption

Furthermore, when analyzing individual sectors or whole countries, many approaches overlook the volatility and interactions among types of energy users. The combined resource requirements of energy input in manufacturing and transportation activities, for example, may increase energy consumption end-used but reduce energy utilization in residential areas. This offsetting impact could eliminate energy consumption fluctuations, i.e. it could erroneously imply unchanged or only slightly changed total energy consumption. If only the total energy consumption is considered, the regression typically overlooks the hidden effect from this phenomenon such as inefficient energy use, and issues relating to energy system structure and economic structure.

*2.3 Issue 3 – partly conflicting results*

When considering multi-countries, the results often present contradictory effects (see Figure 3). Two-thirds of the reviewed studies revealed a positive correlation between urbanization and energy consumption in multi-country approaches as well as in sectoral-level research. For example, with the "fixed effect[2] "Jones (1989, 1991), Parikh and Shukla (1995), York (2007), Shahbaz and Lean (2012) and Elliott *et al.* (2014) determined an urbanization elasticity of around 0.29-0.66 for energy consumption. On the other hand, some studies identified a negative link between urbanization and energy consumption at country level such as Lariviere and Lafrance (1999) conducted for 45 cities in Canada, and Mishra *et al.* (2009) analyzed panel data for Pacific Islands from 1980-2005.

At the sector level, while some authors mention that urbanization causes several important reductions in residential energy use e.g. Ewing and Rong (2008) researching in the USA and Wang (2014) studying China, others (such as Holtedahl and Joutz, 2004) conclude that urbanization is responsible for energy use increasing in this sector. The same contradictory findings were obtained for the transportation sector between Liddle and Lung (2014), who showed a negative effect in 23 OECD countries and Poumanyvong *et al.* (2012a), who found a positive influence of urbanization in 92 countries.

The controversy in earlier literature can be at least partly ascribed to differences in methodologies, data and economical and/or regional characteristics. Therefore, it is necessary to investigate further the relationship between urbanization, energy use and other factors (such as GDP, industrialization, emissions) by placing it within a region-country-sector context.

*2.4 Issue 4 – the urbanization definition*

One of the common issues encountered in the research is the definition of "urbanization". Most of the previous studies (Jones, 1991, 1989, 2004; Parikh and Shukla, 1995) considered the variable "urbanization" as the number of people living in urban areas. The term "urbanization growth rate" is used to refer to the growth rate of urban population in each considered period. Urban areas are categorized by urban morphology such as cities, towns, conurbations or suburbs.

Other authors (Ewing and Rong, 2008) used several forms of urbanization when investigating urban effects on energy use, including the percentage of the population living in urban areas, the population density in urban areas, and the average apartment size, which more accurately reflects the specific energy consumption in the residential and commercial sectors (Liddle and Lung, 2014; Liu and Xie, 2013). In researching the residential sector, Pachauri and Jiang (2008) compared India and China and used the number of households as an urbanization indicator.

The influence of urbanization on energy consumption changes based on the urbanization form considered. Therefore, this paper uses the most common urban indicators in the research field, namely urban population, symbolized as Urban 1, and non-agriculture employee, symbolized as Urban 2, to conduct the investigation.

*2.5 The potential of decomposition analysis*

The decomposition analysis has frequently been used in energy-related studies from the late 1970s until the present to analyze the impact of changes in product mix on energy consumption (Ang and Zhang, 2000; Hoekstra and van den Bergh, 2003). It was introduced with two techniques for decomposing indicator changes, structural decomposition analysis (SDA), which analyzes the input-output effect, and the index decomposition approach (IDA), which compares different effect factors. In assessing the influence of urbanization on energy consumption, Liu (2009) suggested the decomposition method as a new approach.

Wang (2014) and Liu *et al.* (2018) applied SDA to investigate the effects of China's urbanization on residential energy consumption. Wang (2014) conducted independent research on household usage and product usage by dividing total energy consumption into residential energy consumption (REC) and production energy consumption (PEC). Liu *et al.* (2018) analyzed the changes in indirect (IEC) and direct (DEC) energy consumption in household. However, both studies suggested urbanization has a positive effect on household energy consumption.

Secondly, Yang *et al.* (2016) and Fan *et al.* (2017) used IDA to assess the impact of urbanization on renewable energy consumption growth and on residential energy consumption in China respectively. Yang *et al.* (2016) focused on the macro analysis and concluded that the urbanization effect is insignificant for renewable energy use, while Fan *et al.* (2017) concluded that urbanization contributes 15.4 per cent of the residential energy consumption increase.

This paper therefore uses decomposition analysis to investigate the contribution of urbanization to energy consumption growth with a multi-perspective analysis including national and sectorial comparison, order to explore the diverging influences from nations to sectors.

## 3. Methodology

*3.1 Method*

IDA is used in this study to implement index approach and to conduct time-series analysis and cross-country comparisons. An the advantage of IDA over SDA is a lower data requirement, and the ability to assess the effect of a shift in the economic shares and energy mix. Moreover, IDA is based on the specification of the decomposition, whereas SDA has focused attention on distinguishing a large number of input-output effects. IDA is suitable for a top-down approach, whereas SDA is suitable for a bottom-up approach (Hoekstra and van den Bergh, 2003; Wang *et al.*, 2017).

As a result, with limited available data, this paper uses the IDA method with a top-down approach to break down energy consumption data to gain insight into its compositional sub-systems such as sectorial energy demand (commercial, transportation, industrial, residential) in a reverse-engineering technique. The energy consumption characteristics are analyzed in detail until they are reduced to their base elements in terms of the effect of each factor on each sector. This paper separates five factors including activity change (activity effect), modification of activity composition (structure effect), changes in sectorial energy intensity (intensity effect), adjustment in used energy types (energy mix effect) and especially urbanization changes (urban effect).

This paper suggests two approaches to assess the urban effect. The first one examines the energy consumers and estimates all effects mentioned above, except for the structure effect. The second approach analyzes the structure effect by separating the activity effect into the two effects including structure and production effects, to provide more details of economic growth and economic structure change than the first case.

For the first approach, assume that E is an aggregate composed of $n$ factors ($x_1, \ldots, x_n$) and from period 0 to T the aggregate changes from $E_0$ to $E_t$. The objective is to derive the contribution of the $n$ factors to the change in the aggregate, which can be expressed as given in equation (1):

$$\Delta E_{tot} = E_t - E_0 = \Delta E_{x1} + \ldots + \Delta E_{xn} + \Delta E_{rsd} \tag{1}$$

Implementing the concept to analyze the effect of urbanization on energy consumption for each sector is given in equation (2):

$$E_j = \sum_i \frac{E_{ij}}{E_j} \times \frac{E_j}{VA_j} \times \frac{VA_j}{D} \times D \tag{2}$$

whereby:

$E_i$: Energy consumption of energy type i (including fuel, electricity and renewables) in sector j;

$E_j$: Total energy consumption in sector j (including commercial, industrial, residential, and transportation);

$VA_j$: Typical activity for sector j (value added for industrial, commercial and transportation; number of households for residential); and

D: Demographic factor (Population or Urban 1 or Urban 2).

Foreshortening equation (2) by replacing $\frac{E_i}{E_j} = M_{ij}, \frac{E_j}{A_j} = I_j, \frac{VA_j}{D} = A_j$ we have equation (3):

$$E_j = \sum_i M_{ij} \times I_j \times A_j \times D \tag{3}$$

To separate the effect of each of the factors, we calculate the change of energy consumption between years 0 and T following each component by using a logarithmic mean function L (a, b) = (a − b)/(ln a − ln b). As a result, the final decomposition function is carried out in equation (4):

$$\Delta E_j = \Delta E_{mix,ij} + \Delta E_{int,j} + \Delta E_{act,j} + \Delta E_{D,j} + \Delta E_{rsd,j} \tag{4}$$

with:

- $\Delta E_{mix} = \sum_i L\left(E_i^t, E_i^0\right) \ln\left(\frac{M_{ij}^t}{M_{ij}^0}\right)$ – Energy mix effect: the change in the aggregate associated with a change in the mix of energy used type;
- $\Delta E_{int} = \sum_i L\left(E_i^t, E_i^0\right) \ln\left(\frac{I_j^t}{I_j^0}\right)$ – Intensity effect: the change in the aggregate associated with changes in the energy intensities;
- $\Delta E_{act} = \sum_i L\left(E_i^t, E_i^0\right) \ln\left(\frac{A_j^t}{A_j^0}\right)$ – Activity effect: the change in the aggregate associated with a change in the overall level of the activity;

- $\Delta E_D = \sum_i L\left(E_i^t, E_i^0\right) \ln\left(\frac{D_t}{D_0}\right)$ – Demographic effect: the change in the aggregate associated with a change in demographic factor; and
- $\Delta E_{rsd}$ – Residual term.

The cumulative effect's formula is therefore:

$$\Delta E = \sum_j \Delta E_j = \sum_j \Delta E_{mix,ij} + \sum_j \Delta E_{int,j} + \sum_j \Delta E_{act,j} + \sum_j \Delta E_{D,j} + \sum_j \Delta E_{rsd,j} \tag{5}$$

where $\Sigma_j \Delta E_j$ is the total of the change of energy consumption between years 0 and T in sector j.

In a second approach, this paper implements the same method for the country calculation with an additional factor that is the economic structural factor. Therefore, it is capable of comparing each factor's change between sectorial and national levels. To estimate the effect of the shift in the mix of products (production structural effect), the article proposes adjusting the calculation to eliminate residential energy consumption from total energy consumption. Thus, the final effects in this case reflect the ratio of the final energy use of three sectors including commercial, industrial and transportation sectors.

The formulas are converted to equation (6):

$$E_j \sum_i \frac{E_{ij}}{E_j} \times \frac{E_j}{VA_j} \times \frac{VA_j}{\sum_j VA_j} \times \frac{\sum_j VA_j}{D} \times D \tag{6}$$

Foreshortening equation (6) by replacing $\frac{E_i}{E_j} = M_{ij}$, $\frac{E_j}{VA_j} = I_j$, $\frac{VA_j}{\sum_j VA_j} = S_j$, $\frac{\sum_j VA_j}{D} = A_j$ we have equation (7):

$$E_j = \sum_i M_{ij} \times I_j \times S_j \times A_j \times D \tag{7}$$

The cumulative effect is calculated following equation (8)

$$\Delta E = \Delta E_{mix,ij} + \Delta E_{int,j} + \Delta E_{str,j} + \Delta E_{act,j} + \Delta E_D + \Delta E_{rsd} \tag{8}$$

With:

- $\Delta E_{mix} = \sum_i L\left(E_i^t, E_i^0\right) \ln\left(\frac{M_{ij}^t}{M_{ij}^0}\right)$ – energy mix effect: the change in the aggregate associated with a change in the mix of energy used type;
- $\Delta E_{int} = \sum_{ij} L\left(E_{ij}^t, E_{ij}^0\right) \ln\left(\frac{I_i^t}{I_i^0}\right)$ – intensity effect: the change in the aggregate associated with changes in the energy intensities;
- $\Delta E_{str} = \sum_{ij} L\left(E_{ij}^t, E_{ij}^0\right) \ln\left(\frac{S_i^t}{S_i^0}\right)$ – economic structure effect: the change in the aggregate associated with a change in the mix of the activity by sub-sector;

- $\Delta E_{act} = \sum_{ij} L\left(E_{ij}^{t}, E_{ij}^{0}\right) n\left(\frac{A_j^t}{A_j^0}\right)$ – activity effect: the change in the aggregate associated with a change in total value added per capita;
- $\Delta E_{D} = \sum_{ij} L\left(E_{ij}^{t}, E_{ij}^{0}\right) n\left(\frac{D_t}{D_0}\right)$ – demographic effect: the change in the aggregate associated with a change in demographic factor.
- $\Delta E_{rsd}$ – Residual term

This paper considers different demographic factors including population and two urbanization indicators to compare their contributions to energy consumption changes among the different factors. The first urbanization indicator is the total population living in urban areas, named Urban 1, reflecting the general rural-urban migration. The second is the number of non-agriculture employees in the total workforce, named Urban 2, representing the effect of urban pull factors with industrialization and urban-biased policies.

### *3.2 Data selection*

The study is based on multi-country and cross-sectoral data for the period 1995-2013. The demographic data are collected from the World Bank database. Energy consumption is divided into whole consumption and sectorial consumption as well as into fuel energy, renewable energy and electricity. It is collected from the International Energy Agency (IEA 2016) database.

GDP data is collected by cross-country and cross-sectional data. The panel data covers the value-added contribution of all major economic sectors consisting of commercial, industrial, and transportation, and the GDP of the whole economy is summed up from the Asian Development Bank (2015) source. The dataset is validated between alternative sources such as The World Bank (2015), Asian Development Bank (2015) and International Monetary Fund (2015).

Particularly for the residential sector, this paper suggests considering the number of households as an activity indicator. This data is summarized from annual national population reports. Some missing data is encountered, which is accounted for by linear interpolation, see Table I for details.

Missing data is a problem in some countries such as Singapore and Laos, and leads to incalculable results. Moreover, the inconsistency in collecting data in Indonesia when combining value-added from transportation with commercial value-added made it impossible to compare the results with other countries. Therefore, this paper only presents the results for 7 countries, consisting of 1 high-income country (Brunei), two upper-middle-income countries (Malaysia and Thailand) and four low-middle-income countries (Cambodia, Myanmar, the Philippines and Vietnam).

| Sector | Activity | Energy data | Demographic |
|---|---|---|---|
| Residential | Number of households - National population censuses report | Fuel, renewable, electricity - IEA 2015 | World Bank 2015 |
| Commercial<br>Industrial | Added value, GDP – World Bank 2015 and ADB database 2015 | | |
| Transportation | | Fuel – IEA 2015 | |

**Table I.**
Summary of the data set and their sources

## 4. Results

The empirical analysis is conducted by comparing the impact of the energy mix, energy intensity, activity, structure, and three demographic indicators (Population, Urban 1, and Urban 2) on the energy consumption in ASEAN during 1995-2013. Overall results are shown in Tables II and III for the approach without and with the economic structure indicator. In general, energy consumption growth in ASEAN countries is mostly caused by demographic and economic changes. Energy mix contributed positively but insignificantly. Meanwhile, energy intensity is the only factor continuously supporting energy consumption reductions (see Tables II and III).

Without the economic structure approach, demographic effects are the strongest drivers of energy consumption growth in ASEAN from 1995 to 2013, especially from the 2000s (see Figure 4), with average contributions of around 30-70 per cent, 60-150 per cent and 60-240 per cent for population, Urban 1 and Urban 2 respectively (see Table II). Exceptional contributions occur in the Philippines and are discussed in detail in Section 5. With the economic structure approach, production growth is revealed as the strongest driver instead of the demographic effects (see Table III).

For country comparisons, the demographic effect of population change influence on energy consumption is wieghted at 1, thus providing a basis for comparison of the three demographic indicators Population, Urban 1, and Urban 2 across countries and sectors (see Tables IV and V). For example, overall the Urban 1 and Urban 2 effects are on average 1.8 and 2.7 times stronger than the population effects on total energy consumption in all considered countries (Table IV). For individual countries, Urban 1 and Urban 2 have a

| Country | Energy mix | Energy intensity | Economic – Population case | Economic – Urban 1 case | Economic – Urban 2 case | Population | Urban 1 | Urban 2 |
|---|---|---|---|---|---|---|---|---|
| Brunei | 0.48 | −25.49 | 57.40 | 35.14 | 30.61 | 67.62 | 89.88 | 94.41 |
| Cambodia | 0.50 | −35.81 | 67.22 | 34.43 | −105.37 | 68.09 | 100.88 | 240.68 |
| Malaysia | 0.34 | −5.49 | 67.39 | 36.83 | 46.49 | 37.77 | 68.33 | 58.66 |
| Myanmar | 0.19 | −100.04 | 131.69 | 47.27 | −32.42 | 68.16 | 152.57 | 232.26 |
| Philippines | 1.17 | −1235.80 | 815.90 | 911.24 | 366.17 | 520.61 | 425.27 | 970.34 |
| Thailand | 0.14 | −0.39 | 66.56 | −15.69 | −8.55 | 33.69 | 115.94 | 108.80 |
| Vietnam | 2.06 | −49.16 | 123.32 | 85.93 | 36.18 | 23.78 | 61.16 | 110.92 |

**Note:** Unit: %/a

**Table II.** Average weight of each factor's contribution in energy consumption changes in ASEAN between 1995 and 2013 without economic structure concern

| Country | Energy mix | Energy intensity | Economic structure | Production – Population case | Production – Urban 1 case | 3Production – Urban 2 case | Population | Urban 1 | Urban 2 |
|---|---|---|---|---|---|---|---|---|---|
| Brunei | 0.26 | −33.67 | −80.80 | 146.75 | 124.54 | 119.97 | 67.46 | 89.67 | 94.23 |
| Cambodia | 0.48 | −42.29 | 3.22 | 95.16 | 74.33 | −15.46 | 43.43 | 64.27 | 154.05 |
| Malaysia | 0.23 | −10.11 | 15.54 | 58.19 | 28.94 | 38.19 | 36.15 | 65.40 | 56.15 |
| Myanmar | 0.83 | −118.95 | −220.23 | 200.80 | 409.18 | 293.96 | 32.50 | 207.65 | 322.87 |
| Philippines | 0.79 | −277.75 | 66.92 | 188.72 | 211.11 | 84.04 | 121.33 | 98.93 | 226.00 |
| Thailand | 0.04 | −4.71 | 19.02 | 52.21 | −29.40 | −22.31 | 33.43 | 115.04 | 107.95 |
| Vietnam | 2.19 | −66.45 | 16.05 | 130.72 | 103.07 | 66.68 | 17.50 | 45.14 | 81.53 |

**Note:** Unit: %/a

**Table III.** Average weight of each factor's contribution in energy consumption changes in ASEAN between 1995 and 2013 with economic structure concern

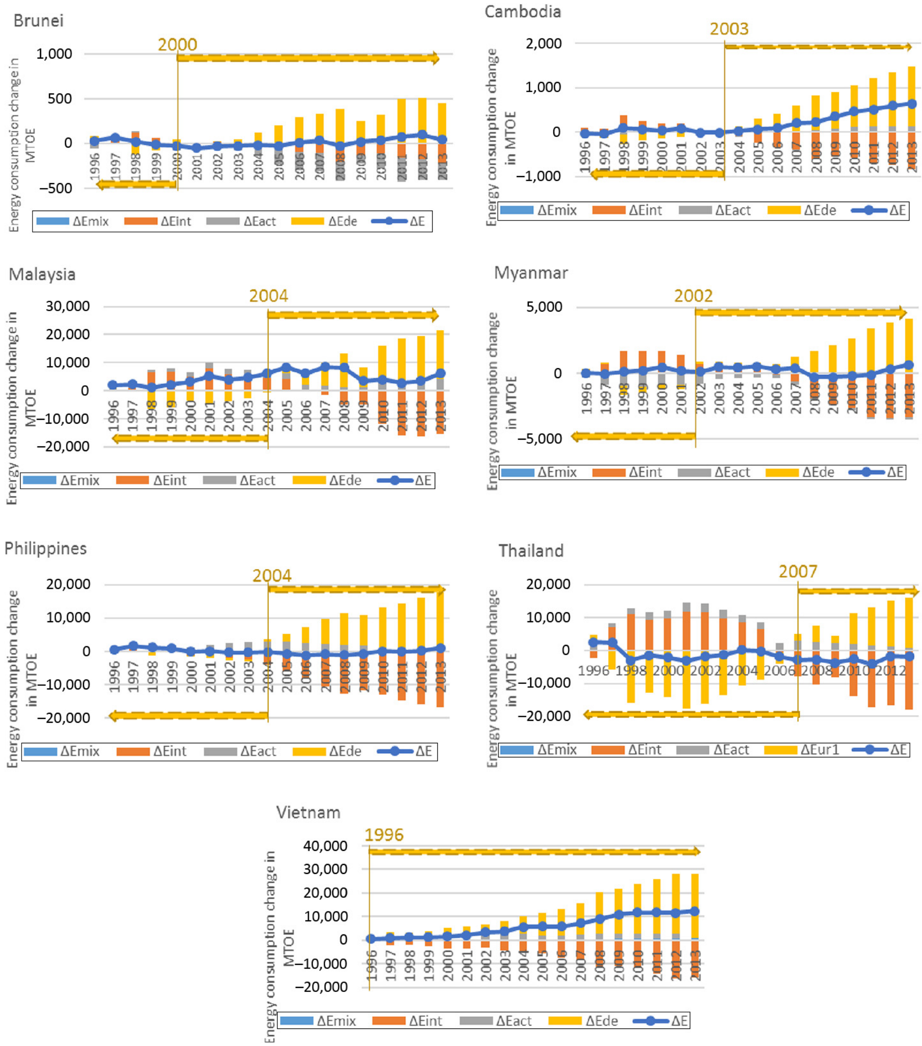



**Figure 4.**
The impact of Urban 1 in relation to other impacts on energy consumption changes in seven ASEAN countries from 1995 to 2013 by decomposed economic effect approach

**Note:** The milestone marks the transition from decreasing to increasing energy consumption of Urban 1

relatively equal influence in Brunei, Malaysia and Thailand. But Urban 2 is significantly stronger than Urban 1 in the other countries (Table V).

For sectorial comparison and cross country-sector comparisons, the demographic effect of population change influence on commercial energy consumption is weighted at 1. Tables VI and VII respectively describe the demographic effect on energy consumption changes across sector and country over the past two decades, relative to this value of unity. Out of all sectors in all cases, Urban 2 or non-agricultural workers ranked highest in industrial and residential sectors with 13.21 and 15.12 respectively

(Table VI). The Urban 1 factor affects most strongly the residential energy consumption in the case of the cumulative economic effect at 8.69, and in transportation in case of the decomposed economic effect at 6.86. Exceptional cases are recorded in Malaysia and Thailand, where Urban 1 impacts stronger than Urban 2, and in the Philippines where the Urban 1 has less influence than population and Urban 2 (Table VII).

Figure 5 provides an assessment of the scaled impact of demographic factors on energy consumption in the 7 analyzed ASEAN countries. This figure describes the relevance of demographic size and its impact on total energy consumption changes. The size of the circles shows the strength of the respective demographic effects (Urban 1, Urban 2, population) over the whole period and the y-axis shows the average annual rate of change. The x-axis is arranged in order of increasing income. The figure clearly illustrates the three different groups of countries according to their income level. In the lower-middle-income group the Urban 2 effect is strongest, followed by Urban 1 and Population, with

**Table IV.** The overall comparison of demographic factors impact on energy consumption change in ASEAN in the period 1995-2013 (population = 1)

| Overall | Population | Urban 1 | Urban 2 |
|---|---|---|---|
| Without economic structure concern | 1.00 | 1.82 | 2.80 |
| With economic structure concern | 1.00 | 1.84 | 2.54 |

**Table V.** Comparison of demographic factors impact on energy consumption growth by country in the period 1995-2013 (population = 1)

| Country | Population | Urban 1 | Urban 2 |
|---|---|---|---|
| Brunei Darussalam | 1.00 | 1.33 | 1.40 |
| Cambodia | 1.00 | 1.48 | 3.53 |
| Malaysia | 1.00 | 1.81 | 1.55 |
| Myanmar | 1.00 | 2.24 | 3.41 |
| Philippines | 1.00 | 0.82 | 1.86 |
| Thailand | 1.00 | 3.49 | 3.25 |
| Vietnam | 1.00 | 2.57 | 4.66 |

**Table VI.** Overall sectorial comparison of demographic factors impact on energy consumption growth in ASEAN in the period 1995-2013 (population in commercial sector = 1)

| Urban indicator | COM | IND | RES | TRA |
|---|---|---|---|---|
| *Without economic structure concern* | | | | |
| Population | 1.00 | 6.50 | 5.48 | 5.28 |
| Urban 1 | 1.99 | 7.45 | 8.69 | 7.39 |
| Urban 2 | 2.85 | 13.21 | 15.12 | 10.99 |
| *With economic structure concern* | | | | |
| Population | 1.00 | 5.66 | | 4.91 |
| Urban 1 | 1.73 | 6.41 | | 6.86 |
| Urban 2 | 2.51 | 11.69 | | 10.29 |

**Notes:** Acronyms: COM – commercial; IND – industrial; RES – residential; TRA – transportation

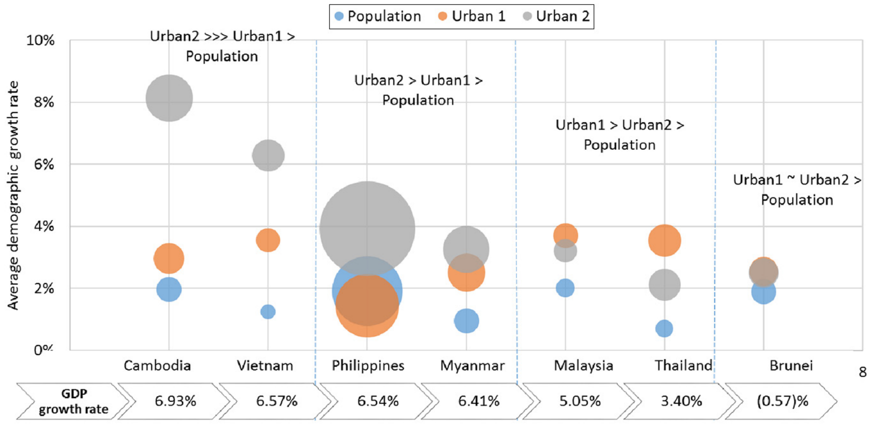
| Urban indicator | Without economic structure concern COM | IND | RES | TRA | With economic structure concern COM | IND | TRA |
|---|---|---|---|---|---|---|---|
| *Brunei* | | | | | | | |
| Population | 0.39 | 1.28 | 1.70 | 1.01 | 0.37 | 0.69 | 1.03 |
| Urban 1 | 0.52 | 1.70 | 2.25 | 1.33 | 0.49 | 0.91 | 1.36 |
| Urban 2 | 0.55 | 1.82 | 2.48 | 1.46 | 0.52 | 1.01 | 1.49 |
| *Cam* | | | | | | | |
| Population | 0.11 | 0.55 | 1.38 | 1.32 | 0.11 | 0.55 | 1.32 |
| Urban 1 | 0.17 | 0.85 | 2.07 | 2.14 | 0.17 | 0.84 | 2.12 |
| Urban 2 | 0.37 | 1.89 | 4.84 | 2.62 | 0.37 | 1.88 | 2.72 |
| *Malay* | | | | | | | |
| Population | 0.22 | 0.42 | 0.60 | 0.31 | 0.22 | 0.42 | 0.31 |
| Urban 1 | 0.40 | 0.76 | 1.09 | 0.57 | 0.40 | 0.76 | 0.57 |
| Urban 2 | 0.35 | 0.65 | 0.96 | 0.49 | 0.35 | 0.60 | 0.49 |
| *Myan* | | | | | | | |
| Population | 0.19 | 0.31 | 1.57 | 0.62 | 0.19 | 0.31 | 0.62 |
| Urban 1 | 0.39 | 0.63 | 3.08 | 1.37 | 0.39 | 0.63 | 1.37 |
| Urban 2 | 0.65 | 1.03 | 5.60 | 2.12 | 0.65 | 1.03 | 2.12 |
| *Phil* | | | | | | | |
| Population | 0.16 | 6.20 | 1.44 | 3.47 | 0.29 | 6.20 | 3.47 |
| Urban 1 | 0.40 | 5.35 | 1.36 | 2.79 | 0.25 | 5.35 | 2.79 |
| Urban 2 | 0.78 | 11.48 | 3.19 | 6.13 | 0.57 | 11.45 | 6.13 |
| *Thai* | | | | | | | |
| Population | 0.20 | 0.35 | 0.71 | 0.69 | 0.20 | 0.35 | 0.69 |
| Urban 1 | 0.56 | 0.88 | 1.53 | 2.03 | 0.56 | 0.88 | 2.03 |
| Urban 2 | 0.61 | 0.93 | 2.15 | 2.15 | 0.61 | 0.93 | 2.15 |
| *Viet* | | | | | | | |
| Population | 0.16 | 0.22 | 0.46 | 0.16 | 0.16 | 0.22 | 0.16 |
| Urban 1 | 0.40 | 0.53 | 1.10 | 0.38 | 0.40 | 0.53 | 0.36 |
| Urban 2 | 0.78 | 1.15 | 2.48 | 0.80 | 0.80 | 1.16 | 0.80 |

**Notes:** Acronyms: COM – commercial; IND – industrial; RES – residential; TRA – transportation

**Table VII.** Cross country-sector comparison of demographic factors impact on energy consumption growth in ASEAN in the period 1995-2013 according to two different approaches (percentage change in energy consumption per 0.1% change in respective demographic factor)

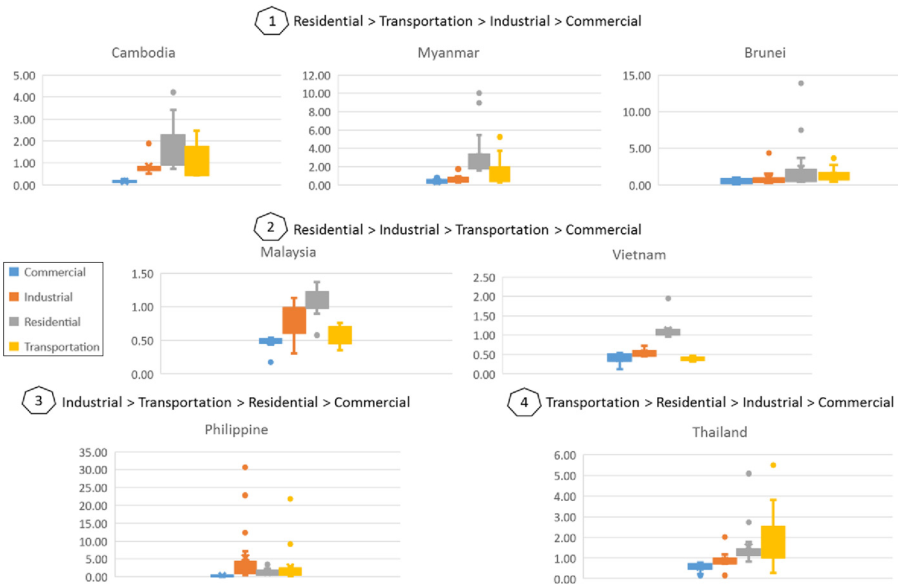
the exception of the Philippines (see next section). The upper-middle-income group is characterised by higher Urban 1 effects, followed by Urban 2 and Population. The third group, high income countries, shows similar effects of both Urban 1 and 2, both stronger than the Population effect.

The overall influence of the different demographic factors on each sectorial energy consumption in the 7 countries is presented in Figure 6. The sectors are shown in turn from left to right including commercial, industrial, and residential sectors and transportation. The vertical axis represents the impact of the demographic factor on the relative sectorial energy consumption changes, in dimensionless units of percentage change of the energy consumption per 1 per cent change in Urban 1. The rectangular boxes show the upper and lower quartiles of the data, the whiskers outside the box indicate the spread outside these quartiles, and the circular points show outliers. In general, changes in both urban dwellers (Urban 1) and employees in the non-agricultural field (Urban 2) made the largest contribution to increasing energy consumption in households. The influence seems to be smaller for the transportation and industrial sectors and very small for the commercial




**Notes:** X-axis: considered countries corresponding with their factors divided into four groups. Y-axis: average demographic growth rate including population, Urban 1 and Urban 2. Bubble size: the level of demographic factor impact on energy consumption by each factor in each country

**Figure 5.**
Cross-country comparison of impact levels by different demographic factors on energy consumption growth in 7 ASEAN countries from 1995 to 2013




**Note:** Percentage change in respective effect per 1% change in Urban 1 indicator

**Figure 6.**
Groups of different annual average effects of Urban 1 on sectors in the 7 ASEAN countries from 1995 to 2013

sector. Detailed results for each sector per year during the considered period can be seen in Table VII.

## 5. Discussion and policy implications

In this section, we discuss our main results and the applied method. The first section focusses on the effects of urbanization on the energy mix, in the context of the question whether urbanization could promote the energy transition. The second section then examines which factors policies are required to consider, to ensure sustainable development. The third section highlights the different impacts of urbanization on energy consumption, according to the income level of the country. The subsequent sections present a sensitivity analysis and critically discuss the method, respectively.

### *5.1 The correlation between urbanization, energy mix and energy consumption effects, and the example of the Philippines*

The decomposition results show that the energy mix effect contribution to the energy changes is generally quite weak, with from 0.1 per cent to 3 per cent (with the exception of the Philippines, discussed below) from 1995 to 2013 (Tables II, III and Figure 7). Despite the extensive government efforts to encourage renewable energy development through national energy policies, the regional reliance on fossil fuels is increasing with an average annual growth rate at 0.8 per cent during the considered period (Figure 7). The results also show that the transition rate from fossil fuels to electricity and renewable energy is happening even more slowly in the considered countries, with an average annual growth rate of 0.35 per cent from 1996 to 2004 compared with a rate of −0.11 per cent from 2005 to 2013 (Figure 7). The decrease is mainly due to the increase in using fossil fuel within the industrial and residential sectors. This could be evidence that the swelling population in cities and industrialization is putting pressure on the region's energy security.

The exception here is the Philippines with a negative impact of the energy mix recorded during the period of 2006 to 2010 (Figure 7). A deeper look at the energy mix impacts by sectors (Figure 8) reveals that these negative values are caused by the dramatic reduction in the residential sector in the Philippines during the 18 studied years, with an average decreasing rate of 1.7 per cent per year. The energy consumption in the residential sector in the Philippines counteracts positive effects in other sectors, thus accounting for the overall negative energy mix effect seen across the entire economy.

The successful strategy in dealing with urbanization in the Philippines could be seen as a positive example to counter increasing energy demand. Since the urbanization crisis became a concern of the Government in the 2000s, the Philippines has played a key role in the global debate on sustainable urbanization. As an active member on Human Settlements or Habitat

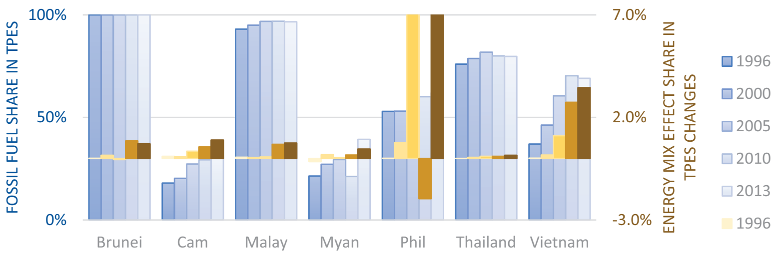



**Figure 7.**
Fossil fuel share in TPES (own calculation based on database of IEA, 2015) and the energy mix effect share in TPES changes from 1995 to 2013 in seven ASEAN countries

II, the Philippines' commitments on infrastructure development have made significant achievements after 20 years[3], by effectively reducing the rapid rate of urbanization growth. Thereby, it successfully limited the urbanization effect on energy consumption to remain even smaller than the population effect (Figure 5). Since 2016, under the auspices of the Habitat III[4] process, this may enable the Philippines to further reduce the urbanization effect on energy consumption as well as providing a good practice example for other countries.

*5.2 The focus of ASEAN energy policy*

Among the studied demographic influences, the urbanization factors generally exhibit a stronger effect on energy demand increases than population in the region (with the exception of the Philippines, Table V and Figure 5). After 1990, along with economic development, ASEAN entered a period of rapid urban population growth (Urban 1), which rose to an average of 3.2 per cent per year (World Bank, 2018). However, after more than 10 years of increasing, since the 2000s, Urban 1 has started to put pressure on energy consumption in ASEANs. It started in Brunei, which has the highest rate of urbanization, in 2000 and then spread all over ASEAN. Vietnam has been affected since 1995, but the effect has become relatively strong since 2004 (Figure 4).

Moreover, ASEAN economies are likely to expand at a rapid pace and have attained high rates of Urban 2 – non-agriculture employment growth. Consequently, Urban 2, which reflects the growth in industrial development in this region, is the strongest effect among the demographic indicators (Tables V and VI).

The results show that, if Urban 1 and Urban 2 would increase by only 0.1 per cent, it will require an energy demand increase by on average 1.44 per cent and 2.59 per cent respectively (Tables II and III). Urbanization is leading to rapidly increasing domestic energy demand, especially in Cambodia, Myanmar and Vietnam (Figure 9), followed by significant growth in industry and transport (ASEAN as a whole in Table VI and detailed by country in Table VII and Figure 9). The urbanization effect on transportation is gradually becoming stronger than on industry, especially in Thailand (Figure 9).

Facing the urbanization challenge, this paper provides an estimation for the energy consumption change in each sector of each considered country corresponding to 0.1 per cent urbanization changes (Table VII). It reveals the potential that controlling urbanization could reduce the pressure on energy supply. For example, Urban 1 in Vietnam is 34 per cent, which indicates that around 32 million people are living in urban areas. Based on the estimation, if the government could avoid 0.1 per cent in Urban 1 increase (meaning 32,000

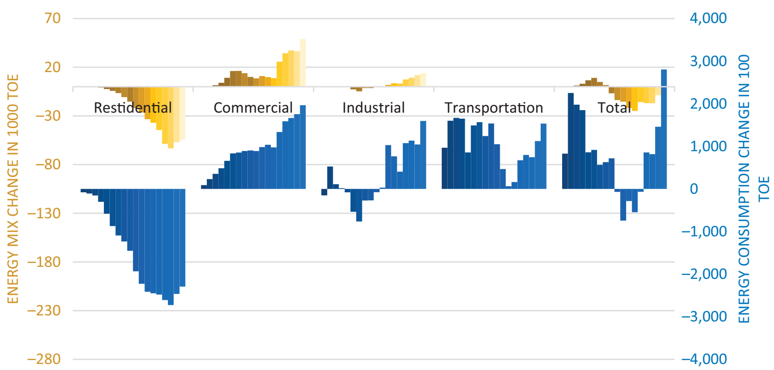
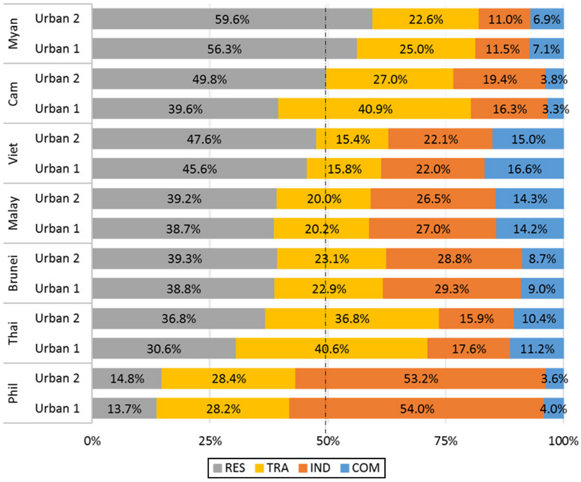



**Figure 8.** Comparing energy mix and energy consumption changes in Philippines by sector – Unit: 1000 TOE




**Notes:** Acronyms: RES – residential, TRA – transportation, IND – industrial, COM – commercial

**Figure 9.**
Cross country-sector comparison of urbanization effects on energy consumption growth in seven ASEAN countries between 1995 and 2013

people) per year, it could help to avoid 0.4 per cent, 0.53 per cent, 1,1 per cent and 0.38 per cent energy demand increases in the commercial, industrial, residential and transportation sectors respectively. The results could be used as a reference for policy makers to integrate energy policy with urban and economic plans.

Because urbanization, and not population, is one of the main drivers for increasing energy consumption and is concentrated in the residential sector, there is an obvious need for specific energy policy at the regional and city levels. It is beyond the remit of government agencies to coordinate among all local bodies and conduct comprehensive policy analysis and performance evaluation, because of lacking capacity and resources at the national level. In addition, responsibility in energy policy, planning and implementation at the city level could be fragmented and contradictory, compared to the respective current sub-sector energy policy. This lack of attention and capacity from national institutions to subnational energy policy could present an opportunity for regional and local organizations. However, city-level decision makers at least need signals and guidelines from the national level to develop effective policies, and the state has to coordinate these activities as much as is feasible. This includes ensuring that local policymakers can effectively engage with stakeholders at all levels and that local experiences with new policies are considered in the national context.

### *5.3 Insights for countries' income-levels on urbanization and energy consumption*

This paper analyzed the two urbanization indicators including Urban 1 (urban population in urban areas) and Urban 2 (non-agricultural employment), which represents industrialization, to investigate the difference between the two indicators on energy consumption. The results show there are three typical groups (Figure 5), which are closely linked to the national income levels:

- *Group 1 as Brunei* – high-income country (based on World Development Indicators, World Bank data, 2016) where Urban 1 and Urban 2 have similar effects on energy consumption growth.
- *Group 2 including Malaysia and Thailand*, upper middle-income countries, where Urban 1 is stronger than Urban 2.
- *Group 3 including Cambodia, Myanmar, Philippines and Vietnam*, lower middle-income countries, where Urban 2 has stronger effect on energy consumption growth than Urban 1.

Thus, it can be seen that, the lower income the country is, the stronger urbanization and industrialization effect energy consumption growth. In other words, lower-income countries are more severely affected by urbanization in increasing energy consumption. Accordingly, the demand for urban management in the context of energy consumption growth in these countries becomes more urgent and the policy development process needs to consider this fact. For example, the high-income countries exhibit effects based on all three factors that are very similar (Figure 5), hence little or no specific urbanization policy is required. The upper-middle-income countries, on the other hand, exhibit strong urbanization according to Urban 1, therefore need effective policies to manage this process and should look to the Philippines for inspiration. The lower-middle-income countries have a much stronger industrialization effect (Urban 2), and therefore need to focus attention on effective policies to manage this rapid change alongside energy demand increases. Whilst the three remaining ASEAN countries were not included in the analysis because of a lack of data, these broad policy insights could also be generalized towards them (i.e. high-income: Singapore, lower-middle-income: Laos PDR, and upper-middle-income: Indonesia).

*5.4 Sensitivity analysis*

This study analyzed the robustness of the results in the presence of uncertainties. The calculated data units and the estimated percentage statistical errors of each variable are listed in Table VIII.

The statistical errors in Table VIII are estimated by comparing different data resources. To calculate the statistical errors in GDP data, this paper determined the difference in percentage in the same referred time and currency between two data sources including the World Bank database 2018 and the ADB database 2015. The statistical errors of population, Urban 1 and Urban 2 are estimated by comparing between the World Bank database 2018, the ADB database 2015 and the IMF database 2015. The results show that the difference between them is around 0.01 per cent to 0.2 per cent respectively. On the other hand, the energy statistical errors from the IEA database represent the amount by which an observation differs from itself, before and after the IEA revises the data every year when they update the database.

To account for the case of unknown statistical errors, the paper varies the input values within the range of ±50 per cent for given input parameters such as demographics, activity

| Variable | Data units | Statistical errors |
|---|---|---|
| Demographic | Billion people | 0.01-0.2 |
| GDP | Billion $ | 0.01-0.2 |
| Energy | 1000 TOE | 0.1-7 |

**Table VIII.** Analysis of the statistical errors and energy consumption. Figure 10 shows that, for every 1 per cent variation in the input, the activity effect will change by around −5.5 per cent and the demographic effect would change by 5.5 per cent. However, it will not affect the energy intensity effect. Similarly, if the activity value changes, every 1 per cent of this will cause energy intensity effect changes of 5.5 per cent and activity effect changes of −5.5 per cent, but this has no impact on the demographic effect.

Furthermore, every 1 per cent error in the energy consumption statistics could cause a 1 per cent change in the energy intensity effect, a −0.5 per cent change in activity effect and a −0.6 per cent error in the demographic effect. The results also show the limitation of the decomposition method, especially for the logarithmic mean divisia index (LMDI). It has trouble dealing with zero values so the results can give an incorrect value. For example, in this case this effect occurs at the point of a 20-25 per cent negative change in the energy consumption.

### *5.5 Critique of the decomposition method in analyzing the relationship between energy and urbanization*

This section discusses the strengths and limitations within the study. Regression may produce unreliable results in describing the relationship between energy consumption and other factors. For example, in the case of Brunei, the *r*-squared is relatively low, around 6 per cent and 16 per cent in the case of analyzing the relationship between energy consumption and GDP, Urban 1 respectively (Figure 11). The decomposition method does not encounter many obstacles in comparing the correlation between variables (Figure 12). Thus, it is an alternative approach to analyze the relationship between energy consumption and urbanization. The decomposition is also superior to regression in case of horizontal (cross-country) and vertical (cross-sector) comparisons.

However, the decomposition method also has its disadvantages, which are the process of collecting and synchronizing data, choosing the appropriate decomposition analysis method, problems associated with considering new variables (e.g. population and urbanization factors), and the errors resulting from a zero difference between the value in two considered periods. The data capable for computing needs to be collected with the same

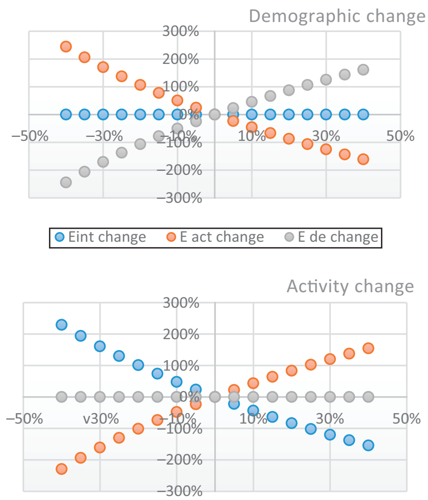
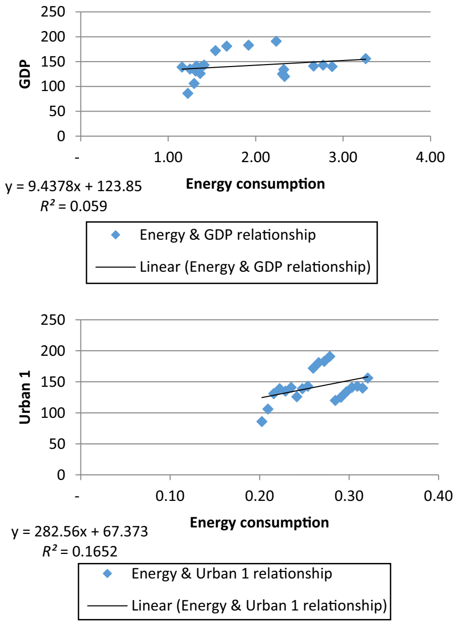



**Figure 10.**
The results of the sensitivity analysis for selected variables – Unit: %




**Notes:** Unit: GDP: million USD 2005, Urban: million people, Energy consumption: 1,000 TOE

**Figure 11.**
The results of relation analysis for selected variables by using regression in Brunei

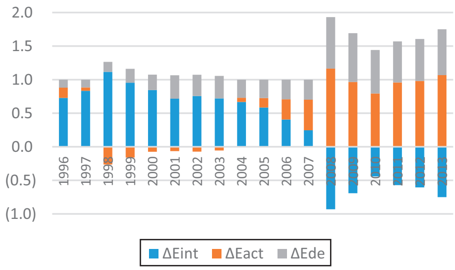



**Figure 12.**
The results of relation analysis for selected variables by using decomposition in Brunei with cumulative economic approach – Unit: 100 MTOE

reference year and statistical method in all countries. Therefore, the end-use database is calculated and synchronized with the reference year as 1995. Moreover, the zero problem was handled following the suggestion of Ang and Liu (2007) by replacing with $\partial$, where $\partial<10^{-20}$.

Finally, the decomposition method describes a relative comparison between variables instead of considering the dependence of different variables. It can therefore provide the correlation of different effects on one or several variables; however, it cannot determine an exact weight representing the level of influence. Hence, the choice of appropriate method always depends on the application and should be made with the above issues in mind.

## 6. Conclusion and outlook

The essential requirement of restraining energy consumption and promoting energy efficiency is becoming more important in the context of economic and urban growth. The first priority of ASEAN governments should therefore be to identify factors that have an effect on energy consumption and developing appropriate policies. A deeper analysis of the disaggregate results for each sector and country enables a more accurate understanding of the urban impacts on energy consumption.

With this purpose, the decomposition method has been implemented in this paper for seven ASEAN countries from 1995 to 2013 to assess the effects of urbanization on energy consumption and compare this effect based on multi-level indicators. This analysis is based on two types of urbanization, including the general urban indicator of urban population and the pull urban indicator of non-agriculture workers. The results decompose the changes of overall energy consumption into intra- and international effects and isolate the contribution of each component factor including energy mix, energy intensity, activity, and urbanization. To the authors' knowledge, this is a novelty, as previous studies have only shown results across sectors or countries.

While there was some controversy about the effect of urbanization on total energy consumption as well as sectorial energy consumption, this paper demonstrates the positive effect of urbanization at national and sectorial levels in the ASEAN region. Although effects are different among the countries, the urbanization effect on energy consumption is stronger in lower income countries. The results show that the effect of urbanization factors is much more significant than the population effect and the other effects including energy intensity and activity in the whole country, as well as in each of the sectors in the region.

The detailed results about urbanization-related energy consumption changes in Table VII could serve as a suggestion for the whole ASEAN region in controlling urbanization and its effects on energy consumption. The strong effect of urbanization on domestic energy consumption poses new questions for policy makers in this field. In particular, they should focus efforts on finding an optimal solution to decentralized, efficient energy systems for current and future urban cities, especially in the commercial and household sectors. Therefore, the paper suggests three key recommendations to policy-makers in setting energy policy: (1) urban areas should be considered as one of the core targets for energy policy; (2) the lower-middle-income countries should pay attention to effective policies to manage the rapid change of the non-agriculture workers' effect; and (3) there is an essential need for energy policy at city-levels besides subsector-levels.

Looking to the future, instead of using energy consumption to assess the impact of urbanization, energy intensity analyses could be implemented. These would require updated and improved databases, and should apply direct approaches, based on energy service demands, rather than the indirect decomposition approach adopted here. For example, a complete dataset should be built, consisting of different and more detailed factors such as housing area for households, commercial building area for the commercial sector, and freight of goods for transportation. Such a database would enable the underlying causes of the urbanization and energy phenomena highlighted here to be examined more closely. Researchers should approach this problem from diverse disciplines, to more fully understand the complex relationship between the urbanization process and the carbon cycle. Moreover, whilst this study was able to provide valuable insights into the relationship between urbanization and energy consumption at the sector level, across ASEAN, for a period of a few decades, future work should analyze these phenomena at the national level and below, as well as differentiating between energy carriers.

## Notes

1. Divided by income group, ASEAN has ten members in three groups: two high-income countries including Brunei Darussalam and Singapore, two upper-middle-income countries including Malaysia and Thailand and six lower-middle-income countries including Cambodia, Indonesia, Lao PDR, Myanmar, the Philippines and Vietnam (World Bank, 2018, last accessed 03.12.2018).
2. The "fixed effect" method is used to treat pooled cross-sectional and time series data. It means the model is calculated with one variable fixed and in a constant proportion across countries.
3. For more information about the Philippines achievements on urbanization programs under Habit II see: www.hudcc.gov.ph/HABITAT_III
4. Habitat III is the New Urban Agenda. It is the outcome of the action plans agreed upon at the Habitat III cities conference in Quito, Ecuador, in October 2016.

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# Analyzing drivers of renewable energy development in Southeast Asia countries with correlation and decomposition methods

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ABSTRACT

The Association of South East Asian Nations (ASEAN) is a diverse region characterized by rapid economic growth, demographic change and urbanization. The dominance of energy supply from non-renewable resources in the region means that the increasing energy demand has implications for energy security, as well as adverse local and global environmental effects. Climatic conditions in the region are favorable for renewable energy (RE) resources, especially but not only wind and solar technologies. ASEAN countries differ strongly in terms of their national policy frameworks and progress in renewable energy development; the overall target of 23% renewables by 2025 is very ambitious under current policy frameworks.

This paper identifies a gap between these national policies and local governance, especially in urban areas, which requires attention to ensure future target fulfilment. By employing a new combined correlation and decomposition approach at country and city levels, we investigate the determinants of RE expansion and explore the trend drivers in ASEAN countries from 1995 to 2013. An Impact Matrix is developed to position and interpret the relative push (e.g. policy) and pull (e.g. market) impacts on RE development, and to derive policy recommendations for countries and sectors. The results highlight that urban areas should be the focus of RE policy and governance in addition to rural areas. The tremendous impact of economic growth creates a great impetus for renewable energy development, but urbanization is the second pull for renewable energy extensions.

Since the two effects are located in the first quadrant of the Impact Matrix, if strategists affect these factors, they will create the most powerful incentive for renewable energy growth. This confirms that if the strategic aim is to promote renewable energy market development, through policy and governance measures, the focus should be on urban areas, non-electricity sectors and the demand side.



## 1. Introduction

ASEAN is a regional organization comprising ten Southeast Asian countries, characterized by rapid urbanization, industrialization, and an increasingly important role of the urban service sector. Urban population in the region is expected to grow by around 100 million people, rising from 280 million people today to 373 million people by 2030. ASEAN is recorded as the second fastest developing region in the world, with an average GDP growth rate of 4.8% in 2016 and 5.1% in 2017 (IMF – Internation Monetary Fund; OECD, 2018), and is predicted to grow faster, by an average 6.3% per year over the period 2018–2022 (OECD, 2018). The changes have occurred historically in megacities and large cities, and nearly 40 percent of ASEAN's GDP growth to 2025 is expected to come from 142 cities with populations between 200,000 and 5 million (The Economist Intelligence Unit, 2016). Due to the fact that highly urbanized countries tend to consume more energy, ASEAN governments are experiencing problems in dealing with local energy shortages (especially power shortages in the Philippines and Vietnam) and GHG emissions from high-density population (ASEAN Centre for Energy (ACE) 2018).

Aware of the challenges and opportunities presented by rapid urban growth, ASEAN Member States engage in sustainable development and regional integration is carried out by the

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Sustainable ASEAN Socio-cultural Community Blueprint 2025. The agreement encourages renewable energy usage to partly lessen the energy supply burden and reduce the environmental impacts of urban expansion. Solar and wind power technologies are predicted as potential renewable energies for urban areas. Benefits due to lower levels of air pollution and $CO_2$ emissions from the expected renewable energy development could potentially result in savings equal to between 0.2% and 1.0% of ASEAN's GDP in 2025 (IRENA and ASEAN Centre for Energy (ACE) 2016). However, after intensive support from the governments, renewable energy capacity (excluding large hydro power and biomass firewood) in the region has not increased as expected. The renewable energy production accounted for only 9.4 percent of total primary energy supplies by 2014. It is expected to reach only 17 percent approximately by 2025, while the original target share is set at 23% (ASEAN Centre for Energy (ACE) 2017).

The most significant challenges to developing renewable energy in the region have been identified as geographical and technical conditions, inadequate regulatory frameworks, persistence of subsidies on conventional energy sources, import tariffs on renewable energy goods, and the lack of public awareness and support (Arie Rahmadi et al., 2017). ASEAN countries are taking important initial steps, but ample opportunities remain for improving the overall renewable energy policy and regulatory environment (IRENA, 2018). Since urbanization mostly happens dramatically in megacities, cities' governance would play a crucial role in enhancing renewable energy usage. Based on their own features, cities could create different and unique programs in the field of energy management, climate change adaptation, improved resource efficiency, and renewable energy planning. This lack of policy integration means that these types of complicated, interconnected issues cannot be appropriately addressed, and is resulting in ineffective and inefficient policy deployment (Runhaar, Driessen and Soer, 2009).

To fill this gap, this paper intends to provide evidence of the importance of governance policy, interaction by common target groups and combining action plans for policy-makers in establishing renewable energy policy. All of these will be addressed by answering three arising scientific questions for renewable energy policy at national and city levels in ASEAN. The first question is why urban areas and cities play an important role in encouraging renewable energy extensions. The second question is where urban policy and urban governance can be most effective. Lastly, the third question is how to review and revise renewable energy policy in the light of constantly-varying influencing factors.

The paper is structured as follows. Section 2 assesses past and possible future renewable energy developments, before discussing policy-supporting schemes to reveal the policy problems and the lack of scientific research in this field. Section 3 addresses solutions from previous studies related to determining the drivers of renewable energy extension, in order to develop a new decision-support method for policy-makers. By analyzing the uncovered points in these studies, this paper proposes a method that combines decomposition and correlation methods to identify policy target groups and focus. The results and discussion are presented in section 4, while section 5 derives policy recommendations and section 6 contains conclusions and an outlook.

## 2. Renewable energy development and policy analysis

The section analyzes the main reasons for renewable energy development in ASEAN. The issues are highlighted and discussed based on theoretical and practical arguments. Since there is a lack of scientific studies in the region, we had to review many regional reports of international (as IEA, IRENA), regional (ACE – ASEAN Centre of Energy), national and banking (ADB, World Bank) research organizations and compared different reports to verify the accuracy and derive conclusions.

### 2.1. Renewable energy potential and developments in ASEAN

ASEAN is richly endowed with diverse renewable energy sources such as wind and solar in the whole region (ASEAN Centre for Energy (ACE) 2017). The significant realizable potential of wind power in Indonesia, Thailand, Vietnam and the Philippines is approximately 63 TWh, 57 TWh, 45 TWh and 22 TWh respectively (International Energy Agency, 2010). Due to being located close to the equator, the countries receive high daily insolation of 4–7 kWh/m2. Consequently, the technical potential of solar power is evaluated at 65 GW in Cambodia, 10 GW in Laos, 26 GW in Myanmar, 33 GW in Thailand and 25 GW in Vietnam (Asian Development Bank, 2015; International Energy Agency, 2010). The rapid growth of renewable energy technology (Terziotti et al., 2012; Ishugah et al., 2014) and a subsequent decline in renewable energy costs (Wei et al., 2014; IRENA, 2018) could lead urban neighborhoods to move away from traditional energy resources and centralized utility models to decentralized energy supply.

Renewable energy accounted for 26% in total primary energy supply (TPES) in 2016, but is dominated by traditional biomass (20%) and hydropower (3%) (Southeast Asia Energy Outlook – OCED, 2017). Due to the concern about the environmental damages due to solid biomass and large hydropower, some ASEAN countries excluded large-scale hydropower from their renewable energy target. However, all of them excluded the traditional form of firewood in their renewable energy supporting schemes since 2015 (Table 1). The remainder, consisting of non-hydro renewable, accounts for a relatively limited percentage in total demand, less than 1% of TPES.

Comparing the installed capacity of all renewable energy types corresponding with their targets in each country (Table 1) shows the large gaps between expectation and reality of ASEAN renewable energy development. Except for Malaysia, where the total renewable energy installed reaches 65% of the 2020 target (mostly coming from increasing hydro with 91%), the other countries are struggling in promoting renewable energy, especially Cambodia, Laos and Myanmar.

Solar and wind are considered the most promising form of renewable energy in general, and urban areas particularly in ASEAN (Ismail et al., 2015; Singh and Banerjee, 2015). However, progress towards reaching these targets seems to be slow. Except for Thailand, by the end of 2015 the total installed capacity of solar arrived at 73% of the expected capacity in the 2020 target. Overall, the shares of installed capacity for wind and solar, however, accounted for only 1% and 2%, respectively, of total existing renewable energy capacity by the end of 2016.

Comparing the development of solar and wind with other types of renewables between 2015 and 2016, reveals strong growth in ASEAN. While hydropower increased the installed capacity by 939 MW, corresponding to a 3.8% annual growth rate, wind extended by 297 MW, equaling a 37% annual growth rate, and solar PV experienced a strong increase by 1621 MW, amounting to a 88% annual growth rate. If this trend continues, solar could become the leader of ASEAN renewable energy developments in the near future.

### 2.2. Political support policies

In recent years, ASEAN governments as a whole as well as individual countries have created many schemes based on their renewable energy development targets to develop renewable

**Table 1**
Progress to renewable energy targets of ASEAN countries in 2015.

| | Target year | Installed capacity target (MW) | Specialization | Installed capacity 2015 (MW) | Progress to target 2015 | Target for solar (MW) | Installed solar 2015 (MW) | Progress to target 2015 |
|---|---|---|---|---|---|---|---|---|
| Brunei | 2025 | 954 (GWh) | All | 2 GWh | 0.2% | – | 1 | – |
| Cambodia | 2020 | 2241 | Hydro | 931 | 41.5% | – | 12 | – |
| Indonesia | 2025 | 46307 | Exclude biomass | 6709 | 14.4% | 80 | 9 | 11.25% |
| Lao PDR | 2025 | 951 | Exclude large hydro | 31 | 3.2% | 33 | 1 | 3% |
| Malaysia | 2020 | 2080 | Solar, biomass, small hydro | 1360 | 65.3% | 4200 | 262 | 6% |
| Myanmar | 2030 | 2000 | Exclude hydro | 12 | 0.6% | – | 12 | – |
| Philippines | 2030 | 15304 | Geothermal, hydro, wind | 6260 | 40% | 350 | 132 | 37.7% |
| Singapore | 2020 | – | – | – | – | 350 | 60 | 17.1% |
| Thailand | 2036 | 19684 | Hydropower, biomass, solar, wind | 7432 | 37.7% | 2000* | 1425 | 72.6% |
| Vietnam | 2030 | 45800 | Total | 11956 | 26.1% | 6000** | 139** | 2.3% |

Note: *: target for 2020. **: target and installed capacity for both wind and solar. Source: IRENA 2018; IRENA statistic 2017; Pranadi, A. D. (2016).

energy in the region. Table 2 provides an overview of renewable energy policy in ASEAN by the end of 2017.

The first five columns in Table 2 summarize the government policy. National programme indicates a promoting programme for different types of renewable energy such as solar heat, solar power, wind, geothermal and biofuel. Among ASEAN countries, Thailand is the only one having a supporting program for solar heat; the other countries rather focus on solar power, wind and biofuels. With verified high geothermal potentials, Indonesia and the Philippines are the only countries with additional programs for developing it.

As leaders in the region for committed renewable energy, Indonesia has completed guidelines for biomass, biogas, small hydropower and geothermal at the end of 2016, while Malaysia completed guidelines for small hydropower and solar implementation. The Philippines and Vietnam finalized their guidelines for solar power in early 2017 (ASEAN Centre for Energy (ACE) 2017; IRENA 2018; IEA - International Energy Agency 2017). Although each country has a different policy, they still collaborate. One such joint effort was the common target and roadmap called Remap Options for a Clean, Sustainable and Prosperous Future, published in 2016 (IRENA and ASEAN Centre for Energy (ACE) 2016). This roadmap provided a breakdown of renewable energy potential by sector and source, and established guidelines to achieve all targets.

Considering investment in renewable in the eighth column of Table 2, ASEAN mostly invests in renewable energy in the power sector (excluding large hydropower) with a very limited amount of over 2.6 billion USD in 2016, which equals to 1% of global and 2% of Asia-Pacific investment (BNEF, 2017). Investment in solar PV increased dramatically in Thailand with 3.8 USD billion in 2015. In addition, the investment trend has increased greatly in Singapore and Indonesia, but has decreased in the Philippines, Malaysia and Vietnam (IRENA, 2018). According to the IRENA report about Renewable Energy Market Analysis (IRENA, 2018), the cost needed to increase the renewable share to reach ASEAN's 23% target would only be USD 1.9 per MWh of final renewable energy in 2025, which is less expensive than the previous period.

In column 7 of Table 2, the funding comes from both national budgets as well as international banking budgets such as ADB – Asian Development Bank. Recently, Singapore is leading the R&D that focuses entirely on solar rooftop deployment, followed by Thailand and the Philippines. The last column specifies the integrated policy between government and governance in ASEAN. Thailand is the first country in ASEAN that implemented governance policy below the government one in 2013, following this is Malaysia with a policy pending approval. Thai government drafts and proposes all policies related to energy, including electric power and renewable energy policies. It is composed of two offices and three departments, which have different responsibilities and missions. However, Thailand has struggled in ensuring efficient and effective corporate governance, and resolving any potential conflicts of authority at the ministerial and regulatory level.

Combining the progress of renewable energy development in Table 1 and the relevant policy in Table 2 shows that renewable energy extension is closely linked to policy support. There are three different developing situations in the region. The first is slow development of renewable energy in Brunei, Cambodia, Laos, and Myanmar. Secondly, countries with marginal investment and R&D like Vietnam can reach only 2.3% of their target. Thirdly, those that are more advanced in expanding renewable energy such as Malaysia, the Philippines, Singapore and Thailand, pay more attention to R&D and investment, and can on average reach the target ten times faster with 17%–37%. The noteworthy progress of

**Table 2**
Overview of renewable energy policy in ASEAN.

| Country | Government policy | | | | | R&D 2013 £Million | Investment status | Integrated Governance Policy |
|---|---|---|---|---|---|---|---|---|
| | National programme | FiT | Subsidy and grants | Tax deduction | Specialization | | | |
| Brunei Darsm | – | – | – | – | – | – | Insignificant | – |
| Cambodia | – | – | X | – | Own PV, Rural, Off-grid | – | Insignificant | – |
| Indonesia | X | X | – | X | – | – | Increasing | – |
| Lao PDR | X | – | X | – | Small hydro | – | Insignificant | – |
| Malaysia | X | X | – | X | Solar, No wind | 28.3 | Increasing | X* |
| Myanmar | – | – | X | – | Off-grid, Rural | – | Insignificant | – |
| Philippines | X | X | X | X | – | 64.5 (ADB) | Decreasing | – |
| Singapore | X | – | X | – | Only solar | 329 | Increasing | – |
| Thailand | X | X | X | – | Bioenergy, Solar heating | 120 | Increasing | X |
| Vietnam | X | X | X | X | Rural | – | Decreasing | – |

Note: *. The policy is being preparing for implementation. Source: ASEAN Plan of Action for Energy Ccoopération (APAEC) 2016–2025. Ismail et al. (2015) 399–412, IRENA 2018.

Thailand in terms of enhancing solar by fulfilling 72% of its 2020 target by the end of 2015 is shown in the last column in Table 1, and can be explained by Thai renewable energy policies. Thailand is the only country focusing on solar heating and urban areas with the integration of government and governance policies (Tongsopit, 2015).

### 2.3. Issues and gaps in renewable energy policy in ASEAN countries

Because of the intimate relationship between renewable energy development and political support in the region, adjusting renewable energy support mechanisms is a key solution to help renewable energy get out of a deadlock situation. Since renewable energy potential is differentiated by geographic location and terrain elevation, local governments with governance policy might play a more important role in increasing the uptake of renewables. They can provide greater understanding of the current and future potential for renewable heating, cooling, electricity and transport biofuels based on their own features. Because of the differentiation of socio-economic, cultural and political situation, local policy makers can invest more wisely and precisely to enhance renewable energy deployment and identify possible benefits for local citizens and businesses (Chimres and Wongwises, 2016; Daniel M. Kammen and Deborah A. Sunter, 2016; Eskew et al., 2018).

However, urban governance policy is either missing or weak in ASEAN. ASEAN governments released several incentives and policy initiatives at a national level, which mentioned the importance of city governments and governance in working together to support the implementation of renewable energy strategies, policies and programs. In fact, 8 out of 10 countries in ASEAN have no governance policy. Besides, Marquardt (2014) indicated three major obstacles for renewable energy development in ASEAN as a lack of awareness for national intentions among subnational authorities and vice versa, weak capacity on the local level and a lack of consultation during policy formulation.

Some countries consider releasing local policy for renewable energy, but the involvement of governance is still a political bottleneck in the region. In the case of Malaysia, the New Energy Policy released in 2010 mentioned governance roles in the energy transition (Gouldson et al. 2016; Lee). A procedure and structure of sustainable development governance are proposed in the Review 2017 of the High-level Polical Forum in the Philippines (High-level Political Forum, 2017). It is included in the draft law, which is awaiting approval, however, the main challenges are the governance of the energy sector in Malaysia, which is not only fragmented but also incoherent (Yatim et al., 2016).

Thailand was the only country that released a general governance policy in the region in 2013. However, despite the presence of the Alternative Energy Development Plan (AEDP) and its targets, there is no mechanism to ensure that the targets are met and that relevant agencies in the public sector undertake their responsibilities in the most effective manner. Moreover, the permitting procedures are complicated by low transparency (Tongsopit et al., 2015). Thailand's governance in the energy sector is weak, particularly concerning independence, transparency, public participation and accountability (Sirasoontorn et al., 2017). The Energy Regulatory Commission (ERC) for governance policy in Thailand has been criticized, particularly in the area of autonomy and independence from political interference.

## 3. Methods

This section provides all the details about the methodology used in the study. It is divided into four subsections. The first sub-section reviews common methods used in renewable energy impacts analysis. The second subsection proposes a combined method of the most two popular ones, regression and correlation analysis. After that the paper proposes an Impact Matrix that will help to interpret the messages from the results of regression and correlation analysis in subsection 3. Lastly, subsection 4 describes the data used in the paper to implement the suggested method.

### 3.1. Review of previous studies

Research on the influences on renewable energy consumption most often employs regression and decomposition analysis. Many previous studies build on a nonparametric regression analysis at the sector level as well as indices constructed from a decomposition of this index, e.g. Ang (2005), 2006; Ang et al., (2009); Ang et al., (2004); Ang (2004); Boyd and Roop (2004); Ang et al., (2003); Hoekstra and van den Bergh (2003); Heinen 2013. A regression analysis with dynamic and statistical models was used in most studies in this field until Liu (2009) compared the results between an autoregressive-distributed lag (ARDL) and a factor decomposition model (FDM) in China to show the limitations of the regression method. They concluded that regression methods are limited in multi-tiered analysis, especially when applied to diverging influences on energy use from national sector levels to sectorial levels.

The decomposition method has frequently been utilized in energy-related analysis from the late 1970s until now (Zhang and Ang, 2001; Hoekstra and van den Bergh, 2003). It has proved to be an effective and powerful tool to explain the changes and impacts that occur in any variables over time or space. In particular, it allows the application of multi-level data to assess the effect of different factors on different energy users. This technique is used to study the impact of changes in product mix on energy consumption. Decomposition can be conducted by two techniques including Structural Decomposition Analysis (SDA) and Index Decomposition Analysis (IDA). While SDA uses input-output data to distinguishing a large number of specific determinant input-output effects mostly at the micro scale of sub-sectors and companies, IDA uses aggregated data to distingue the effect with macro scale such as sector, multi-sector and national scale s(Hoekstra and van den Bergh, 2003; Wang et al., 2017).

In assessing the influence of urbanization on energy consumption, Lin et al. (2008) and Liu (2009) suggested to use the decomposition method to separate the urbanization effect out of the aggregate effect. Following this idea, Wang (2014) applied the structure decomposition method (SDA) to investigate the effects of China's urbanization on residential energy consumption and production energy consumption. He did independent research for household usage and product usage by dividing total energy consumption into residential energy consumption (REC) and production energy consumption (PEC). The results showed different effects of urbanization on PEC, by dividing the study period into three stages. However, the results were limited due to lacking annual input-output data for several sectors in China.

Yang et al. (2016) used the index decomposition method (IDA) to assess the impact of urbanization on renewable energy consumption growth in China by analyzing five effects including energy mix, energy intensity, economic structure, GDP and urbanization effects. However, the calculation only focused on the macroeconomic level. The comparison of urban with other effects on total energy consumption and renewable energy consumption were expressed as weighted order averages of effect shares and relative renewable energy change.

Few previous studies came up with the idea of combined decomposition and regression analyses in the energy literature such as Zhang and Jiang (2016); Shakouri and Khoshnevis Yazdi

(2017); Karimu et al., (2017); Nicholas Apergis and Dan Constantin Danuletiu; Saad and Taleb (2017); Metcalf (2008); Mulder and de Groot (2012); Wing (2008). However, the studies mostly focused on energy efficiency advice. For example, Metcalf (2008) and Sue Wing (2008) only focused on energy intensity determinants and trend analysis, respectively, whereas Mulder and de Groot (2007) focused on trend and energy convergence of similar sectors across countries.

### *3.2. The combined decomposition - correlation method*

Based on the idea of combining the two techniques, this paper intends to take advantage of both methods in measuring the impact of different influencing factors on renewable energy developments. It will disentangle the contributions by comparing them in a multi-level, regional-country-sectorial analysis. The results will show the main driving factors for renewable energy extension and suggest key groups and specific incentives to policy makers in ASEAN.

The method is the combination model of correlation analysis and decomposition analysis. The model uses a multiplicative model for cross-classified data including regional analysis, cross-country and cross-sector analyses. It employs renewable energy cross-classified by renewable energy types and renewable energy users. The concept of the method is illustrated in Fig. 1.

First, total renewable energy increase is decomposed into the various contributions including adjustment in share of renewable energy consumption in total energy consumption (energy mix effect), changes in sectorial energy intensity (intensity effect), modification of activity composition (structure effect), activity change (activity effect), and especially urbanization changes (urban effect). The total change in renewable energy growth is the result of adding the disparities in indicators of renewable energy resources such as solar, wind, hydro, and biomass. The decomposition analysis allows comparing across countries and sectors. If results show negative values, it means the weighted average impact of a factor is less than 0. Therefore, the factor has negative interaction on renewable energy growth over the considered period and vice versa.

The model exploits the panel data by observing the cross-section of individual sectors over annual periods. The renewable energy changes or effect indicators function is expressed as (for symbols see Table 4):

$$\Delta RE_{(i)} = f(\Delta E_{mix}, \Delta E_{int}, \Delta E_{str}, \Delta E_{act}, \Delta E_{ur}) + E_{rsd} \quad (1)$$

Decomposition equations for sector:- Industrial:

$$RE_{in} = RE_{in}/\sum E_{in} \times \sum E_{in}/VA_{in} \times VA_{in}/GDP \times GDP/Ur \times Ur \quad (1.1)$$

- Residential:

$$RE_{r} = RE_{r}/\sum E_{r} \times \sum E_{r}/EXP \times EXP/GDP \times GDP/Ur \times Ur \quad (1.2)$$

- Transportation:

$$RE_{tr} = RE_{tr}/\sum E_{tr} \times \sum E_{tr}/VA_{tr} \times VA_{tr}/GDP \times GDP/Ur \times Ur \quad (1.3)$$

- Power Generation:

$$RE_{el} = RE_{el}/\sum E_{el} \times \sum E_{el}/PG \times PG/GDP \times GDP/Ur \times Ur \quad (1.4)$$

Symbols, detailed equations by sectors and the explanation of the meaning of each indicator are given below in Table 3 and Table 4.

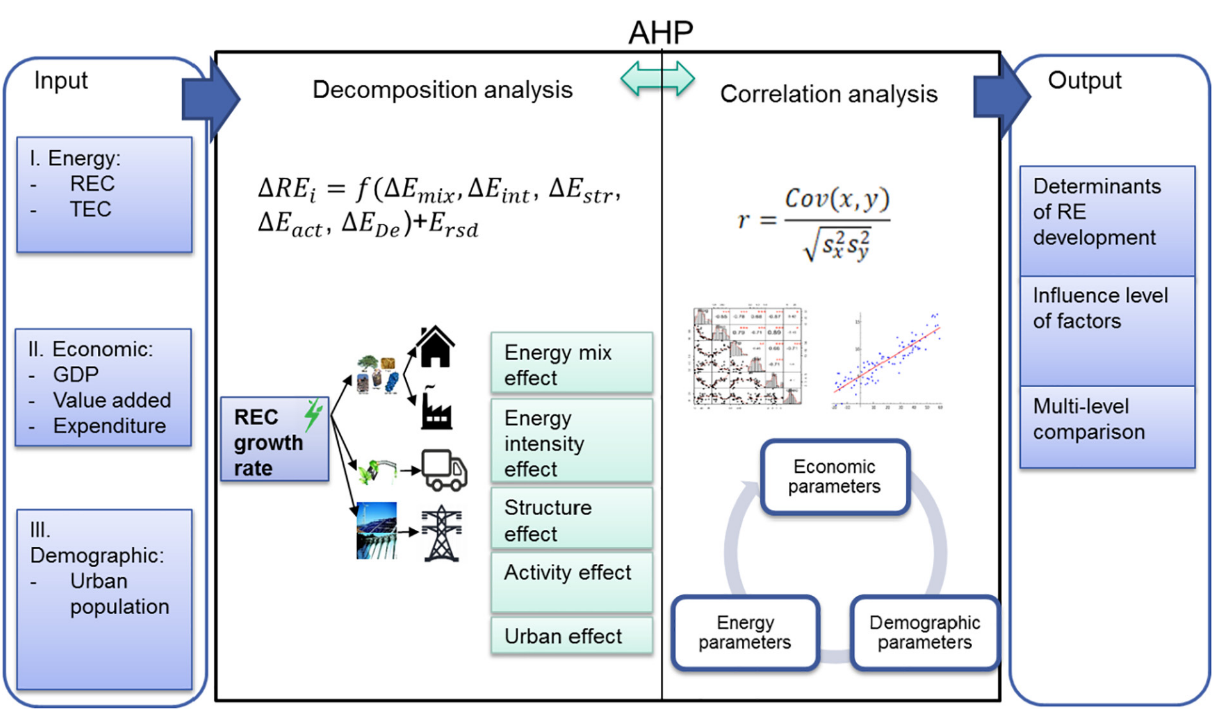


**Fig. 1.** Model concept for quantitative analysis. Acronyms: RE – Renewable Energy; REC – Renewable Energy Consumption; TEC – Total Energy Consumption; AHP - Analytic Hierarchy Process.

**Table 3**
Definition of symbols.

| Symbol | Name | Symbol | Name |
|---|---|---|---|
| *RE* | Renewable energy type i | *PG* | Generated power |
| *E* | Total energy consumption | r | Residential consumption |
| *VAj* | Value added sector j | tr | Transportation sector |
| *GDP* | Gross domestic production | *el* | Power generation sector |
| *EXP* | Expenditure on GDP | *in* | Industrial sector |
| *Ur* | Urban population | | |

Subsequently, a correlation analysis is used to assess the correlation between renewable energy change and its effect indicators. This is a bivariate analysis that measures the strength of association between each combination of two variables. It has the advantage of arbitrary factors, which offer more flexible specifications in the analysis that is not granted by the traditional decomposition methods. The goal of using correlation analysis is to analyze whether two measurement variables co-vary, and to quantify the strength of the relationship between the considered indicator and renewable energy change.

The formula for the sample correlation coefficient is

$$r = \frac{Cov(x,y)}{\sqrt{s_x^2 s_y^2}} \tag{2}$$

where Cov(x,y) is the covariance of x and y defined as

$$Cov(x,y) = \frac{\sum(X-\overline{X})(Y-\overline{Y})}{n-1} \tag{3}$$

$s_x^2$ *and* $s_y^2$ are the sample variances of x and y, defined as $s_x^2 = \frac{\sum(X-\overline{X}^2)}{n-1}$ and

$$s_y^2 = \frac{\sum\left(Y-\overline{Y}^2\right)}{n-1} \tag{4}$$

The variances of x and y measure the variability of the x scores and y scores around their respective sample means ($\overline{X}$and $\overline{Y}$, considered separately).

### 3.3. The impact matrix

Based on the physical force concept, the paper proposes an assessment method to support policy-makers in making strategy decisions by combining results of the two techniques in an Impact Matrix. The Impact Matrix provides the relative positioning for aggregate impact on the vertical axis based on decomposition results, and the relative positioning for the direction of the impact on the horizontal axis based on correlation results. The higher its placement on the vertical axis, the greater the impact the process has on the perception of value.

The impact on renewable energy growth is defined as the rate of increase of the vector, which is the combination of aggregate impact and direction impact (cf. Fig. 2). This means that the force, which produces acceleration for renewable energy growth in a given direction, has two components connected by a definite relation. One is the aggregate impact that pulls the renewable energy according to its scale; the other impacts give direction for the growth.

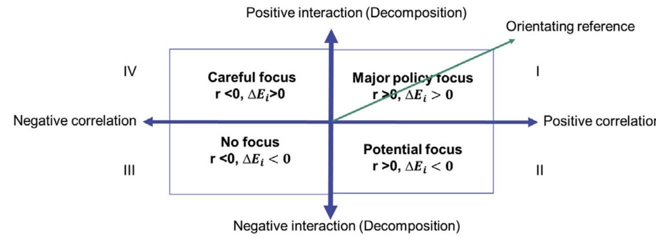


**Fig. 2.** Proposed impact matrix to support policymaking.

In general, decomposition results uncover the tension of different factors in enhancing renewable energy development. The struggle between the influencing factors results in renewable energy increase or decrease. Therefore, to promote renewable energy development, it is necessary to affect the whole market with the right impact factor at the right time.

To illustrate, renewable energy consumption increases linearly, when population increases, and economic growth results in more demand. This effect is described by the X-axis. However, if there is no movement in the Y direction, there would be no acceleration for renewable energy development. It indicates that renewable energy share in TPES would decrease. When governments encourage renewable energy development, they push in the vertical direction, which therefore pulls renewable energy growth faster.

To determine the order of impacts on the renewable energy growth rate from strongest to weakest, we propose dividing the matrix into four parts (seen Fig. 2):

- Zone I – major policy focus area, where the decomposition result (ΔEi) and the correlation result (r) have positive values.
- Zone II – potential focus area, where the decomposition result (ΔEi) is negative, but the correlation result (r) is positive.
- Zone III – no focus area, where both the decomposition result (ΔEi) and the correlation result (r) are negative.
- Zone IV – careful focus area, where the decomposition result (ΔEi) is positive, but the correlation result (r) is negative.

Zone I, with positive interaction and positive correlation, illustrates the strongest impact. Consequently, if policy-makers would focus on this area, it could accelerate renewable energy growth rate the most. We called Zone I the Major Policy Focus area.

Zone II, with positive correlation but negative interaction, covers the impacts that have naturally positive correlation with renewable energy growth rate, however, have insignificant motivation to promote faster growth. This part is called the Potential Focus area, which means if policy-makers focus on the influence elements in Zone II, they could move from insignificant impacts to a greater

**Table 4**
Declaration of indicators and their meaning.

| Symbol | Effect | Calculation | Meaning |
|---|---|---|---|
| $\Delta E_{mix}$ | Energy mix effect | Change of renewable energy share in total energy supply | Energy transition performance |
| $\Delta E_{int}$ | Intensity effect | Units of energy consumption per unit of added-value | Energy efficiency changes |
| $\Delta E_{str}$ | Structure effect | Sector's unit profit share in GDP | Economic bias: industrialization or commercialization |
| $\Delta E_{act}$ | Activity effect | GDP unit per demographic unit | Economic growth |
| $\Delta E_{ur}$ | Demographic effect | Urban population in urban areas | Market size growth |

impact in Zone I.

Zone III includes all the factors that have plainly negative impact on renewable energy growth. It is called the No Focus area. Note that, no focus indicates that it is not a favorable focus to accelerate renewable energy increase for policy-makers.

Zone IV covers the factors that have a negative correlation with renewable energy growth rate, however, still shows its positive interaction. If the considered factors are placed in this area, policy-makers should be careful in creating more renewable energy supporting schemes, because it does not ensure a positive effect. This zone is called the Careful Focus area.

The most efficient option for policy makers to accelerate a renewable energy development is to keep the driving factor moving along the dissection of the major policy focus quadrant, as can be seen in Fig. 2 as the orientating reference.

### 3.4. Collecting and sorting data

In previous papers, researchers collected historical data at aggregate or country levels. This paper consecutively collects all these data as well as sector level for the period between 1995 and 2013 (see Table 6). It therefore approaches diverse perspectives of comparing different effects on renewable energy extension in ASEAN. However, since data collection is still lacking in ASEAN, only seven of ten countries are considered. However, since renewable energy in Brunei Darussalam is recorded with almost no development, all the results are shown in this study for only the other six countries.

With the purpose of focusing on understanding how the factors interact on renewable energy changes at the multi-level, this paper uses divergent data for renewable energy types. It means energy data is divided by sectors (end-used customers) and energy types (solar, wind, hydro, etc.). To ensure data reliability, we collected and adjusted data by comparing it from different sources (as seen in Table 5). It prevents errors in the first place since data is crucial in the calculation. For instance, renewable energy data is combined from IEA 2017 (IEA, 2017) and IRENA (2017). While IEA 2017 provides an entire picture of the energy balance in the countries, IRENA (2017) focuses on renewable energy in general and particular types of it. However, there is a slight difference between this data, around 10% on average. Especially in case of individual renewable energy types, we used IRENA (2017) after collating it with national reports.

## 4. Results and discussion

The results explain the trend of increasing renewable energy usage in the region by revealing the interdependency between renewable energy growth and other impact factors such as economic growth, urbanization growth, economic structure change and energy intensity change in the considered period from 1995 to 2013.

### 4.1. Decomposition results

We obtained the first results with the decomposition method from three different levels: the regional level (considering ASEAN as a whole), the country level and the sector level.

The regional level results reveal that renewable energy growth in ASEAN, as a whole (see Fig. 3), is mostly driven by $\Delta E_{act}$ and $\Delta E_{ur}$, economic growth and urbanization growth (urban population growth) respectively. Compared to the two effects, the structure effect $\Delta E_{str}$ is relatively small. The energy transition effect ($\Delta E_{mix}$) and especially the energy efficiency effect ($\Delta E_{int}$) delay renewable energy growth.

By separating these effects into country perspectives (see Fig. 4 for all effects and Fig. 5 for detailed economic growth and urbanization growth effects), the effects of economic growth and urbanization growth maintain their positive influence in all countries while other effects such as structure and energy mix effects show their positive or negative influence depending on the individual country. The economic growth and urbanization growth effects contribute estimated significant increases of renewable energy growth in all ASEAN countries. In contrast, the energy intensity effect is the main negative effect among the five considered effects on renewable energy growth (see Fig. 4).

Looking at the two significant positive effects, the economic growth effect ($\Delta E_{act}$) is more than twice as strong as the urbanization effect $\Delta E_{ur}$ in most of the countries, except for Malaysia and Thailand. In Malaysia, urbanization is almost as important as economic growth in motivating renewable energy. While in Thailand, it is indeed the most important factor, at roughly 10% stronger than the economic effect (detailed in Fig. 5).

Meanwhile the structure effect $\Delta E_{str}$ is recorded positively in Thailand and Myanmar with a calculated increasing effect of about 153 and 28 thousand TOE respectively. The structure effect not only recorded an inhibitory effect on renewable energy growth in other

**Table 5**
Symbols and data sources.

| Symbol | Illustration | Unit | Sources |
|---|---|---|---|
| *REi* | Renewable energy consumption in sector i | 1000 TOE | IEA 2017, IRENA Statistics 2017 |
| *Ei* | Energy consumption in sector i | 1000 TOE | IEA (2017) |
| *VAj* | Value-added of sector I at 2000 market prices | Millions US $ | Adjusted from World bank 2018 & ADB 2015 |
| *GDP* | Gross Domestic Production at 2000 market prices | Millions US $ | World bank 2018, ADB 2015 |
| *Ur* | Urban population | people | World bank 2018 |
| *Ex* | Expenditure on GDP at 2000 market prices | Millions US $ | Adjusted from ADB 2015 & World bank 2018 |

Note: Data lacking: Laos, Indonesia, Singapore.

**Table 6**
Correlation between impact effects with renewable energy growth in whole ASEAN and countries over period 1995–2013.

| | ASEAN | Cambodia | Malaysia | Myanmar | Philippines | Thailand | Vietnam |
|---|---|---|---|---|---|---|---|
| $\Delta r_{mix}$ | 0.74** | 0.73** | 0.96** | 0.68** | 0.79** | 0.72** | 0.95** |
| $\Delta r_{int}$ | −0.04 | 0.59** | −0.14 | −0.48* | 0.24 | −0.03 | −0.40 |
| $\Delta r_{str}$ | −0.07 | −0.04 | −0.27 | 0.24 | 0.07 | −0.36 | 0.09 |
| $\boldsymbol{\Delta r_{act}}$ | 0.28** | −0.10 | 0.19 | 0.65** | −0.05 | 0.60** | 0.28 |
| $\boldsymbol{\Delta r_{ur}}$ | 0.48** | 0.45* | 0.09 | 0.46* | 0.40* | 0.44* | 0.46* |

Note: ** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

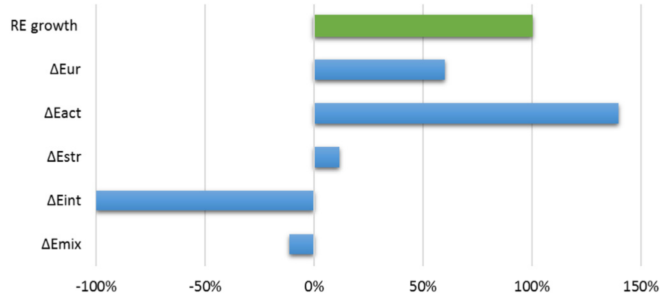


**Fig. 3.** Cumulated effect of impact factors on renewable energy growth in 7/10 ASEAN countries from 1995 to 2013.

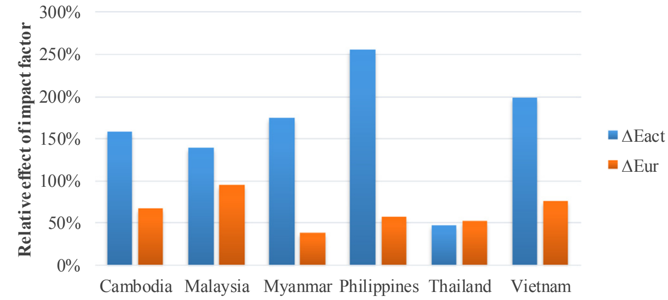


**Fig. 5.** Decomposed effect of economic growth and urbanization on renewable energy growth by country in ASEAN from 1995 to 2013.

countries, but also a positive effect followed by a negative effect during the considered period. Given all ASEAN economies bias towards industrialization, especially after 2000, it could increase energy consumption in these countries. Unfortunately, with mostly limited finance conditions in the region such as in Cambodia, the Philippines and Vietnam, it enhances fossil fuel consumption instead of renewables in these countries.

In contrast, the energy intensity effect $\Delta E_{int}$, which reflects the efficiency of energy utilization, and improvement in energy efficiency, does not create renewable energy demand in any country. It has a dramatically negative impact of about 400 thousand TOE of renewable energy consumption in the Philippines, and about 342 thousand TOE in Thailand, corresponding to reductions of 163% and 74% of the renewable energy growth rate respectively. Hence, the energy intensity effect is the main force tending to decrease the renewable energy development.

The energy mix effect $\Delta E_{mix}$ represents the energy transition process, by describing the structural change in the energy system. The positive calculated value of $\Delta E_{mix}$ is observed only in Thailand, encouraging a 41% renewable energy increase over the studied time period. In general, the energy transition is more effective in Thailand than revealed by the results in the other countries.

As mentioned, one of the paper's objectives is conducting comparative analysis at country and sector levels. Thus, to explore profoundly the factors influencing the extension of renewable energy, we employ a multi-sector analysis using the data of the same period. However, instead of using aggregate data, we use the sectorial data that has some distinctness between different sectors including electricity, industrial, residential and transportation. For instance, in case of electricity, energy intensity is energy efficiency in electricity generation, thus, it is the fraction of total energy use for this purpose per total electricity generation and there is no economic structure effect for this sector. Alternatively, in the residential case, we acknowledge the effect of household expenditure/GDP ratio instead of Value-added/GDP ratio as the industrial and transportation cases.

Detailed results are presented in Fig. 6. The majority of the calculated cases show similar results in a region-level and country-level analysis, which determined a strong effect from economic growth $\Delta E_{act}$ with estimated pulling renewable energy increase of more than 100 thousand TOE in electricity and industrial sectors, and much greater in residential with more than 800 thousand TOE. This may suggest that economic growth as well as urbanization growth play relatively important roles in encouraging renewable energy.

The feature, however, is different in the case of transportation, where the energy transition effect ($\Delta E_{mix}$) overtakes the economic growth effect as the most significant force in driving renewable energy increases. Estimated calculation shows it almost five times stronger than the economic growth effect ($\Delta E_{act}$) and almost eight times stronger than the urbanization effect ($\Delta E_{ur}$).

### 4.2. Correlation analysis

Before analyzing the relation between renewable energy and its effects, the study carries out a test for normality. The results show the individual time-series data does not deviate significantly from the normal distribution at 1% and 5% significance levels. It qualifies for correlation analysis that is conducted to detect the trend of

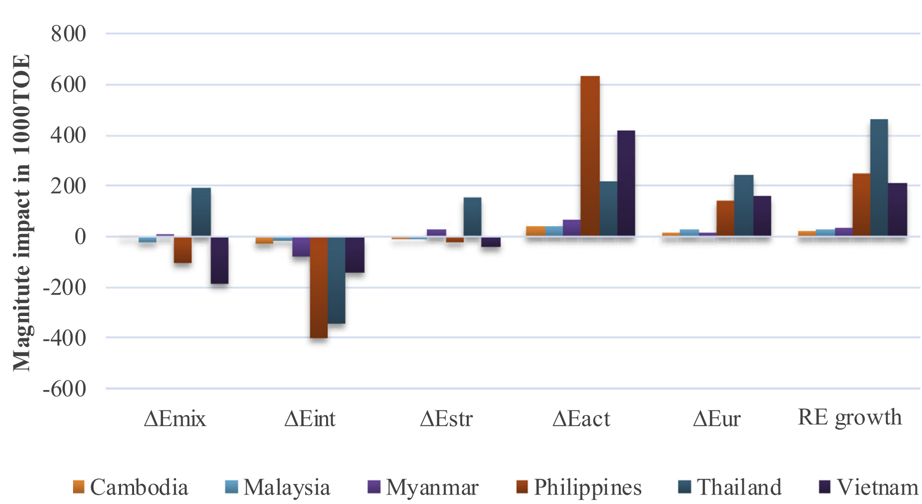


**Fig. 4.** Dispersed effect of impact factors on renewable energy growth in ASEAN from 1995 to 2013.

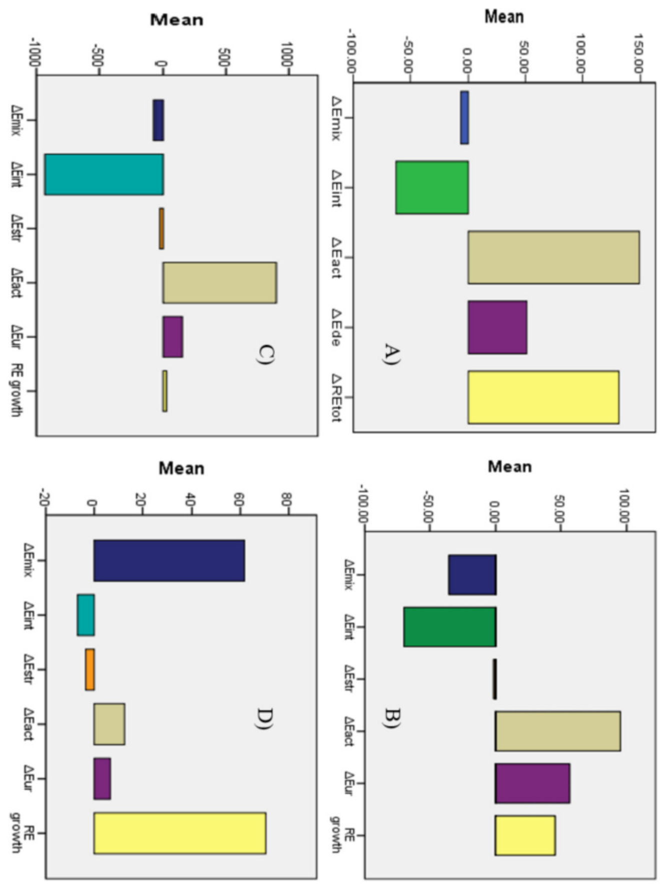


**Fig. 6.** Decomposition analysis results. Mean of effects on a) electricity sector, b) industrial sector, c) residential sector, d) transportation sector in ASEAN countries by 1995–2013. Unit: 1000 toe.

renewable energy growth following the trend of other factors.

The results in Table 6 illustrate the correlation analysis between renewable energy growths with their influence factors at 1% and 5% significance levels. In ASEAN, obviously, energy transition ($\Delta E_{mix}$) has the strongest relationship with renewable energy growth. The faster the energy transition process, the more renewable energy development. Following this, it is the economic growth effect and the urbanization effect, $\Delta E_{act}$ and $\Delta E_{ur}$ respectively. In contrast, economic structure $\Delta E_{str}$ changes and energy efficiency $\Delta E_{int}$ improvements have negative correlations with renewable energy growth, with $r_{str} = -0.07$ stronger than $r_{int} = -0.04$.

To investigate the correlation between renewable energy growth and its influencing factors, tests for correlation and cross-country comparisons are conducted. The presence of correlation between renewable energy and energy transition ($\Delta E_{mix}$) is strongest with $\boldsymbol{r_{mix}}$ ranging from about 0.68 to 0.96, correlation is significant at the 0.05 level (2-tailed). It means renewable energy growth depends significantly on the energy transition progress in all analysed countries.

The urbanization effect ($\Delta E_{ur}$) demonstrates the second strongest effect on renewable energy extension at the 1% significance level, except for Malaysia. Positive signs of economic growth effect ($\Delta E_{act}$) are shown in Myanmar, Thailand and Vietnam, in descending order respectively.

The correlation results of$\boldsymbol{r_{int}}$ show the dependence of renewable energy growth on the energy efficiency effect ($\Delta E_{int}$). Apparently, $\boldsymbol{r_{int}}$ is greater than zero in the case of Cambodia (0.59) and the Philippines (0.24), meaning energy efficiency improvement is proportional to a renewable energy increase. There is a need for more evidence to conclude about the special cases that will be conducted by the Impact Matrix in the following sub-section.

Table 7 shows the results of the correlation analysis at the sector level. There is evidence to conclude that the energy transition ($r_{mix}$) correlates actively with renewable energy growth, especial in transportation with $r_{mix} = 0.993$, and electricity with $r_{mix} = 0.881$. In other words, it could mean the energy transition has a more direct effect on renewable energy growth than the other factors, followed by the urbanization effect ($r_{ur}$). The economic growth effect ($r_{act}$) only shows an active effect on the industrial sector, but relatively weak. The energy intensity effect($r_{int}$), structure effect ($r_{str}$) in industrial and transportation sectors, and expenditure effect in the residential case($r_{exp}$), all present relatively limited correlations with renewable energy growth.

### 4.3. Impact matrix analysis

As discussed above, to overcome deficiencies of individual analyses, the Impact Matrix combines the results and reveals sufficient and convincing evidence about which factor is driving renewable energy development. At all three analysis levels including regional (see Fig. 7), country (see Fig. 8) and sectoral (see Fig. 9) levels, there are similar findings.

#### 4.3.1. Zone I: major policy focus

Overall, economic growth (ΔEact) and urbanization (ΔEur) are the two factors placed in the major policy focus, in which economic growth (ΔEact) has a much higher position than urbanization (ΔEur), but on the left side. It means that despite the strong correlation between urbanization (ΔEur) and renewable energy growth, economic growth (ΔEact) is the main pull factor for renewable energy market development.

By country, the economic growth generates the strongest promotion for renewable energy in Vietnam, followed by urbanization (Fig. 8), while urbanization is the best motivator for Thailand, the Philippines, and Malaysia. However, the motivation of urbanization in Myanmar seems to be very low due to their place almost on the horizontal axis.

By sector, the development in the power sector is most strongly affected by the economic factor, while demography as urbanization affects the most on renewable energy development in the residential sector (Fig. 9). However, these two factors do not show a significant effect on transportation.

#### 4.3.2. Zone II: potential policy focus

Energy transition (ΔEmix) is normally placed in the potential policy focus zone of the three analysis results, but much closer to the X-axis than the Y-axis. It shows that renewable energy increase depends strongly on the energy transition progress. However, the rate of the transformation process is slow.

Looking at the country analysis, we see a bright spot for the

**Table 7**
Correlation between impact effects with renewable energy growth by sector in ASEAN over period 1995–2013.

| | Electricity | Industrial | Residential | Transportation |
|---|---|---|---|---|
| $\Delta E_{mix}$ | .881** | .698** | .439** | .993** |
| $\Delta E_{int}$ | -.057 | -.143 | .054 | -.061 |
| $\Delta E_{str}$ | – | .071 | – | -.141 |
| $\Delta E_{act}$ | .053 | .373** | -.006 | .164 |
| $\Delta E_{ur}$ | .385** | .312** | .294** | .449** |
| $\Delta E_{exp}$ | – | – | -.059 | – |

Note: ** Correlation is significant at the 0.01 level (2-tailed).

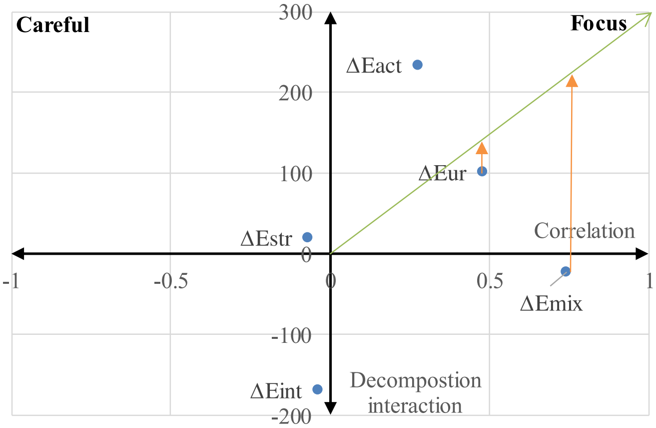


**Fig. 7.** Impact matric analysis for ASEAN as a whole. Unit of y-axis: 1000 toe.

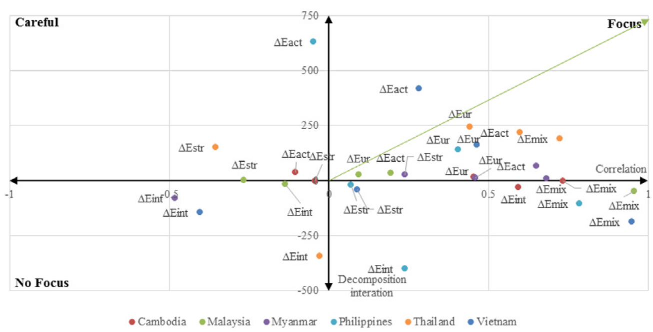


**Fig. 8.** Impact matric analysis for ASEAN by countries. Unit of y-axis: 1000 toe.

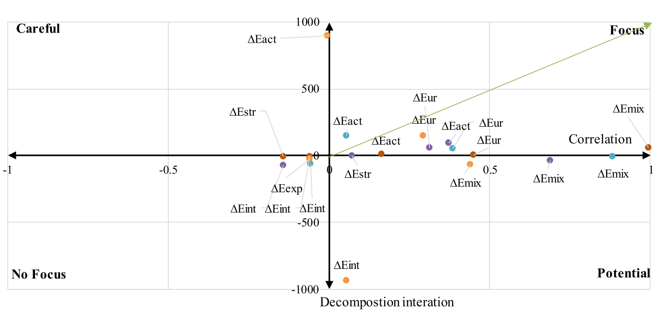


**Fig. 9.** Impact matric analysis for ASEAN by sector. Unit of y-axis: 1000 toe.

energy transition in Thailand. Moreover, looking at the sector level, we recognize ΔEmix located in the major focus area. Energy restructuring in Thailand and energy transition policy for transportation could be considered as best practice cases for other countries to follow.

#### *4.3.3. Zone III: No focus*

The energy efficiency effect (ΔEint) commonly falls into the no focus area since there exists theoretically a negative relationship between the two variables. This is related to the fact that because of energy efficiency improvement, consumers demand less energy for the same condition, therefore they are not motivated to invest in alternative energy such as renewable energy.

#### *4.3.4. Zone IV: careful focus*

The impact of economic structure ΔEstr appears in all four quarters of the Impact Matrix. However, it usually can be seen in the corner of careful focus. This argues that promoting industrialization does not necessarily have a positive impact on renewable energy development.

For example, there is a special appearance of the economic structure ΔEstr factor of Myanmar in the major focus area. To discover the reason for that, we have inspected the cause from the dataset of all countries and recognized a distinguished trend in Myanmar's economy. Compared with other countries, the industry share in total GDP in Myanmar decreased from 78% in the beginning of the considered period (1995) to around 60% in the last considered year 2013, while other countries recorded an increasing share of industry in total GDP. In addition, the economic structure ΔEstr factor can be noticed in the potential area for the cases of the Philippines and Vietnam, where the industry share increases at a slower pace.

### *4.4. Critical discussion of the method*

By dividing impact factors according to their strength and direction to a certain priority level, the presented method represents a combination of two quantitative approaches. Starting with the decomposition approach, the method aims to calculate numeric values that describe the association of each factor with renewable energy change. Thereafter, a correlational analysis is conducted on variables to measure and demonstrate the presence of relationship between the impact factors and renewable energy growth. Combining two quantitative results, the impact matrix makes relative judgments in order to categorize the importance of the impact such as focus, potential, no focus and careful. The weight-scaled impact score is the combination of the correlation score and decomposition score. Therefore, it is able to compare different alternatives.

The Impact Matrix is developed to help determine how different factors affect renewable energy development. Therefore, it could support policy-makers to decide where to focus attention and reduce the problem of transparency between policy formulation and impacts. Due to this ability of cross comparing between region-country-sector-city, it could help to better understand the complex interactions between renewable energy development and the effects of energy transition, economic structure change, economic growth, and demographic change. It could therefore be useful in generating and analyzing scenarios by using historical data combined with future projections.

Despite the usefulness of the Impact Matrix, it has some weaknesses. Firstly, it is unsuitable for application to prediction, but can assess the efficiency of the prediction according to defined objectives. Secondly, the Impact Matrix must be applied after a certain time ex post, in order to control for the efficiency of the energy policy. For example, urban population changes cause economic and energy demand changes, but the impacts have a non-linear relationships and due to many simultaneous impacts on renewable energy, there is the possibility of a time delay in their realization. Thirdly, the Impact Matrix shows the interactions between each impact factors with renewable energy change. However, it is difficult to understand the interactions between the factors themselves. In the case of one impact propagating from one component to another, it is not necessarily linked directly to the other impacts. Furthermore, the Impact Matrix does not allow to depict the interconnection in a causal style between the impact factors. So it is difficult to conclude which impact factor causes other impact factor changes. Fourthly, the Impact Matrix only considers relative changes in effects through decomposition and correlation between the start and end of the period studied. It therefore overlooks changes in these effects between these points in time. Hence the developed method with the Impact Matrix should be extended in the context of further work and employed to analyze the potential impact of current and future renewable energy policies, by comparing the situation before and after (e.g. using scenarios) the policy implementation.

### 4.5. Policy recommendations

Because of the similarity at different levels, the results reveal a good argument for matching multi-level policy. Renewable energy programmes could be merged between regional, country and local levels. The European Union (EU) provides the obvious example for this type of harmonization. In the EU, regional targets at the European level for RE shares are broken down to and agreed with member states, according to the potentials for specific RE technologies and progress to date. Progress towards these national targets is achieved based on national and local policy instruments, a model that could also be applied in ASEAN. By doing so, ASEAN countries could save national and local resources in preparing and implementing renewable energy policy. From the results in section 4, we propose using economic growth and urbanization as two of the main criteria to select the target audience and use the Impact Matrix as one of the tools to review and revise policy.

As discussed in section 4, since they are the main drivers of renewable energy development, urban areas are crucial in the process of promoting renewable energy. Indeed, rural areas include masses of low-income people, who could mostly not afford the extra cost of decentralized renewable energy investment such as solar PV. On the other hand, urban areas concentrate high- and middle-income groups of people, who are more likely to be capable of investing. Secondly, energy consumption is mostly concentrated in urban areas with 75% of total energy consumption, compared to only 25% in rural areas (EIA, 2017). Low demand in rural areas, consequently, would create much less motivation to use renewable energy compared to urban area. Lastly, rural areas have a much lower density than urban areas, which would require more investment in energy system transmission and distribution infrastructure. Hence, it seems advantageous to concentrate future policy and governance measures on urban areas. Policy-makers should have more supporting schemes to promote public investment in decentralizing the energy system instead of only focusing on supporting large investors.

At a national level, in general, the priority for urban areas and cities should be either as much as or even higher than rural areas in renewable energy policy. They should be one of the main target audiences for accelerating renewable energy growth. Some countries focusing on enhancing renewable energy consumption in rural areas such as Cambodia, Myanmar and Vietnam (Table 2) should consider adjusting their policy target groups. Countries without target groups such as Indonesia, Laos and the Philippines (Table 2) should consider establishing them because goals and objectives are a direction-setting base for renewable energy development. Besides the electricity sector, industrial and transportation sectors have three of four impact indicators in Zone I of the Impact Matrix (Fig. 9). Therefore, policy makers should not only focus on the electricity sector but also need to support more non-electricity sectors.

Detailed recommendations for each country by sector are presented in Table 8. Each country could use this table as a suggestion in deciding whether the policy should stay at government or governance level. For example, looking at the results of the electricity sector, it reveals that Cambodia need to focus on improving all the impact factors including energy transition, energy intensity, economic factor and urbanization factor. It would be too difficult for the governance to handle all of them alone without direct and strong support from government policy. Therefore, in this case, policy-makers should focus on improving their government policy.

**Table 8**
Recommendations of focus target for future renewable energy policy by sector for ASEAN countries from Impact Matrix analysis.

| | Electricity | | | | |
|---|---|---|---|---|---|
| | *ΔEmix* | *ΔEint* | *ΔEstr* | *ΔEact* | *ΔEur* |
| Cambodia | Focus | Focus | – | Focus | Focus |
| Malaysia | Focus | Potential | – | Careful | Focus |
| Myanmar | Focus | No focus | – | Focus | Focus |
| Philippines | Potential | No focus | – | Careful | Focus |
| Thailand | Focus | No focus | – | Focus | Focus |
| Vietnam | Potential | No focus | – | Focus | Focus |
| | Industrial | | | | |
| | *ΔEmix* | *ΔEint* | *ΔEstr* | *ΔEact* | *ΔEur* |
| Cambodia | Potential | Potential | Potential | Careful | Focus |
| Malaysia | Potential | No focus | Focus | Focus | Focus |
| Myanmar | Potential | No focus | Potential | Focus | Focus |
| Philippines | Careful | No focus | No focus | Focus | Careful |
| Thailand | Focus | No focus | Potential | Focus | Focus |
| Vietnam | Potential | No focus | Focus | Careful | Focus |
| | Residential | | | | |
| | *ΔEmix* | *ΔEint* | *ΔEstr* | *ΔEact* | *ΔEur* |
| Cambodia | Potential | Potential | Potential | Careful | Focus |
| Malaysia | No focus | Potential | Careful | Focus | Focus |
| Myanmar | Potential | Potential | No focus | Careful | Careful |
| Philippines | Potential | Potential | Potential | Careful | Careful |
| Thailand | Potential | Focus | Potential | Potential | Focus |
| Vietnam | Potential | Potential | No focus | Focus | Focus |
| | Transportation | | | | |
| | *ΔEmix* | *ΔEint* | *ΔEstr* | *ΔEact* | *ΔEur* |
| Cambodia | – | – | – | – | – |
| Malaysia | Focus | Focus | Focus | Focus | Focus |
| Myanmar | – | – | – | – | – |
| Philippines | Focus | Potential | Potential | Careful | Focus |
| Thailand | Focus | No focus | No focus | Focus | Focus |
| Vietnam | – | – | – | – | – |

The necessary conditions to improve renewable energy increase are economic growth and urbanization. The wealthier and more densely populated the area, the faster the renewable energy development stands to be. Thus, local policy makers should also focus on urban districts in accelerating renewable energy. Energy mix, which has a strong relationship with renewable energy development but is still located in the potential zone, would be one of the sufficient conditions for renewable energy development in the area. By granting both necessary and sufficient conditions, renewable energy in the region would be ready to accelerate. To make the energy mix more strongly based on renewable energy development, policy makers should concentrate on improving planning for future grid extension and complete net-metering systems, for example.

Because the socio-economic situation in developing countries like ASEAN has changed at a rapid pace, policy makers at all levels should conduct the assessment after the specific period to adjust policy target audiences matching with the new situation. To assess the efficiency of the policy changes, the government and governance could compare the changes by assessing the differences between the current Impact Matrix and the previous Impact Matrix. If the influencing factors move from Zone III and IV to Zone II and I, the policy seems to work adequately. If the influencing factors in Zone II move in the direction of Zone I, and/or influencing factors in Zone I move from the 45° bottom corner to the 45° upper corner, the policy changes seem to work efficiently.

Using the same methodology to set up target audiences and assess policy efficiency could enhance co-ordination between public authorities, donor agencies and project developers. Since policy makers, stakeholders and the public often have similar visions, it is better for them to reduce conflict potential and collaborate in planning. However, doing that requires the database synchronization at all levels that could be one of the first priorities for ASEAN to focus on in creating common strategies for cooperation to develop renewable energy in the region.

## 5. Conclusion and outlook

The ASEAN region has large potentials and favorable climatic conditions for renewable energies, but their exploitation is often hindered by geographical and technical conditions, inadequate regulatory frameworks, persistence of subsidies on conventional energy sources, import tariffs on renewable energy goods, and the lack of public awareness and support. ASEAN countries are taking important initial steps, but many opportunities remain for improving the overall renewable energy policy and regulatory environment. This paper provides evidence of the importance of governance policy, interaction by common target groups and combining action plans for policy-makers in establishing renewable energy policy.

By employing a correlation decomposition approach at regional, country and city levels, this paper investigates the determinants of renewable energy expansion and explores the trend drivers in ASEAN countries from 1995 to 2013. The results highlight the potential of economic growth associated with urban effects on renewable energy development, whilst at the same time ensuring rapid economic growth and urbanization. It confirms that urban areas should also be the focus of renewable energy policy in addition to rural areas. The tremendous impact of economic growth creates a great impetus for renewable energy development; urbanization ($\Delta Eur$) is the second pull for renewable energy extensions. Since the two effects are located in the first quadrant of the Impact Matrix, if strategists affect these factors, they will create the most powerful incentive for renewable energy growth. This confirms that if the strategic aim is to promote renewable energy market development, it is clear that the target must be focused on the richer and more crowded places. Due to the inverse effect of energy intensity, it supposes that the idea of integrating promotion policy for energy efficiency and renewable energy seems to be not a priority focus for renewable energy strategies. The energy transition should not only focus on the electricity sector but also needs more supporting mechanisms and schemes in non-electricity sectors, especially in promoting the strategy of smart and green cities.

The overall target for renewable energy development in ASEAN seems ambitious if current policies are maintained. To achieve the 23 percent renewable target in 2025, each country within ASEAN needs to consider changing their individual policies. Having clear, well-defined goals and objectives is a critical first step in improving their policies. These could give a direction for setting strategies, plans and policies, whether they are used for regulation or governance at the national and/or local level. If a sector needs high attention on all the impact factors, it is a clear message to the policy-maker to keep focusing on government policy and governance policy at national level.

The main problem in renewable energy policy in the region is the insufficient regulatory framework, lacking clear specific targets at the national level, and no target at a local level. The root cause seems to be that they do not have the tools to make decisions and select target audiences, with confusion in translating national objectives into local targets. Some countries are combining electrification with smart and green city targets in designing renewable energy policy. So local governments do not know what should be the first priority. The clear selection criteria and assessing policy matrix as proposed in this paper would provide a systematic approach to developing renewable energy policy at national and local levels. The criteria and the Impact matrix provide a common 'language' for urban government and governance in collaborating. They can be used to make policy more transparent and convincing stakeholders by providing quantitative answers to questions of target setting in a specified period.

If Southeast Asian countries should redirect their renewable energy support schemes to make the urbanization trend environmentally sustainable, many actors need to work together to come up with solutions. For example, not only the government, but also businesses, citizens and governance processes should be involved. Economic growth in urban areas could encourage household investment in renewable energy, especially in solar PV. It also helps to tackle increasing energy consumption in the area. Therefore, renewable energy policy should create supporting mechanisms not only for the supply side but also for the demand side.

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# A Cost-Effective and Transferable Methodology for Rooftop PV Potential Assessment in Developing Countries

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**Abstract:** The efficient uptake of decentralized solar rooftop photovoltaics (PV) is in some cases hindered by ineffective energy and political framework conditions. These may be based on inaccurate and uncertain potential assessments in the early development stage of the solar market. This paper develops a more accurate, cost-effective, and robust potential assessment for emerging and developing economies. Adjusting the module efficiency corresponding to regional and household conditions improves the output accuracy. The rooftop PV market changes are simulated regarding different input changes and policy designs, including changing the Feed-In Tariff (FIT), grid tariff, and technology development. In the case study, the market potential in Vietnam is estimated at 260–280 TWh/a and is clustered into six groups in priority order, in which Hanoi and Ho Chi Minh need the most policy focus. Changing the FIT from 8.83 to 9 Euro cent/kWh and using different regional FITs can activate an additional 16% of the market and lead to a possible 28 million Euro benefit. Increasing the grid tariff to 8.7 cents/kWh could activate the self-consumption model, and the self-sufficient market can be guaranteed in the case of CAPEX and OPEX being lower than 650 Euro/kWp. Future developments of the method should focus on combining this top-down method with detailed bottom-up approaches.

**Keywords:** rooftop PV; resource assessment; renewable support policies; self-consumption; developing countries

## 1. Introduction

Renewable energy technologies have gained momentum in cost competition with conventional thermal electricity generation and have become significant in the global electricity transition. They had a share of 14% in global electricity generation by 2018, with around 53% of all renewable energy investments in developing and emerging economies [1]. In the countries concerned, distributed solar PV systems not only play a prominent role in spreading energy access to households in remote areas [1] but also promise an effective alternative to serving the highly increased urban electricity demand [2–4].

Many sub-national governments have become leaders of solar development by setting even more ambitious targets than their national counterparts [1]. However, national and local governments in the countries are dependent on generic rooftop PV assessments. These assessments often have a rather low accuracy, which could direct investors into suboptimal locations and configurations [5,6]. As a result, the diffusion of PV power projects is spatially heterogeneous between the different regions in a country [7–9]. If the development goes in one direction only, this could have a far-reaching impact on both grid and market congestion [9–12]. To avoid this, policymakers urgently need a superior method to provide their market with transparent targets and stable policies so that the market will continue growing without threatening the stability of national electricity systems.

Previous studies focus on investigating rooftop areas for solar PV with many different methodologies such as GIS [13–17], 3D models [18–20], and LIDAR technology [16,19,21–23]. The 3D model is the most advanced and accurate method that allows the digitization of features, followed by simulations of insolation and shading of buildings [5,18–21]. However, it is challenging to employ this approach at the national level in developing countries because their data conditions and financial budgets will take years to reach the sufficiency for 3D model estimation.

In this context, this paper proposes an accurate, cost-effective, and transferable potential assessment method with a geostatistical approach across cities to assist policymakers in assessing their local and national rooftop PV potential. The proposed method is suitable for application in a country with unfavorable data conditions and a meager investment budget for conducting a high-resolution assessment. To improve the accuracy of the technical assessment, this paper adjusts solar irradiation and corrects the module efficiency of the PV system corresponding to the geographic and climate conditions, as well as dwelling design. A novel approach to control model accuracy is introduced by identifying and classifying the impact level of the uncertain parameters used in this paper. Considering the findings, we build different scenarios to observe market reactions as a result of various technological, investment, and policy changes. The paper comprehensively presents a three-step model, which is instantly applicable to different levels of detail of rooftop PV potential assessment and policy design, such as sub-regional, regional, and national scales. This model is used for deploying the rooftop PV potential strategically, and for preventing aggressive local development and structure-inherent rooftop PV conflicts between different regions. The results provide a more realistic picture of the medium-term growth and the interaction of various impacts, e.g., technology and policy changes, on the rooftop PV market in the considered country.

The paper is structured into six sections. Section 2 provides a succinct comparison between different levels of spatial resolution techniques and points out the advantages of our methodology. The detailed method is described in Section 3, including the methodology flow chart, methods for geographical, technical, and economic potential assessments as well as the case study. Section 4 reports the study results, and Section 5 contains the discussion and suggestions for policymakers based on shifting and bending market distribution under different possible framework conditions. The final section is the conclusion and outlook.

## 2. Literature Review of Potential Assessments for Rooftop PV

The studies of photovoltaic energy potential assessment can be categorized into three groups: low-, medium-, and high-level spatial resolution techniques [24,25]. Low-level assessment is usually based on statistical data, which are supposed to be homogeneous throughout the investigated area [24,26]. It can be employed on a large scale, e.g., many cities all around the world, based on the correlation between solar insolation and population density. However, due to the uneven distribution of population and buildings between different areas, this type of assessment provides poor quality and inaccurate results due to the general assumptions.

The existing medium-resolution assessment is claimed to be inaccurate for tailored policy designs [24]. Because they are faced with the uncertainty caused by using many assumptions due to data deficiency [27], their outputs tend to vary widely from 16% to 207% when compared with other resolution assessments over the same geographies [5,6]. To conquer the uncertain and applicable issues, studies in this field usually focus on developing high-level assessments on a small scale, e.g., for buildings [18,21,22] or district(s) [5], to avoid inaccurate results. When studying a larger scale, e.g., at city-level or multi-cities level, researchers are limited to estimating only geographic potential based on different assumptions such as roof area available [15,26,28,29], land use data [8,26], and type of building [26]. Some studies investigate the technical potential [14,16,30], but detailed uncertainty analyses to measure the error are not covered.

To calculate a high-resolution PV potential, previous studies have used advanced and accurate technologies such as 3-D models to calculate geometry, insolation, and shading of buildings [5,18–21]. Even though the methods are more precise, the main barrier to employing them at national and international scales is the associated challenge of an exponentially increasing number of uncertain parameters with an increase in the sample size or studied space. This leads to computationally intensive models and expensive data collection [25], especially for 3D models [18–20] or solar detective models [31]. Therefore, these methods are not currently economically viable for developing countries [24,27].

This paper provides a less costly and more accurate solution that is able to cover a large scale by estimating rooftop PV potential for each region corresponding to its climatic, geographic, and demographic conditions. The available roof for installing solar PV and the expected electricity production are calculated based on housing characteristics such as the type of roof, the azimuth of the building, and the roof. Statistical data and previous research results are used to determine housing architecture. Uncertainty in the data coming from the natural variability of the data generating, measuring, and sampling processes is then simulated by using an iterative process. The results of the simulation are the output distributions (Section 5.3). The details of the method are presented in Section 3.

## 3. Methodology for Rooftop PV Potential Assessment

Figure 1 describes the method of PV potential assessment proposed in this paper. The outputs of each step are highlighted in blue, and the dark blue arrows show the direction of the mathematical flow. Input data are collected from (*) national/international statistical sources, (**) the assumptions based on previous studies, and/or (***) a collection from manufacturers' catalogues. The iterative process to create datasets are represented by orange arrows. There are in total four different loops numbered in Figure 1.

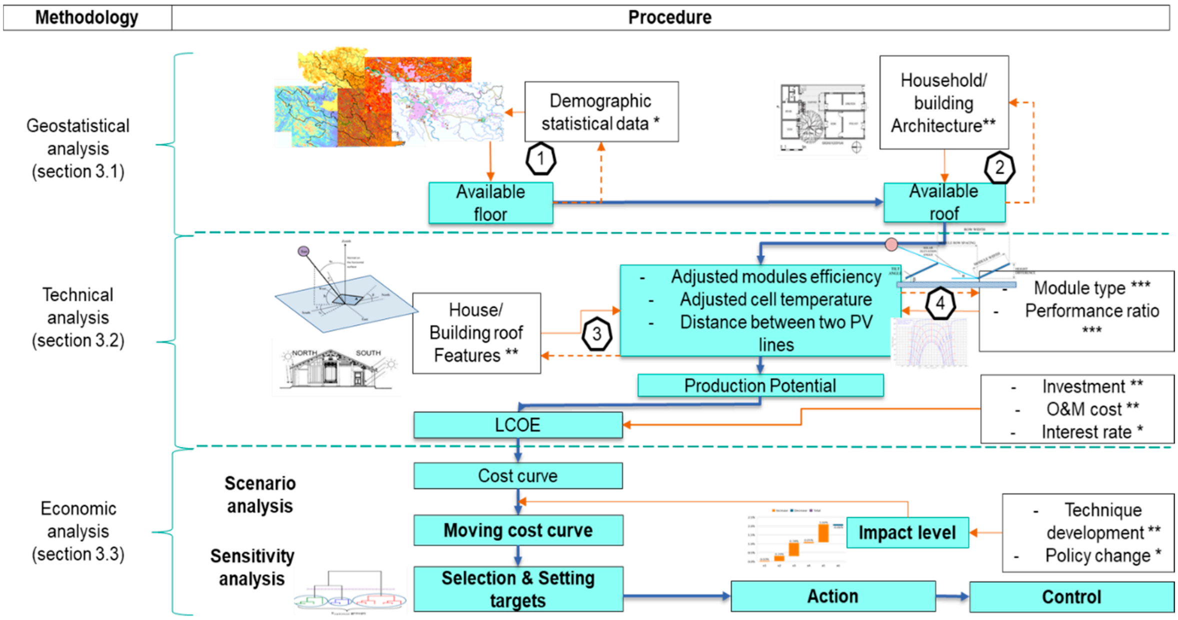



**Figure 1.** Methodology flow chart of the proposed potential assessment model for rooftop PV. Pictures are own illustrations, based on sources for Figures 2–5 and reference [32].

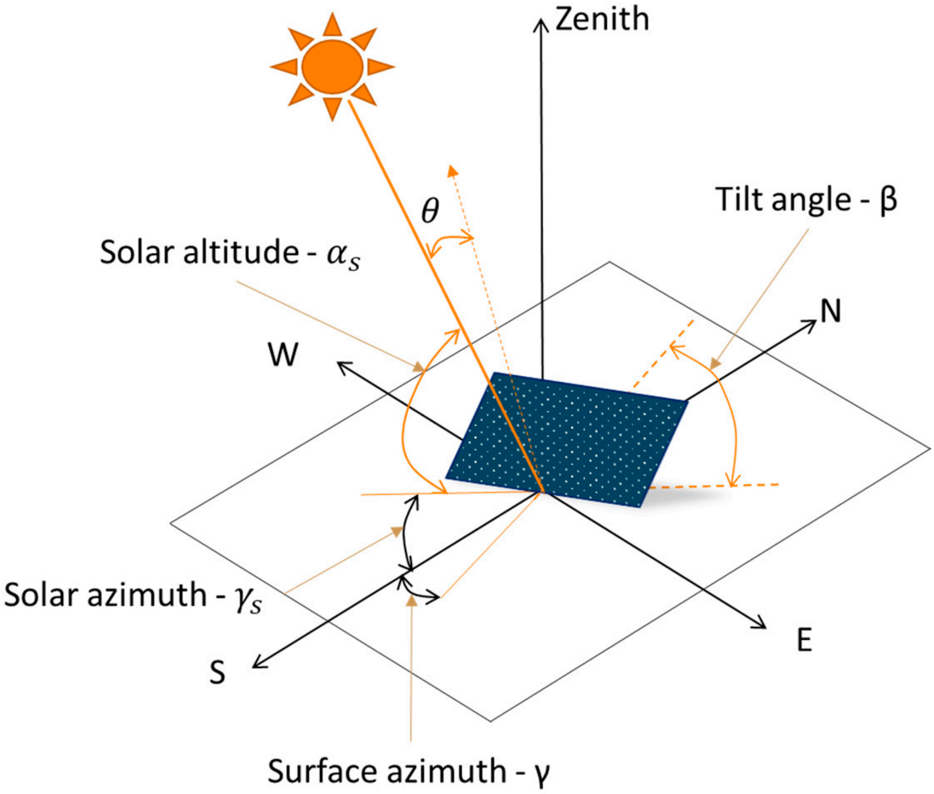



**Figure 2.** Solar and PV module characteristic angles. Reproduced with permission from the authors of "Submerged and Floating Photovoltaic Systems", Copyright Elsevier Science Publishing Co Inc., 2018 [33].

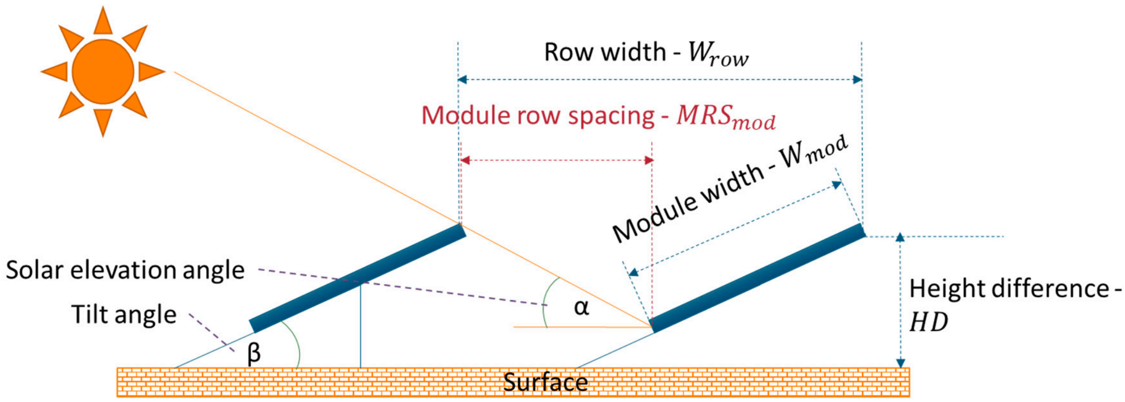



**Figure 3.** Schematic of two simulated photovoltaic rows at solar noon. Reproduced with permission from the authors of "Submerged and Floating Photovoltaic Systems", Copyright Elsevier Science Publishing Co Inc., 2018 [33].

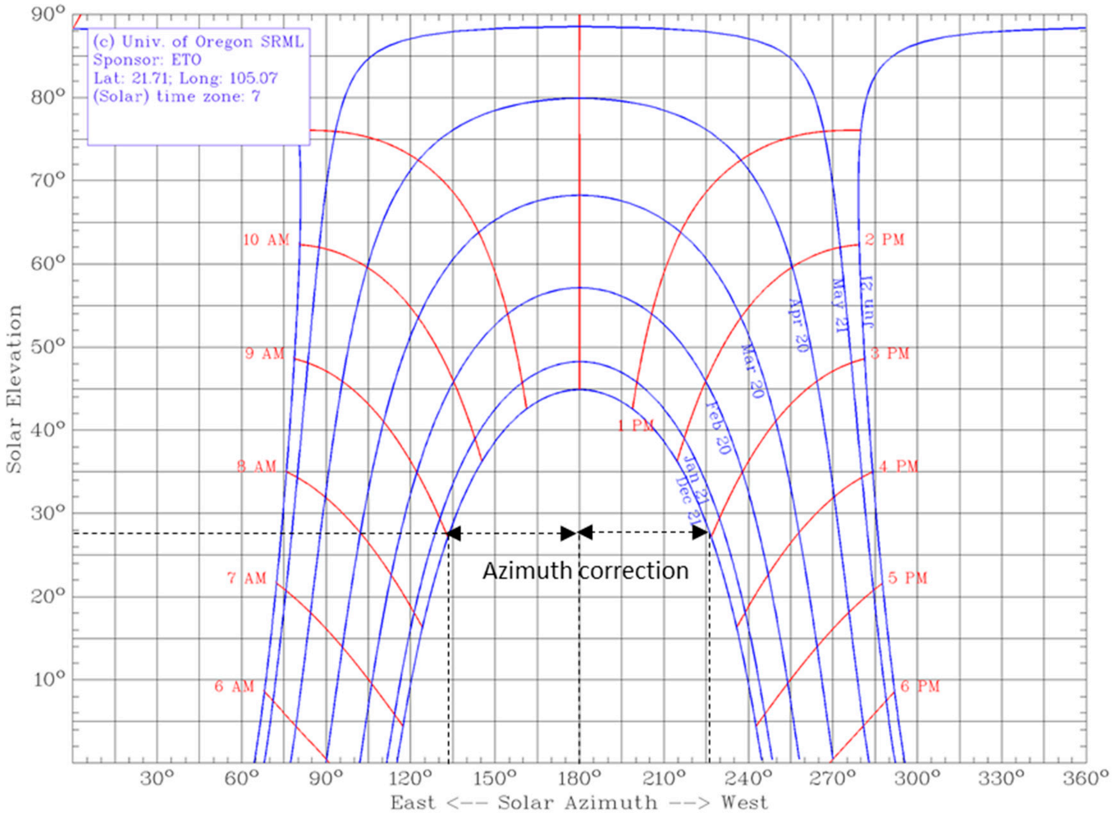
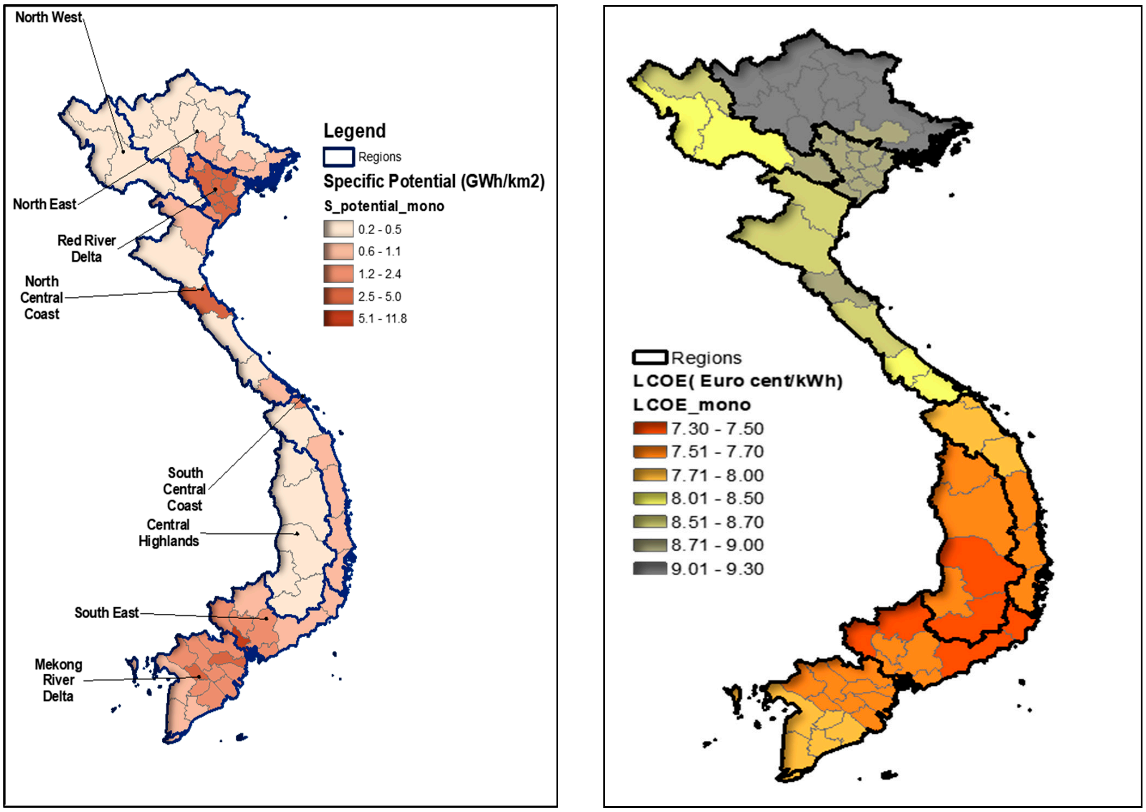



**Figure 4.** Example of the Cartesian plot of the sun path chart for North Vietnam. Adapted with permission from the Solar Radiation Monitoring Laboratory, University of Oregon, 2015. http://solardat.uoregon.edu/SunChartProgram.html.




(**a**) (**b**)

**Figure 5.** Maps of distributed electricity potential (**a**) and average LCOE (**b**) of rooftop PV by regions. Please refer to the online version of the article for references to color in this figure. Detailed region and province can be found in Figure A2. Detailed maps are extracted from the library of The University of Texas at Austin. http://legacy.lib.utexas.edu/maps/topo/vietnam/. Latest access on 20.05.2019.

The method proposed in the paper consists of three steps. The first step is determining the geographical potential using ArcGis and geostatistical analysis (Section 3.1), which is proposed in previous studies [25]. The second step is identifying the technical potential (Section 3.2), in which the authors improve the assessment accuracy by determining the electricity output of the solar cell regarding the expected operating temperature of the PV module and the corresponding solar cell efficiency for the specific considered region. The last step is the economic and sensitivity analyses (Section 3.3). Section 4 presents data, assumptions and results for our case study, which is used to illustrate the methodology proposed.

### *3.1. Geographical Potential*

In the case of unavailable high-resolution street maps, household data from government statistical offices can be used to calculate the available roof area for PV installation $A_{roof}$ ($m^2$) for detached houses and apartment buildings. Equation (1) is suggested based on previous studies [25].

$$\begin{aligned} A_{roof} &= S_{roof} \times \mu \times \frac{1}{\cos(v)} \\ &= \begin{cases} \textit{Detached house}: \; S_F \times (1 - b_1) \times \mu \times \frac{1}{\cos(v)} \\ \textit{Apartment building}: \; \left(S_F \times \frac{n_A}{F}\right) \times (1 - b_1 + b_2) \times \mu \times \frac{1}{\cos(v)} \end{cases} \end{aligned} \quad (1)$$

The total roof area, $S_{roof}$ ($m^2$), is calculated by subtracting the exterior area, $b_1$ (percent of total roof area), such as garden, back yard, etc., and adding the interior area, $b_2$(percent of total roof area), such as stairway, corridors, etc. for an apartment building, to the ground area of a household $S_F$ (m$^2$). For apartment buildings, $\frac{n_A}{F}$ is the average number of apartments, $n_A$, in a building on one floor, $F$.

The available roof for installing rooftop PV, $A_{roof}$ (m$^2$), is determined by multiplying the total roof area, $S_{roof}$ (m$^2$), with the utilization factor, $\mu$ (%), which is a percentage of the roof area that can be used for PV installations. The factor $\mu$ excludes the utilized area of antennas, chimneys, HVAC systems, and unusable area such as shades from the total roof area, $S_{roof}$ (m$^2$). It can be identified based on national statistical data of household architecture or based on previous studies [25]. $\nu$ is the average house/building roof slope (degrees).

Figure 2 demonstrates the two angles related to the sun position, which are the solar altitude angle $\alpha_s$, and the solar azimuth angle $\gamma_s$, the angles $\beta$ and $\gamma$ that define the PV module position. $\beta$ is the tilt angle, and $\gamma$ is the surface azimuth angle. Further, the angle $\theta$ between the normal to the PV surface and the incident beam radiation is indicated [33,34].

The solar irradiation at different azimuths, inclination angles, and horizontal positions regarding different locations is calculated as in Equation (2), in which $SI_{dir}$ and $SI_{diff}$ are the direct and diffuse solar irradiations, respectively.

$$SI = f(SI_{dir}, \beta, \theta) = SI_{dir} \times \cos\theta + SI_{diff} \times \cos\left(\frac{\beta}{2}\right) \quad (2)$$

The geographical potential is determined by using ArcGis to match available roof area, $A_{roof}$, and relative solar irradiation with data of the topographic, population distribution, and cadastral maps.

The raster maps [17,35] only provide the solar irradiation at 90° to the horizontal. However, the irradiation changes depending on the solar position and its relation to an oriented panel. To improve the accuracy of the geographical potential, this paper calculates relative solar irradiations corresponding to the northern, central, and southern horizontal surface in different azimuth and inclination angles.

The geographical potential is determined by using ArcGis to match available roof area, $A_{roof}$, and relative solar irradiation with data of the topographic, population distribution, and cadastral maps.

### 3.2. Technical Potential

A PV module will typically be rated at standard test conditions (STC), which indicates a condition of a cell temperature of 25 °C and an irradiance of 1000 W/m$^2$ with an air mass 1.5 (AM1.5) spectrum [36], ensuring a relatively independent comparison and output evaluation of different modules. However, when operating in the field, they typically operate at higher temperatures and at somewhat lower insolation conditions. To improve the accuracy of technical potential assessments, the paper determines the power output of the solar cell regarding the expected operating temperature of the PV module and the corresponding solar cell efficiency.

First, the paper identifies the operating cell temperature $T_{mod}$ (°C) based on nominal operating cell temperature (NOCT °C) Equation (3).

$$T_{mod} = T_{air} + (\mathrm{NOCT} - 20) \times \frac{G_{mod}}{G_{\mathrm{NOCT}}} \quad (3)$$

NOCT is defined as the temperature reached by open-circuited cells in a module under the conditions of the maximum irradiance, $G_{NOCT}$ = 800 W/m$^2$, air temperature is 20 °C, wind velocity is 1 m/s, and an open rear surface mounting. NOCT can be calculated from the NOCT model [37] or taken from the information given by the module specification. The equation is a literature model [38] that gives a reasonable estimate of the operating temperature of the module as a function of the ambient temperature ($T_{air}$ °C) and the irradiance at the instant $G_{mod}$ (W/m$^2$) when the ambient temperature is $T_{air}$ (°C). $T_{air}$ (°C) can be obtained from Raster data or extracted manually from the climate map [39]. As can be seen in Equation (3), because the irradiance and temperature changes over a calendar year, we would see an effect of both irradiance and temperature on the electricity output of a solar cell across the seasons.

Another factor that affects the electricity output is the solar cell efficiency. Because the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell [40], the paper calculates the corrected energy conversion efficiency ($\eta_{cor}$) of a solar cell corresponding to the operating temperature $T_{mod}$, which is reflected in the latitude and climate of the considered region. The corrected temperature factor $\eta_{TC}$ and the corrected efficiency of the module cell $\eta_{cor}$ are determined via Equation (4). A constant value (CT) can be extracted from the module datasheet (%/K). $T_{STC}$ and $\eta_{STC}$ are the temperature and efficiency at STC conditions.

$$\eta_{cor} = f(T_{mod}) = \eta_{CT} \times \eta_{STC} = \left[1 + \frac{CT}{100} \times (T_{mod} - T_{STC})\right] \times \eta_{STC} \tag{4}$$

Moreover, to be more precise in assessing technical potential, this paper identifies the least space distance between PV modules to minimize shading effects. To calculate the module row spacing between two lines of modules, the first step is to calculate the height difference, HD (m), from the back edge of the module to the surface [34]. Equation (5) is used for this purpose. $\beta$ (degrees) is the tilt angle and $W_{mod}$ (m) is the module width.

$$HD = \sin(\beta) \times W_{mod} \tag{5}$$

The module row spacing ($MRS_{mod}$) is determined by using the Sun Elevation Angle. The row width, $W_{row}$, which is the distance from the trailing edge of one row to the trailing edge of the subsequent row, is calculated as in Equation (6), in which α is the solar elevation angle (degrees) (Figure 3) and κ is the azimuth correction angle (degrees) (Figure 4). The shadow between rows falls perpendicular to a south-facing array only when the sun is located at true south in the sky. At solar noon, the length of the shadow cast between rows would be equal to the minimum row spacing ($MRS_{mod}$). In this paper, $MRS_{mod}$ is calculated in the worst case from 9 AM to 3 PM of the winter solstice, therefore an azimuth angle correction is required (Figure 4).

$$W_{row} = MRS_{mod} \times \cos\beta \times W_{mod} = \frac{HD}{\tan(\alpha)} \times \cos\kappa \times \cos\beta \times W_{mod} \tag{6}$$

The number of PV modules, $n_{mod}$, on a rooftop for each raster map unit corresponding to the available roof area for PV, $A_{roof}$, is obtained from Equation (7), in which $L_{mod}$ is the length of the PV module (m).

$$n_{mod} = f\left(A_{roof},\ A_{mod},\ HD\right) = \frac{A_{roof}}{L_{mod} \times W_{row}} = \frac{A_{roof}}{A_{mod} \times \frac{HD}{\tan(\alpha)} \times \cos\kappa \times \cos\beta} \tag{7}$$

The electricity output of the solar system, $M_{el}$, is obtained from Equation (8), in which PR is performance ratio of the module, SI is the adjusted solar irradiation (kWh/m$^2$) and $A_{mod}$ is the module area (m$^2$)

$$\begin{aligned} M_{el} &= PR \times A_{mod} \times f(T_{mod}) \times f\left(A_{roof},\ A_{mod},\ HD\right) \times f(SI_{dir},\ \beta,\ \theta) \\ &= PR \times A_{mod} \times \eta_{cor} \times n_{mod} \times SI \end{aligned} \tag{8}$$

### 3.3. Levelized Cost of Electricity (LCOE)

The Levelized Cost of Electricity (LCOE) is a measure of the average net present cost of electricity generation for a generating plant over its lifetime, which is assumed to be 20 years in this study [41]. The LCOE depends on costs (i.e., the initial capital investment, maintenance, and operational costs), local condition (load profile), and financial condition (i.e., the discount rate).

The LCOE is calculated as in Equation (9) [42]

$$\text{LCOE} = f(I_0,\ A_t, M_{el}) = \frac{I_0 + \sum_{t=1}^{n_s} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n_s} \frac{M_{el}}{(1+i)^t}} \tag{9}$$

where $I_0$ (Euro) stands for the total initial investment, which is the product of module size (in kW) and specific investment $i_0$ as the investment cost per installed kW (€/kW); $A_t$ (Euro) is the yearly operating cost; i (%) is the discount rate; $n_s$ (year) is the life span; and $M_{el}$ (kWh) is the annual electricity production.

### *3.4. Sensitivity Analysis*

The proposed model is computationally intensive and highly parameterized with model input uncertainty, which can reduce the accuracy of the model outputs. To provide a robust assessment at medium resolution, this paper suggests a solution to estimate the impact and significance of uncertain parameters in the model by using variance-based sensitivity analysis. A variance-based method is a probabilistic approach, which quantifies the input and output uncertainties as probability distributions and decomposes the output variance into parts attributable to input variables and combinations of variables.

The sensitivity of the output to an input variable is therefore measured by the amount of variance in the output caused by that input.

Considering our model in Equation (10):

$$\begin{cases} M_{el} = PR \times A_{mod} \times f(T_{mod}) \times f\Big(A_{roof},\ A_{mod},\ HD\Big) \times f(SI_{dir},\ \beta,\ \theta) \\ LCOE = f(I_0,\ A_t, M_{el}) \end{cases} \tag{10}$$

As $Y = f(X)$ for $X = \{X_1, X_2, \ldots, X_k\}$, a measure of the sensitivity of the $i$th variable $X_i$ is given as{\displaystyle \operatorname {Var} \left(E_{{\textbf {X}}_{\sim i}}\left(Y\mid X_{i}\right)\right)} $Var(E_{X_{\sim i}}(Y|X_i))$, where "Var" and "E" denote the variance and expected value operators, respectively, and $X_{\sim i}$ denotes the set of all input variables except $X_i$. This expression essentially measures the contribution of $X_i$ alone to the uncertainty (variance) in $Y$ (averaged over variations in other variables) and is known as the first-order sensitivity index or main effect index, $S_i$, which is determined as in Equation (11). Importantly, it does not measure the uncertainty caused by interactions with other variables.

$$S_i = \frac{Var_{X_i}(E_{X_{\sim i}}(Y|X_i))}{Var(Y)} \tag{11}$$

This method allows exploration of the input space, accounting for linear and nonlinear responses. As demonstrated in Figure 1, four loops, represented by orange arrows, repeatedly run to generate the final outputs until all the possibilities of the inputs are covered. The first input set is built based on the available data and assumptions from previous studies.

Subsequently, this paper fits a linear and/or nonlinear regression to the model response and the standardized regression coefficients are used to measure the level of impact of each uncertain parameter on the output. The relationship between the uncertain parameters and the output is presented as in Equation (12), for example.

$$\Delta y_j = a_1 \Delta x_i^{\,2} + a_2 \Delta x_i + b \tag{12}$$

This paper uses hierarchal clustering in the manner of the Pareto principle to generate the ranking of the uncertainty factors $x_i$ according to their relative contribution to the output variability. The influencers are categorized into different groups, including "strong influencer", "moderate influencer", and "negligible influencer". The goals of the analysis are to provide different references for policymakers and stakeholders to choose an appropriate interaction with the current rooftop PV market status. One goal focuses on quantifying the uncertainty in the output of the model, thus it is used as a control tool for modelers and policymakers in order to ensure the accuracy of the output. The other goal focuses on apportioning output uncertainty to the different sources of uncertainty inputs and will be used for designing policy and for supporting the decision-making of investors in the rooftop PV market.

## 4. Case Study and Results

### 4.1. Data and Assumptions

Vietnam is taken as a case study for demonstrating our method and findings. It is one of the 65 emerging countries in the world with typical features and struggles to develop solar PV [2–4]. The Vietnamese population is 94 million people, with annual GDP growth of around 7%, the total electricity demand of 227,421 GWh, total supply capacity of 48.57 GW [43], and power demand surging at an average rate of 12% per year since 2010 and expected to continue growing by 8%/year until 2030 (Vietnam energy outlook 2018). Residential demand for electricity accounts for almost a third of the total electricity demand [43], with the average retail tariff of 9.3 Euro cents/kWh (Appendix A Table A1). However, during the period 2016–2030, the original estimation of the additional capacity is estimated to be decreased by 16% (~15.2 GW) because of the delay of some natural gas projects. This would be likely to increase the power shortage in the south, especially from 2022 onwards (EVN June 2019).

Under these circumstances, solar and wind power are expected to play significant roles as alternative resources and turn Vietnam into a hot spot for energy investors. Renewable energy supply, including small hydro, wind, solar, and biomass power plants, currently covers 7.16% of total national supply [43]. However, given a local overload, transmission losses, and uneven infrastructure between different regions, the Vietnamese government has been provoking significant investment in power infrastructure with net metering. As a result, by June 2019, the country has shown a surge of centralized solar capacity connected to the national grid of 4.46 GW. This accounts for 8.28% of the Vietnamese electricity supply mix, which is far more than the 1000 MW target set for 2020 (EVN report, June 2019), while PV rooftop projects only grow at a very modest level. Moreover, because of lacking integrating policy, management, and compensation mechanisms to support rooftop PV development in the whole country, it has developed rapidly solely in Ninh Thuan. This region accounts for 90% of the total national solar capacity, which has caused significant grid congestion and reduced the spread of the development.

To solve the issue of the lacking integrating policy and mechanisms to support rooftop PV development, this paper focuses on assessing rooftop PV potentials in 63 provinces in Vietnam and proposes different suggestions for the government to unleash their PV potentials.

This paper uses a previous study of house design in Vietnam [32], in which the average number of apartments on one floor of the building, $\frac{n_A}{F}$, is 5, the exterior area, $b_1$, is 0.2, and the interior area, $b_2$, is 0.1 to calculate the available roof area for installing rooftop PV. The roof of the apartment buildings is considered flat, so $\nu$ for them is 0. For single-detached houses, $\nu$ is presented in Table 1. A sensitivity analysis for these assumptions is conducted in this paper.

**Table 1.** Average of relative solar irradiation in accordance with different roof slopes in Vietnam.

| Region | Detached House Roof Slope—$\nu$ (degrees) | Average of Relative Solar Irradiation—*SI* |
|---|---|---|
| **North Vietnam** | 25 | 0.95 |
| | 32 | 0.93 |
| **Central Vietnam** | 25 | 0.95 |
| | 26 | 0.95 |
| **South Vietnam** | 34 | 0.90 |
| | 24 | 0.93 |

The utilization factor of the flat roof is estimated to be 50% based on previous studies [5,9,14,44], which concluded that 35% to 65% of residential flat roofs are available for PV because 5% of the roof is covered by HVAC equipment or other building components, which would shade over 35% of the entire rooftop, and trees and other construction would shelter from 0% to 30% of the rest. The utilization factor of a slanted roof is assumed to be 58%, which considers that a north-facing roof also has the potential for installing PV systems [25].

Based on Equation (2), the relative solar irradiation for different roof types in three different parts of Vietnam is calculated. The results are presented in Table 1.

In this paper, two main models of PV modules, i.e., monocrystalline and polycrystalline, are considered. The characteristics of these two models, extracted from the catalogue, are given in Table 2. The performance ratio is considered as 0.85 [25].

**Table 2.** Specifications of the PV modules.

| Module | Type | Watt Price—*I* (Euros/W) | Maximum Power—*E* (W) | Efficiency of Module—*STC* (%) | Performance Coefficient—*CT* (%K) | Length—$L_{mod}$ (mm) | Width—$W_{mod}$ (mm) |
|---|---|---|---|---|---|---|---|
| **Monocrystalline [45]** | NeMo | 0.59 | 275 | 16.4 | −0.4 | 1670 | 1006 |
| **Polycrystalline [46]** | NeMo | 0.53 | 260 | 16 | −0.42 | 1640 | 991 |

To assess the effect of uncertainty parameters on the outputs, this paper alters the assumptions and the values of input variables, which have been referenced from other studies but for which sensitivity analyses have not been performed in previous studies. The used values of these inputs and the considered variation range are presented in Table 4.

## *4.2. Results of the Potential Analysis*

Section 4.2.1, firstly, presents the spatial potential distribution of rooftop PV with detailed potential for 63 provinces as well as the cumulative potential for eight classified territories of the country: Northern Midlands (NML), Northern Mountains (NM), Red River Delta (RRD), North-Central Coast (NCC), South-Central Coast (SCC), Central Highlands (CH), Southeast (SE), and Mekong River Delta (MRD). Section 4.2.2 then presents the results of the sensitivity analysis for two purposes: (1) to control the accuracy of the output; and (2) to measure the output variability regarding possible input changes in order to support policy decision making.

### 4.2.1. Spatial Potential Distribution of Rooftop PV

This paper breaks down the estimated theoretical potential of solar with a total of around 120 thousand TWh per year (TWh/a) from the solar irradiation raster map [17,34,49] to geographical and technical potentials of rooftop PV with 1407.2 $km^2$ available rooftop and 278 TWh/a, respectively. The technical potential is calculated with the results of roof-mounted solar cells in the whole country being 228.3 and 215.8 GWp or 278.1 and 262.7 TWh/a with monocrystalline and polycrystalline solar cells, respectively (detailed results for each region are given in Table A3).

Comparing different regions in Vietnam, 58% of the total national rooftop PV potential is concentrated in three territories, including the two river deltas and the southeast with an almost equally divided potential of around 20%, equivalent to an average installable capacity of 43.9 GWp. The remaining potential is divided among the coastal areas and the midlands at approximately 10% or 22 GWp, and the mountains and highlands have the lowest potential with about 5% or 11 GWp in each territory.

Taking economic factors into account, the cost per kWh of rooftop PV varies greatly depending on the region and the prevailing economic conditions, in particular regarding different capital costs and discount rates. This paper determines the LCOE (Euro/kWh) of rooftop PV for each province in order to assess the economic attractiveness of the rooftop PV assumed at the current discount rate of 8%.

The distributed PV potentials, including the specific production potential per total area (GWh/km$^2$) and the LCOE (Euro/kWh) in Vietnam, are shown in Figures 5 and 6. The potential density is significantly high in the two river delta regions, which are Red River Delta (RRD) and Mekong River Delta (MRD) in Vietnam, especially in the two largest cities of the country, Hanoi (in the RRD) and Ho Chi Minh (in the MRD), with the most enormous potential of electricity production of about 12 and 5 GWh/km$^2$ (Figure 6) or around 24.8 and 15.2 TWh/a or 18 and 15.1 GWp, respectively. These cities are the largest metropolitans and most populous cities with an estimated population of 7.7 million and 8.4 million, corresponding to 8.6% and 9.3% of the national population, respectively, and they also have the largest household area in Vietnam (Government statistical reports, 2018). Hanoi has 407 km$^2$ of housing land, of which around 93.9 km$^2$ rooftop available to install solar cells, while Ho Chi Minh City has about 282 km$^2$ housing land but can provide an estimated 110 km$^2$ roof for installing solar. Moreover, since Ho Chi Minh City is in the southern part of Vietnam, it could potentially generate in total 24.8 or 23.4 TWh/a with monocrystalline or polycrystalline solar cells, respectively, which is nearly 60% more than the electricity production potential from solar in Hanoi. This gives Ho Chi Minh City the most significant potential for solar power throughout the country, while Hanoi is ranked second. Currently, Ho Chi Minh City has only installed around 44.56 MWp of its 18 GWp total potential [50].

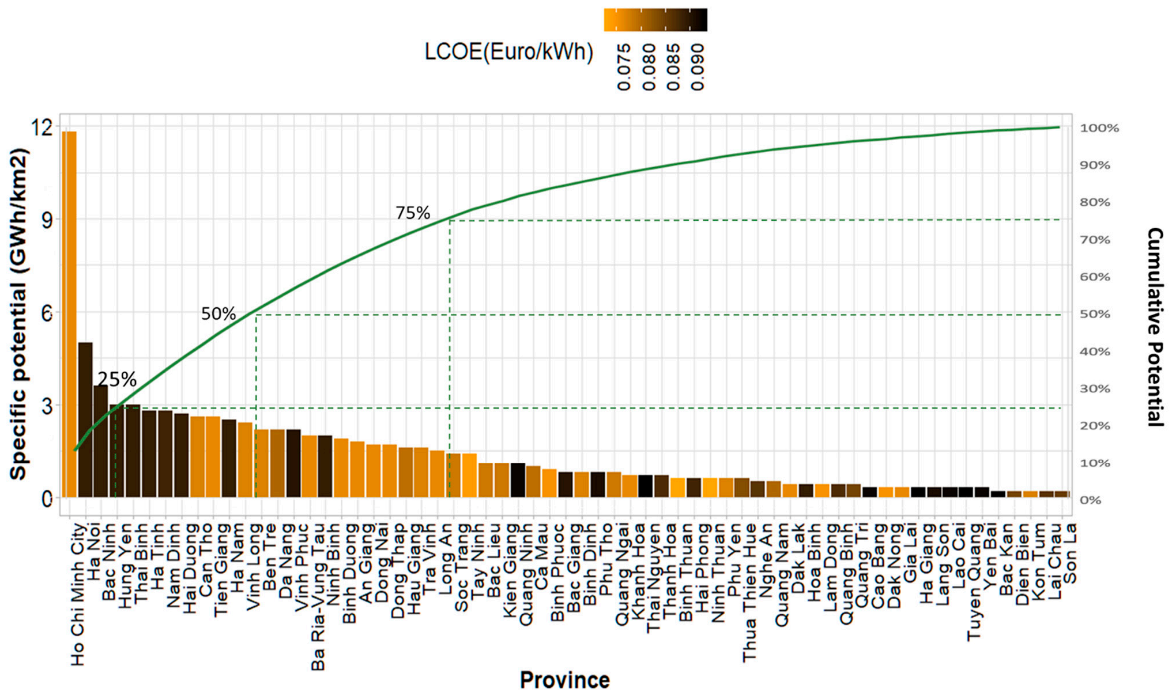



**Figure 6.** The electricity production potential (TWh/a) and average LCOE (Euro/kWh) at the discount rate 8% in 63 regions in descending order.

The LCOE ranges from 7.5 to 9.2 Euro cents/kWh at a discount rate of 8% across 63 provinces in Vietnam (Figure 5). In the regions with a vigorous radiation intensity such as Central Highland, Mekong River Delta, South Central Coast, and Southeast (see Figure 5 for regions), rooftop PV is more economical than in other areas with the LCOE being around 0.075 Euro/kWh. Among the eleven cities, which account for 50% of the total specific potential (GWh/km$^2$) in the whole country, there are only four cities, namely Ho Chi Minh City, Can Tho, Tien Giang, and Vinh Long, with the average LCOE being less than 0.076 Euro/kWh (Figure 6). Despite having a sizeable available roof area, Hanoi and the rest do not have a convincing economic potential due to their low radiation intensity, which leads to a relatively high LCOE of around 0.085–0.089 Euro/kWh. The other quarter of potentials consists of 12 provinces that are relatively promising for investment with high potentials of approximately 2–3 GWh/km$^2$ and a low LCOE of about 0.075–0.080 Euro/kWh, except for Vinh Phuc and Ninh Binh.

However, Ninh Thuan and Binh Thuan, which are the best places for investing in rooftop PV with the lowest LCOE in Vietnam at around 0.073 Euro/kWh, have relatively small solar resources at about only 0.6 GWh/km$^2$.

Figure 7 illustrates the cost–potential curves for monocrystalline solar deployment in Vietnam at different discount rates ranging from 5% to 11%. With varying rates of discount, the cost curve for solar PV in Vietnam shifts vertically. The total electricity potential in the case of considering monocrystalline and polycrystalline cells adds up to around 278 and 262 TWh/a, respectively. The total electricity demand in 2018 in Vietnam is 192.36 TWh, which implies that the total solar rooftop could cover the current demand of the country. However, Vietnam has only exploited about 0.1% of its potential [43].

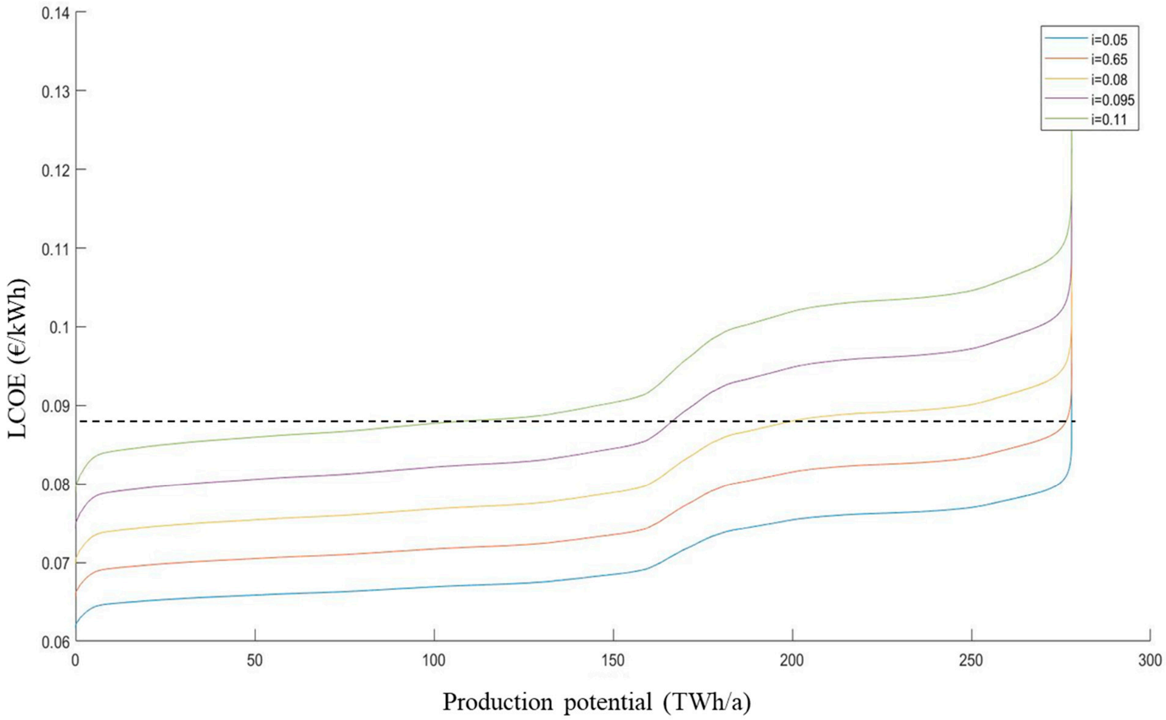



**Figure 7.** The cost–potential curves for electricity generation from monocrystalline solar cells at different discount rates and the average FIT 2.0 of 0.088 Euro/kWh as a dashed line.

The step in the curve (see Figure 7) results from the LCOE jumping from high irradiation in the southern part to low radiation to the northern part of Vietnam. It reveals the significant difference in solar irradiation along with the country, which causes a drastic increase in LCOE from south to north. Referring the LCOE results to FIT [51] reveals a favorable condition for the rooftop solar development because the FIT can cover the LCOE cost. Details of the relation between LCOE and FIT are discussed in Section 5.2.

Finally, we analyze the results of the present paper in the context of additional studies relating to rooftop PV in Vietnam. As compared to other studies in Vietnam, this method poses its advantages of providing a reasonably accurate result at low-cost (Table 3), even though it deals with insufficient data and meager budget. When normalizing for the area covered to 80% of the cities' area, this paper determines the potentials for rooftop PV in HCM and DN with a relative error of 4% and 6% compared with the field study, respectively.

**Table 3.** Comparison of the results of the suggested model and the field study in Ho Chi Minh (HCM) and Da Nang (DN).

| Subject | This Paper | Field Study [52] |
|---|---|---|
| **Coverage** | Whole country | Only urban areas of HCM and DN |
| **Method to identify technical potential** | Geostatistical analysis, GIS, Monte Carlo Simulation | Deep learning, Photogrammetry, GIS, Image processing, Digital surface, and elevation models |
| **Production potential for the specific cities (TWh/a)** | HCM: 23.4 (100% of the city area)<br>DN: 2.7 (100% of the city area) | HCM: 18 (80% of the city area)<br>DN: 2.3 (80% of the city area) |

4.2.2. Sensitivity Analyses

Similar to many other developing countries, Vietnam has deficient and inadequate data conditions even to estimate rooftop PV potential at medium spatial resolution. It is worth mentioning that conducting such an assessment for countries with similar unfavorable data condition requires significant manual processing of inputs and maps, for example matching geographic and population distributions and building densities with 11,050 clusters of the topographic map in the case of Vietnam.

This section assesses the effect of each mentioned input or assumption on technical and economic potentials and identifies an acceptable confidence interval of every particular variable required to achieve specific confidence in the result. The results are demonstrated in Figures 8 and 9.

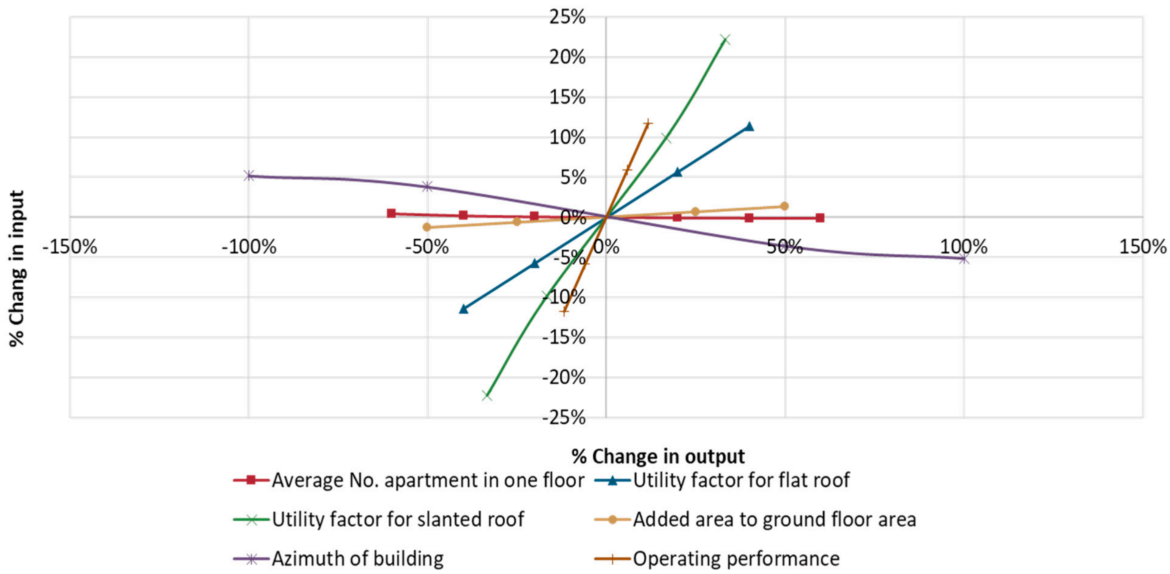



**Figure 8.** Sensitivity analysis of input variation effect on technical potential output.

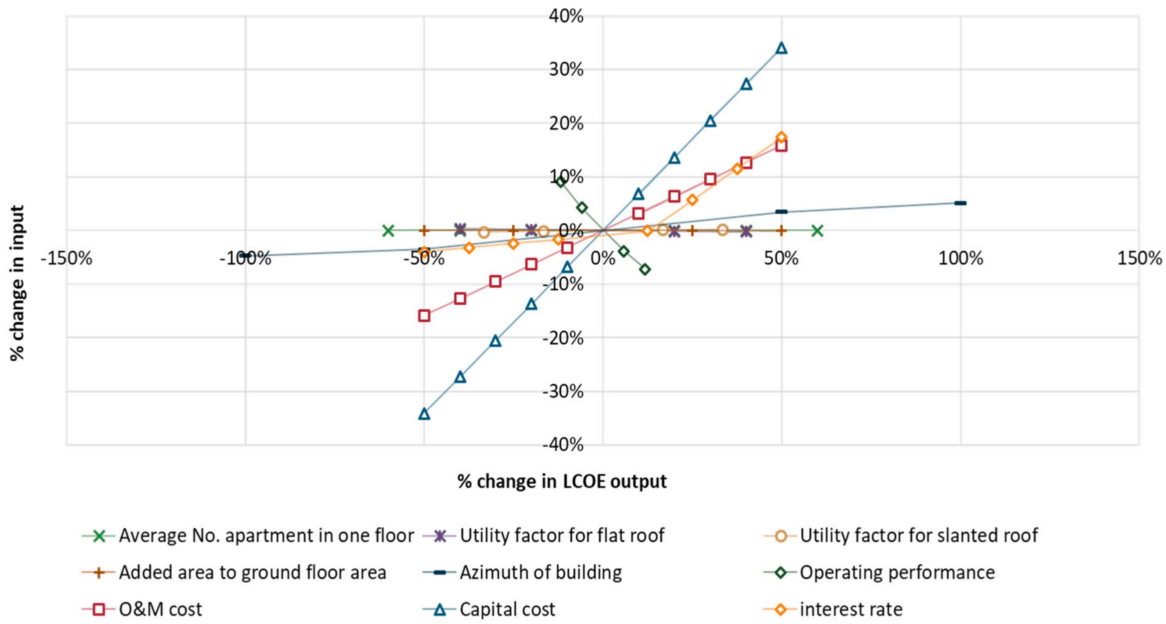



**Figure 9.** Sensitivity analysis of input variation effect on LCOE output.

The results show that, among the uncertain parameters that are used to calculate the geographical and technical potentials, the utilization factors for flat and slanted roofs and the efficiency or performance ratio of a considered PV system are the most critical parameters influencing the accuracy of the technical potential output (Figure 8). Considering the economic potential, all the uncertain geographical inputs, such as the average number of apartments on one floor in a building, area added to the ground floor area, and utilization factors for different roofs, are irrelevant to the LCOE output. However, technical inputs, especially the efficiency of the PV module, show significant effects on the LCOEs. Lastly, the economic data, such as costs and interest, have the most significant impact on the LCOE output, especially the capital cost (Figure 9).

To verify the correlation of the variation of these variables with the output, we use regression techniques, including curve fitting and linear fitting, to specify the model that provides the best explanation of the relationships between the uncertain parameters and outputs. The considered outputs are the technical potential ($y_1$) and the LCOE ($y_2$). The uncertain parameters are indicated below:

| | | | |
|---|---|---|---|
| x1 | Area added to a ground floor area | x6 | Azimuth of building |
| x2 | Utilization factor for flat roof | x7 | Capital cost |
| x3 | Utilization factor for slanted roof | x8 | O&M cost |
| x4 | Average number of apartments on one floor | x9 | Discount rate |
| x5 | Performance ratio | | |

Figure 10 shows the strong influence of the uncertain parameters on the outputs in descending order. Using the Pareto principle [53,54] indicating that roughly 80% of the effects come from 20% of the causes, this paper divides them into three groups. The first group is called "strong influencer", which consists of $x_3$, $x_5$, $x_5$, and $x_7$ that are responsible for more than 80% of the impact on the technical and economic outputs, respectively. The second one is the "moderate influencer", which includes $x_2$ for technical output and $x_8$ for economic output, and accounts for the next 15% of the impact on the outputs. The other factors belong to the "negligible influencer" group. By selecting impacts based on their strength, we can measure the change of the outputs based on the different possible alterations of the uncertain parameters, as in Equations (13) and (14).

$$y_1 = 0.2851\ x_2 + 0.7401\ x_3 + x_5 + 0.025 \quad (13)$$

$$y_2 = -0.6908\ x_5 + 0.6827\ x_7 + 0.3173\ x_8 + 0.3128x_9^2 + 0.1965x_9 + 0.364 \quad (14)$$

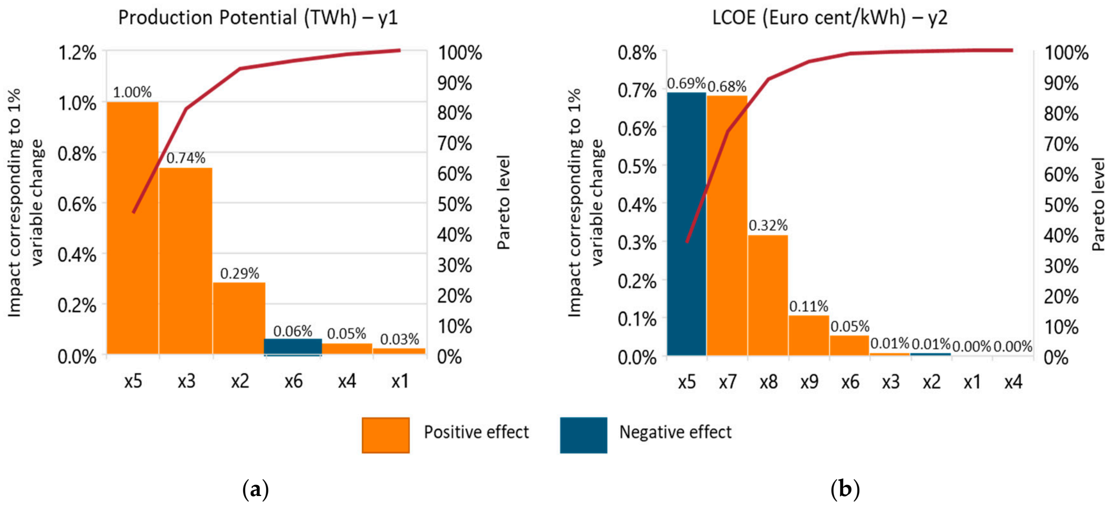



**Figure 10.** Comparing the influence of the considered parameters on the technical potential (**a**) and LCOE (**b**). Columns in orange, positive value; columns in blue, negative value; red lines, Pareto lines.

The results show how dependent the output is on a particular input value. The performance ratio - $x_5$ has the most significant impact on both outputs of the model, which are the electricity potential - $y_1$, and the LCOE - $y_2$. While the electricity potential is also changed considerably when the utilization factors change, the LCOE is not be affected by these two variables. It alters when the costs and discount rates vary.

These results can be used to assist policymakers for decision making by predicting the outcome of a decision in case they intend to change inputs using policy incentive/subsidy. It helps in assessing the riskiness of a strategy and in making informed and appropriate decisions. A detailed discussion of and examples for this argument are presented in Section 5.

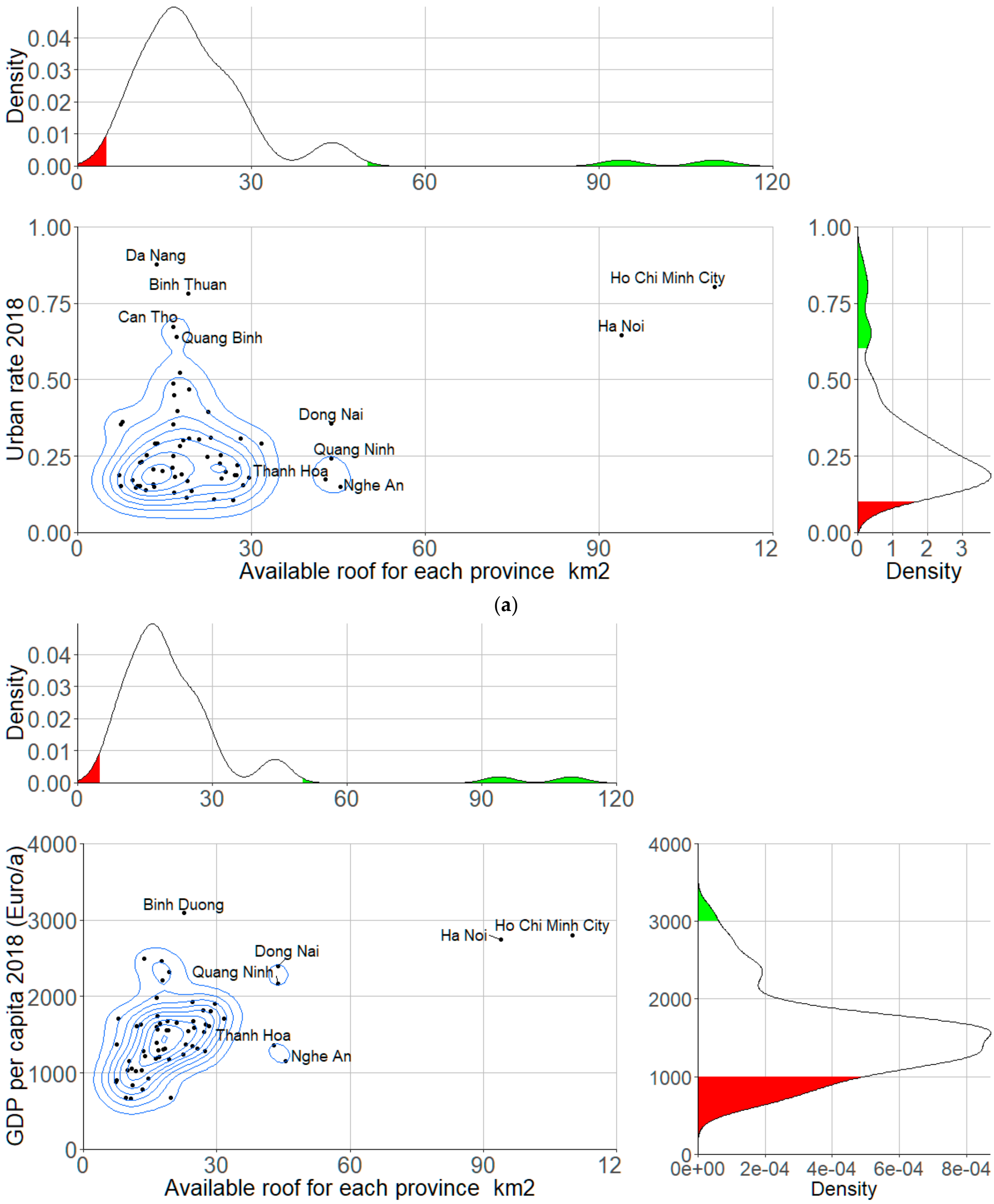
## 5. Deriving Policy Implications from the Potential Assessment Results

Based on the results from the sensitivity analysis, we identified that factors including the performance ratio of the PV system, capital and O&M costs, and the discount rate are the variables with the most significant impact on the results of LCOE. To design a practical and transferable tool for policymakers in planning rooftop PV and a reference for stakeholders, this paper explores changes in each area when these variables change. First, we identify target groups based on their PV potential and demographic characteristics (Section 5.1). Then, we build the market distribution curves based on the techno-economic results and then observe the possibilities of shifting and bending distribution curves under different possible impact changes (Sections 5.2 and 5.3). This paper compares different desirable policies to help policymakers select effective strategies to promote their desire for the rooftop PV market.

### *5.1. Defining Target Groups*

From the results in Section 4.2.1, national and regional governments can choose the most economic provinces directly from the potential ranking in Figure 6. However, the main drivers for solar development in developing countries are urbanization and GDP [2,55]. This means the chance of higher-income people investing in rooftop solar PV is higher in urban than in rural areas.

Figure 11 shows the available rooftop PV distribution corresponding to the level of urbanization (left) and the GDP per capita in 2018 (right) distributions in 63 regions in Vietnam. The distributions highlighted in red, which consist of 14 provinces, indicate the minimal potential area, with less than 5 km$^2$ of roof area, 15% of urbanization, and 1000 Euro/a income. The green distributions illustrate the outstanding potential area, including nine provinces with more than 35 km$^2$ of the available roof, 60% of urbanization, and 2000 Euro/a income. Details of potential assessment results and demographic indicators can be found in Tables A2 and A3.




(**a**)

(**b**)

**Figure 11.** Rooftop PV potential distribution corresponding to the level of urbanization (**a**) and income per capita (**b**) [46] in 63 provinces in Vietnam.

**Table 4.** Employed values of the uncertain parameters and their considered variation range in this study.

| Uncertain Parameter | Variable | Symbol | Used Value (unit) [ref] | Variation Range |
|---|---|---|---|---|
| Geographical input | Utilization factor for flat roof | M | 50 (%) [16] | ±40% |
| | Utilization factor for slanted roof | M | 58 (%) [25] | ±33% |
| | The average number of apartments on one floor of the building | $\frac{n_A}{F}$ | 10 (-) [47] | ±60% |
| | Added area to the ground floor area | $b$ | 10 (%) [47] | ±50% |
| Technological input | The azimuth of the slanted roof | $\gamma$ | 90 (degrees) [32] | ±100% |
| | Performance ratio | PR | 85 (%) [25] | ±10% |
| Economic input | O&M cost | $A_t$ | 0.036 (Euro/kWh) [48] | ±50% |
| | Capital cost | $I_0$ | 0.59 (Euro/W) [48] | ±50% |
| | Discount rate | $i$ | 8 (%) [47] | ±50% |

Because most of the provinces have a relatively low (15–60%) urban rate and humble economic (1000–2000 Euro/a income) development, the success of the first adopters plays a crucial role in the new market due to their potential impacts on followers. To improve rooftop solar development, the role of local and government authorities is equally essential. However, in practice, sub-national or local governments are constrained by limited resources, weak institutional capacity, inadequate mechanisms, and limited availability of information [3,7,26,29]. These circumstances, as well as the complication of land ownership and attractiveness, constitute a narrow space for the policymakers to encourage rooftop PV development at the local level without significant support from the government. This means that there is an obvious need for selecting target groups that is unified from national to local levels.

Based on the market characteristics, this paper suggests determining target groups based on k-means clustering of the development dynamics of 63 provinces in Vietnam with the criteria, i.e., their techno-economic potentials including the available roof ($km^2$), the production potential (TWh/a), LCOE (Euro cent/kWh), the level of urbanization (%) [47], and GDP (Euro/a) [47] (See Table A2 for detailed information). The results are shown in Table 5, Figure 12, and Figure A1. Because there are more than two dimensions (variables), Table 5 shows the principal component analysis and plots the data points according to the first two principal components (Dim1 and Dim2) that explain the majority of the variance and shows an illustration of the clusters. Figure A1 shows the clusters corresponding to their geographic position in the country.

**Table 5.** Priority groups and their specific characteristics.

| Priority | Cluster Name | Available Roof $km^2$ | Average LCOE (euro cent/kWh) | Production Potential (TWh/a) | GDP per Capita (Euro) | Urban Rate | No. Province |
|---|---|---|---|---|---|---|---|
| 1 | 6 | 101.95 | 8.25 | 20.20 | 2260.53 | 65% | 2 |
| 2 | 2 | 17.11 | 8.06 | 3.51 | 1558.96 | 51% | 7 |
| 3 | 1 | 29.04 | 7.59 | 6.59 | 1431.55 | 29% | 9 |
| 4 | 3 | 26.12 | 8.92 | 4.42 | 1307.08 | 22% | 13 |
| 5 | 5 | 17.03 | 7.69 | 3.74 | 1143.27 | 26% | 18 |
| 6 | 4 | 12.57 | 8.96 | 2.07 | 794.10 | 19% | 14 |

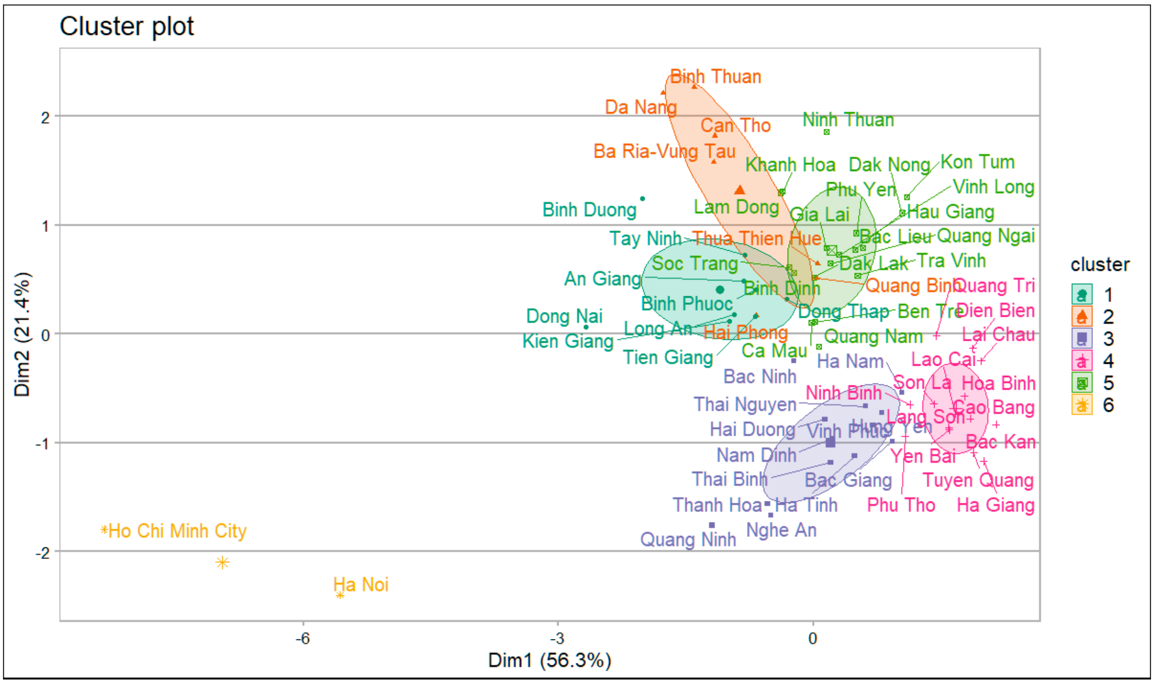



**Figure 12.** The results of clustering provinces based on their potentials and characteristics.

Ranked in order of priority for rooftop PV policies, Hanoi and Ho Chi Minh are classified as Priority 1, which requires the most policy focus due to their most favorable condition for rooftop PV development, followed by Ba Ria Vung Tau, Binh Duong, Can Tho, and Da Nang. Detailed clustering and priority ranking results for each region can be found in Table A4.

The results do not only recommend policy priority but also support national policymakers to redirect and balance the PV development between different regions. For example, the government can provide a favorable policy to the higher LCOE but potentially fast-uptake regions, e.g., cities and provinces of Priorities 1 and 2.

### 5.2. Assessing the Market Attractiveness and FIT

Rather than just analyzing the sensitivity of the output analysis to changes in the variable assumptions, as above, this section also looks at the probability distribution of the outcome in order to make decisions or take actions accordingly. Scenario analysis is designed to analyze the change of output regarding the different sets of inputs and then based on the various possible outcomes. In this paper, we use competitive prices to compare the potential benefit of installing rooftop PV between different scenarios. The competitive prices are the differences between the FIT and LCOE and between LCOE and the grid tariff ($T_G$) (Equation (15)).

$$\begin{cases} Delta_1 = \text{FiT} - \text{LCOE} \\ Delta_2 = T_G - \text{LCOE} \end{cases} \quad (15)$$

Table 6 summarizes the different possibilities of different metering models concerning LCOEs and grid tariffs. The business model indicates that residential customers can sell generated electricity on the grid to the system operator. The self-consumption model indicates that consumption of PV electricity takes place directly at the house/building—either immediately or delayed through the use of storage systems.

**Table 6.** Competitive prices and corresponding metering models in the rooftop PV market ("x", beneficial; "-", not beneficial).

| Competitive Price | | Metering Model | |
|---|---|---|---|
| *Delta*$_1$ | *Delta*$_2$ | Business | Self-Consumption |
| >0 | >0 | x | x |
| >0 | <0 | x | - |
| <0 | >0 | - | x |
| <0 | <0 | - | - |

The results support policymakers in making decisions and testing the robustness of an effect. By understanding the relationships between input and output variables, policymakers can encourage rooftop PV market development in certain areas by keeping the risk of investors at a comfortable level. With each specific decision, policymakers can measure the effect coverage, as well as the cost and benefit of their choice, and can compare and therefore decide which action should be taken.

Vietnam has an attractive solar market. However, it is undergoing a period of intense transformation. In 2017, the Vietnamese Ministry of Industry and Trade (MOIT) introduced the first FIT, called FIT 1.0, of 8.83 Euro cent/kWh for all solar projects under Decision No. 11. It officially laid the primary foundation for solar power development. To promote market development, in February 2019, MOIT released the draft Decision with new FITs, called FIT 2.0, of an average of 9 Euro cents/kWh for rooftop solar [56] to replace Decision No. 11. FIT 2.0 proposed FITs ranging from 7.45 to 10.26 Euro cents/kWh depending on the four classified irradiation regions of Vietnam. However, in December 2019, a final draft submission letter from MOIT (with a signature but no stamp) for another FIT, called FIT 2.1, has been internally circulated. The FIT 2.1 for rooftop PV projects would be set at 7.91 Euro cents/kWh (Currency exchange rate (Nov 2019): 1 Euro = 1.06 Dollar US), which is around 1 Euro cent/kWh less than the first proposal.

This paper compares the effect of the three FITs on the fledgling market (Figure 13). FIT 1.0, set at 8.83 Euro cent/kWh, generated significant interest in the whole market, especially in the southern regions of Vietnam, which have the highest levels of irradiation. If this price was maintained, the Vietnamese rooftop market would continue to flourish. The expected total return per kWh of the whole market for rooftop PV would be 0.56 Euro cents (blue line). However, 24% of areas would remain unattractive.

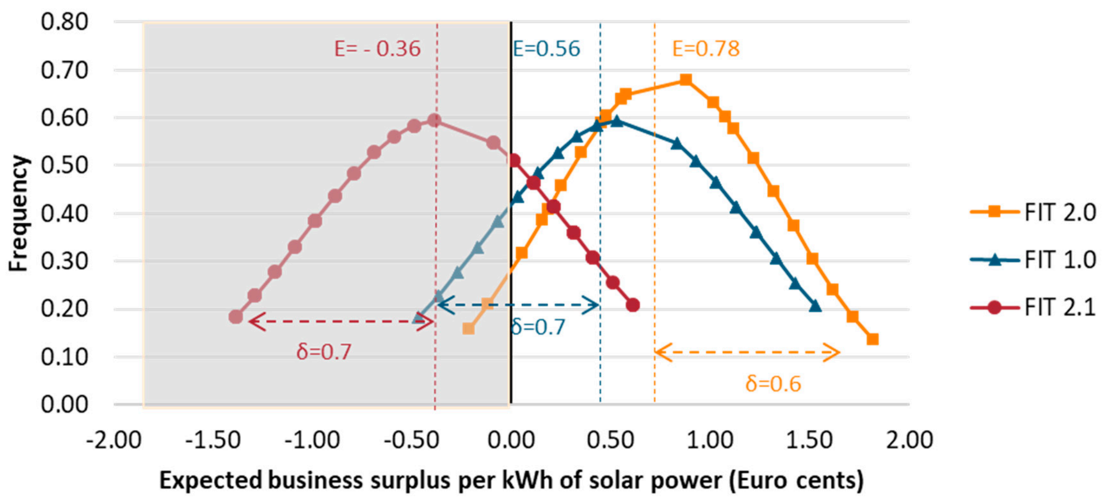



**Figure 13.** Analyzing the market attractiveness corresponding to the three different FITs.

If the FIT 2.0 was approved, it would create a momentum pushing the entire market moving up and to the right of the coordinate axes. This means the expected profit per kWh would increase by

0.12 cents in all localities (orange line). By increasing 0.07 cents/kWh of the average FIT and specified regional price, FIT 2.0 would increase the possible activated market from 76% to 92% and create an additional exploitable 56 TWh potential, equivalent to a possible of 28 million Euro of profits. More than 30 provinces could show their aggressive competition of more than 1 Euro cent profit per kWh.

While the FIT 2.0 promises a bright future for rooftop PV, only some areas may qualify for the FIT 2.1 if the Prime Minister agrees with this approach. More than 60% of the market would be pushed into a difficult situation (red line), causing damage of 900 million Euro in the whole market (Table A5). The possibility of suppressing development or even market recession due to this FIT 2.1 needs to be borne in mind [57].

### 5.3. The Role of Grid Tariffs and PV Module Costs in Self-Sufficiency Developments

According to Vietnam EVN reports, the country's retail electricity price is projected to gradually increase by around 6.12% per year so that the electricity supply units, including EVNs, can offset costs. This paper analyzes the grid tariff changes reflecting on the self-consumption rooftop PV market by ranging it from 7.2 Euro cent/kWh in 2018 to a projected tariff of 8.7 Euro cent/kWh in 2025 (Figure 14). The left chart displays the current market with the grid tariff of 7.2 Euro cent/kWh with different discount rates of 4% and 12%. The right one presents the market when the grid tariff increases to 8.7 Euro cent/kWh. Increasing the grid tariff undeniably creates a favorable condition for the self-consumption business by increasing the expected benefit to −0.5 and 1.2 Euro cent/kWh at a 12% and 4% discount rate, respectively. Detail results for each region can be found in Table A6. As the grid tariff increases, the chance for self-consumption will also increase. However, it should be noted that, even though the policy seems to be effective in encouraging rooftop PV development, it faces many mixed reactions from the public. While researchers and banks complain that electricity price policy in Vietnam is inappropriate for investment because of its relative low grid tariff compared with the grid tariff in neighbor countries [58,59], the increasing grid tariff has led to an increase in the price of finished products, making it particularly tricky for domestic manufacturing enterprises and public consumers.

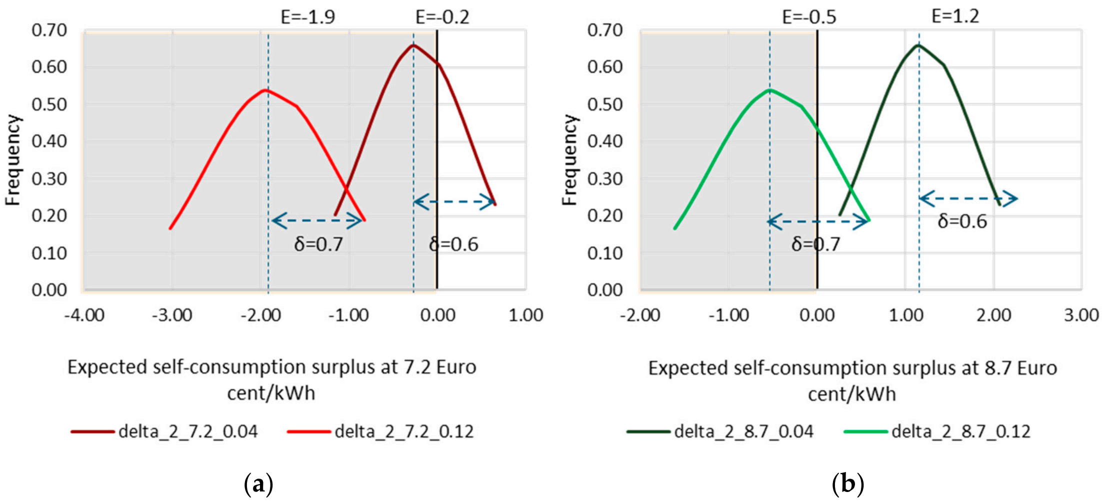
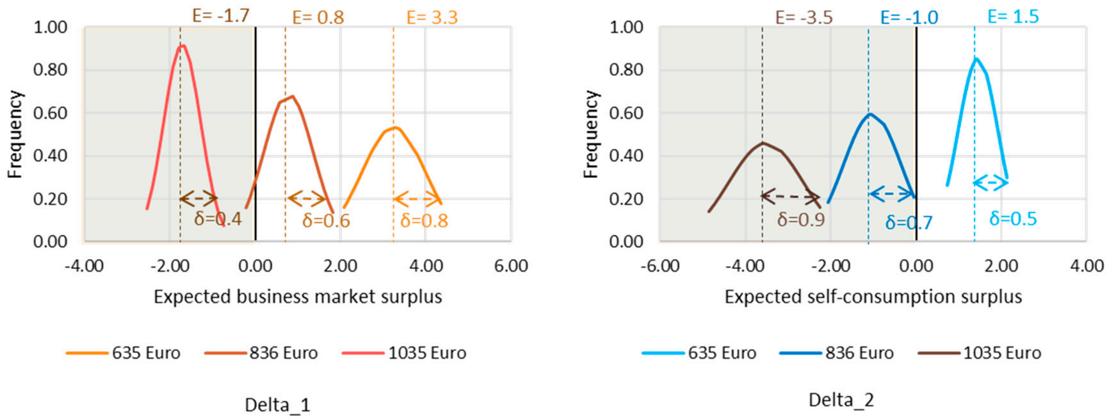



**Figure 14.** Competitive prices change in accordance with the projected grid tariff increases from (**a**) 7.2 to (**b**) 8.7 Euro cent/kWh.

In this paper, we observe the effect of the reduction in specific investment for rooftop PV in Vietnam by adjusting the capital expenditure (CAPEX) of the small rooftop PV systems (1–15 kWp), which will also affect O&M costs (OPEX). The current total costs (CAPEX + OPEX) range from 635 to 1038 Euros/kWp in Vietnam. At a discount rate of 8% and under the FIT 1.0 or FIT 2.0, the business project can expect an average benefit ranging from −1.7 to 3.3 Euro cent/kWh and the self-consumption project can expect from −3.5 to 1.5 Euro cent return per kWh (Figure 15). If the total cost is lower than 650 Euros/kWp, it is feasible to invest in either of the metering models. However, the projects, whose total cost is higher than 836 Euros/kWp, are not recommended in Vietnam.




(**a**) (**b**)

**Figure 15.** Expected business market (**a**) and expected self-consumption (**b**) surplus change in accordance with investment costs increase from 635 to 1038 Euros/kWp.

Rooftop PV technology is becoming more efficient and cost-competitive compared to other traditional energies. A dramatic decrease in the average wholesale price for crystalline modules is reported in China with a reduction from about 530 to 400 Euros/kWp in less than two years from 2016 to the first quarter of 2018 [60]. Moreover, while in 2005 solar modules constituted almost 75% of the system costs, this share amounts to around 50% today, even for rooftop PV systems [60]. In light of the reduced prices for crystalline modules in the global market [60,61], if the total cost for a rooftop PV system is lower than 650 Euros/kWp, it will provide a significant impetus to self-sufficient developments for the rooftop PV market in Vietnam.

*5.4. Critical Discussion*

A cost-effective and transferable methodology for rooftop PV potential assessment in developing countries has been developed. The accuracy of the proposed method has been improved. However, challenges related to the data input still exist. The paper uses digital maps, which are prepared by using satellite imagery, combined with a manual spatial data collection method to conduct geospatial analysis. For example, the final map of Vietnam requires matching geographic and population distributions and building densities within 11,050 clusters of the topographic map in the case of Vietnam. The uncertainty issue arises when different maps often exhibit different accuracy levels depending on their application and spatial extent. The final map incorporates the mistakes of all component maps. The geo-referencing errors, the tilt angle of the sensor, the spatial resolution of the digital data, etc. affect the accuracy of the final map. The performance of the raster map of Vietnam in monthly means compared to measurements at 11 ground stations results in a mean bias error of −0.05 kWh $m^{-2}$ $day^{-1}$ (which represents −1.2% in relative mean bias error) and a root mean square error of 0.32 kWh $m^{-2}$ $day^{-1}$ (8.3% in relative root mean square error) [49]. The data collecting methods and the limitations/errors associated with those methods disturb the spatial accuracy. For example, different classification and interpolation methods were used in preparing the population distribution map for data presented with different errors of around 2–5% in the final map [47]. This paper conducts a sensitivity analysis to assess the effect of these uncertainties on the final results.

This paper considers the temperature and solar radiation, which have significant effects on the performance of photovoltaic (PV) systems; PV cell temperature, which is related to the ambient temperature; and the solar radiation incident on the PV surface, which depends on the slope and azimuth of the PV panels. Another factor that affects the solar radiation incident on the PV surface and hence influences its performance is the ground reflectance (albedo). This paper does not consider this factor due to the renowned complicated vertical distribution of cloud and aerosol layers of Vietnam [62]. Moreover, based on the literature, the albedo effect seems to be relatively small in Vietnam. Vietnam has a diffuse broadband solar irradiance (310–2100 nm) with the normalized solar wavelength of 532 mm [62]. The corresponding albedo spectrum and the effective albedo value, thus, range from around 5% to 15% and 0.1 to 0.35, depending on the rooftop materials such as brick, red shingle, ceramic tiles, and green paint, respectively [63]. The effective albedo can lead to errors of less than 1.6% and 6.7% for the module tilt angles from horizontal of 40° and 90° [64]. Further studies, especially field studies on a small scale, can use this effective albedo value to optimize PV system design and take advantage of the reflected albedo resource.

This study improves the accuracy of technical potential output by calculating the corrected temperature based on the NOCT model. As mentioned in Section 3, NOCT is obtained under predetermined environmental conditions, while STC is the test condition used to rate the performance of a PV panel. STC is the idealized condition, which can overpredict PV performance [65,66]. Since the NOCT is based on realistic data, it is simple and easy to apply. Manufacturers usually include NOCT in the module characteristic data. However, NOCT can overpredict the PV cell temperature by around 10% [67], and can also vary around 2–5 °C, depending on the module materials [68]. Thus, it can underpredict the PV performance [36]. Another option for calculating the expected PV system yield for specific provinces or even buildings is the free online tool PVGIS, provided by the European Commission [69]. The tool uses the real measured values of solar radiation at specific location and provides an overview information about PV system performance. However, while PVGIS is certainly more accurate for a specific building, it would not be feasible to perform a national analysis with this tool.

When calculating the cost for decentralized PV generation technologies, this paper uses LCOE, which is the most widely used metric for a cost comparison between different generation technologies. However, since the renewable energy share in total electricity supply increases, it poses a difficulty for LCOE to make comparisons between different categories of supply, e.g., residual load, load following, and variable load. Another concern regarding LCOE is that it is becoming more difficult to justify applying the same weighted average cost of capital to technologies with very different climate policy risks. To deal with these drawbacks, the new measure, called the Value-Adjusted Levelized Cost of Electricity (VALCOE), is now recommended by the IEA [70], which includes three adjustments to LCOE: energy, value, and flexibility. Although the VALCOE may be a better measure of cost for grid managers, the IEA needs to provide the data for the added factors from their World Energy Model (WEM) regional hourly dispatch models. Once these data are available and the flexibility value, outside of the WEM model, in the VALCOE equation, are well defined, future studies can replace LCOE by this new measurement.

## 6. Conclusions and Policy Implications

Rooftop PV is driving the decentralization of electricity production, which is a cornerstone of the sustainable development concept, whereby households become more independent of the electricity grid due to a thorough integration of renewable energy sources. However, it is still often seen as a novelty, and legally, local authorities have difficulties enforcing this specific technology in their detailed development plans partly because of the lack of expertise and capital. Therefore, it is relevant to address decentralized PV potentials as early as possible when the state and local governments start planning for the type of energy source. Since different regions have different climatic, geographic, and demographic profiles, this paper provides an affordable, robust and high-resolution potential assessment for rooftop PV and suggests target groups alongside policy solutions with clear national and local goals, based on the findings. The proposed method considers construction and design constraints, obstacles on the rooftop, and the proper orientation on the roof, including shading effects and the slum areas (informal settlements). The paper considers Vietnam as an example for other emerging countries to apply the method. The results can provide an overview plan as well as an integrated strategy for developing rooftop PV between different administrative levels.

The physical potential in the raster maps, which encompasses the maximum amount of solar energy received in a particular area, is broken down into the geographic potential of in total 1407 $km^2$ available rooftop by gradually excluding the zones reserved for other uses and restricting the locations where solar energy can be gathered. The technical potential is calculated with the results of roof-mounted solar cells in the whole country being about 228 and 216 GWp or about 278 and 263 TWh/a with monocrystalline and polycrystalline solar cells, respectively. The LCOE is also calculated, ranging from about 7.6 to 9.2 Euro cents/kWh at a discount rate of 8% in 63 provinces in Vietnam. However, since the techno-economic potential of PV is associated with a certain degree of uncertainty, we measure the error regarding the uncertainty of data assumptions and inputs and the inherently unknowable reaction of the market. Overcoming the unfavorable data conditions, this paper provides a practical and useful tool for policy-making processes. We suggest dividing the market by target group and priority level based on their PV potentials, demographics, and economic status. Hanoi and Ho Chi Minh City should be classified as the highest priority cities for policy focus based on their high potential and robust internal economic and demographic conditions.

This paper also provides systematic guidance to help policymakers design political strategies to support market development. For example, only projects with total costs (CAPEX + OPEX) and discount rates lower than 850 Euros/kWp and 8% respectively, can be beneficial in the current market. With total costs of around 650–850 Euros/kWp, the only attractive investment option is the business model, which is selling generated PV electricity directly on the state grid, while total costs lower than 650 Euros/kWp make a choice between the business and the self-consumption models possible for their rooftop PV projects. For self-consumption, there is no clear strategy, but the situation improves due to increasing grid tariffs. Consumers must, however, wait until around 2025 when their grid tariff should rise to at least about 8.7 cents/kWh and self-consumption will become attractive, but this date could be sooner if costs for solar technology continue to decrease. By simulating the rooftop PV market in different projected FITs, we recommend that the government consider their tariff strategies carefully. In the case of changing the average FIT from 8.83 to 9 Euro cents/kWh and establishing regional FITs, they can activate an additional 16% of the total market, equivalent to around 56 TWh and approximately 28 million Euro of profit. However, if they were to reduce the FIT to 7.79 Euro cents/kWh, it would deactivate about 60% of the rooftop PV market and would reduce total market benefits of approximately 900 million Euro (Table A5).

This paper presents a methodology to carry out resource assessments for rooftop PV in developing countries, as applied to Vietnam. The method is a top-down method that can be employed where detailed, accurate data on buildings, their outlines, and associated infrastructure are lacking. It represents an improvement beyond state of the art and has an absolute error of about 5% compared to detailed bottom-up city models, which is very low for a method at this spatial scale and resolution. Uncertainties relating to the input data are significant but are considered in the sensitivity analysis, which should be borne in mind when interpreting the results. Especially the accuracy of the assumptions relating to the building location, size, orientation, and shading impacts are country-specific and require further research to be employed elsewhere. One promising avenue in this context is the combination of open mapping data with satellite images to automatically identify suitable geometries for rooftop PV [31]. By further validating the top-down results from this study with bottom-up results from 3D models (e.g., Effigis Geo-Solutions 2018), the method could be improved and applied to other contexts. Finally, this and related studies have tended to focus on the supply side for rooftop PV, but there is a need for future research to analyze the demand side, especially public opinion and willingness to pay for PV systems.

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## Nomenclature

| | |
|---|---|
| PV | Photovoltaics |
| LIDAR | Light detection and ranging |
| HVAC | Heating, Ventilation and Air Conditioning |
| STC | Standard test conditions |
| AM | Air mass |
| NOCT | Nominal operating cell temperature |
| CT | Constant value |
| HD | Height difference |
| MRS | Module row spacing |
| PR | Performance ratio |
| LCOE | Levelized Cost of Electricity |
| GDP | Gross domestic product |
| Dim | Dimension |
| FIT | Feed-in tariff |
| MOIT | Vietnamese Ministry of Industry and Trade |
| EVN | Vietnam Electricity Enterprise |
| CAPEX | Capital expenditure |
| OPEX | Operational and maintenance expenditure |

## Appendix A

**Table A1.** Retail electricity tariff for household customers (published 20/03/2019).

| | Customer Group | Rate (VND/kWh) | Rate (Euro cents/kWh) |
|---|---|---|---|
| 1 | *Retail price for household electricity* | | |
| | Rate 1: For 0–50 kWh | 1678 | 6.33 |
| | Rate 2: For 51–100 kWh | 1734 | 6.54 |
| | Rate 3: For 101–200 kWh | 2014 | 7.60 |
| | Rate 4: For 201–300 kWh | 2536 | 9.57 |
| | Rate 5: For 301–400 kWh | 2834 | 10.69 |
| | Rate 6: For 401 kWh onwards | 2927 | 11.05 |
| 2 | *Retail price for household electricity via prepaid card meter* | 2461 | 9.29 |

**Table A2.** Provinces in Vietnam and their demographic characteristics.

| ID | Province | Region | Total Area ($km^2$) | Household Area ($km^2$) | % of Household Area | Population | Urban Rate 2018 (%) | Gdp/a/person 2018 (Euro/a) |
|---|---|---|---|---|---|---|---|---|
| 1 | **An Giang** | Mekong river delta | 3536 | 135 | 3.8% | 2164.2 | 30.8% | 1612.1 |
| 2 | **Ba Ria-Vung Tau** | Southeast | 1979 | 71 | 3.6% | 1112.9 | 52.4% | 2210.3 |
| 3 | **Bac Giang** | Northern midlands | 3895 | 185 | 4.7% | 897.0 | 11.5% | 1562.3 |
| 4 | **Bac Kan** | Northern midlands | 4860 | 26 | 0.5% | 327.9 | 18.8% | 880.8 |
| 5 | **Bac Lieu** | Mekong river delta | 2668 | 49 | 1.8% | 1691.8 | 29.1% | 1222.2 |
| 6 | **Bac Ninh** | Red river delta | 822 | 104 | 12.7% | 1247.5 | 28.3% | 2466.1 |
| 7 | **Ben Tre** | Mekong river delta | 2395 | 81 | 3.4% | 1268.2 | 10.8% | 1543.7 |
| 8 | **Binh Dinh** | South central coast | 6066 | 94 | 1.5% | 2163.6 | 31.0% | 1369.4 |
| 9 | **Binh Duong** | Southeast | 2696 | 136 | 5.0% | 1534.8 | 39.4% | 3089.7 |
| 10 | **Binh Phuoc** | Southeast | 6878 | 65 | 0.9% | 979.6 | 22.0% | 1632.0 |
| 11 | **Binh Thuan** | South central coast | 7946 | 89 | 1.1% | 1239.2 | 78.2% | 1560.0 |
| 12 | **Ca Mau** | Mekong river delta | 5221 | 65 | 1.2% | 1229.6 | 22.7% | 1352.2 |
| 13 | **Can Tho** | Mekong river delta | 1439 | 82 | 5.7% | 540.4 | 67.3% | 1979.3 |
| 14 | **Cao Bang** | Northern midlands | 6701 | 56 | 0.8% | 1282.3 | 23.2% | 840.5 |
| 15 | **Da Nang** | South central coast | 1286 | 75 | 5.8% | 1080.7 | 87.8% | 2493.3 |
| 16 | **Dak Lak** | Central highlands | 13030 | 150 | 1.2% | 1919.2 | 24.7% | 1244.4 |
| 17 | **Dak Nong** | Central highlands | 6513 | 55 | 0.8% | 645.4 | 15.3% | 1372.1 |
| 18 | **Dien Bien** | Northern Mountains | 9542 | 50 | 0.5% | 3086.1 | 15.1% | 668.8 |
| 19 | **Dong Nai** | Southeast | 5863 | 177 | 3.0% | 1693.3 | 35.6% | 2400.0 |
| 20 | **Dong Thap** | Mekong river delta | 3383 | 146 | 4.3% | 576.7 | 17.8% | 1584.9 |
| 21 | **Gia Lai** | Central highlands | 15511 | 183 | 1.2% | 1458.5 | 30.9% | 1171.0 |

**Table A2.** *Cont.*

| ID | Province | Region | Total Area (km$^2$) | Household Area (km$^2$) | % of Household Area | Population | Urban Rate 2018 (%) | Gdp/a/person 2018 (Euro/a) |
|---|---|---|---|---|---|---|---|---|
| 22 | **Ha Giang** | Northern midlands | 7929 | 71 | 0.9% | 846.5 | 15.1% | 781.1 |
| 23 | **Ha Nam** | Red river delta | 859 | 63 | 7.3% | 808.2 | 15.9% | 1633.8 |
| 24 | **Ha Noi** | Red river delta | 3360 | 407 | 12.1% | 7520.7 | 64.6% | 2741.4 |
| 25 | **Ha Tinh** | North central coast | 5990 | 121 | 2.0% | 1277.5 | 18.7% | 1287.8 |
| 26 | **Hai Duong** | Red river delta | 1666 | 167 | 10.0% | 1807.5 | 25.3% | 1672.3 |
| 27 | **Hai Phong** | Red river delta | 1561 | 145 | 9.3% | 2013.8 | 46.8% | 2316.7 |
| 28 | **Hau Giang** | Southeast | 1622 | 45 | 2.8% | 776.7 | 25.4% | 1606.6 |
| 29 | **Ho Chi Minh City** | Mekong river delta | 2062 | 282 | 13.7% | 8598.7 | 80.5% | 2797.1 |
| 30 | **Hoa Binh** | Northern Mountains | 4591 | 140 | 3.0% | 846.1 | 14.8% | 1039.2 |
| 31 | **Hung Yen** | Red river delta | 929 | 96 | 10.3% | 3558.2 | 13.0% | 1740.2 |
| 32 | **Khanh Hoa** | South central coast | 5139 | 67 | 1.3% | 1188.9 | 45.0% | 1564.5 |
| 33 | **Kien Giang** | Mekong river delta | 6348 | 137 | 2.2% | 1232.4 | 29.2% | 1711.2 |
| 34 | **Kon Tum** | Central highlands | 9675 | 84 | 0.9% | 1810.5 | 35.5% | 908.8 |
| 35 | **Lai Chau** | Northern Mountains | 9069 | 29 | 0.3% | 535.0 | 17.3% | 676.1 |
| 36 | **Lam Dong** | Central highlands | 9780 | 125 | 1.3% | 790.5 | 39.8% | 1648.8 |
| 37 | **Lang Son** | Northern midlands | 8310 | 81 | 1.0% | 1312.9 | 20.3% | 926.9 |
| 38 | **Lao Cai** | Northern Mountains | 6366 | 52 | 0.8% | 456.3 | 22.9% | 1052.4 |
| 39 | **Long An** | Mekong river delta | 4496 | 266 | 5.9% | 705.6 | 18.0% | 1908.7 |
| 40 | **Nam Dinh** | Red river delta | 1669 | 112 | 6.7% | 1503.1 | 18.7% | 1532.4 |
| 41 | **Nghe An** | North central coast | 16482 | 256 | 1.6% | 1854.4 | 15.1% | 1151.5 |
| 42 | **Ninh Binh** | Red river delta | 1385 | 68 | 4.9% | 3157.1 | 21.1% | 1191.4 |

**Table A2.** *Cont.*

| ID | Province | Region | Total Area ($km^2$) | Household Area ($km^2$) | % of Household Area | Population | Urban Rate 2018 (%) | Gdp/a/person 2018 (Euro/a) |
|---|---|---|---|---|---|---|---|---|
| 43 | **Ninh Thuan** | South central coast | 3354 | 49 | 1.5% | 973.3 | 36.2% | 1710.8 |
| 44 | **Phu Tho** | Northern midlands | 3535 | 106 | 3.0% | 611.8 | 19.1% | 1309.6 |
| 45 | **Phu Yen** | South central coast | 5022 | 54 | 1.1% | 1404.2 | 29.1% | 1284.7 |
| 46 | **Quang Binh** | North central coast | 7999 | 63 | 0.8% | 909.5 | 63.9% | 1207.2 |
| 47 | **Quang Nam** | South central coast | 10574 | 204 | 1.9% | 887.6 | 19.8% | 1315.9 |
| 48 | **Quang Ngai** | South central coast | 5157 | 116 | 2.2% | 1501.1 | 30.3% | 1313.2 |
| 49 | **Quang Ninh** | Northern midlands | 6179 | 82 | 1.3% | 1272.8 | 24.3% | 2163.2 |
| 50 | **Quang Tri** | North central coast | 4623 | 43 | 0.9% | 1266.5 | 15.2% | 1151.5 |
| 51 | **Soc Trang** | Mekong river delta | 3314 | 57 | 1.7% | 630.6 | 30.6% | 1654.2 |
| 52 | **Son La** | Northern Mountains | 14124 | 86 | 0.6% | 1315.9 | 13.7% | 671.5 |
| 53 | **Tay Ninh** | Southeast | 4042 | 92 | 2.3% | 1242.7 | 22.6% | 1928.2 |
| 54 | **Thai Binh** | Red river delta | 1588 | 136 | 8.6% | 1133.4 | 10.5% | 1818.1 |
| 55 | **Thai Nguyen** | Northern midlands | 3526 | 123 | 3.5% | 1793.2 | 35.3% | 1606.2 |
| 56 | **Thanh Hoa** | North central coast | 11116 | 552 | 5.0% | 1268.3 | 17.3% | 1365.3 |
| 57 | **Thua Thien Hue** | North central coast | 4901 | 95 | 1.9% | 1163.6 | 48.9% | 1396.5 |
| 58 | **Tien Giang** | Mekong river delta | 2512 | 100 | 4.0% | 1762.3 | 15.5% | 1804.1 |
| 59 | **Tra Vinh** | Mekong river delta | 2356 | 49 | 2.1% | 1049.8 | 18.3% | 1299.2 |
| 60 | **Tuyen Quang** | Northern midlands | 5868 | 61 | 1.0% | 780.1 | 13.9% | 1024.3 |
| 61 | **Vinh Long** | Mekong river delta | 1524 | 60 | 3.9% | 1051.8 | 25.0% | 1398.8 |
| 62 | **Vinh Phuc** | Red river delta | 1237 | 79 | 6.4% | 1092.4 | 17.0% | 1675.0 |
| 63 | **Yen Bai** | Northern Mountains | 6887 | 54 | 0.8% | 815.6 | 20.7% | 1037.0 |

**Table A3.** Results of potential assessment.

| ID | Province | Available Roof (km²) | LCOE Mono (Euro cents/ kWh) | LCOE Poly (Euro cents/ kWh) | Production Potentials Mono (TWh/a) | Production Potentials Poly (TWh/a) | Installable Potentials Mono (GWP) | Installable Potentials Poly (GWP) | Specific Potential Mono (GWh/ km2) | Specific Potential Poly (GWh/ km2) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **An Giang** | 28.2 | 7.6 | 7.2 | 6.3 | 6 | 4.6 | 4.4 | 1.8 | 1.7 |
| 2 | **Ba Ria-Vung Tau** | 17.7 | 7.6 | 7.2 | 4 | 3.8 | 2.9 | 2.7 | 2 | 1.9 |
| 3 | **Bac Giang** | 18.8 | 9 | 8.5 | 3.1 | 2.9 | 3 | 2.8 | 0.8 | 0.8 |
| 4 | **Bac Kan** | 7.2 | 9.3 | 8.7 | 1.1 | 1.1 | 1.2 | 1.1 | 0.2 | 0.2 |
| 5 | **Bac Lieu** | 13.8 | 7.8 | 7.4 | 3 | 2.8 | 2.3 | 2.1 | 1.1 | 1.1 |
| 6 | **Bac Ninh** | 17.6 | 8.9 | 8.4 | 2.9 | 2.8 | 2.8 | 2.7 | 3.6 | 3.4 |
| 7 | **Ben Tre** | 23.5 | 7.7 | 7.2 | 5.3 | 5 | 3.9 | 3.6 | 2.2 | 2.1 |
| 8 | **Binh Dinh** | 23 | 7.7 | 7.3 | 5.1 | 4.8 | 3.8 | 3.6 | 0.8 | 0.8 |
| 9 | **Binh Duong** | 22.6 | 7.6 | 7.2 | 5.2 | 4.9 | 3.7 | 3.5 | 1.9 | 1.8 |
| 10 | **Binh Phuoc** | 27.5 | 7.5 | 7.1 | 6.4 | 6 | 4.5 | 4.2 | 0.9 | 0.9 |
| 11 | **Binh Thuan** | 19.1 | 7.3 | 6.9 | 4.6 | 4.4 | 3.1 | 2.9 | 0.6 | 0.6 |
| 12 | **Ca Mau** | 24.5 | 7.9 | 7.5 | 5.2 | 4.9 | 4 | 3.8 | 1 | 0.9 |
| 13 | **Can Tho** | 16.5 | 7.7 | 7.3 | 3.6 | 3.4 | 2.7 | 2.6 | 2.6 | 2.4 |
| 14 | **Cao Bang** | 11 | 9.2 | 8.7 | 1.7 | 1.6 | 1.7 | 1.7 | 0.3 | 0.2 |
| 15 | **Da Nang** | 13.7 | 8 | 7.6 | 2.8 | 2.7 | 2.2 | 2.1 | 2.2 | 2.1 |
| 16 | **Dak Lak** | 22.4 | 7.6 | 7.2 | 5.1 | 4.8 | 3.6 | 3.4 | 0.4 | 0.4 |
| 17 | **Dak Nong** | 7.5 | 7.5 | 7.1 | 1.7 | 1.6 | 1.2 | 1.1 | 0.3 | 0.2 |
| 18 | **Dien Bien** | 10.7 | 8.4 | 7.9 | 1.9 | 1.8 | 1.7 | 1.6 | 0.2 | 0.2 |
| 19 | **Dong Nai** | 43.8 | 7.6 | 7.2 | 9.9 | 9.4 | 7.1 | 6.8 | 1.7 | 1.6 |
| 20 | **Dong Thap** | 24.9 | 7.6 | 7.2 | 5.7 | 5.3 | 4.1 | 3.8 | 1.7 | 1.6 |
| 21 | **Gia Lai** | 19.3 | 7.6 | 7.2 | 4.3 | 4.1 | 3.1 | 2.9 | 0.3 | 0.3 |

**Table A3.** *Cont.*

| ID | Province | Available Roof (km$^2$) | LCOE Mono (Euro cents/ kWh) | LCOE Poly (Euro cents/ kWh) | Production Potentials Mono (TWh/a) | Production Potentials Poly (TWh/a) | Installable Potentials Mono (GWP) | Installable Potentials Poly (GWP) | Specific Potential Mono (GWh/ km2) | Specific Potential Poly (GWh/ km2) |
|---|---|---|---|---|---|---|---|---|---|---|
| 22 | **Ha Giang** | 13.2 | 9.3 | 8.7 | 2 | 1.9 | 2.1 | 2 | 0.3 | 0.2 |
| 23 | **Ha Nam** | 13 | 8.9 | 8.4 | 2.2 | 2.1 | 2.1 | 2 | 2.5 | 2.4 |
| 24 | **Ha Noi** | 93.9 | 8.9 | 8.4 | 15.6 | 14.8 | 15.1 | 14.3 | 5 | 4.7 |
| 25 | **Ha Tinh** | 27.4 | 8.9 | 8.4 | 4.6 | 4.3 | 4.4 | 4.2 | 2.8 | 2.6 |
| 26 | **Hai Duong** | 24.7 | 8.9 | 8.3 | 4.2 | 3.9 | 4 | 3.8 | 2.7 | 2.6 |
| 27 | **Hai Phong** | 19.2 | 8.8 | 8.3 | 3.4 | 3.2 | 3.2 | 3 | 0.6 | 0.5 |
| 28 | **Hau Giang** | 11.9 | 7.9 | 7.4 | 2.5 | 2.4 | 2 | 1.8 | 1.6 | 1.5 |
| 29 | **Ho Chi Minh City** | 110 | 7.6 | 7.2 | 24.8 | 23.4 | 18 | 17 | 11.8 | 11.2 |
| 30 | **Hoa Binh** | 10 | 8.9 | 8.4 | 1.7 | 1.6 | 1.6 | 1.5 | 0.4 | 0.3 |
| 31 | **Hung Yen** | 16.6 | 8.9 | 8.4 | 2.8 | 2.6 | 2.7 | 2.5 | 3 | 2.9 |
| 32 | **Khanh Hoa** | 16.7 | 7.6 | 7.2 | 3.8 | 3.6 | 2.7 | 2.6 | 0.7 | 0.7 |
| 33 | **Kien Giang** | 31.7 | 7.8 | 7.4 | 6.8 | 6.5 | 5.2 | 4.9 | 1.1 | 1 |
| 34 | **Kon Tum** | 7.5 | 7.7 | 7.3 | 1.6 | 1.5 | 1.2 | 1.1 | 0.2 | 0.2 |
| 35 | **Lai Chau** | 9.5 | 8.6 | 8.1 | 1.6 | 1.6 | 1.5 | 1.4 | 0.2 | 0.2 |
| 36 | **Lam Dong** | 17.2 | 7.5 | 7.1 | 3.9 | 3.7 | 2.8 | 2.6 | 0.4 | 0.4 |
| 37 | **Lang Son** | 14.6 | 9.1 | 8.6 | 2.3 | 2.2 | 2.3 | 2.2 | 0.3 | 0.3 |
| 38 | **Lao Cai** | 10.8 | 9.2 | 8.7 | 1.7 | 1.6 | 1.7 | 1.6 | 0.3 | 0.3 |
| 39 | **Long An** | 29.6 | 7.6 | 7.2 | 6.8 | 6.4 | 4.8 | 4.6 | 1.5 | 1.4 |
| 40 | **Nam Dinh** | 27.1 | 8.8 | 8.3 | 4.7 | 4.4 | 4.4 | 4.1 | 2.8 | 2.7 |
| 41 | **Nghe An** | 45.4 | 8.6 | 8.1 | 8.1 | 7.7 | 7.4 | 7 | 0.5 | 0.5 |
| 42 | **Ninh Binh** | 16.3 | 8.9 | 8.3 | 2.8 | 2.6 | 2.6 | 2.5 | 2 | 1.9 |

**Table A3.** *Cont.*

| ID | Province | Available Roof ($km^2$) | LCOE Mono (Euro cents/ kWh) | LCOE Poly (Euro cents/ kWh) | Production Potentials Mono (TWh/a) | Production Potentials Poly (TWh/a) | Installable Potentials Mono (GWP) | Installable Potentials Poly (GWP) | Specific Potential Mono (GWh/ km2) | Specific Potential Poly (GWh/ km2) |
|---|---|---|---|---|---|---|---|---|---|---|
| 43 | **Ninh Thuan** | 7.8 | 7.3 | 6.9 | 1.9 | 1.8 | 1.3 | 1.2 | 0.6 | 0.5 |
| 44 | **Phu Tho** | 17.9 | 9.1 | 8.6 | 2.9 | 2.7 | 2.9 | 2.7 | 0.8 | 0.8 |
| 45 | **Phu Yen** | 13.4 | 7.7 | 7.3 | 3 | 2.8 | 2.2 | 2.1 | 0.6 | 0.6 |
| 46 | **Quang Binh** | 17.1 | 8.7 | 8.2 | 3 | 2.9 | 2.8 | 2.7 | 0.4 | 0.4 |
| 47 | **Quang Nam** | 25.6 | 8 | 7.6 | 5.3 | 5 | 4.2 | 4 | 0.5 | 0.5 |
| 48 | **Quang Ngai** | 18.3 | 7.8 | 7.4 | 3.9 | 3.7 | 3 | 2.8 | 0.8 | 0.7 |
| 49 | **Quang Ninh** | 43.8 | 9.2 | 8.6 | 7 | 6.6 | 7 | 6.6 | 1.1 | 1.1 |
| 50 | **Quang Tri** | 10.3 | 8.4 | 7.9 | 1.9 | 1.8 | 1.7 | 1.6 | 0.4 | 0.4 |
| 51 | **Soc Trang** | 20.9 | 7.8 | 7.4 | 4.5 | 4.3 | 3.4 | 3.2 | 1.4 | 1.3 |
| 52 | **Son La** | 19.7 | 8.5 | 8 | 3.5 | 3.3 | 3.1 | 3 | 0.2 | 0.2 |
| 53 | **Tay Ninh** | 24.5 | 7.4 | 7.1 | 5.8 | 5.4 | 4 | 3.8 | 1.4 | 1.3 |
| 54 | **Thai Binh** | 26.9 | 8.9 | 8.3 | 4.6 | 4.3 | 4.3 | 4.1 | 3 | 2.8 |
| 55 | **Thai Nguyen** | 16.5 | 9.3 | 8.7 | 2.6 | 2.4 | 2.7 | 2.5 | 0.7 | 0.7 |
| 56 | **Thanh Hoa** | 42.8 | 8.7 | 8.2 | 7.5 | 7.1 | 6.9 | 6.6 | 0.7 | 0.6 |
| 57 | **Thua Thien Hue** | 16.5 | 8.3 | 7.8 | 3.2 | 3 | 2.7 | 2.5 | 0.6 | 0.6 |
| 58 | **Tien Giang** | 28.6 | 7.6 | 7.2 | 6.4 | 6.1 | 4.7 | 4.4 | 2.6 | 2.4 |
| 59 | **Tra Vinh** | 16.8 | 7.7 | 7.3 | 3.7 | 3.5 | 2.7 | 2.6 | 1.6 | 1.5 |
| 60 | **Tuyen Quang** | 11.7 | 9.3 | 8.7 | 1.8 | 1.7 | 1.9 | 1.8 | 0.3 | 0.3 |
| 61 | **Vinh Long** | 16.5 | 7.7 | 7.3 | 3.6 | 3.4 | 2.7 | 2.6 | 2.4 | 2.3 |
| 62 | **Vinh Phuc** | 18.9 | 9 | 8.5 | 3.1 | 2.9 | 3 | 2.9 | 2.2 | 2.1 |
| 63 | **Yen Bai** | 13.1 | 9.2 | 8.7 | 2.1 | 1.9 | 2.1 | 2 | 0.3 | 0.3 |

**Table A4.** Results of clustering.

| ID | Province | Available Roof ($km^2$) | LCOE Mono (Euro cents/kWh) | Production Potentials Mono (TWh/a) | Urban Rate 2018 (%) | gdp/a/Person 2018 (Euro/a) | Clustering Result | Priority |
|---|---|---|---|---|---|---|---|---|
| 1 | **An Giang** | 28.2 | 7.6 | 6.3 | 30.8% | 1612.1 | 1 | 5 |
| 2 | **Ba Ria-Vung Tau** | 17.7 | 7.6 | 4.0 | 52.4% | 2210.3 | 2 | 3 |
| 3 | **Bac Giang** | 18.8 | 9.0 | 3.1 | 11.5% | 1562.3 | 3 | 4 |
| 4 | **Bac Kan** | 7.2 | 9.3 | 1.1 | 18.8% | 880.8 | 4 | 6 |
| 5 | **Bac Lieu** | 13.8 | 7.8 | 3.0 | 29.1% | 1222.2 | 5 | 2 |
| 6 | **Bac Ninh** | 17.6 | 8.9 | 2.9 | 28.3% | 2466.1 | 3 | 4 |
| 7 | **Ben Tre** | 23.5 | 7.7 | 5.3 | 10.8% | 1543.7 | 5 | 2 |
| 8 | **Binh Dinh** | 23.0 | 7.7 | 5.1 | 31.0% | 1369.4 | 5 | 2 |
| 9 | **Binh Duong** | 22.6 | 7.6 | 5.2 | 39.4% | 3089.7 | 1 | 5 |
| 10 | **Binh Phuoc** | 27.5 | 7.5 | 6.4 | 22.0% | 1632.0 | 1 | 5 |
| 11 | **Binh Thuan** | 19.1 | 7.3 | 4.6 | 78.2% | 1560.0 | 2 | 3 |
| 12 | **Ca Mau** | 24.5 | 7.9 | 5.2 | 22.7% | 1352.2 | 5 | 2 |
| 13 | **Can Tho** | 16.5 | 7.7 | 3.6 | 67.3% | 1979.3 | 2 | 3 |
| 14 | **Cao Bang** | 11.0 | 9.2 | 1.7 | 23.2% | 840.5 | 4 | 6 |
| 15 | **Da Nang** | 13.7 | 8.0 | 2.8 | 87.8% | 2493.3 | 2 | 3 |
| 16 | **Dak Lak** | 22.4 | 7.6 | 5.1 | 24.7% | 1244.4 | 5 | 2 |
| 17 | **Dak Nong** | 7.5 | 7.5 | 1.7 | 15.3% | 1372.1 | 5 | 2 |
| 18 | **Dien Bien** | 10.7 | 8.4 | 1.9 | 15.1% | 668.8 | 4 | 6 |
| 19 | **Dong Nai** | 43.8 | 7.6 | 9.9 | 35.6% | 2400.0 | 1 | 5 |
| 20 | **Dong Thap** | 24.9 | 7.6 | 5.7 | 17.8% | 1584.9 | 1 | 5 |
| 21 | **Gia Lai** | 19.3 | 7.6 | 4.3 | 30.9% | 1171.0 | 5 | 2 |

**Table A4.** *Cont.*

| ID | Province | Available Roof (km$^{2)}$ | LCOE Mono (Euro cents/kWh) | Production Potentials Mono (TWh/a) | Urban Rate 2018 (%) | gdp/a/Person 2018 (Euro/a) | Clustering Result | Priority |
|---|---|---|---|---|---|---|---|---|
| 22 | **Ha Giang** | 13.2 | 9.3 | 2.0 | 15.1% | 781.1 | 4 | 6 |
| 23 | **Ha Nam** | 13.0 | 8.9 | 2.2 | 15.9% | 1633.8 | 3 | 4 |
| 24 | **Ha Noi** | 93.9 | 8.9 | 15.6 | 64.6% | 2741.4 | 6 | 1 |
| 25 | **Ha Tinh** | 27.4 | 8.9 | 4.6 | 18.7% | 1287.8 | 3 | 4 |
| 26 | **Hai Duong** | 24.7 | 8.9 | 4.2 | 25.3% | 1672.3 | 3 | 4 |
| 27 | **Hai Phong** | 19.2 | 8.8 | 3.4 | 46.8% | 2316.7 | 2 | 3 |
| 28 | **Hau Giang** | 11.9 | 7.9 | 2.5 | 25.4% | 1606.6 | 5 | 2 |
| 29 | **Ho Chi Minh City** | 110.0 | 7.6 | 24.8 | 80.5% | 2797.1 | 6 | 1 |
| 30 | **Hoa Binh** | 10.0 | 8.9 | 1.7 | 14.8% | 1039.2 | 4 | 6 |
| 31 | **Hung Yen** | 16.6 | 8.9 | 2.8 | 13.0% | 1740.2 | 3 | 4 |
| 32 | **Khanh Hoa** | 16.7 | 7.6 | 3.8 | 45.0% | 1564.5 | 5 | 2 |
| 33 | **Kien Giang** | 31.7 | 7.8 | 6.8 | 29.2% | 1711.2 | 1 | 5 |
| 34 | **Kon Tum** | 7.5 | 7.7 | 1.6 | 35.5% | 908.8 | 5 | 2 |
| 35 | **Lai Chau** | 9.5 | 8.6 | 1.6 | 17.3% | 676.1 | 4 | 6 |
| 36 | **Lam Dong** | 17.2 | 7.5 | 3.9 | 39.8% | 1648.8 | 5 | 2 |
| 37 | **Lang Son** | 14.6 | 9.1 | 2.3 | 20.3% | 926.9 | 4 | 6 |
| 38 | **Lao Cai** | 10.8 | 9.2 | 1.7 | 22.9% | 1052.4 | 4 | 6 |
| 39 | **Long An** | 29.6 | 7.6 | 6.8 | 18.0% | 1908.7 | 1 | 5 |
| 40 | **Nam Dinh** | 27.1 | 8.8 | 4.7 | 18.7% | 1532.4 | 3 | 4 |
| 41 | **Nghe An** | 45.4 | 8.6 | 8.1 | 15.1% | 1151.5 | 3 | 4 |
| 42 | **Ninh Binh** | 16.3 | 8.9 | 2.8 | 21.1% | 1191.4 | 4 | 6 |

**Table A4.** *Cont.*

| ID | Province | Available Roof (km$^{2}$) | LCOE Mono (Euro cents/kWh) | Production Potentials Mono (TWh/a) | Urban Rate 2018 (%) | gdp/a/Person 2018 (Euro/a) | Clustering Result | Priority |
|---|---|---|---|---|---|---|---|---|
| 43 | **Ninh Thuan** | 7.8 | 7.3 | 1.9 | 36.2% | 1710.8 | 5 | 2 |
| 44 | **Phu Tho** | 17.9 | 9.1 | 2.9 | 19.1% | 1309.6 | 4 | 6 |
| 45 | **Phu Yen** | 13.4 | 7.7 | 3.0 | 29.1% | 1284.7 | 5 | 2 |
| 46 | **Quang Binh** | 17.1 | 8.7 | 3.0 | 63.9% | 1207.2 | 2 | 3 |
| 47 | **Quang Nam** | 25.6 | 8.0 | 5.3 | 19.8% | 1315.9 | 5 | 2 |
| 48 | **Quang Ngai** | 18.3 | 7.8 | 3.9 | 30.3% | 1313.2 | 5 | 2 |
| 49 | **Quang Ninh** | 43.8 | 9.2 | 7.0 | 24.3% | 2163.2 | 3 | 4 |
| 50 | **Quang Tri** | 10.3 | 8.4 | 1.9 | 15.2% | 1151.5 | 4 | 6 |
| 51 | **Soc Trang** | 20.9 | 7.8 | 4.5 | 30.6% | 1654.2 | 5 | 2 |
| 52 | **Son La** | 19.7 | 8.5 | 3.5 | 13.7% | 671.5 | 4 | 6 |
| 53 | **Tay Ninh** | 24.5 | 7.4 | 5.8 | 22.6% | 1928.2 | 1 | 5 |
| 54 | **Thai Binh** | 26.9 | 8.9 | 4.6 | 10.5% | 1818.1 | 3 | 4 |
| 55 | **Thai Nguyen** | 16.5 | 9.3 | 2.6 | 35.3% | 1606.2 | 3 | 4 |
| 56 | **Thanh Hoa** | 42.8 | 8.7 | 7.5 | 17.3% | 1365.3 | 3 | 4 |
| 57 | **Thua Thien Hue** | 16.5 | 8.3 | 3.2 | 48.9% | 1396.5 | 2 | 3 |
| 58 | **Tien Giang** | 28.6 | 7.6 | 6.4 | 15.5% | 1804.1 | 1 | 5 |
| 59 | **Tra Vinh** | 16.8 | 7.7 | 3.7 | 18.3% | 1299.2 | 5 | 2 |
| 60 | **Tuyen Quang** | 11.7 | 9.3 | 1.8 | 13.9% | 1024.3 | 4 | 6 |
| 61 | **Vinh Long** | 16.5 | 7.7 | 3.6 | 25.0% | 1398.8 | 5 | 2 |
| 62 | **Vinh Phuc** | 18.9 | 9.0 | 3.1 | 17.0% | 1675.0 | 3 | 4 |
| 63 | **Yen Bai** | 13.1 | 9.2 | 2.1 | 20.7% | 1037.0 | 4 | 6 |

**Table A5.** Market benefit changes according to different FIT strategies.

| ID | Province | FIT_2.0 (Euro cents/kWh) | Delta_1_1.0 (Euro cents/kWh) | Delta_1_2.0 (Euro cents/kWh) | Delta_1_2.1 (Euro cents/kWh) | Benefit_1.0 (10^6 Euro) | Benefit_2.0 (10^6 Euro) | Benefit_2.1 (10^6 Euro) |
|---|---|---|---|---|---|---|---|---|
| 1 | **An Giang** | 7.95 | 1.23 | 0.35 | 0.31 | 77.49 | 22.25 | 19.53 |
| 2 | **Ba Ria-Vung Tau** | 7.95 | 1.23 | 0.35 | 0.31 | 49.20 | 14.13 | 12.40 |
| 3 | **Bac Giang** | 10.32 | −0.17 | 1.32 | −1.09 | −5.27 | 40.90 | −33.79 |
| 4 | **Bac Kan** | 10.32 | −0.47 | 1.02 | −1.39 | −5.17 | 11.21 | −15.29 |
| 5 | **Bac Lieu** | 7.95 | 1.03 | 0.15 | 0.11 | 30.90 | 4.60 | 3.30 |
| 6 | **Bac Ninh** | 10.32 | −0.07 | 1.42 | −0.99 | −2.03 | 41.16 | −28.71 |
| 7 | **Ben Tre** | 7.95 | 1.13 | 0.25 | 0.21 | 59.89 | 13.42 | 11.13 |
| 8 | **Binh Dinh** | 7.95 | 1.13 | 0.25 | 0.21 | 57.63 | 12.91 | 10.71 |
| 9 | **Binh Duong** | 7.95 | 1.23 | 0.35 | 0.31 | 63.96 | 18.37 | 16.12 |
| 10 | **Binh Phuoc** | 7.95 | 1.33 | 0.45 | 0.41 | 85.12 | 29.01 | 26.24 |
| 11 | **Binh Thuan** | 7.48 | 1.53 | 0.18 | 0.61 | 70.38 | 8.47 | 28.06 |
| 12 | **Ca Mau** | 7.95 | 0.93 | 0.05 | 0.01 | 48.36 | 2.77 | 0.52 |
| 13 | **Can Tho** | 7.95 | 1.13 | 0.25 | 0.21 | 40.68 | 9.12 | 7.56 |
| 14 | **Cao Bang** | 10.32 | −0.37 | 1.12 | −1.29 | −6.29 | 19.03 | −21.93 |
| 15 | **Da Nang** | 8.88 | 0.83 | 0.88 | −0.09 | 23.24 | 24.61 | −2.52 |
| 16 | **Dak Lak** | 7.48 | 1.23 | −0.12 | 0.31 | 62.73 | −5.91 | 15.81 |
| 17 | **Dak Nong** | 7.95 | 1.33 | 0.45 | 0.41 | 22.61 | 7.70 | 6.97 |
| 18 | **Dien Bien** | 8.88 | 0.43 | 0.48 | −0.49 | 8.17 | 9.10 | −9.31 |
| 19 | **Dong Nai** | 7.95 | 1.23 | 0.35 | 0.31 | 121.77 | 34.97 | 30.69 |
| 20 | **Dong Thap** | 7.95 | 1.23 | 0.35 | 0.31 | 70.11 | 20.13 | 17.67 |
| 21 | **Gia Lai** | 7.48 | 1.23 | −0.12 | 0.31 | 52.89 | −4.98 | 13.33 |

**Table A5.** *Cont.*

| ID | Province | FIT_2.0 (Euro cents/kWh) | Delta_1_1.0 (Euro cents/kWh) | Delta_1_2.0 (Euro cents/kWh) | Delta_1_2.1 (Euro cents/kWh) | Benefit_1.0 (10^6 Euro) | Benefit_2.0 (10^6 Euro) | Benefit_2.1 (10^6 Euro) |
|---|---|---|---|---|---|---|---|---|
| 22 | **Ha Giang** | 10.32 | −0.47 | 1.02 | −1.39 | −9.40 | 20.38 | −27.80 |
| 23 | **Ha Nam** | 10.32 | −0.07 | 1.42 | −0.99 | −1.54 | 31.22 | −21.78 |
| 24 | **Ha Noi** | 10.32 | −0.07 | 1.42 | −0.99 | −10.92 | 221.40 | −154.44 |
| 25 | **Ha Tinh** | 10.32 | −0.07 | 1.42 | −0.99 | −3.22 | 65.29 | −45.54 |
| 26 | **Hai Duong** | 10.32 | −0.07 | 1.42 | −0.99 | −2.94 | 59.61 | −41.58 |
| 27 | **Hai Phong** | 10.32 | 0.03 | 1.52 | −0.89 | 1.02 | 51.65 | −30.26 |
| 28 | **Hau Giang** | 7.95 | 0.93 | 0.05 | 0.01 | 23.25 | 1.33 | 0.25 |
| 29 | **Ho Chi Minh City** | 7.95 | 1.23 | 0.35 | 0.31 | 305.04 | 87.60 | 76.88 |
| 30 | **Hoa Binh** | 10.32 | −0.07 | 1.42 | −0.99 | −1.19 | 24.13 | −16.83 |
| 31 | **Hung Yen** | 10.32 | −0.07 | 1.42 | −0.99 | −1.96 | 39.74 | −27.72 |
| 32 | **Khanh Hoa** | 7.48 | 1.23 | −0.12 | 0.31 | 46.74 | −4.40 | 11.78 |
| 33 | **Kien Giang** | 7.95 | 1.03 | 0.15 | 0.11 | 70.04 | 10.42 | 7.48 |
| 34 | **Kon Tum** | 7.95 | 1.13 | 0.25 | 0.21 | 18.08 | 4.05 | 3.36 |
| 35 | **Lai Chau** | 10.32 | 0.23 | 1.72 | −0.69 | 3.68 | 27.51 | −11.04 |
| 36 | **Lam Dong** | 7.95 | 1.33 | 0.45 | 0.41 | 51.87 | 17.68 | 15.99 |
| 37 | **Lang Son** | 10.32 | −0.27 | 1.22 | −1.19 | −6.21 | 28.04 | −27.37 |
| 38 | **Lao Cai** | 10.32 | −0.37 | 1.12 | −1.29 | −6.29 | 19.03 | −21.93 |
| 39 | **Long An** | 7.95 | 1.23 | 0.35 | 0.31 | 83.64 | 24.02 | 21.08 |
| 40 | **Nam Dinh** | 10.32 | 0.03 | 1.52 | −0.89 | 1.41 | 71.40 | −41.83 |
| 41 | **Nghe An** | 10.32 | 0.23 | 1.72 | −0.69 | 18.63 | 139.26 | −55.89 |
| 42 | **Ninh Binh** | 10.32 | −0.07 | 1.42 | −0.99 | −1.96 | 39.74 | −27.72 |

**Table A5.** *Cont.*

| ID | Province | FIT_2.0 (Euro cents/kWh) | Delta_1_1.0 (Euro cents/kWh) | Delta_1_2.0 (Euro cents/kWh) | Delta_1_2.1 (Euro cents/kWh) | Benefit_1.0 (10^6 Euro) | Benefit_2.0 (10^6 Euro) | Benefit_2.1 (10^6 Euro) |
|---|---|---|---|---|---|---|---|---|
| 43 | **Ninh Thuan** | 7.48 | 1.53 | 0.18 | 0.61 | 29.07 | 3.50 | 11.59 |
| 44 | **Phu Tho** | 10.32 | −0.27 | 1.22 | −1.19 | −7.83 | 35.36 | −34.51 |
| 45 | **Phu Yen** | 7.48 | 1.13 | −0.22 | 0.21 | 33.90 | −6.48 | 6.30 |
| 46 | **Quang Binh** | 10.32 | 0.13 | 1.62 | −0.79 | 3.90 | 48.58 | −23.70 |
| 47 | **Quang Nam** | 8.88 | 0.83 | 0.88 | −0.09 | 43.99 | 46.58 | −4.77 |
| 48 | **Quang Ngai** | 8.88 | 1.03 | 1.08 | 0.11 | 40.17 | 42.08 | 4.29 |
| 49 | **Quang Ninh** | 10.32 | −0.37 | 1.12 | −1.29 | −25.90 | 78.35 | −90.30 |
| 50 | **Quang Tri** | 8.88 | 0.43 | 0.48 | −0.49 | 8.17 | 9.10 | −9.31 |
| 51 | **Soc Trang** | 7.95 | 1.03 | 0.15 | 0.11 | 46.35 | 6.89 | 4.95 |
| 52 | **Son La** | 10.32 | 0.33 | 1.82 | −0.59 | 11.55 | 63.67 | −20.65 |
| 53 | **Tay Ninh** | 7.95 | 1.43 | 0.55 | 0.51 | 82.94 | 32.09 | 29.58 |
| 54 | **Thai Binh** | 10.32 | −0.07 | 1.42 | −0.99 | −3.22 | 65.29 | −45.54 |
| 55 | **Thai Nguyen** | 10.32 | −0.47 | 1.02 | −1.39 | −12.22 | 26.50 | −36.14 |
| 56 | **Thanh Hoa** | 10.32 | 0.13 | 1.62 | −0.79 | 9.75 | 121.44 | −59.25 |
| 57 | **Thua Thien Hue** | 8.88 | 0.53 | 0.58 | −0.39 | 16.96 | 18.52 | −12.48 |
| 58 | **Tien Giang** | 7.95 | 1.23 | 0.35 | 0.31 | 78.72 | 22.61 | 19.84 |
| 59 | **Tra Vinh** | 7.95 | 1.13 | 0.25 | 0.21 | 41.81 | 9.37 | 7.77 |
| 60 | **Tuyen Quang** | 10.32 | −0.47 | 1.02 | −1.39 | −8.46 | 18.35 | −25.02 |
| 61 | **Vinh Long** | 7.95 | 1.13 | 0.25 | 0.21 | 40.68 | 9.12 | 7.56 |
| 62 | **Vinh Phuc** | 10.32 | −0.17 | 1.32 | −1.09 | −5.27 | 40.90 | −33.79 |
| 63 | **Yen Bai** | 10.32 | −0.37 | 1.12 | −1.29 | −7.77 | 23.50 | −27.09 |

Note: FIT 1.0 = 8.83 Euro cents/kWh & FIT 2.1 = 7.91 (Euro cents/kWh) are applied for all regions.

**Table A6.** Market benefit changes according to different grid tariff strategies.

| ID | Province | Delta_2_2019 (Euro cents/kWh) | Delta_2_2025 (Euro cents/kWh) | Benefit_2019 (10ˆ6 Euro) | Benefit_2025 (10ˆ6 Euro) |
|---|---|---|---|---|---|
| 1 | **An Giang** | −0.40 | 1.10 | −25.20 | 69.30 |
| 2 | **Ba Ria−Vung Tau** | −0.40 | 1.10 | −16.00 | 44.00 |
| 3 | **Bac Giang** | −1.80 | −0.30 | −55.80 | −9.30 |
| 4 | **Bac Kan** | −2.10 | −0.60 | −23.10 | −6.60 |
| 5 | **Bac Lieu** | −0.60 | 0.90 | −18.00 | 27.00 |
| 6 | **Bac Ninh** | −1.70 | −0.20 | −49.30 | −5.80 |
| 7 | **Ben Tre** | −0.50 | 1.00 | −26.50 | 53.00 |
| 8 | **Binh Dinh** | −0.50 | 1.00 | −25.50 | 51.00 |
| 9 | **Binh Duong** | −0.40 | 1.10 | −20.80 | 57.20 |
| 10 | **Binh Phuoc** | −0.30 | 1.20 | −19.20 | 76.80 |
| 11 | **Binh Thuan** | −0.10 | 1.40 | −4.60 | 64.40 |
| 12 | **Ca Mau** | −0.70 | 0.80 | −36.40 | 41.60 |
| 13 | **Can Tho** | −0.50 | 1.00 | −18.00 | 36.00 |
| 14 | **Cao Bang** | −2.00 | −0.50 | −34.00 | −8.50 |
| 15 | **Da Nang** | −0.80 | 0.70 | −22.40 | 19.60 |
| 16 | **Dak Lak** | −0.40 | 1.10 | −20.40 | 56.10 |
| 17 | **Dak Nong** | −0.30 | 1.20 | −5.10 | 20.40 |
| 18 | **Dien Bien** | −1.20 | 0.30 | −22.80 | 5.70 |
| 19 | **Dong Nai** | −0.40 | 1.10 | −39.60 | 108.90 |
| 20 | **Dong Thap** | −0.40 | 1.10 | −22.80 | 62.70 |
| 21 | **Gia Lai** | −0.40 | 1.10 | −17.20 | 47.30 |

**Table A6.** *Cont.*

| ID | Province | Delta_2_2019 (Euro cents/kWh) | Delta_2_2025 (Euro cents/kWh) | Benefit_2019 (10ˆ6 Euro) | Benefit_2025 (10ˆ6 Euro) |
|---|---|---|---|---|---|
| 22 | **Ha Giang** | −2.10 | −0.60 | −42.00 | −12.00 |
| 23 | **Ha Nam** | −1.70 | −0.20 | −37.40 | −4.40 |
| 24 | **Ha Noi** | -1.70 | -0.20 | -265.20 | -31.20 |
| 25 | **Ha Tinh** | -1.70 | -0.20 | -78.20 | -9.20 |
| 26 | **Hai Duong** | -1.70 | -0.20 | -71.40 | -8.40 |
| 27 | **Hai Phong** | -1.60 | -0.10 | -54.40 | -3.40 |
| 28 | **Hau Giang** | -0.70 | 0.80 | -17.50 | 20.00 |
| 29 | **Ho Chi Minh City** | -0.40 | 1.10 | -99.20 | 272.80 |
| 30 | **Hoa Binh** | -1.70 | -0.20 | -28.90 | -3.40 |
| 31 | **Hung Yen** | -1.70 | -0.20 | -47.60 | -5.60 |
| 32 | **Khanh Hoa** | −0.40 | 1.10 | −15.20 | 41.80 |
| 33 | **Kien Giang** | −0.60 | 0.90 | −40.80 | 61.20 |
| 34 | **Kon Tum** | −0.50 | 1.00 | −8.00 | 16.00 |
| 35 | **Lai Chau** | −1.40 | 0.10 | −22.40 | 1.60 |
| 36 | **Lam Dong** | −0.30 | 1.20 | −11.70 | 46.80 |
| 37 | **Lang Son** | −1.90 | −0.40 | −43.70 | −9.20 |
| 38 | **Lao Cai** | −2.00 | −0.50 | −34.00 | −8.50 |
| 39 | **Long An** | −0.40 | 1.10 | −27.20 | 74.80 |
| 40 | **Nam Dinh** | −1.60 | −0.10 | −75.20 | −4.70 |
| 41 | **Nghe An** | −1.40 | 0.10 | −113.40 | 8.10 |
| 42 | **Ninh Binh** | −1.70 | −0.20 | −47.60 | −5.60 |

**Table A6.** *Cont.*

| ID | Province | Delta_2_2019 (Euro cents/kWh) | Delta_2_2025 (Euro cents/kWh) | Benefit_2019 (10ˆ6 Euro) | Benefit_2025 (10ˆ6 Euro) |
|---|---|---|---|---|---|
| 43 | **Ninh Thuan** | −0.10 | 1.40 | −1.90 | 26.60 |
| 44 | **Phu Tho** | −1.90 | −0.40 | −55.10 | −11.60 |
| 45 | **Phu Yen** | −0.50 | 1.00 | −15.00 | 30.00 |
| 46 | **Quang Binh** | −1.50 | 0.00 | −45.00 | 0.00 |
| 47 | **Quang Nam** | −0.80 | 0.70 | −42.40 | 37.10 |
| 48 | **Quang Ngai** | −0.60 | 0.90 | −23.40 | 35.10 |
| 49 | **Quang Ninh** | −2.00 | −0.50 | −140.00 | −35.00 |
| 50 | **Quang Tri** | −1.20 | 0.30 | −22.80 | 5.70 |
| 51 | **Soc Trang** | −0.60 | 0.90 | −27.00 | 40.50 |
| 52 | **Son La** | −1.30 | 0.20 | −45.50 | 7.00 |
| 53 | **Tay Ninh** | −0.20 | 1.30 | −11.60 | 75.40 |
| 54 | **Thai Binh** | −1.70 | −0.20 | −78.20 | −9.20 |
| 55 | **Thai Nguyen** | −2.10 | −0.60 | −54.60 | −15.60 |
| 56 | **Thanh Hoa** | −1.50 | 0.00 | −112.50 | 0.00 |
| 57 | **Thua Thien Hue** | −1.10 | 0.40 | −35.20 | 12.80 |
| 58 | **Tien Giang** | −0.40 | 1.10 | −25.60 | 70.40 |
| 59 | **Tra Vinh** | −0.50 | 1.00 | −18.50 | 37.00 |
| 60 | **Tuyen Quang** | −2.10 | −0.60 | −37.80 | −10.80 |
| 61 | **Vinh Long** | −0.50 | 1.00 | −18.00 | 36.00 |
| 62 | **Vinh Phuc** | −1.80 | −0.30 | −55.80 | −9.30 |
| 63 | **Yen Bai** | −2.00 | −0.50 | −42.00 | −10.50 |

Note: Grid tariff in 2019 = 7.2 Euro cents/kWh & Grid tariff in 2025 = 8.7 (Euro cents/kWh) are applied for all regions.

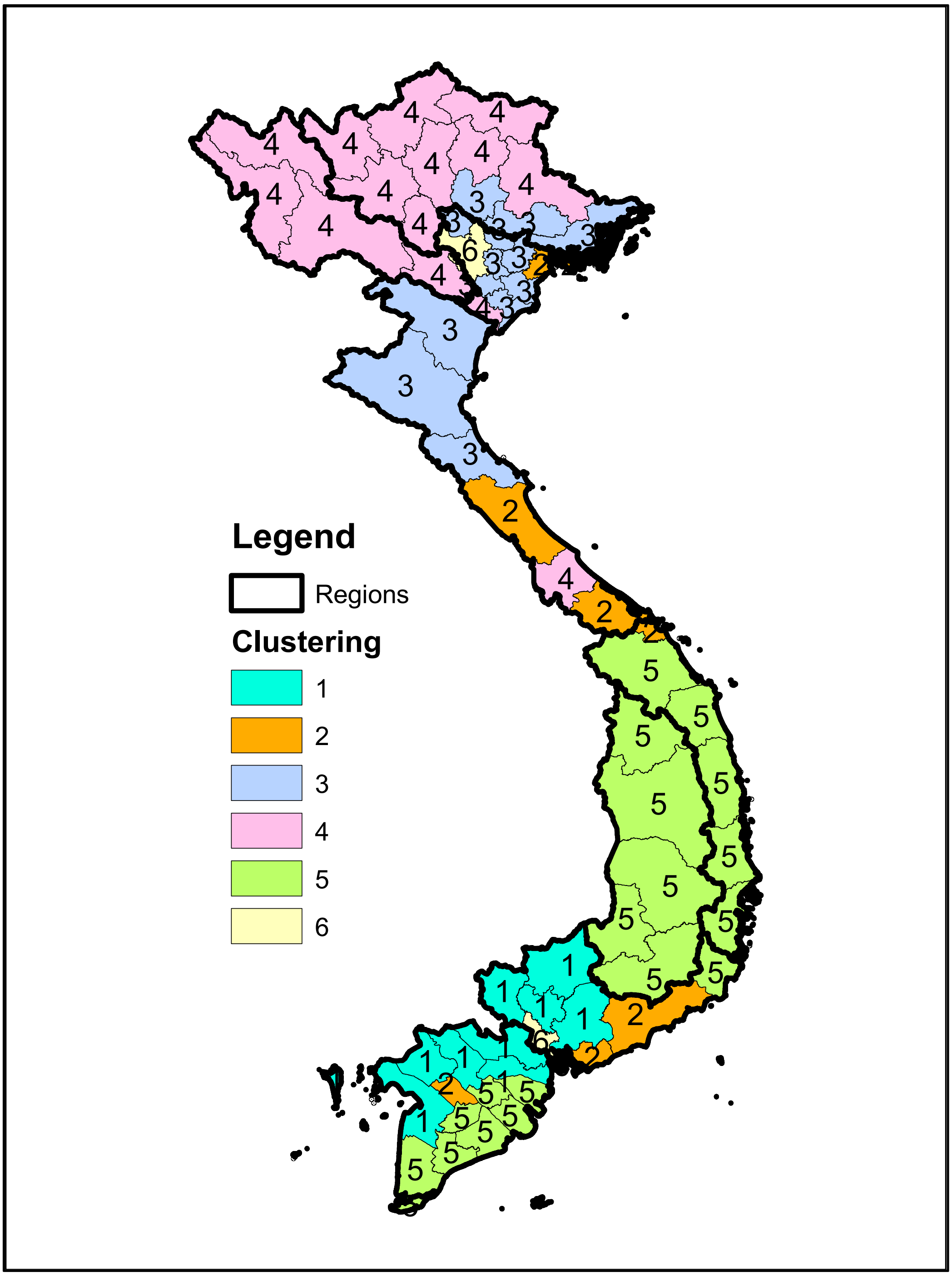
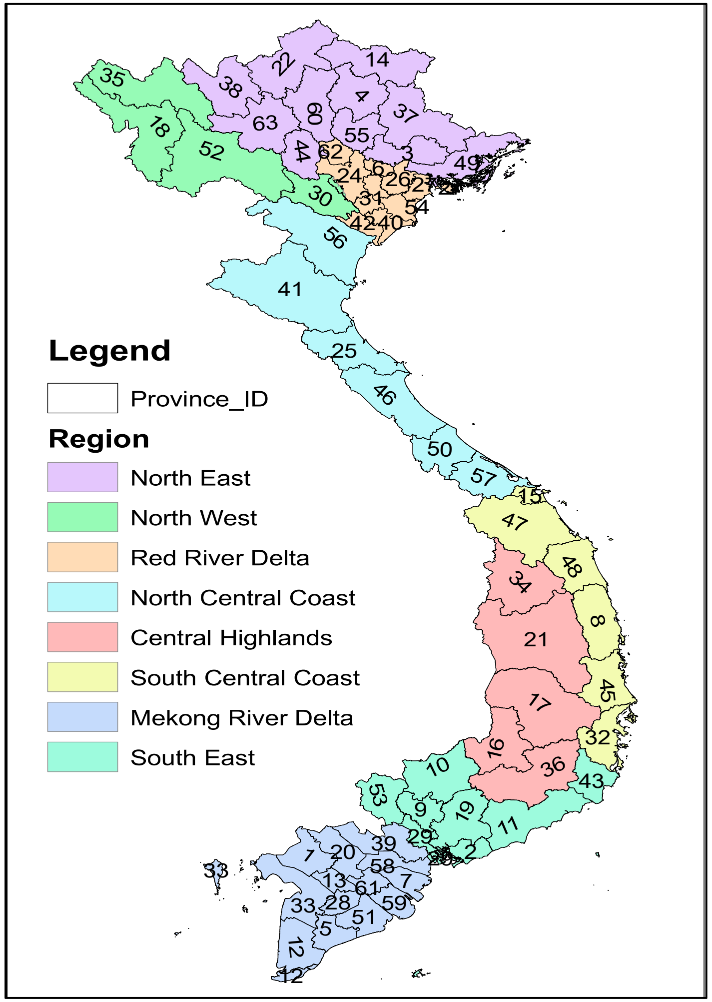



**Figure A1.** The clustering distribution on map.




| ID | Province | ID | Province | ID | Province |
|---|---|---|---|---|---|
| 1 | An Giang | 22 | Ha Giang | 43 | Ninh Thuan |
| 2 | Ba Ria–Vung Tau | 23 | Ha Nam | 44 | Phu Tho |
| 3 | Bac Giang | 24 | Ha Noi | 45 | Phu Yen |
| 4 | Bac Kan | 25 | Ha Tinh | 46 | Quang Binh |
| 5 | Bac Lieu | 26 | Hai Duong | 47 | Quang Nam |
| 6 | Bac Ninh | 27 | Hai Phong | 48 | Quang Ngai |
| 7 | Ben Tre | 28 | Hau Giang | 49 | Quang Ninh |
| 8 | Binh Dinh | 29 | Ho Chi Minh City | 50 | Quang Tri |
| 9 | Binh Duong | 30 | Hoa Binh | 51 | Soc Trang |
| 10 | Binh Phuoc | 31 | Hung Yen | 52 | Son La |
| 11 | Binh Thuan | 32 | Khanh Hoa | 53 | Tay Ninh |
| 12 | Ca Mau | 33 | Kien Giang | 54 | Thai Binh |
| 13 | Can Tho | 34 | Kon Tum | 55 | Thai Nguyen |
| 14 | Cao Bang | 35 | Lai Chau | 56 | Thanh Hoa |
| 15 | Da Nang | 36 | Lam Dong | 57 | Thua Thien Hue |
| 16 | Dak Lak | 37 | Lang Son | 58 | Tien Giang |
| 17 | Dak Nong | 38 | Lao Cai | 59 | Tra Vinh |
| 18 | Dien Bien | 39 | Long An | 60 | Tuyen Quang |
| 19 | Dong Nai | 40 | Nam Dinh | 61 | Vinh Long |
| 20 | Dong Thap | 41 | Nghe An | 62 | Vinh Phuc |
| 21 | Gia Lai | 42 | Ninh Binh | 63 | Yen Bai |

**Figure A2.** Administration map of Vietnam: Regions and Name & ID of Provinces.

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# Willingness to pay for residential PV: reconciling gaps between acceptance and adoption

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# Willingness to pay for residential PV: reconciling gaps between acceptance and adoption

*Phuong M. Khuong, IIP, KIT, Fabian Scheller, DTU, Russell McKenna, DTU, Dogan Keles, DTU, and Wolf Fichtner, IIP, KIT*

Photovoltaic (PV) has recorded an impressive development in the last years. The increasing economic potential and further technological improvement will continue to reduce the cost of PV. However, it is not yet well adopted by household customers. Adversely, there is lacking empirical evidence for understanding residential PV adoption behaviour, which this study addresses with empirical research. Although a variety of models can be used to explain social acceptance (SA) and willingness to pay (WTP) for renewable energy, they overlook the connection between SA and WTP in the final purchase decision of a decision-maker. Based on a survey of both SA and WTP in the same observation sample of 2039 Vietnamese residents, this study introduces well-established models with a new linking psychological and economic aspects to measure multiple outcomes involving residential PV behaviours to testing hypotheses with no precedent in the literature. The theoretical and integrative moderated mediation models help to understand residential PV behaviour and suggest solutions for development by revealing how different factors affect SA and WTP in different manners. Environmental interest reveals the predictive power within the SA and WTP behaviour models. Meanwhile, PV knowledge drives SA, but not WTP in Vietnam. Attitude and Perceived behavioural control not only impact SA and WTP directly but also mediate the effect of Environmental interest and SA and WTP. Age & Marital status & Children and Place of residence are important covariates that drive in the SA and WTP models, respectively. Lastly, Income is the covariate in the SA model, but the moderator in the WTP model. In practical implications, this study provides evidence that residential PV is a lifestyle product rather than an economical product, but it is not considered as an essential good for household customers. Thereby, suggestions are given to policymakers and stakeholders to promote market development.

## 1 INTRODUCTION

From 2011 till now, reports show strong growth of solar PV, with the power sector leading the way (IEA, 2019). New technological advances over the last twenty years have driven this increased reliance on solar by decreasing costs, and new technological developments promise to augment this solar usage by further decreasing costs and increasing solar panel efficiency (Aramesh et al., 2019). Currently, emerging countries such as China, India, and Brazil have been world leaders in renewable energy use, especially solar. However, residential solar uptake has been struggling in many other Asian developing countries for the last few years (Burke et al., 2019; IEA, 2019).

One of the most mentioned barriers is the lack of information dissemination and consumer awareness about technology (Seetharaman et al., 2019). Additionally, the existing problem in communication and intervention levels to accelerate solar uptake under limited resource conditions in the developing countries has not been resolved after significant effort made in research (Rai et al., 2016; Barroco and Herrera, 2019).

The main issue lies in the most applied approaches to investigate the topic. Most studies in residential solar focus on top-down and technically-orientated analyses using economic models (Rao and Kishore, 2010) and techno-economic assessments (Burke et al., 2019) to determine the domestic and international political effect (Shidore and Busby, 2019), infrastructure and local roles (Geall et al., 2018) as well as prioritising targets (Behuria, 2020). Economic models study price-responses based on revealed preference data, e.g., historical and demographic data. However, they have proven to be incomplete and to have restricted explanatory power without supplementation of psychological and sociological models, especially for studying the new-born markets for residential PV (Liebe et al., 2011). Residential PV promotion can not only be addressed by a purely top-down study, but a bottom-up study is required with a focus on the social aspects because the adoption decision is made based on psychological profiles — personality, values, opinions, attitudes, interests, and lifestyles.

Literature shows that Social Acceptance (SA) and Willingness To Pay (WTP) are equally, if not more important than technological advances for the successful adoption of residential solar (Dunphy and Herbig, 1995; Schumacher et al., 2019; Klaus et al., 2020). However, in the few socially-designed studies on this topic, the majority have been conducted in developed countries (Wolsink, 2018), where the issue of high up-front investment is less relevant than in developing countries (Waseem and Hammad, 2015; Alsabbagh, 2019). That makes the findings hardly applicable to developing countries due to the different ethically-minded consumer behaviours (Sudbury-Riley and Kohlbacher, 2016). Nevertheless, the knowledge gap related to the social aspects of residential solar PV in developing countries needs to be filled (Sommerfeld et al., 2017; Alsabbagh, 2019) to boost the residential PV technology uptake in these countries.

Nonetheless, the complex interplay of the various factors that influence SA and WTP, along with the dynamic nature of SA and WTP makes defining and measuring them a difficult task. Firstly, direct or indirect methods could evoke the hypothetical bias, and extant evidence is mixed (e.g. Miller et al. 2011). Secondly, among the socio-economic researches on renewable energy, the confused interpretation of SA and WTP is often addressed (Wolsink, 2018). SA speculates public responses to political and social changes, e.g. towards the penetration of renewable energy, while WTP estimates public reaction in the real market (Wolsink, 2018). The confusion leads to an existing issue of misconstructed support policy. Thirdly, throughout the prior work, although some business models already exist, hardly any econometric model exposes the determinants of SA and WTP and the correlation between them (Rai et al., 2016). Without a clear definition and measurement of SA and WTP, policymakers cannot be expected to create sufficient and transferable policies to conform to these concepts.

Focusing on end-user decision-making in developing countries, a case study on Vietnam is conducted, which investigates the SA and WTP towards the residential PV technology and their influencing factors in order to provide suggestions to overcome the social resistance of adoption. This paper integrates theoretical ideas from the social psychology of The Theory of Planned Behaviour (TPB) and from the market response of Choice-Based Conjoint (CBC), which are designed to reveal the self-interest of a respondent. The psychological TPB measures SA provides a relatively complex explanation of the informational and motivational influences of the psychological driving factors (Attitude, social pressure, risk control) in the execution of a particular behaviour of SA, especially in the field of environmental science (Klöckner, 2013; Si et al., 2019). The CBC, measuring the WTP, is used to determine how people value different attributes (feature, function, benefits) that make up an individual product or service (Ratcliffe, 2000). Combining both questions of SA and WTP for residential PV in one survey allows us to extend our analysis beyond literature with tracking the gap between a person's perception toward the product and reaction in the store.

In this manner, the main contributions of this paper are:

- Discover the econometric models explaining the relationship between impact factors of SA and WTP, SA and WTP.
- Identify and compare drivers, mediators and moderators of the two concepts and then to combine them to support each other in order to provide robust policies.
- Identify the gap between a person's perception of the product and his/her behaviour in the marketplace.

The remainder of this paper is organised as follows: Section 2 presents the literature review of the related research topic, as well as identify gaps concerning communication in general and residential PV in particular. We discuss the questionnaire styles, hypotheses based on the well-known factors driving residential customers adopting residential solar and propose our methodology in Section 3. The results and findings of the driving factors of the SA and WTP are presented in section 4. The discussions and policy implication are provided in section 5. Conclusion and outlook are summarised in section 6.

## 2 LITERATURE REVIEW

Residential PV is crucial to lowering the environmental impact of the residential sector (Shahsavari and Akbari, 2018). However, the broad implementation and extensive use require customer adoption (Yaqoot et al., 2016). Therefore, it is necessary to investigate customer behaviour towards this technology to understand the process of interesting, accepting, selecting and purchasing such a product (Sovacool, 2014). Policymakers need to explore public opinion toward this product to create a sustainable development plan for residential PV adoption (Richard, 2016; Bhowmik et al., 2017). Yet, although the research field is growing, its merits for understanding and predicting individual adoption of residential PV can only hardly unfold (Geels et al., 2018). There is only a few empirical research in the energy field, i.e., 2.2%, dedicated to understanding end-user behaviour (Sovacool, 2014). Far too little attention has been paid to specific behaviours related to residential PV SA and WTP (Si et al., 2019).

Even though customers' awareness and acceptance are often considered as one of the biggest barriers in technology spread (Barroco and Herrera, 2019), it only gets attention in behaviour research recently (Table 1). Most of the research has focused on customer's preferences and WTP toward residential PV (Column 3, Table 1) with the favourite CBC method used (Column 4, Table 1) for developed countries (Column 5, Table 1).

*Table 1. Summary of social research on residential PV from 2010 to 2019*

| Source | **Objective** | **Object** | **Subject** | **Direct/ Indirect survey** | **Sample size** | **Region** | **Correlation model** |
|---|---|---|---|---|---|---|---|
| (Alsabbagh, 2019) | Public perception & policy suggestion | Random | SA & WTP | D/ TPB | 764 valid | Bahrain | - |
| (Hille et al., 2018) | Drivers for PV adoption | PV owners | Preference & WTP | I/ ACBC | 6104 representative sample; 408 valid | Switzerland | - |
| (Sommerfeld et al., 2017) | Public perception | PV owners | SA | D | 22 valid | Queensland, Australia | - |
| (Wolske et al., 2017) | Interest in residential PV panels | Non- adopter homeowners | SA | D/ DOI, TPB, and VBN | 904 valid | US | Direct impact |
| (Korcaj et al., 2015) | Intention to adopt PV system | Homeowners | WTP | TPB | 200 valid | Germany | Direct impact |
| (Ida et al., 2014) | Greenhouse gas emissions reduction | Random | Preferences & WTP | I/ CBC | 8997 valid; 649 from high- and 694 from low-interest | Japan | - |
| (Islam and Meade, 2013) | Technology attributes & adoption time | Random | Preferences & adoption time | I/ CBC | 298 valid | Ontario, Canada | - |
| (Wissink et al., 2013) | PV impact on home purchasing | Dwelling buyers | Preferences & WTP | I/ CBC | 227 valid | Netherlands, Eindhoven | - |
| (Chen et al., 2013) | Market analysis | PV owners | Preferences | I/ ML | 22 valid | California, USA | - |
| (Scarpa and Willis, 2010) | Policy suggestion | Random | WTP | I/ CBC | 1241 valid | UK | - |

*Acronyms: "-": not implied, "x": implied, DOI: Diffusion of Innovations theory, TPB: Theory of Planned Behaviour, VBN: Value-Belief-Norm theory, ACBC: Adaptive Choice-Based Conjoint, CBC: Choice-Based Conjoint, ML: Machine Learning*

Apart from the lack of empirical research on residential PV in developing countries, we noticed two other main research problematics, including the importance of considering both SA and WTP, and the possibility of different factors interaction impact on SA and WTP, which will be discussed in turn in Section 2.1 and Section 2.2.

### 2.1 **The importance of considering both SA and WTP**

SA research focuses on understanding the complex, multi-level and polycentric process of transforming social-technological systems, while WTP estimation presents a proxy attitude and focuses at the public trade-off point. Literature confuses these two definitions, such as claims WTP as a reflection of SA. The confusion needs to be uncovered (Wolsink, 2018). ***SA*** is a multi-dimensional conceptual model, which covers the social responsibility in government and law; informs business and policy through social and commercial marketing. Whereas WTP studies are of limited value for evaluating social acceptance, the method can reflect ***market acceptance*** in real-life decisions with individual cost-benefit assessments (Wüstenhagen et al., 2007). Because WTP does not reflect any acceptance process, such as the recognition of consumers or the engagement of citizens in the process of establishing renewable energy infrastructure, the combination view of social and market acceptance is a proper approach to understand comprehensively residential PV behaviour. Comparing SA and WTP forms the distinguish contrast aspects of acceptance involving different actors and emphasises upon each dimension inter-relates across different segments.

As outlined in *Figure 1*, SA and WTP are the two stages of adoption when measuring customer behaviour towards a specific technology. While economists rely on the concept of preferences in order to determine what people value and identify the WTP, psychologists and sociologists have a strong affinity to the attitude concept and determine the SA. The main difference between the two concepts is that preferences pertain two choices between alternatives, whereas attitudes focus on "the desirability of a single action or object" (Liebe et al., 2011).

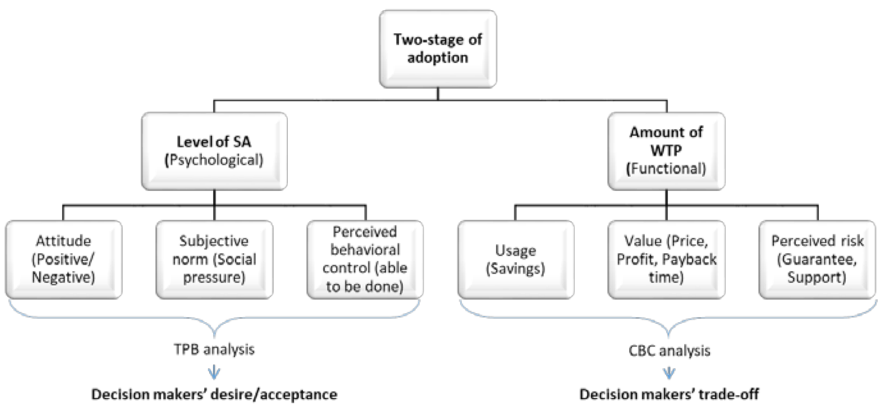



*Figure 1. Two-stage of adoption behaviour (Ram and Sheth, 1989; Ajzen, 1991)*

SA is a personal intention towards technology, and various factors influence it. This was a necessary amendment once behaviour was being measured, as a consumer may have a very favourable attitude towards a product, but not towards the act of purchasing it (Solomon, 2006). However, if a person buys the product but does not accept it, it is unlikely that full adoption will occur. There are other stages beyond simple WTP, and this is where acceptance plays an important role. In this paper, we focus on finding the factors influencing progression through different approaches. Therefore, a common consideration of planned behaviour analysis (Theory of Planned Behaviour, TPB) and conjoint analysis (Choice-Based Conjoint, CBC) are necessary.

### 2.2 **Possibility of different factors interaction affecting SA and WTP**

Eco-friendly behaviour results from multiple motivations (Chandel et al., 2016; Yadav and Pathak, 2017). In the context of residential PV behaviour, consumers may apply some additional environmental criteria in the decision-making process (Michelsen and Madlener, 2016; Bashiri and Alizadeh, 2018) to find a practical trade-off between environmental concern and traditional criteria, such as price, quality, availability, etc. Meanwhile, consumers also need information gathering and relevant knowledge to assist them to make a choice, which is consistent with traditional decision-making, where consumers are confident in choosing the cheapest product (Michelsen and Madlener, 2016; Bashiri and Alizadeh, 2018).

Existing empirical studies on environmental behaviour generally extend two to five other variables into behaviour models to explain behaviour. The extension factors are some of the commonly used latent variables, especially Environmental interest (e.g. environmental concern, environmental awareness) and Knowledge (e.g. environmental knowledge, and environmental education). Table 2 shows the results of various scholars integrated concepts of Environmental interest and Knowledge from different theoretical frameworks. Scholars have proven that product knowledge is one of a leading factor in people's intention towards green consumption (Chen and Deng, 2016; Choi and Johnson, 2019). The same has been shown for energy-efficient and energy-saving behaviour (Tan et al., 2017; Li et al., 2019), and on renewable energy consumption (Bang et al., 2000). Therefore, in this study, these two variables are considered in order to discover the impact factors on SA and WTP.

Although research on consumer behaviour considers a wide range of factors influencing consumers and acknowledges a broad range of consumption activities beyond purchasing (Wüstenhagen et al., 2007; Chandel et al., 2016), previous research in the residential PV and relating topics focuses mostly on explaining the relation between two specific variables (Table 2). However, in psychological research, the role of the three variables is vital (Chmura Kraemer et al., 2008; Mackinnon, 2011; Bolin, 2014). X may cause the third variable M and M may cause Y; both X and M may cause Y, and the relation between X and Y may differ for each value of M, along with others. M can play the role of mediation or moderation, which researchers need to discover in their study.

*Table 2. An overview of different behavioural models explaining renewable energy behaviour*

| Topic | Ref | Relation | Y | Determinant factors | | | Demographic factors | | | | | | | Extended factors | | Method | Country |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Att | SN | PBC | F | Age | In | MS | HHS | EB | EL | K | EI | | |
| Residential PV system | (Wolske et al., 2017) | X→Y | SA | + | + | + | - | - | - | | - | + | + | | + | TPB | US |
| | (Korcaj et al., 2015) | X→Y | WTP | + | + | + | | | | | | | | | + | TPB | Germany |
| Energy-Efficient Appliances | (Li et al., 2019) | X→M→Y | WTP | + | + | + | | | | | | | | + | + | TPB | China |
| Green electricity | (Litvine and Wüstenhagen, 2011) | X→Y | SA | + | - | + | | | | | | | | | | TPB | Switzerland |
| | | | WTP | + | ~ | + | | | | | | | | | | | |
| | (Borchers et al., 2007) | X→Y | WTP | | | | - | - | + | | | ~ | | | | Re | US |
| Renewable energy | (Sardianou and Genoudi, 2013) | X→Y | WTP | | | | + | + | + | + | | + | + | | | Re | Greece |
| | (Bang et al., 2000) | X→Y | WTP | + | | | | | | | | | | + | + | TRA | US |
| Energy choices | (Spence et al., 2010) | X→Y | SA | | | | | | | | | | | | + | Re | UK |
| Sustainable innovations | (Noppers et al., 2014) | X→Y | WTP | | | | | | | | | | | | + | | Netherlands |
| Green products | (Choi and Johnson, 2019) | X→Y | WTP | + | + | ~ | | | | | | | | + | ~ | TPB | UK |
| | (Yadav and Pathak, 2017) | X→Y | WTP | + | + | + | | | | | | | | | | TPB | India |
| | (Maichum et al., 2016) | X→M→Y | WTP | +* | +* | +* | | | | | | | | + | + | TPB | Thai |
| | (Chen and Deng, 2016) | X→M→Y | WTP | + | + | + | | | | | | | | +* | | TPB | China |

*Note:*
*Factors: Att: Attitude, SN: Subjective norm, PBC: Perceived behavioural control, F: Female, In: Income, MS: Marital status, HHS: Household size, EB: Electricity bill, EL: Education level, K: Related knowledge, EI: Envirolmental Interest.*
*Method: Re: Regression, TRA: Theory of reasoned action*
*Symbol: *: moderators, +: positive effect, -: negative effect, ~: insignificant effect, Blank: The factor has not been analysed in the study.*

Many different approaches have been adopted in the study of consumer decision making, but the residential PV topic has not been intensively studied. Consumer behaviour models in this field are not sufficient enough to aid in understanding different behavioural conditions toward residential PV. In this study, we have to refer to several social-psychological theories and empirical research in similar topics, e.g. green electricity, renewable energy, green purchase to build our theoretical model.

However, this research will not focus on explaining the relationship between only two variables, but try to answer the sequence X → M → Y, with M can be a moderator or a mediator. We solve the problem of the unclear role of the impact variables on SA and WTP by answering the question of which variables should be considered as a target, moderator, mediator, and covariate variables. Thereby, three main questions (1) what is it motivates people to accept residential PV and purchase it, (2) how the motives interact and (3) how the interaction changes individual orientation for solar PV adoption will also be answered.

The hypothetical method proceeds by formulating a hypothesis in a form that can be falsifiable, using a test on observable data where the outcome is not yet known. It is used to research customer behaviour during the product development process, especially in the new-born market. We use the two widely used methods to measure SA and WTP, which is the Theory of Planned Behaviour (TPB) uses direct questions to discover people's perception of a product (Ajzen, 1991), and Choice-Based Conjoint analysis (CBC) uses indirect surveys (Schmidt and Bijmolt, 2019). Aware of these methods could evoke the hypothetical bias, and therefore extant evidence is mixed, we conducted factor analyses to check the possibility of common method bias.

## 3 METHODOLOGY

There are many influences on purchasing behaviour, including social, technological, political, economic, and personal factors. Taking into account the gaps indicated in Section 2, this section presents our theoretical framework model and its components in Section 3.1. Section 3.2 proposes the statistical methods used for the analysis of the data. Section 3.3 and 3.4 are devoted to revealing the design and process used to conduct this research, respectively.

### 3.1 Framework model and main contributions

Relevant hypotheses, ignored by other studies, are developed, and then, a framework model is set up (Figure 2). The framework acts as the basic baseline for this study. Three main groups of variables that are claimed to impact the final SA and WTP are the determinant factors (Attitude, Subjective norm and Perceived behavioural control), socio-demographic variables (e.g. Gender, Age, Income, Level of education, etc.), and extended factors (PV knowledge and Environmental interest). The main critical content is to choose our hypotheses of which variables is considered as the target, covariate, moderator and mediator variables effect on SA and WTP.

In order to identify the role for each variable, we use the idea of cognitivism that an individual is viewed as an 'information processor' making a decision based on intrapersonal causation (Ajzen, 1991). The recognised problem will be the target variable, which indicates the origin of the demand for residential PV. The information search, alternative evaluation, and choices will be considered as mediator or moderator factors. The outcome evaluations are SA and WTP. Based on this theory, we propose 6 hypotheses from H1 to H6. Detailed hypothesis' foundation can be found in Appendix B.

- *H1: Environmental interest and/or PV knowledge is the target variable impact SA and WTP.*
- *H2: SA and WTP towards residential PV are positively related to Attitude, Subjective norm and Perceived behavioural control.*
- *H3: Attitude, Subjective norm and Perceived behavioural control mediate the relationship between the target variable and SA and WTP.*
- *H4: Any demographic factor causes SA and WTP is the determinant of SA and WTP.*
- *H5: Any demographic factor divides the population into different groups is the covariate factors.*
- *H6: Demographic factors moderate the indirect relationship between the target variable and SA and WTP.*

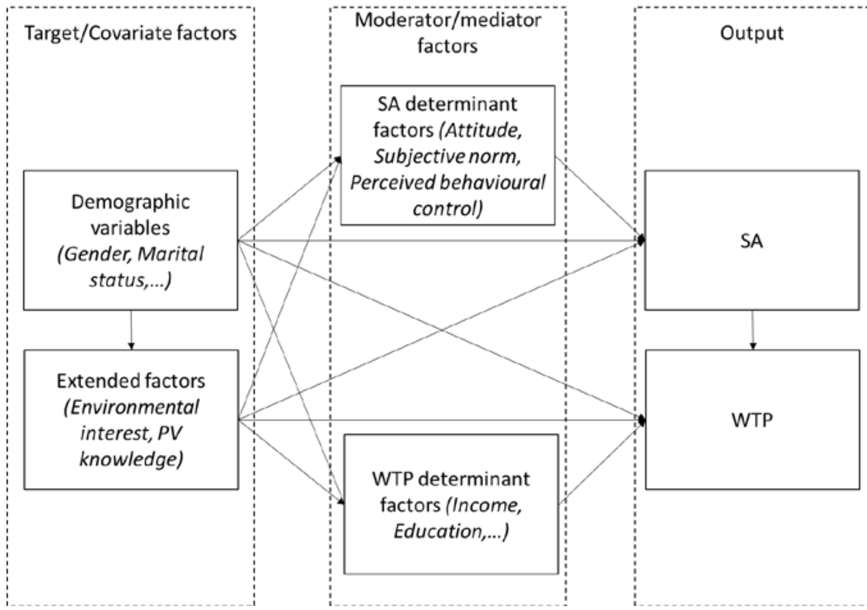



*Figure 2. Model construction of the influencing factors of residents' acceptance toward rooftop PV.*

### 3.2 **Moderated mediation model**

In this paper, we also use the Theory of Planned Behaviour (TPB) and Choice-Based Conjoint (CBC) analyses to study SA and WTP for residential PV (Appendix C). Different from previous studies (Sardianou and Genoudi, 2013; López-Mosquera et al., 2014; Bashiri and Alizadeh, 2018), the decision of the participant is not a binary choice, but the probability of buying the product. The relation between different groups of variables with SA and WTP is analysed based on Spearman's rank correlation (for skewed variables), and simulation analyses with detailed methods are indicated in Appendix D.

An examination of the raw data carried out before data analysis revealed to ensure that data of all participants were included, multiple imputations were used to estimate values for the missing data. For all variables, mean ± standard deviations and medians with ranges were used. The statistical significance level for all the tests was set at a P-value of below 0.05.

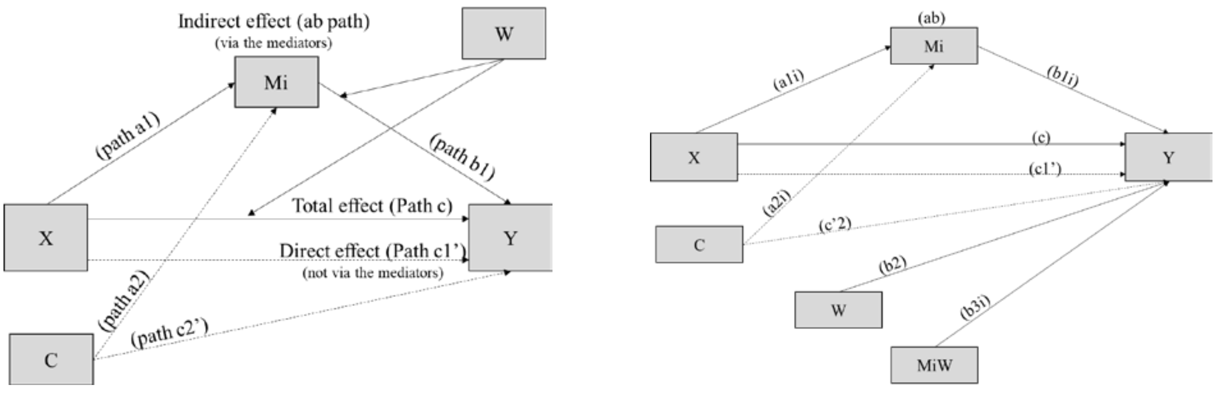
First of all, this paper uses construct validity and reliability of the questionnaire to control the effectiveness of the questionnaire items. Construct validity is reflected by two parameters: factor loading and cross-loading. The reliability of the questionnaire is reflected by Cronbach's alpha coefficient and combined reliability (Aizstrauta et al., 2015). All the parameters are calculated using SPSS and R.

Secondly, to test the research hypotheses, the standardised path coefficients and their significance level are calculated to judge the validity of hypotheses. If the level of the t-test is smaller than the significance level of 0.05, then the hypothesis is tenable. The standardised path coefficients reflect the influence degree of each factor. To improve the reliability of the results, SPSS – PROCESS V3.5 and the bootstrap method are used to test the mediating and moderating effects and verify the significance of the mediating effects.

The dependent variables are the acceptance score for SA and the Price sensitivity for WTP. Twelve socio-demographic features (Table A. 4) and two extended moderating variables (PV knowledge level and Environmental interest), which are suspected of having a relationship with SA, are considered as possible independent variables. We apply the Chi-Square test to analyse their independence from each other. This research tests the theory through deductive approaches.

For moderated mediation analysis, the SPSS macro PROCESS was applied with different moderators and mediators. The regression/path coefficients are all in unstandardised form as standardised coefficients generally have no useful substantive interpretation (Bolin, 2014). Model fit was also examined using the following criteria: a chi-square/df of $\leq 2$, a P-value of $>0.05$, a comparative fit index of $\geq 0.95$, and a root mean square error approximation of $<0.06$ (Hu and Bentler, 1999).

Logistic regression analyses are conducted to identify the predictors of SA and WTP outcomes with the potential predictors, including demographic variables and extended moderating/mediating variables. Correlation test is made for each outcome. A hierarchical model building procedure is used to select variables for inclusion in the final set of models. Variables are separated into three conceptual blocks: demographics, moderating factors and determinants of the output. Each block of predictors was regressed separately on each outcome in a logistic regression model. Significant predictors ($p < 0.05$) in any block model are retained in the set of final models used to estimate the simultaneous effects of predictors. This procedure ensures the inclusion of the same set of participants in each outcome and to facilitate interpretability of results. Three interactions are also considered for each outcome to provide for the exploration of moderation effects. All variables in an interaction block model with a significant interaction term for a given outcome are included in the final model for that specific outcome.




(a) (b)

*Figure 3. Statistical diagrams for the moderated mediation model: (a) concept used in this paper and (b) the concept interpretation. Illustrated using a directed acyclic graph showing the causal pathways between target variable X and outcome Y, mediators ($M_i$), moderate (W), and measured covariates (C).*

A regression model with the bootstrapping function of 20000-50000 bootstrap samples is used to perform testing of hypotheses, which have SA and Price elasticity (represented for WTP) as dependent variables, respectively. We run regular, mediator and moderator regression models to test the statistical significance and to find the best explanation for the independent variables—the level of confidence for all confidence intervals in output 95%. A heteroscedasticity consistent standard error and covariance matrix estimator are used. The F-test is used to test the statistical significance of the model and the critical values for one-tailed t-tests greater than 2.33 (significance level =1%) was applied for each independent variables.

The concept of the model with one target variable (X) and one final behavioural output (Y), is illustrated in Figure 3. X has both direct (c1'-path) and indirect (through M with a-path and b-path) effects on Y. The total effect is c-path, which is the summary of c1'-path and ab-path. The effects between mediators are d-path which is not illustrated in Figure 3 to simplify. Covariates (C), characteristics of the participants in an experiment, are included in all models to strengthen the results' validity.

W might moderate the indirect and/or direct effect of X on Y It means the effects of X on Y are conditional, depending on the value of W. There are two locations within the model where W may serve as a moderator: the direct effect of X on Y and the effect of X on M.

The relationship between all mentioned independent and dependent variables is described in the moderated mediation model to perform how the direct/indirect effects are calculated and how moderators and mediators and covariates are integrated. The moderated mediation model equations (Bolin, 2014):

$$Y = b_0 + \sum b_{1i} M_i + b_2 W + \sum b_{3i} M_i W + c'_1 X + c'_2 C + \varepsilon \qquad \textit{eq.3-1}$$

$$M_i = a_{0i} + a_{1i} X + a_{2i} C + \sum d_{ik} M_{ik} + \varepsilon \qquad \text{eq.3-2}$$

$d_{ik}$ is the d-path effect between the mediator $M_i$ and the mediator $M_k$.

To calculate the total, indirect and/or conditional effects by substituting equation eq.3-2 in equation eq.3-1 with $M_1, \dots, M_k$, we have eq.3-3.

$$Y = b_0 + \sum b_{1i}(a_{0i} + a_{1i}X + a_{2i}C + \sum d_{ik}M_{ik}) + b_2W + \sum b_{3i}W(a_{0i} + a_{1i}X + a_{2i}C + \sum d_{ik}M_{ik}) + c_1'X + c_2'C + \varepsilon \quad \text{eq.3-3}$$

Multiplying out brackets, we have eq.3-4.

$$Y = b_0 + \sum a_{0i}b_{1i} + \sum a_{1i}b_{1i}X + \sum a_{2i}b_{1i}C + \sum a_{i1}b_{1i}d_{ik}X + b_2W + \sum a_{0i}b_{3i}W + \sum a_{1i}b_{3i}XW + \sum a_{2i}b_{3i}CW + \sum\sum b_{3i}d_{ik}M_{ik}W + c_1'X + c_2'C + \varepsilon \quad \text{eq.3-4}$$

The indirect effect of X on Y through $M_1, \dots, M_k$ is $a_{i1}b_{1i}d_{ik}$.

### 3.3 Survey design

Apart from the questionnaire of PV awareness and ownership, the survey consists of four other parts. The first one contained questions about the respondent's house ownership, their house type, and their role in the household decision. This part aims to identify the house suitability for installing residential PV and the chance of respondent's adoption.

In the second part, in order to recognise SA based on TPB, the participants were asked to indicate their knowledge about residential PV based on levels from no knowledge to expert, their opinion and perception based on the 5-point Likert scale plus an option to refuse to answer the question. For further details about the questionnaire, refer to Table A. 2. The measurement scale items used in the study were borrowed from past studies, which have been validated.

The third part was designed for WTP investigation by repeatedly giving the participants different technology choices with different attributes and levels (Figure A. 1). While the attributes are features of the PV system, the attribute levels are certain specifications of these features. For realistic but also meaningful choice scenarios, product attributes, and attribute levels with high relevance have been based on a broad literature review.

Previous studies consider four main attributes: technical, cost, saving, polity attributes (Table A. 1). In this study, we adjust the four main attributes into five attributes. Each attribute has different attribute levels based on current and expected future of solar PV in Vietnam and other developing countries (Energy Initiative, 2015; Ludin et al., 2018; Qazi et al., 2019). Details of the attributes and levels are presented in Table A. 3.

The survey presented customers with six sets of three alternative combinations of attributes of an available or expected available PV system in the market. Participants can select compiled preference bundles and the no-purchase option. Repeated choices by participants from sets of alternatives reveal their trade-offs between different attributes. Each individual was asked to choose one alternative from each choice set. This choice is modelled using Random Utility Theory, which is based on the hypothesis that individuals will make choices based on the characteristics of a good (an objective component) along with some degree of randomness (a random component). This way helps the analyst reconcile theory with the observed choice. The random component arises either because of randomness in the preferences of the respondent or the fact that the researcher does not have the complete set of information available to the respondent. However, if the participant chooses no-purchase or purchase of all visible bundles, it means the price levels do not overlap with a consumer’s WTP range. This response will be considered exhibiting extreme response behaviour. The Sawtooth Software's module SSI Web has been used to design the survey.

The fourth part collects demographic characteristics of the respondents, such as gender, age, marital status, number of children, place of residence, Household size (HH size), electricity bill (Euro/month), income (Euro/month), level of education, house type, house ownership, household decision, which are summarised from previous studies (Table 2). They were claimed to be a major influencing factor for residential PV, green and energy-efficient purchasing.

### 3.4 Procedure for recruitment of participants

The research sample is a typical emerging country of low middle-income countries, Vietnam, selected based on the abundant untapped solar resources conditions, and emerging economic and social development. The country is facing a continuous surge in power demand and consumption over the coming decade, which will stimulate an urge for the development of alternative energy sources. Residential energy consumption has risen at twice the rate of annual economic growth, 13% vs 6% on average (Pablo-Romero et al., 2017; Le Phu, 2020). Positive demographics and rapid urbanisation will also further stoke its electricity consumption growth rates (Khuong et al., 2019). The larger economic potential for solar PV (Khuong et al., 2020), coupled with an increasingly supportive regulatory environment, the country's solar PV sector is poised for a new dawn.

This paper analysed data from the survey of random individual consumers aged from 20 to 69 years old living in urban and non-urban areas in Vietnam. The survey was conducted in March and April 2020 with one pilot and two real surveys. Firstly, a trial version was conducted with 202 respondents, including 15 psychologist, 22 solar energy experts, and the rest are randomly surveyed by emailing. After a revision, the second version was partly distributed by emailing (300 mails sent), randomly asked in the field trips (at ten different locations), and via social network across Vietnam and partly via direct distribution to relatives, friends, working adults at their workplace. 1719 responses were qualified out of 2174 completed surveys. In order to analyse the PV adopter's typical characteristics, we released the third survey focusing only on current PV adopters and finally got 320/420 completed feedbacks. In total, both surveys made up the gross sample N=2039 observations. The composition and distribution of the samples are shown in Table A. 4.

## 4 SURVEY RESULTS AND SA AND WTP MODELS

This section presents the survey results (Section 4.1) and the results of regression modelling for SA (Section 4.2) and WTP (Section 4.3). After testing different fit-in models for SA and WTP, a mediation model is used to predict SA, while a moderated mediation is used for WTP.
Extreme and bias responses are deleted based on normality and validation tests (Table D.1. 1). A moderated mediation model is a multiple linear regression model for analysing multifactor data. The major problem in dealing with regression analysis is the presence of outliers in data, which is the observations of extreme and/or bias lie outside the overall pattern of distribution. It is an observation whose dependent-variable value is unusual, given its value on the predictor variables. In this study, all variables are tested normality and skew. Then we use Cooks and Mahalanobis distances at the proportion of outliers 10% to identify outliers (Hadi and Simonoff, 1993). The cleaned data of the gross sample N = 2002, which excluded outliers, is processed for the moderated mediation model for assessing the model-to-data fit.

### 4.1 General results from the survey

The survey was conducted to investigate SA and WTP of the people in Vietnam toward residential PV. In general, residential PV received a positive reaction from the random respondents with more than 60% of them finding residential PV is a purchasable product. However, the acceptance level seems to be less optimistic, with only around 20% of the population having the SA score above 4 out of the maximum 5 (Figure 4). We also observe a positive signal of WTP toward residential PV with more than 55% of participants willing to pay for the product. However, along with this, we see that almost 20% of respondents completely neglecting the product. Most of the higher-approval people are at an average of 40-49 years old, with the highest level of knowledge about PV system (average of 2.75/5), the highest electricity bill (3.15/5) and the highest Income (5/8).

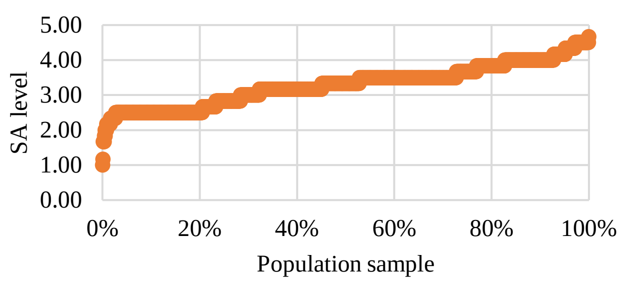



*Figure 4. Overall SA toward residential PV*

Among all the five considered attributes, including total investment (price), guarantee and manufacturer (or product origin) show their importance relative to others in a person's decision in buying PV system for their home (Figure 5). Meanwhile, the different saving potential and scheme support are less significant in people's decision-making process.

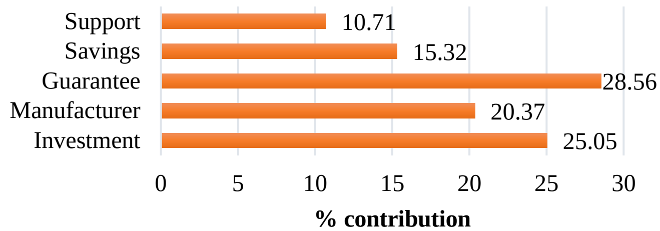



*Figure 5. The contribution of each factor to the customer's final decision*

The calculated WTP values show people, in general, would pay about 100 Euro more for a product with a guarantee. However, it does not matter for them if the guarantee is 10 or 15 years. Among all the suppliers, Japan and Germany are the favourites of the public (Figure 6). Accordingly, consumers are willing to pay around 30 to 60 Euro more in total for these products than for products from Korea, Taiwan and China, respectively.
There is a possibility of an interaction effect between investment and guarantee (Table D.2. 7 ). It means that people expect prices to come with a warranty. However, this effect is insignificant.

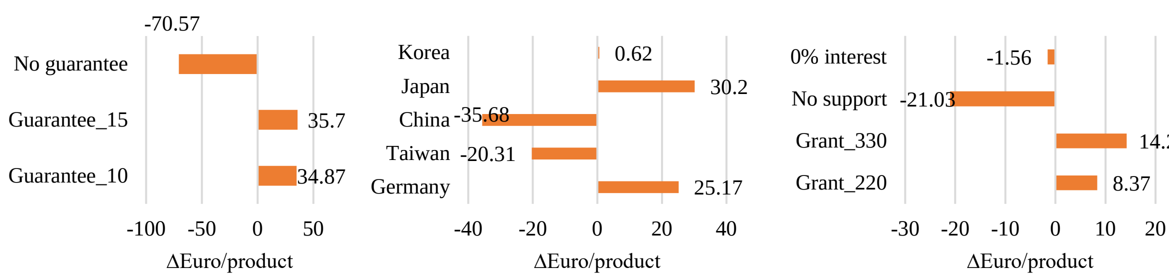



*Figure 6. The difference that customer will pay compared with the average WTP*

### 4.2 **Mediation model for SA**

First, we tested the correlation between all variables to select the correlated variables for the SA model (Table D.2. 1). Age & Marital status & Children (AMC), Income, Electricity bill and Place of residence can be used for calculating the action paths between variables in the moderated mediation model. Based on that, different model constructs are defined and pretested before identifying the final model (Appendix E. 1).

In the final model, a mediation model (Model 11, Table 3) is identified to predict SA (Y) toward residential PV. Environmental interest is recognised as the main intervention (X) or target variable, the two demographic factors (AMC and Income) are covariates (C1, C2) and PV knowledge, Subjective norm, Attitude, and Perceived risk are the mediators (M1 to M4), respectively.

Environmental interest has the strongest positive impact on the mediators and SA, especially on PV knowledge (a11=.588) and Perceived behavioural control (a14=.120). It means that people with more interest in the environmental topic seem to have more knowledge about PV (model 7, Table 3) and have a positive effect on personal Attitude (model 9, Table 3) and perceived risk (model 10, Table 3). Interestingly, people with higher Environmental interest are less affected by social pressure – Subjective norm (a12=-.077) when it comes to accepting residential PV (model 8, Table 3).

Subjective norm represents social pressure impacts heavily on personal Attitude (d32=.405 in model 9) and Perceived behavioural control (d42=.300 in model 10). However, it has an insignificant impact on SA (model 11).

Covariates, AMC and Income, are not influenced by the intervention, Environmental interest, but explain a part of the variability of SA. Covariates do not change the relationship between Environmental interest and SA. On their own, covariates predict at least part of the mediators and SA. AMC impacts negatively on Attitude, but positively on Perceived behavioural control. In comparison, Income has a positive impact on PV knowledge and Subjective norm.

*Table 3. Results of the mediation models for predicting SA towards residential PV.*

*Highlighted cell: **. Or *.Correlation is significant at the 0.01 or 0.05 level (2-tailed).*

| Model | Dependent variable | *Covariates* | | *Target variable* | *Mediators* | | | | R-sq | F(HC0) | p-value | Sig. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *AMC (ci1-path)* | *Income (ci2-path)* | Eco *(a-path)* | PVK *(di1-path)* | SN *(di2-path)* | Att *(di3-path)* | PBC *(di4-path)* | | | | |
| 7 | PVK (M1) | .039 | .052** | .588** | | | | | .197 | 206.207 | .000 | Yes |
| 8 | SN (M2) | -.033 | .071** | -.077 | -.003 | | | | .030 | 14.459 | .000 | Yes |
| 9 | Att (M3) | -.082* | .009 | .086** | -.017 | .405** | | | .255 | 98.455 | .000 | Yes |
| 10 | PBC (M4) | .072** | -.009 | .120** | .002 | .300** | .433** | | .477 | 282.738 | .000 | Yes |
| 11 | SA (Y) *(b and c'-paths)* | .086** | .016* | .073** | .052** | .005 | .225** | .195** | .236 | 85.840 | .000 | Yes |

*Factors: Eco: Environmental interest, PVK: PV knowledge level, Att: Attitude, SN: Subjective norm, PBC: Perceived behavioural control.*

The results show that all the models in Table 3 used to regress (or analyse) PV acceptance are statistically significant. With the involvement of mediators, the moderated mediator model (model 11, Table 3) has significantly higher R-sq values than no mediator models (model 6, Table E.1. 2), which means 23.6% (R-sq= 23.6%, F=85.840, p-value =0.000) and 4.4% (R-sq= 4.4%, F=29.828, p-value =0.000) of the independent variable can be explained by the dependent variables, respectively.

The final model (model 11) reveals a significant positive relationship between the Attitudes and Perceived behavioural control of a person towards PV products. Among all the impact factors on SA, the Attitude factor is the decisive factor with b2=.225, followed by the Perceived behavioural control factor b4=.195. Moreover, the high Environmental interest with c1'=.073 and PV knowledge with b1=.052 and would possibly convert into higher acceptance of respondents towards a PV system.

*Table 4. The significance of direct and indirect effects and their magnitude*

| **X impacts Y** | **Model** | **Path** | **Effect** | **SE** | **LLCI** | **ULCI** | **Significant** |
|---|---|---|---|---|---|---|---|
| **Total effect** | **Eco → SA** | **c** | **.137** | **.018** | **.101** | **.173** | Yes |
| **Direct effect** | **Eco → SA** | **c'** | **.073** | **.019** | **.035** | **.111** | Yes |
| **X impacts Y through** | | **Total indirect effect** | **.064** | **.013** | **.039** | **.089** | **Mediated** |
| M1 | Eco → PVK → SA | a1 b1 | 0.036 | 0.01 | 0.016 | 0.057 | Complementary |
| M4 | Eco → PBC→ SA | a4 b4 | 0.028 | 0.006 | 0.017 | 0.04 | Complementary |
| M2 x M3 | Eco → SN→ Att → SA | a2 d32 b3 | -0.008 | 0.003 | -0.015 | -0.002 | Competitive |
| M2 x M4 | Eco → SN→ PBC→ SA | a2 d42 b4 | -0.005 | 0.002 | -0.01 | -0.001 | Competitive |
| M3 x M4 | Eco → Att → PBC→ SA | a3 d43 b4 | 0.009 | 0.002 | 0.004 | 0.013 | Complementary |
| M2 x M3 x M4 | Eco → SN→ Att → PBC→ SA | a2 d32 d43 b4 | -0.003 | 0.001 | -0.006 | -0.001 | Competitive |

*Factors: Eco: Environmental interest, PVK: PV knowledge level, Att: Attitude, SN: Subjective norm, PBC: Perceived behavioural control, SE: booted standard error, LLCI & ULCI are booted lower and upper levels for confidence interval a path.*

Table 4 shows that the direct effect c′, which is the effect of Environmental interest explaining a portion of SA independently of M, and some of the significant indirect effects representing partial mediation. Indirect effects are calculated as in eq.3-4, and the value of the indirect effects are presented in Table 4. The direct effect of Environmental interest on SA is c1'=.073. However, the total effect is c = .137 with .064 indirect impact coming from mediator impact. The whole models include 15 possible indirect effects, but only 6 of them are significant (Table 4). The relationship between Environmental interest and SA is mediated by Subjective norm, and Attitude, but not from PV knowledge and Perceived behavioural control.

Two types of partial mediation can be distinguished, which are complementary and competitive partial mediations. The complementary partial mediation is where the direct effect c′ and indirect effect point in the same positive direction, which indicates that a portion of the effect of Environmental interest on SA is mediated through PV knowledge (M1), Perceived behavioural control (M4) and other combination of the mediators (Table 4).

In a competitive partial mediation, the direct effect c′ and indirect effect a × b point in a different direction, e.g. the combination of M2xM3, M2xM4 and M2xM3xM4 (Table 4). In the competitive partial mediation, we see that Subjective norm is played as the opposer. It can be concluded that the Subjective norm or social pressure will reduce the magnitude of the relationship between Environmental interest and SA. However, the effect strength is quite miniature of around -.008 to -.003 (Table 4).

### 4.3 **Moderated mediation model for WTP**

Different from the SA model in Section 4.2, we discovered a more complex model involving both mediator and moderator variables to predict WTP with Y being the Price sensitivity of the population. The best model explaining Price sensitivity (Y) consists of one target variable, one covariate, five mediators and two moderators (detail model in Table 5). The mediator variables, including PV knowledge (M1), Subjective norm (M2), Attitude (M3), Perceived behavioural control (M4) and SA (M5), are the variables that can explain how internal psychological significance take on person reaction in the market. The moderator variables, e.g. Income (W) and Age (Z) of the respondents, are quantitative and can affect the direction and strength of the relationship between the target variable, Environmental interest (X), and the dependent or criterion variable, Price sensitivity (Y). The moderator variables specify when certain effects will hold, while the mediators explain how or why such effects occur. Place of residence (C1) and Children (C2) play the role of the covariates in this moderated mediation model.

The model can explain 7.72% of the Price sensitivity of the population (R-sq= 7.72%, F=8.445, p-value =0.000). Among all the possible effects, there are four significant direct effects on the Price sensitivity coming from Environmental interest (X), Perceived behavioural control (M4), Income (W) and Place of residence (C1). Perceived behavioural control (M4) has the strongest effect with b14= 1.593, followed by Income (W) with b2 = 1.183. Environmental interest (X), and Place of residence (C1) has a similar effect on the Price sensitivity of c2' = 0.7 (Table 5). When these variables' values increases, the Price sensitivity is decreased.

Five significant indirect effects are revealed, which are the interaction of PV knowledge (M1), Subjective norm (M2) with the two moderators, and Perceived behavioural control (M4) with Income (W). All the significant indirect effects are quite weak compared with the direct effects. Two of them lessen the Price sensitivity, while others enhance it when they increase (Table 5).

*Table 5. Results of the moderated mediation model for predicting personal Price sensitivity towards residential PV*

| Variable | **Symbol** | **Effect** | **Coefficient** | **SE** | **p-value** | **LLCI** | **ULCI** | **Significant** | **Price sensitivity** |
|---|---|---|---|---|---|---|---|---|---|
| **PBC** | M4 | Direct | 1.593 | 0.505 | 0.002 | 0.603 | 2.584 | Yes | Lessen |
| **Income** | W | Direct | 1.183 | 0.375 | 0.002 | 0.448 | 1.918 | Yes | Lessen |
| **Eco** | X | Direct | 0.750 | 0.153 | 0.000 | 0.450 | 1.049 | Yes | Lessen |
| **PoR** | C1 | Direct | 0.720 | 0.132 | 0.000 | 0.461 | 0.979 | Yes | Lessen |
| **PVK x Age** | M1 x Z | Indirect | 0.286 | 0.079 | 0.000 | 0.132 | 0.441 | Yes | Lessen |
| **SN x Income** | M2 x W | Indirect | 0.220 | 0.075 | 0.003 | 0.073 | 0.366 | Yes | Lessen |
| **PVK x Income** | M1 x W | Indirect | -0.154 | 0.050 | 0.002 | -0.253 | -0.056 | Yes | Enhance |
| **SN x Age** | M2 x Z | Indirect | -0.244 | 0.111 | 0.029 | -0.463 | -0.026 | Yes | Enhance |
| **PBC x Income** | M4 x W | Indirect | -0.376 | 0.097 | 0.000 | -0.565 | -0.186 | Yes | Enhance |
| SA | M5 | Direct | -0.845 | 0.497 | 0.089 | -1.819 | 0.129 | No | - |
| Att | M3 | Direct | -0.776 | 0.481 | 0.107 | -1.720 | 0.168 | No | - |
| Age | Z | Direct | -0.609 | 0.575 | 0.290 | -1.737 | 0.519 | No | - |
| SN | M2 | Direct | -0.308 | 0.384 | 0.424 | -1.061 | 0.446 | No | - |
| Children | C2 | Direct | -0.252 | 0.263 | 0.337 | -0.768 | 0.263 | No | - |
| Att x Income | M3 x W | Indirect | -0.082 | 0.089 | 0.360 | -0.257 | 0.093 | No | - |
| PVK | M1 | Direct | 0.001 | 0.288 | 0.998 | -0.564 | 0.565 | No | - |
| SA x Age | M5 x Z | Indirect | 0.056 | 0.151 | 0.710 | -0.241 | 0.353 | No | - |
| PBC x Age | M4 x Z | Indirect | 0.072 | 0.148 | 0.627 | -0.218 | 0.363 | No | - |
| SA x Income | M5 x W | Indirect | 0.083 | 0.095 | 0.382 | -0.104 | 0.270 | No | - |
| Att x Age | M3 x Z | Indirect | 0.099 | 0.149 | 0.503 | -0.192 | 0.391 | No | - |

*Factors: PBC: Perceived behavioural control, Eco: Environmental interest, PoR: Place of residence, PVK: PV knowledge level, SN: Subjective norm, Att: Attitude, SE: booted standard error, LLCI & ULCI are booted lower and upper levels for confidence interval a path.*

The conditional indirect effect was calculated based on different Income and Age groups, using 10,000 bootstraps resamples. Results revealed that the indirect effect between Environmental interest and Price sensitivity through

PV knowledge, Subjective norm and Perceived behavioural control was significant in nine different groups of Income and Age respondents (Table E.2. 1).

The indirect effect of PV knowledge and Subjective norm was recognised positive with the older groups (age from 50-69) but negative with other groups. The indirect effect of PV knowledge was significantly different among the nine groups, while the indirect effect of Subjective norm and Perceived behavioural control were less different among them.

The index of moderated mediation was negative for Income and positive for Age, with 95% confidence. As this confidence interval does not include zero, the conclusion is that the indirect effects (PV knowledge (PVK), Subjective norm (SN) and Perceived behavioural control (PBC) of Environmental interest) on Price sensitivity welcomed negatively moderated by Income and positively moderated by Age. It means that Income increase enhances the Price sensitivity, while Age increase lessens the Price sensitivity (the total effect in Table E.2. 2).

# 5 DISCUSSION AND POLICY IMPLICATIONS

Detail model interpretation and comparison with literature will be discussed in Section 5.1 to reveal the drivers and barriers of SA and WTP toward residential PV products. Policy implication will be discussed in Section 5.2. The theoretical contribution, the limitations, and directions for further research are discussed in Section 5.3.

## 5.1 Drivers, mediators and moderators of SA and WTP

*Environmental interest is a game-changer*

Among all considered variables, Environmental interest plays the most important role as the target variable or significant predictor causing SA and WTP. The results indicate that people's higher interest in protecting the environment will potentially translate into positive SA and increase the likelihood of adoption. This finding is generally in line with the hypotheses and confirm previous research that Environmental interest has a direct and positive effect on WTP (Schwarz, 2007; Claudy et al., 2011) and is the most matters to people's WTP (Maichum et al., 2016; Li et al., 2019). In contrast to previous studies, this study emphasises the importance of the indirect effect of Environmental interest not only on WTP but also on personal SA, Attitude and Perceived behavioural control.

The indirect effect of Environmental interest is almost equally important to the direct effect, as reported coefficient of .073 and .064 on SA. It means the SA level is regulated passively and proactively through individual Environmental interest. However, there is a large deviation between direct and indirect effects of Environmental interest on WTP, with .75 compared to -.045 (Table E.2. 1). The conditional indirect effects of Environmental interest (X) on Price sensitivity (Y) through moderators are presented in Table E.2. 1. It can indicate that with people's increased concern about environmental problems, they seem to be strongly motivated in deciding on investing in PV, even though they may not see the item less risky than the other people do.

Apart from that, PV knowledge does not have a direct or indirect impact on WTP, but a slightly indirect effect on SA (b1=.052). Environmental interest is the original motivation to raise PV knowledge (a11=.588). It means that if the government wants to encourage people to use residential PV, the first thing they should do is to draw people's attention to the environmental matter, which will associate with a higher chance of SA for the PV product.

*Behavioural intention, not interpersonal behaviour mediates SA and WTP*

In the SA and WTP models, the two behavioural intention, including Attitude, Perceived behavioural control, but not the interpersonal behaviour, Subjective norm, play the mediated role in the chain. This finding is in contrast to previous studies on green energy (Low Carbon Technologies - LCTs), which claimed social pressure in Asian countries plays a vital role promoting LCTs (Sudbury-Riley and Kohlbacher, 2016; Quoquab and Mohammad, 2019). A plausible explanation may be related to the lag of cultural acceptance of new concepts within the society in Asian countries.

Although not showing the strong effect on SA and WTP, Subjective norm is emphasised as a vital effect on Attitude (d32 = .40) and Perceived behavioural control (d42 = .30) (Table 3). It means that while Attitude and Perceived behavioural control significantly predict SA and WTP, Subjective norm would play the role of a bridge between interpersonal behaviour and outcome consume behaviours.

*Demographic feature covariates and moderates SA and WTP*

Through structural equation modelling, we support hypotheses of previous studies about age (Gilly and Zeithaml, 1985; Lunsford and Burnett, 1992; Barr et al., 2005), and Income (Welsch and Kühling, 2009), which can be used to establish customer segmentation when considering SA and WTP. This study also supports the assumption that people with higher Income seem to be more likely to adopt a PV system than the averages (Jager, 2006; Islam and Meade, 2013; Rai et al., 2016). Moreover, Income promotes personal attitudes and perceived behavioural control with residential PV, but also contributes to lessening people's sensitivity toward price changes of residential PV. Conversely, in Vietnam, we did not find evidence of higher education lead to higher SA and WTP or difference between gender toward SA and WTP as proposed by (Borchers et al., 2007; Sardianou and Genoudi, 2013; Wolske et al., 2017).

Going beyond previous studies, this study does not provide a vague relationship between Income, Age and SA and WTP, but it emphasises the different reactions of nine subgroups of Income & Age combinations (Table E.2. 1). For example, the groups which are most sensitive to price changes are the group of 50-69 years old with low and middle Income, and the two groups of 20-29 and 30-49 years old with high Income. The increasing Environmental interest in these groups leads to increased PV knowledge and then change their Price sensitivity significantly. However, interestingly, the 50-69-year-old group had an increased sensitivity, while the other two groups had decreased Price sensitivity. This should be taken into account in terms of market segmentation strategies.

However, as the level of PV knowledge increases, the change in Price sensitivity decreases. When the level of PV knowledge increases to a certain level (3/5), the Price sensitivity levels between groups are asymptotic (Figure 7).

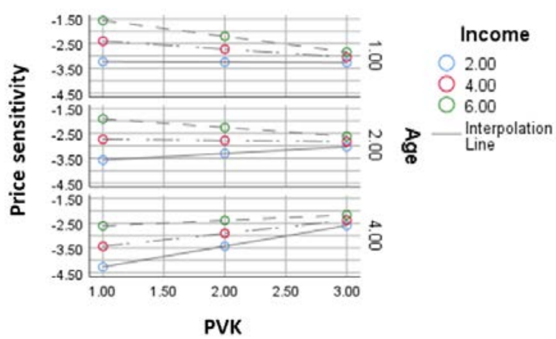



*Figure 7. Interaction between PV knowledge and WTP in different Income & Age groups*

This study added some demographic characters, which reflect people's living condition, such as household size, house type, house owner and household decision to investigate whether the living condition can become a motive for SA and WTP toward residential PV. However, the results reveal only the direct effect of the Place of residence on the Price sensitivity. It means people who live in urban and suburban areas seem to be less sensitive when residential PV products change in price.

*Unexposed relation between SA and WTP*

While (Guagnano et al., 1986) and (Labay and Kinnear, 1981) found a negative correlation between SA and WTP toward solar technology in general, the study by (Faiers and Neame, 2006) points to a positive correlation. Using similar moderating variables and including both SA and WTP in the survey, we are able to compare the control and cushion effects of different variables on producing behaviour toward residential PV. The findings in this study reject both hypotheses and conclude that there is no direct or indirect effect between SA and WTP in Vietnam. It may indicate that increasing SA will not necessarily lead to higher adoption. Alternatively, if people in general willing to pay more for residential PV, it may not indicate that they accept the product.

### 5.2 **Policy implications**

This study offers insights about residential PV behaviour for policymakers and stakeholders. This study identifies the factors that boost customers intention to accept and adopt residential PV and defines different roles for different characters of the behaviour. Therefore, policymakers and stakeholders can refer to when attaining residential PV development and success in developing countries.

*Why are people not buying?*

First of all, the proposed models suggested main results behind the refusal behaviour of the public toward purchasing rooftop PV for their own house.

- Relatively low Environmental interest in society. Despite the decisive role on SA and WTP, Environmental interest level in Vietnam remain relatively low at the average of 2.88/5 (Figure 4).
- Lack of knowledge. By comparing between PV owner and people who willing to buy PV product at any price (Unconditional WTP), at a certain price (Conditional WTP) and who will very unlikely buy PV product at all (Unlikely), we see that the PV knowledge of the PV owner is not so much better than the other, around 2.8/5 and 2.3/5, respectively (Figure 8, left).
- Lack of understanding about customer preference. People do not buy products solely based on price. They do factor in price with around 25% of their decision, but they will buy based on the guarantee and brand, which leads to another issue. It is an access problem. People prefer a product from Germany or Japan. However, they are not available everywhere and also expensive (Figure 5).
- Not yet an essential-product. Consumers will reach out to the product when their electricity bill and Income reach a certain level (Figure 8, right).

It may be time for the policymakers and stakeholders to evaluate why the market is not working and whether they target the right market with the right policy and message.

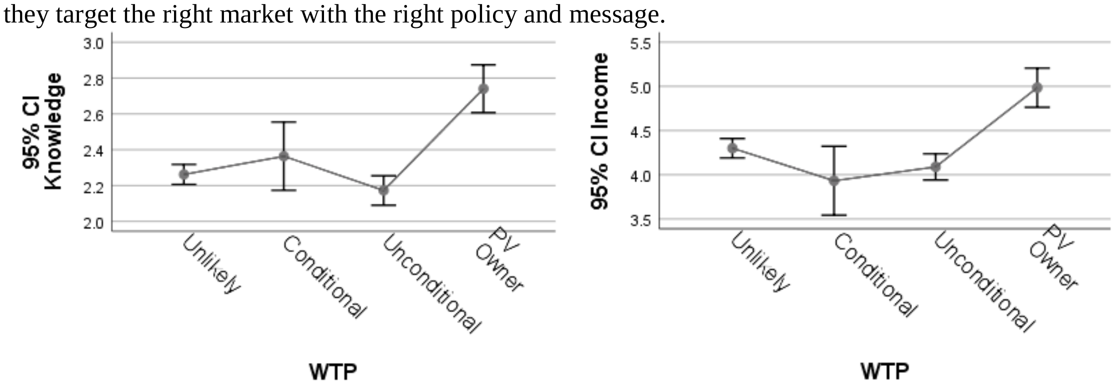



*Figure 8. Comparing knowledge and Income of different customer groups based on their WTP at 95% Confidence interval (CI)*

*Residential PV is a lifestyle product*

In the field of energy research, these lifestyle approaches are utilised to conclude energy consumption and environmental awareness concerning different lifestyle groups. The final decision to install is dominated by financial and environmental benefits delivered through residential PV systems. Older stakeholders with a higher income tend to live a greener and more energy-efficient lifestyle, while principally younger, mixed-income lifestyles are more likely to have low environmental awareness (Hierzinger et al., 2011). In terms of residential PV adoption, adopters rank significantly higher on Environmental interest than average (Jager, 2006).

In this paper, we also find out that the demand is driven by four main factors, including two demographic factors (Income and age-family-children) and two psychological factors (Environmental interest and PV knowledge). By itself, residential PV seems to be quite potential for self-sufficient development since these factors are projected to continue increasing in all scenarios without any strong external impacts such as policy and force in the national master plan in Vietnam (Ministry of Planning and Investment Portal, 2020).

*Policy suggestions*

For policymakers, it seems that they should mostly focus on the fundamental of residential PV need, which is Environmental interest. By developing environment-friendly awareness and promotion activities within the population, policymakers can educate the population about the importance of protecting the environment and how using renewable energy can support this idea in daily life. The education on environment and the importance of PV in reducing environmental effect can be directly translated to higher SA and WTP as well as indirectly to the more positive Attitude and perceived behavioural control, which can also lead to higher SA and WTP. However, since SA does not affect WTP, it means that even if SA is favourable, it does not mean that PV product will be consumed. Policymakers alone cannot heat the PV market. It requires joint efforts from all stakeholders.

For stakeholders, first of all, it is necessary to establish a market segmentation policy. Since Income and Age play the role of moderator and covariate in residential PV behaviour, it seems logical to use these characters to divide the whole market into different segments and then develop a different strategy for each segment separately. Moreover, the findings of the Place of resident effect on WTP suggested that the people living in Urban and Suburban are less price-sensitive than in Non-urban areas. Therefore, if stakeholders, instead of continually searching for financial support from the government to establish a market in rural areas in developing countries, they could enter the market with less resistance from customers in Urban and Suburban areas.

## 5.3 The theoretical contributions and critical discussion

This study was undertaken to develop a theoretical and integrative model in support of residential PV understanding and development. As such, the current research made an effort linking psychological and economic aspects to measure multiple outcomes involving residential PV behaviours. To date, psychological and adoption behaviour combination have been considered minimally (discussed in Section 2.1) as an antecedent of other measures within the renewable energy literature.

### *5.3.1 Theoretical contributions*

The findings offered the theoretical premise of a complex interaction between different variables and SA and WTP, as evidenced in the structural equation model and moderated mediation analysis. We determine the role of each variable in contact with SA and WTP and compare the effect between the two models. In both models, Environmental interest is identified as the target variable, causing people behaviour toward residential PV. PV knowledge, Attitude and Perceived behavioural control not only impact SA and WTP directly but also mediate the effect of Environmental interest and SA and WTP. AMC and Place of residence are covariates in the SA and WTP models, respectively. Lastly, Income is the covariate in the SA model, but the moderator in the WTP model moderating the indirect effect of Environmental interest and SA and WTP through PV knowledge, Subjective norm and Perceived behavioural control. These contributions are beyond recent studies.

The proposed integrative framework and models allow identifying direct and indirect relationships between Environmental interest, Income and Perceived behavioural control with both SA and WTP. The proposed models can improve the predictive utility of the original TPB model from around 4.4% to 23.5% for SA and from around 2% to 7.7% for WTP.

This study provides continued support for an amended mediation model in previous studies of green purchase behaviour (Litvine and Wüstenhagen, 2011; Chen and Deng, 2016; Maichum et al., 2016) but brings it one step forward with a more complex model of extra consideration for covariates and moderators to create the moderated mediation models. Additionally, the current work serves to provide support (through the use of PROCESS macro) for the continued utilisation of moderated mediation models within the renewable energy literature; for which little other research exists to date.

It is not common to test more than two mediators, even though the previous studies found many more variables that are related to the outcome, SA or WTP. To our knowledge, this study might be the first test of a four/five-serial-mediator model for renewable energy behaviour study. Using four/five-serial mediators together forms a highly complex model, particularly for interpretation purposes, as the model can create up to twelve distinct effects that Environmental interest has on SA and WTP, eleven indirect effects and one direct effect. Discovering chains of causality is not only important for confirming theory and giving a basic understanding of the processes in question, but it also represents a first step toward understanding residential PV behaviour properly, as it provides possible targets for intervention. Serial mediation also made the data fit the model perfectly, more so than parallel multiple mediator models.

The complex nature of behaviour toward residential PV entangles more than just linear relations between a variety of behavioural determinants and the final behaviour as in most of the literature in the related field has been explained. The relationship between or among behavioural antecedents has an indirect influence on final behaviour, SA and WTP, through a mediating variable, such as PV knowledge, Attitude and Perceived behavioural. This study is the first attempt to develop a model integrating SA, WTP, demographic and extended variables in the residential PV behaviour study. The combination of SA and WTP, especially in which WTP is not a binary variable but a quantitative variable of Price sensitivity, is largely non-existent in the related literature.

### *5.3.2 Critical discussion*

This study has many strengths, including being the first test of the theoretical predictions made concerning residential PV behaviour based on the use of multiple variables within a psychosocial and economic framework. This study, therefore, provided the opportunity to compare mechanisms and theories between integrated models of SA and WTP. Besides, using serial mediation allowed us to identify how one mediator impacts upon others in a chain of indirect effects.

Since this study goes beyond literature by combining SA and WTP in moderated mediation models to explain residential PV behaviour, the results should be cautiously interpreted. The study is conducted with survey data in a developing country, Vietnam, with 2004 qualified samples. Results do not primarily permit the generality of the model outside the context of developing countries. Future research should replicate this model in other destination contexts that may help cross-validate the current findings. Data for the proposed model was cross-sectional and correlational, prohibiting the inference of causal relationships within the model. Concomitantly, all the predictor and outcome variables were obtained from the same population, and the interpretations are offered tentatively.

Further research should address these limitations by using the longitudinal analysis to capture and control disparities and the causal direction among variables. Because residential PV is relatively new in Vietnam, bias and extreme responses could be a limitation of this study. Further research is needed to validate the findings.

The findings of this study showed a potential of dividing the population into different segments based on their characters and the conditional indirect effects of Environmental interest on SA and WTP via different mediators, e.g. Attitude, Perceived behavioural control. Future research should deepen into this subject to build market diffusion of residential PV in Vietnam.

The study is also susceptible to confounding or epiphenomenal associations, for even though statistical control was applied, there was an absence of randomness. Further analysis as part of a prospective study should, therefore, be carried out in such a way that includes randomness. The random assignment cannot by itself guarantee the presence of a causal order; however, a longitudinal study might provide stronger evidence.

The theory of planned behaviour in WTP studies is often interpreted in favour of economic valuation. In our approach, the price was incorporated in conjoint designs as an additional attribute in order to provide WTP estimates. This practice, however, has some shortcomings. For example, WTP does not only depend on the composite product and a budget constraint but also on alternative product offerings, so-called reference products. Therefore, the theoretical problem of including price as an attribute in conjoint analysis remains unresolved.

## 6 CONCLUSION AND OUTLOOK

Over the last years, residential PV shows more techno-economic potential, especially in developing country, which has stimulated increasing attention of policymakers, stakeholders as well as public. Moreover, it has been recognised as a positive environmental contributor. In order to understand residential PV behaviour, this study attempts to define the conceptual framework of key drivers of SA and WTP toward residential PV. Different from previous studies, WTP has not measured by a binary choice, but the probability of buying the product. This theoretical framework links with several social-psychological theories, which are the theory of planned behaviour and conjoint-based economic theory model. The current research is one of the first of its kind linking psychological and economic aspects to measure multiple outcomes involving residential PV behaviours.

The main investigative survey was then conducted in Vietnam. Total data of 2039 participants were collected in 2019, using web-based questionnaires. Factor analysis was used to assess the measurement models of the proposed conceptual framework. Moderated mediation model then is used to test all of the proposed hypotheses. This study confirms and emphasises the importance of Environmental interest effect not only direct but also indirect on WTP and SA. Moreover, it is found to impact directly and positively on Attitude and Perceived behavioural control.

Attitude and Perceived behavioural control represent interpersonal behaviour toward residential PV is discovered not only predicting SA and WTP but also mediating the effect of Environmental interest on SA and WTP. Although Subjective norm shows the strong impact in promoting Attitude and Perceived behavioural control, it was not a significant direct predictor of SA and WTP toward residential PV.

Through structural equation modelling, this study confirms the assumption that people with higher Income seem to have a more positive attitude and better perceived behavioural control as well as more likely to adopt PV system than the averages. However, we did not find evidence of higher education lead to higher SA and WTP or difference between gender toward SA and WTP.

This study added some demographic characters reflecting people living condition. However, only the Place of residence shows an effect on Price sensitivity, which shows the more WTP of people in urban and suburban than in rural areas. While the previous study claimed a positive correlation between SA and WTP toward solar technology (Faiers and Neame, 2006), this study rejects this hypothesis and concludes that there is no direct or indirect effect between SA and WTP in Vietnam.

Based on the moderated mediation models, this study identifies the factors that boost customers intention to accept and adopt residential PV and suggests policymakers and stakeholders act accordingly to promote residential PV development in developing countries. Policymakers should mostly focus on promoting Environmental interest among society by providing environment-friendly awareness and promotion activities. This education can be directly translated to higher SA and WTP as well as indirectly to the more positive Attitude and perceived behavioural control, which can also lead to higher SA and WTP. Stakeholders should divide the market into different segments and then develop a different strategy for each segment separately. Moreover, they should establish a market in Urban and Suburban areas instead of focusing on rural areas in developing countries.

This study has many contributions to the theoretical predictions of residential PV behaviour based on the use of multiple variables within a psychosocial and economic framework. It provided the opportunity to compare mechanisms and theories between integrated models of SA and WTP and identified how one mediator impacts upon others in a chain of indirect effects. However, the results should be cautiously interpreted and validated when using outside the context of developing countries. Future research should replicate this model in other destination contexts that may help cross-validate the current findings.

## APPENDIX A. SURVEY CONSTRUCTION AND SAMPLES

*Figure A. 1 CBC survey example*

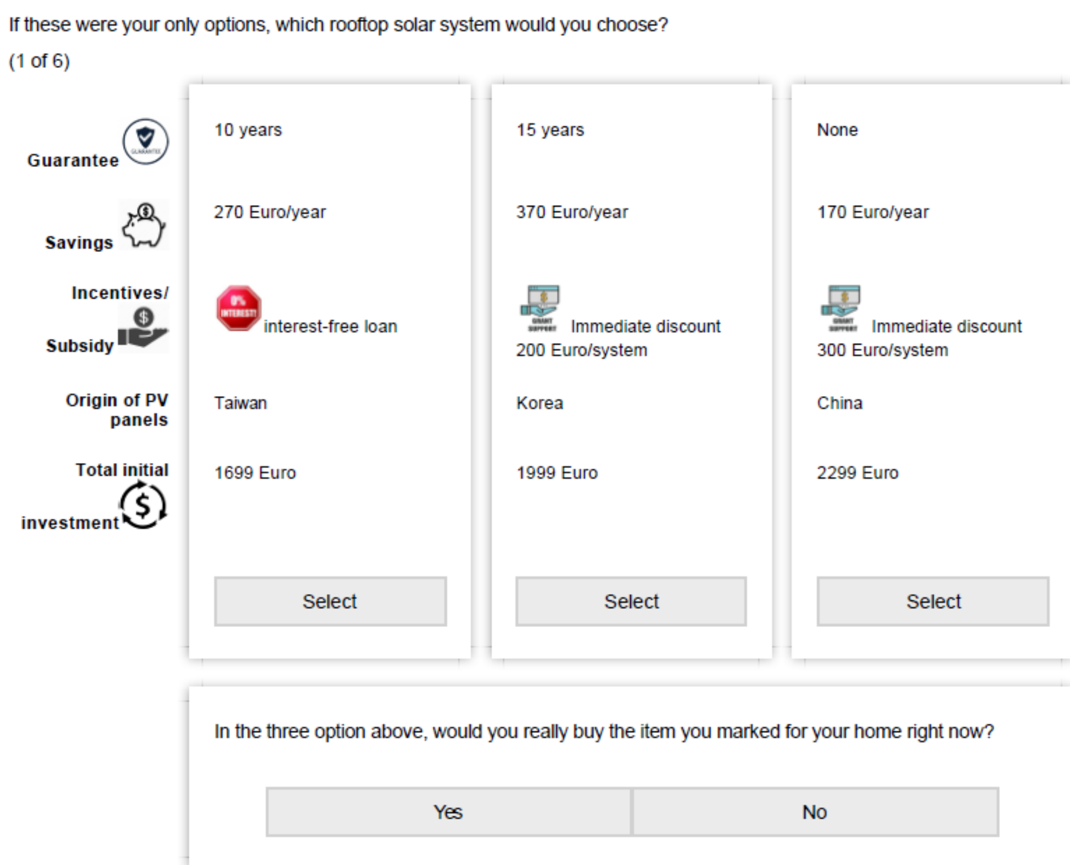



*Table A. 1 Overview of product attributes used in previous conjoint surveys related to residential PV*

| Source | **Objective** | **Subject** | **Technical attribute** | **Cost attribute** | **Saving attribute** | **Policy attribute & others** | **Utility model** | **Country** |
|---|---|---|---|---|---|---|---|---|
| (Hille et al., 2018) | Financial and non-financial factors drivers for PV | Building installed PV | Roof type (+base price); Color PV system/ roof, Origin of PV; | Investment costs, Revenues from electricity sales | Reduction in electricity costs | Purchase premium | | **Switzerland** |
| (Ida et al., 2014) | Potential for greenhouse gas emissions reduction due to smart equipment: PV & home energy management systems | HH | Stylish designed PV | The initial cost of introducing PV | Reduction in greenhouse gas emissions; Annual reduction in fuel and lighting charges | Free inspection & maintenance period | Mixed logit models | Japan |
| (Islam and Meade, 2013) | Causal link: technology attributes & adoption time | HH | | Total investment; Payback period; Inflation on fossil fuel cost | Energy cost saving; Saving in carbon emission | Tax incentives; export reward; policy changes | Random utility theory & discrete-time survival mixture | Canada |
| (Wissink et al., 2013) | Impact of PV systems to home purchasing | Dwelling buyers | Existing system; Dwelling size; Location; | | | Price | Random utility theory & multi Nominal Logit model | The Netherlands |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Building period | | | | | |
| (Chen et al., 2013) | Key attributes contribute to a product's market success | | Electrical (e.g. Power variance, Power ratio, Efficiency), Physical (e.g. Weight, Length, Width) | Economics (e.g. Cost, Time on the market) | | Certification (e.g. IEC and IS0), Warranty (e.g. Workmanship) | | US |
| (Axsen and Kurani, 2012) | Influence of energy policies & specific policy risks | PV project developers | | | | FIT; Duration of the administrative process; Policy changes | Maximisation of a utility function | |
| (Scarpa and Willis, 2010) | Policy context of renewable energy production in the EU | HH | Type of technology | Capital cost; Maintenance cost | Energy saved by the technology | Recommendation (e.g.Friend, plumber) | Conditional & mixed logit models; | England |

*Table A. 2 Item and construct measures (translated from Vietnamese)*

| Type | Factor | No. Items | Question | Items | Ref | Measurement |
|---|---|---|---|---|---|---|
| Extended variables | PV Knowledge | 1 | How do you rate your general knowledge of residential PV? | | (Schumacher et al., 2019) | 5 Likert-scale of quality: 1: very poor, 2: poor, 3: fair, 4: good, 5: excellent. |
| | Environmental interest | 8 | How often do you discuss this topic in daily life? | Climate change<br>Pollution<br>Eco Inventions<br>Saving energy<br>Solution for a power blackout<br>Renewable energy<br>PV power<br>PV household | (Klaus et al., 2020) | 5 Likert-scale of frequency: 1: never, 2: rarely, 3: sometimes, 4: often, 5: always; plus refuse to answer option |
| SA's determinant | Attitude | 4 | I think the idea of using a PV system for a house is | Feasible<br>Useful<br>Ecological<br>Electricity saving | (López-Mosquera et al., 2014; Li et al., 2019) | 5 Likert-scale of agreement: 1: strongly disagree, 2: disagree, 3: neither nor, 4: agree, 5: strongly agree; plus refuse to answer option |
| | Subjective norm | 3 | "The people who are important to me think that ......... will pay for installing PV system." | Everyone<br>I<br>They | (Claudy et al., 2011; López-Mosquera et al., 2014; Li et al., 2019) | |
| | Perceived behavioural control | 5 | Installing rooftop PV in my house would be | Cost-effective<br>Fit lifestyle<br>Fit technology<br>Saving bills<br>Reliable | (Klaus et al., 2020) | |
| SA | SA | 6 | Please indicate if you agree with the following statements | Like the idea<br>Support the idea<br>I will install<br>Not like the idea<br>Not support the idea<br>Not install | (Klaus et al., 2020) | |

*Table A. 3 Residential PV attributes and attribute levels used in the conjoint survey in this study*

| Attribute in literature | Modification | Explanation | Data type | Level | Ref |
|---|---|---|---|---|---|
| Cost attribute | Total investment (Euro/kWp) | The total investment expenditure of the system made at t=0 consists of capital cost and working capital. | Continuous data | 799<br>1099<br>1399<br>1699<br>1999<br>2299 | (Scarpa and Willis, 2010; Islam and Meade, 2013; Ida et al., 2014; Hille et al., 2018) |
| Saving attribute | Bill saving* (Euro/year) | The total electricity cost saved per year by using a residential PV system. The calculation is based on data from (EREA, 2019). | Continuous data | 170<br>270<br>370<br>470<br>570 | (Islam and Meade, 2013; Hille et al., 2018) |
| Policy attribute | Guarantee | The period of time for which the supplier guarantees the stability of the quality indexes of the product. | Discrete data | None<br>10 years<br>15 years | (Ida et al., 2014; Hille et al., 2018) |
| | Support | The expected financial support from the government for residential PV(Magazine, 2020). | Discrete data | None<br>0% Interest<br>200 Euro/system | (Axsen and Kurani, 2012; |

| | | | | | |
|---|---|---|---|---|---|
| | | | | 300 Euro/system | Wissink et al., 2013) |
| Technical attribute | Origin | Country of origin represents the country or countries of manufacture, production, design, or brand origin where the product comes from. | Discrete data | Taiwan<br>Korea<br>China<br>Germany<br>Japan | (Hille et al., 2018) |

*Table A. 4 Distribution of sample*

| | Description | Scale | N | % | Cumulative % | Mean | Std. Error of Mean | Std. Deviation | Variance |
|---|---|---|---|---|---|---|---|---|---|
| Gender | Of respondent | M | 1231 | 60.4 | 60.4 | 1.4 | 0.011 | 0.489 | 0.239 |
| | | F | 808 | 39.6 | 100 | | | | |
| Age | Of repondent | 20-29 | 498 | 24.4 | 24.4 | 2.52 | 0.026 | 1.191 | 1.42 |
| | | 30-39 | 542 | 26.6 | 51 | | | | |
| | | 40-49 | 593 | 29.1 | 80.1 | | | | |
| | | 50-59 | 262 | 12.8 | 92.9 | | | | |
| | | 60-69 | 144 | 7.1 | 100 | | | | |
| Marital status | Of respondent | Single | 488 | 23.9 | 23.9 | 2.53 | 0.021 | 0.961 | 0.924 |
| | | Engaged | 133 | 6.5 | 30.5 | | | | |
| | | Married | 1310 | 64.2 | 94.7 | | | | |
| | | Divorced | 62 | 3 | 97.7 | | | | |
| | | Others | 46 | 2.3 | 100 | | | | |
| Children | Of respondent | No | 590 | 28.9 | 28.9 | 1.71 | 0.01 | 0.454 | 0.206 |
| | | Yes | 1449 | 71.1 | 100 | | | | |
| Place of residence | Place of the respondent' home | Urban | 1030 | 50.5 | 50.5 | 1.7 | 0.017 | 0.784 | 0.614 |
| | | Suburban | 599 | 29.4 | 79.9 | | | | |
| | | Countryside | 410 | 20.1 | 100 | | | | |
| H.H. size | Number of people in the respondent'shouse | 1 | 130 | 6.4 | 6.4 | 2.24 | 0.014 | 0.611 | 0.373 |
| | | 2-4 | 1349 | 66.2 | 72.5 | | | | |
| | | 5-7 | 497 | 24.4 | 96.9 | | | | |
| | | >7 | 63 | 3.1 | 100 | | | | |
| Electricity bill (Euro/month) | Electricity bill of the household | <20 | 283 | 13.9 | 13.9 | 2.68 | 0.026 | 1.163 | 1.352 |
| | | 20-39 | 698 | 34.2 | 48.1 | | | | |
| | | 40-59 | 633 | 31 | 79.2 | | | | |
| | | 60-79 | 292 | 14.3 | 93.5 | | | | |
| | | 80-99 | 72 | 3.5 | 97 | | | | |
| | | >100 | 61 | 3 | 100 | | | | |
| Income (Euro/month) | Net income of the household | <250 | 147 | 7.2 | 7.2 | 4.33 | 0.041 | 1.87 | 3.498 |
| | | 250-499 | 237 | 11.6 | 18.8 | | | | |
| | | 500-749 | 343 | 16.8 | 35.7 | | | | |
| | | 750-999 | 335 | 16.4 | 52.1 | | | | |
| | | 1000-1249 | 365 | 17.9 | 70 | | | | |
| | | 1250-1499 | 364 | 17.9 | 87.8 | | | | |
| | | 1500-1749 | 150 | 7.4 | 95.2 | | | | |
| | | >1750 | 98 | 4.8 | 100 | | | | |
| Education | Of respondent | High school | 245 | 12 | 12 | 2.86 | 0.022 | 0.978 | 0.956 |
| | | College | 340 | 16.7 | 28.7 | | | | |
| | | Uni | 962 | 47.2 | 75.9 | | | | |
| | | After Uni | 434 | 21.3 | 97.2 | | | | |
| | | Others | 58 | 2.8 | 100 | | | | |
| House type | of the respondent's house | Apartment | 265 | 13 | 13 | 2.28 | 0.021 | 0.954 | 0.91 |
| | | Single | 1316 | 64.5 | 77.5 | | | | |
| | | Complex | 154 | 7.6 | 85.1 | | | | |
| | | Row | 228 | 11.2 | 96.3 | | | | |
| | | Others | 76 | 3.7 | 100 | | | | |
| House ownership | Of respondent | No | 522 | 25.6 | 25.6 | 1.74 | 0.01 | 0.437 | 0.191 |
| | | Yes | 1517 | 74.4 | 100 | | | | |
| Household decision | Of respondent | No | 292 | 14.3 | 14.3 | 2.09 | 0.014 | 0.61 | 0.372 |
| | | Together | 1262 | 61.9 | 76.2 | | | | |
| | | Own | 485 | 23.8 | 100 | | | | |

#### APPENDIX B. HYPOTHESIS FOUNDATION

In order to identify the role for each variable, we use the idea of cognitivism that an individual is viewed as an 'information processor' making a decision based on intrapersonal causation (Ajzen, 1991). Typically they tend to follow the traditional five-step classification outlining problem recognition, information search, alternative evaluation, choice and outcome evaluation as the key stages in their decision processes (Solomon, 2006). The recognized problem will be the target variable, which indicates the origin of the demand for residential PV. The information search, alternative evaluation, and choices will be considered as mediator or moderator factors. The outcome evaluations are SA and WTP.

First of all, environmental knowledge and Environmental interests are the most matters to people's Willingness to purchase green products (Maichum et al., 2016; Li et al., 2019). Taking into account environmental awareness, Environmental interests, and environmental knowledge, can improve the predictive utility of the original TPB model (Chen and Deng, 2016; Maichum et al., 2016; Li et al., 2019). Based on that, we propose the hypothesis H1.

The target variable is hypothesised to influence SA and WTP via the mediating variables, e.g. SA's and WTP's determinants. That is, consumers are more likely to accept and buy residential PV if they think this kind of action has positive consequences for the target variable.

TPB measure SA with three determinants of behavioural intention (Ajzen, 1991). The attitude towards behaviour refers to an individual's positive or negative evaluation of buying a residential PV system. The subjective norm captures an individual's perception of social pressure from reference group members to enact the behaviour. Perceived behavioural control includes the perceived ease or difficulty of adopting the residential PV system (Litvine and Wüstenhagen, 2011; López-Mosquera et al., 2014).

The literature claims that the higher level of attitude, subjective norm and perceived behavioural control strengthens the individual's intention toward residential PV (Korcaj et al., 2015; Wolske et al., 2017). Attitudes and perceived behavioural control had a critical impact on emission reduction behaviour (Shi et al., 2017; Ru et al., 2019). The subjective norm factors and perceived behaviour control usually are reported as important factors driving an individual's willingness to save energy (Gao et al., 2017; Ru et al., 2018). The perceived behavioural control factor usually indicated as "risk" or "uncertainty", which is often cited as an essential factor with a positive effect on influencing adoption (Labay and Kinnear, 1980; Guagnano et al., 1986; Dunphy and Herbig, 1995; Arts et al., 2011; Ozaki, 2011). However, among the developing countries, people in Peninsular Malaysia have a negative attitude toward the use of renewable energy (Kardooni et al., 2016). These findings will be verified in Vietnam by the following the hypotheses H2 and H3:

Socio-economic and demographic factors that either determine or strongly correlate with SA and WTP are claimed in the literature. A determinant is a factor or cause that makes something happen or leads directly to a decision, while covariates are characteristics of the participants in an experiment (Miller and Chapman, 2001). These characteristics could be used to understand how the final decision is different between different groups or populations, and provide a suggestion regarding how to control for the influence of any covariate. Determinant and covariates are usually confused in behaviour research. This paper will test whether any demographic factor will work as the determinant or covariate factor of SA and WTP.

For example, older consumers show a negative correlation between age and innovativeness (Gilly and Zeithaml, 1985; Arts et al., 2011). Therefore, it is used to distinguish customer group by age. Other variables, such as the level of education and income, have been attributed to the positive effect on innovation adoption (Arts et al., 2011). People in California (the US) and Groningen (the Netherlands) with higher income and higher education seem to more likely to adopt PV system than the averages (Jager, 2006; Islam and Meade, 2013; Rai et al., 2016). Based on these, we test the hypotheses H4 to H6.

## APPENDIX C. STATISTICAL ANALYSIS METHOD

### *Appendix C. 1 SA analysis*

The three determinants are measured using statements answered on 5-point Likert scales plus the option of "do not know". The variable *attitude towards PV system* consisted of an index based on four items and had a standardised Likert range from 1 to 5. The items measured to what extent respondents perceived the product as pleasant and beneficial. The question aiming at the *subjective norm* revealed to what extent friends, relatives, and society, in general, are in favour of installing PV. The *perceived behavioural control* was also an index based on five items measuring to what extent respondents perceived the adoption as easy and feasible.

The construct perceived behavioural control is formed by combining the perceived presence of factors that may facilitate or impede the performance of behaviour and the perceived power of each of these factors. Actual behavioural control refers to the extent to which a person has the skills, resources, and other prerequisites needed to perform a given behaviour. Actual behavioural control is difficult to assess accurately, and so perceived behavioural control is measured through specially designed questionnaires and serves as a proxy measure of the influence. In the TPB, behavioural intention is controlled by a dynamic mix of the attitude, subjective norm, and perceived behavioural control variables (eq. C.1. 1). Actual behaviour is again derived mainly from behavioural intention but is mediated to some degree by perceived behavioural control.

$$A_k = \sum_{i=1}^{N} B_i a_i \text{ (Solomon, 2006)} \qquad \textit{eq. C.1. 1}$$

Where, $A_k$ is the person's overall SA towards the product k with i attribute characteristics. $B_i$ is the strength of belief that the product possesses attribute i, and $a_i$ is the evaluation of the intensity of feeling (liking or disliking) towards attribute i. N is the number of relevant beliefs considered by that person

*Appendix C. 2 WTP analysis*

This paper uses CBC to identify the WTP of a person who faces different choices when he/she intends to purchase a residential PV system (Scarpa and Willis, 2010; Franceschinis et al., 2017). CBC is a survey-based statistical technique used in market research that helps determine how people value different attributes (feature, function, benefits) that make up an individual product or service. To estimate product choice probabilities at different prices based on CBC, we assume the existence of a (preferred) status quo product. The respondents of the interview are a priori assumed to buy this product. The WTP for a competing product is then estimated as the price at which the respondent would switch away from the status quo product. With this set of assumptions, WTP cannot be estimated for customers who would actually not buy the status quo product in the first place or have a different (unknown) status quo product.

The residential PV production is described with $i$ attributes and $j$ alternatives of each attribute. Total utility of the person is $U_{ij}$ when purchasing one product with $i$ attributes, and each attribute has one specific alternative. The person will choose alternative $j_2$over $j_1$ of attribute i if and only if $U_{i2} > U_{i1}$. Based upon random utility theory, individuals will make choices based on the characteristics of a good (an objective component) along with some degree of randomness (a random component) which helps the analyst reconcile theory with observed choice. The random component arises because of randomness in the respondent's preferences or absence of their ideal set in the survey. The utility that an individual $i$ assigns to some alternative can be described as in eq. C.2. 1eq. C.2. 1.

$$U_{ij} = \nu_{ij} + \varepsilon_{ij} \qquad \textit{eq. C.2. 1}$$

This paper assumes that utility $U_{ij}$ is composed of $\nu_{nij}$, a non-stochastic utility function and $\varepsilon_{ij}$ is a random component. If it is assumed that $\nu_{ij}$ is a linear utility function then $\nu_{ij} = \beta x_{ij}$. $x_{ij}$ is systematic component. The systematic component $x_{ij}$ separates the price attribute, $p_{ij}$, from non-price attributes, $z_{ij}$, as can be seen in eq. C.2. 2. The coefficient δ presents that with every price change, the utility will change by $\delta$.

$$\nu_{ij} = \delta p_{ij} + \varphi' z_{ij} \qquad \textit{eq. C.2. 2}$$

$p_{ij}$ is the price of a normalised system, $z_{ij}$ are other attributes such as manufacturer, ease of use.

By differentiating eq. C.2. 2 concerning each attribute $\frac{\partial \nu_{ij}}{\partial z_{ij}}$, we obtained the marginal utility provided by the attribute. By differentiating concerning price $\frac{\partial \nu_{ij}}{\partial p_{ij}}$, we got the marginal utility of price. By differentiating concerning the ratio of saving and income $\frac{\partial \nu_{ij}}{\partial q_{ij}}$, we got the marginal utility of benefit. The WTP or the marginal rate of substitution between attribute $z_{ij}$ and price is the ratio between these two derivatives. Thus, the WTP is the ratio between the coefficient of the other k attributes and the coefficient of the price variable (Breidert et al., 2006) as in eq. C.2. 3.

$$\omega = -\frac{\hat{\varphi}}{\hat{\delta}} = -\left[\frac{\widehat{\varphi_1}}{\hat{\delta}}, \frac{\widehat{\varphi_2}}{\hat{\delta}}, \dots, \frac{\widehat{\varphi_k}}{\hat{\delta}}\right] \quad \textit{eq. C.2. 3}$$

$\hat{\varphi}, \hat{\delta}$ is the mean of all ϕ and δ. The negative sign represents the inverse relationship between price and WTP. When the price increases, the WTP is decreased.

Using the coefficient of WTP, ω, eq. C.2. 2 can be rewritten as in eq. C.2. 4. Instead of calculating ϕ and δ, the parameter of the model is ω, and the unit changes from the utility in eq. C.2. 1 to currency in eq. C.2. 4.

$$\nu_{nij} = \delta(\omega' z_{ij} - p_{ij}) \quad \textit{eq. C.2. 4}$$

To account for consumer heterogeneity and overcome the information inefficiency, we assume that a common multivariate normal distribution links respondents' preferences. This assumption does not constrain the data very much but offers a high level of detail, so hierarchical Bayes is currently the most widespread technique applied to CBC data (Eggers and Sattler, 2011).

## APPENDIX D. DATA PREPARATION AND ANALYSIS

*Appendix D. 1 Validation test for TPB questionnaires*

Construct validity is used to reflect the confidence level of the sample measurements representing the true overall score. The measurement results show that the factor loading is larger than the cross-loading. A factor loading with a value above 0.50 is valid, and that item should be retained (Hair, 2017). Conversely, if the factor loading value of the item is less than 0.50, the item should be deleted. As shown in Table D.1. 1, the factor loading values of all the question items are higher than 0.50, which indicates that the scale used in this study had high construct validity.

Cronbach analyses are conducted on all the subscale of psychological questions (Table D.1. 1). The results show that the Cronbach alpha of all subscales is greater than 0.7, which is the recommended value (Cho, 2016). This value indicates that the subscales have an adequate level of inter-item reliability. Further analyses found that deleting any of the items would not have significantly increased the alpha level of the attitude and the Environmental interest questions. However, analyses revealed that by deleting the item about "self-reflection" in the Subjective norm question, the item defining residential PV as an expensive product in the Perceived Risk, the alpha level could be raised about 5-10% score. If deleting the item of "installing residential PV" in the Acceptance questions, the alpha level of this question is not significantly increased. After the pilot-test, instead of deleting, we rephrase the "self-reflection" and "expensive" items in the subjective norm and perceived risk to ensure the reliability of the question.

*Table D.1. 1 Validation tests for the reliability of the SA questionnaire*

| | Loading | Cronbach's Alpha | N of Items | Delete item | Cronbach's Alpha if item deleted |
|---|---|---|---|---|---|
| Attitude | .711 | .758 | 4 | - | - |
| Sub_norm | .725 | .714 | 3 | Sub_me | .759 |
| Perceived_risk | .752 | .744 | 5 | Expensive | .761 |
| Eco_interest | .810 | .870 | 8 | - | - |
| Acceptance | .785 | .737 | 6 | Implement | .745 |

*Appendix D. 2 Correlation and variable selection*

In this paper, the SA and WTP analysis were conducted using different indices based on demographics and psychological determinants. Demographics are broken down by any combination of age, gender, income, education, marital status, household type and size, and place of residence, which can explain the most of the deviations between different levels of SA. Some factors can produce spurious associations, particularly in a nonexperimental study such as this one. Therefore, demographic and extended factors were statistically accounted for (Table D.2. 1).

There was a significant correlation between all demographic and extended factors with SA with the possibility of both direct and indirect effect. Exceptions are the factors place of residence, HH size and Education. Among these three, HH size and eduction do not show any significant correlation with any determinants of SA, so these two factors will not be considered as impact factors on SA. In contrast, Place of residence reveals significant effects on SA's determinants. Thus it may have an indirect effect on SA.

*Table D.2. 1 Correlation between the possible intervention variables and the SA and its determinant variables*

*Highlighted cell: **. Or *.Correlation is significant at the 0.01 or 0.05 level (2-tailed).*

| Variable | | Attitude | Subjective_norm | Perceived | SA | Indirect/ direct effect |
|---|---|---|---|---|---|---|
| Demographic | Age | -0.003 | .074** | 0.033 | .054** | Both |
| | Marital status | -.068** | .065** | -0.003 | .066** | Both |
| | Children | 0.022 | .118** | .087** | .152** | Both |
| | Place of residence | -.051** | -.069** | -.038* | -0.034 | Indirect |
| | HH size | 0.016 | 0.015 | 0.020 | -0.020 | No |
| | Electricity bill | 0.023 | .084** | .067** | .087** | Both |
| | Income | .053** | .127** | .069** | .092** | Both |
| | Education | 0.033 | -0.024 | -0.028 | 0.028 | No |
| Extended | Environmental interest | .050** | -.056** | .066** | .098** | Both |
| | Knowledge | .039* | 0.000 | .060** | .129** | Both |

After excluded two unimportant factors, all the proposed mediators here, including demographic and extended variables, were analyzed with the autocorrelated test to assess whether to include them in the moderated mediation model. The analysis found that the demographic variables are highly correlated with each other (Table D.2. 2). Therefore, we used factor analysis to reduce 15 demographic variables into fewer numbers of factors.

*Table D.2. 2 Correlation between the possible intervention variables*

*Highlighted cell: **. Or *.Correlation is significant at the 0.01 or 0.05 level (2-tailed).*

| | Demographic factors | | | | | | Extended factors | |
|---|---|---|---|---|---|---|---|---|
| | Age | Marital status | Children | Place of residence | Electricity bill | Income | Environmental interest | Knowledge |
| Age | 1.000 | .459** | .481** | -0.037 | .160** | .226** | -.153** | -.043* |
| Marital status | | 1.000 | .651** | -.126** | .196** | .215** | -.096** | -0.011 |
| Children | | | 1.000 | -.061** | .140** | .238** | -.126** | -0.002 |
| Place of residence | | | | 1.000 | -.211** | -.216** | -0.029 | 0.010 |
| Electricity bill | | | | | 1.000 | .381** | 0.016 | .063** |
| Income | | | | | | 1.000 | -.033* | .060** |
| Environmental interest | | | | | | | 1.000 | .322** |
| Knowledge | | | | | | | | 1.000 |

Factor loading shows the variance explained by the variable on the new-formed factors. Results show the three possibilities of new-formed factors (highlighted in Table D.2. 3) that extract maximum common variance from all variables.

*Table D.2. 3 Factor analysis results*

| Variable | | Component | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Demographic factors | Age | .769 | -.152 | -.184 |
| | Marital status | .861 | -.027 | -.251 |
| | Children | .872 | -.087 | -.167 |
| | Place of residence | -.072 | -.005 | .678 |
| | Electricity bill | .159 | .089 | -.747 |
| | Income | .353 | .051 | -.743 |
| Extended factors | Knowledge | .012 | .809 | -.057 |
| | Ecological | -.237 | .750 | -.001 |

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

We conduct a reliability test for the new factors (Table D.2. 4). However, only the Age& Marital status& Children has factor loading higher than 0.7 and F-test significant, represents that the factor extracts sufficient variance from the constructed factors. The Electricity &Income factor has factor loading lower than 0.7, and F-test non-significant means that the new factor is insufficient. Age& Marital status& Children is used for calculating the action paths between variables in the moderated mediation model.

*Table D.2. 4 Reliability test results of the new-formed demographic factors*

| New factor | Constructed factors | Loading | F | P-value | Sig. | New factor | Constructed factors | Loading | F | P-value | Sig. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Age& Marital status& Children | Age<br>Marital status<br>Children | .785 | 4.020<br>3.796<br>18.804 | .003<br>.004<br>.000 | Yes<br>Yes<br>Yes | Electricity bill &Income | Electricity bill<br>Income | .509 | 1.349<br>2.580 | .249<br>.036 | No<br>No |

*Table D.2. 5 Correlation between Price sensitivity with the WTP's determinant candidates*

*Highlighted cell: **. Or *.Correlation is significant at the 0.01 or 0.05 level (2-tailed).*

| | Age | Marital status | Children | Place of residence | HH size | Electricity bill | Income | Education | Knowledge | Ecological |
|---|---|---|---|---|---|---|---|---|---|---|
| Correlated coefficient | -0.021 | -0.009 | -.047* | .107** | 0.033 | 0.043 | 0.029 | .057* | .068** | .127** |
| Sig. (2-tailed) | 0.338 | 0.701 | 0.035 | 0.000 | 0.137 | 0.053 | 0.191 | 0.011 | 0.002 | 0.000 |

*Table D.2. 6 Correlation between Price sensitivity with the WTP's determinant mediators*

| | Attitude | Subjective_norm | Perceived | Acceptance |
|---|---|---|---|---|
| Correlated coefficient | -.128** | -.071** | -.048* | -.074** |
| Sig. (2-tailed) | 0.000 | 0.001 | 0.031 | 0.001 |

*Table D.2. 7 Testing interaction effects between different attributes of a PV system*

| Effect | Log-Likelihood Fit | Chi-Square Value | P-Value | Gain over Main Effects | Interaction effect |
|---|---|---|---|---|---|
| Main Effects | -10059.65 | | | | |
| + Investment x Guarantee | -10040.08 | 39.15 | 0.00 | 0.17% | Slightly |
| + Guarantee x Savings | -10049.80 | 19.71 | 0.00 | 0.09% | Unsignicant |
| + Investment x support | -10056.87 | 5.56 | 0.14 | 0.02% | No |
| + Guarantee x support | -10055.54 | 8.22 | 0.22 | 0.04% | No |
| + Manufacturer x support | -10052.92 | 13.45 | 0.34 | 0.06% | No |
| + Manufacturer x Savings | -10057.38 | 4.53 | 0.34 | 0.02% | No |
| + Investment x Manufacturer | -10057.48 | 4.34 | 0.36 | 0.02% | No |
| + Manufacturer x Guarantee | -10055.68 | 7.93 | 0.44 | 0.03% | No |
| + Savings x support | -10058.66 | 1.99 | 0.58 | 0.01% | No |
| + Investment x Savings | -10059.59 | 0.11 | 0.74 | 0.00% | No |

## APPENDIX E. MODEL RESULTS

*Appendix E. 1 No-mediated regression models for SA*

The first group of regression models are no-mediated models using demographic factors as target variables (). The second group are the regression model with extended variables (). In the first group, AMC (Age& Marital status & Children) and Income accounted for 2.1% of the unique variance in SA in model 2, while Electricity bill and place of resident do not reveal significant effects in model 3 and 4 (Table D.2. 5 ).

*Table E.1. 1 Using demographic factors as the only interventions*

Model Summary[e]

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | Change Statistics: R Square Change | F Change | df1 | df2 | Sig. F Change | Durbin-Watson | Significant |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .101[a] | .010 | .010 | .64344 | .010 | 20.933 | 1 | 2037 | .000 | | Yes |
| 2 | .140[b] | .020 | .019 | .64053 | .009 | 19.546 | 1 | 2036 | .000 | | Yes |
| 3 | .145[c] | .021 | .020 | .64025 | .001 | 2.828 | 1 | 2035 | .093 | | No |
| 4 | .145[d] | .021 | .019 | .64038 | .000 | .125 | 1 | 2034 | .724 | .380 | No |

a. Predictors: (Constant), AMC
b. Predictors: (Constant), AMC, Income
c. Predictors: (Constant), AMC, Income, Electricity bill
d. Predictors: (Constant), AMC, Income, Electricity bill, Place of residence
e. Dependent Variable: Acceptance

To improve the explanation of the model, we add the effects of Environmental interest or PV knowledge into model 2. Model 5 with PV knowledge added is significant with the explanation of 3.5% of the population (R-sq=.035, F=21.812, P<0.0001). Model 6 replaces PV knowledge by Environmental interest and can increase the explanation to 4.4%. Because the model 6 with the Environmental interest factor has a much stronger effect on SA compared with PV knowledge effect, .137 and .083, respectively, we choose the Environmental interest as the intervention to run the moderated mediator models (Table D.2. 6 ).

*Table E.1. 2 The extended regression models*

*Highlighted cell: **. Or *.Correlation is significant at the 0.01 or 0.05 level (2-tailed).*

| Model | Dependent variable | AMC | Income | Environmental interest | PV knowledge | R-sq | F(HC0) | p-value | Significant |
|---|---|---|---|---|---|---|---|---|---|
| 5 | SA | .070** | .027** | | .083** | .035 | 21.812 | .000 | Yes |
| 6 | SA | .083** | .033** | .137** | | .044 | 29.828 | .000 | Yes |

*Appendix E. 2 Results of the WTP model*

*Table E.2. 1 The conditional indirect effects of Environmental interest (X) on Price sensitivity (Y) through moderators.*

| Income (Euro/month) | Age | Coefficient | SE | BootLLCI | BootULCI | Significant |
|---|---|---|---|---|---|---|
| **Eco ↑→ PVK ↑→ Pr↓** | | | | | | |
| <500 | 20-29 | -0.013 | 0.114 | -0.239 | 0.205 | No |
| <500 | 30-49 | 0.155 | 0.098 | -0.039 | 0.346 | No |
| <500 | 50-69 | 0.489 | 0.124 | 0.247 | 0.735 | Yes |
| 500-1249 | 20-29 | -0.193 | 0.096 | -0.385 | -0.005 | Yes |
| 500-1249 | 30-49 | -0.026 | 0.068 | -0.163 | 0.108 | No |
| 500-1249 | 50-69 | 0.309 | 0.091 | 0.133 | 0.492 | Yes |
| >1250 | 20-29 | -0.373 | 0.114 | -0.604 | -0.148 | Yes |
| >1250 | 30-49 | -0.206 | 0.086 | -0.375 | -0.032 | Yes |
| >1250 | 50-69 | 0.128 | 0.094 | -0.047 | 0.322 | No |
| Total effect | Income | -0.090 | 0.031 | -0.151 | -0.028 | Yes |
| | Age | 0.167 | 0.046 | 0.077 | 0.260 | Yes |
| **Eco↑ → SN↑ → Pr↓** | | | | | | |
| <500 | 20-29 | 0.007 | 0.017 | -0.029 | 0.044 | No |
| <500 | 30-49 | 0.023 | 0.017 | -0.006 | 0.063 | No |
| <500 | 50-69 | 0.053 | 0.030 | 0.004 | 0.123 | Yes |
| 500-1249 | 20-29 | -0.021 | 0.017 | -0.061 | 0.005 | No |
| 500-1249 | 30-49 | -0.005 | 0.010 | -0.028 | 0.014 | No |
| 500-1249 | 50-69 | 0.026 | 0.019 | -0.003 | 0.069 | No |
| >1250 | 20-29 | -0.048 | 0.027 | -0.111 | -0.005 | Yes |
| >1250 | 30-49 | -0.033 | 0.019 | -0.077 | -0.002 | Yes |
| >1250 | 50-69 | -0.002 | 0.015 | -0.032 | 0.029 | No |
| Total effect | Income | -0.014 | 0.008 | -0.030 | -0.001 | Yes |
| | Age | 0.015 | 0.010 | 0.000 | 0.039 | Yes |
| **Eco↑ → PBC↑ → Pr↓** | | | | | | |
| <500 | 20-29 | 0.12 | 0.05 | 0.03 | 0.22 | Yes |
| <500 | 30-49 | 0.12 | 0.04 | 0.05 | 0.22 | Yes |
| <500 | 50-69 | 0.14 | 0.06 | 0.04 | 0.27 | Yes |
| 500-1249 | 20-29 | 0.02 | 0.04 | -0.06 | 0.10 | No |
| 500-1249 | 30-49 | 0.03 | 0.03 | -0.02 | 0.09 | No |
| 500-1249 | 50-69 | 0.05 | 0.04 | -0.02 | 0.13 | No |
| >1250 | 20-29 | -0.07 | 0.05 | -0.18 | 0.02 | No |
| >1250 | 30-49 | -0.06 | 0.04 | -0.15 | 0.01 | No |
| >1250 | 50-69 | -0.05 | 0.04 | -0.13 | 0.03 | No |
| Total effect | Income | -0.047 | 0.016 | -0.082 | -0.020 | Yes |
| | Age | 0.009 | 0.019 | -0.028 | 0.048 | No |

*Factors: Eco: Environmental interest, PVK: PV knowledge level, PBC: Perceived behavioural control, Pr: Price sensitivity, SE: booted standard error, LLCI & ULCI are booted lower and upper levels for confidence interval a path.*

*Table E.2. 2 Summary of the complex interaction between variables of the SA and WTP models and the hypothesis results*

*Note: "~": tested but insignificant, "-": tested but no interaction, black highlighted: not be tested.*

| Variable | Description | Mean | Std. Deviation | Mediators | | | | Impact on SA | | Impact on Price sensitivity | | Role in the SA model | Hypothesis result | Role in the WTP model | Hypothesis result |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | PV knowledge | Att | SN | PBC | Direct | Indirect | Direct | Indirect | | | | |
| Environmental interest | Of respondent | 2.807 | 0.75977 | .588 | .086 | - | .120 | .073 | 0.064 | 0.750 | -.047 | Target variable | Support | Target variable | Support |
| Income (Euro/month) | Net income of the household | 4.33 | 1.87 | .052 | ~ | .071 | ~ | .016 | - | 1.183 | ~ | Covariate | Support | Moderator | Support |
| PoR | Place of the respondent' home | 1.7 | 0.784 | - | ~ | ~ | ~ | - | - | 0.720 | ~ | - | - | Covariate | Support |
| Age | Of respondent | 2.52 | 1.191 | ~ | ~ | ~ | - | ~ | - | ~ | ~ | Covariate | Reject | Moderator | Reject |
| Marital status | Of respondent | 2.53 | 0.961 | - | - | ~ | - | ~ | - | - | - | Covariate | Reject | Moderator | Reject |
| Children | Of respondent | 1.71 | 0.454 | - | - | ~ | ~ | ~ | - | ~ | - | Covariate | Reject | Covariate | Reject |
| Electricity bill (Euro/month) | Electricity bill of the household | 2.68 | 1.163 | ~ | - | ~ | ~ | ~ | - | - | - | Covariate | Reject | Covariate | Reject |
| Education | Of respondent | 2.86 | 0.978 | - | - | - | - | - | - | ~ | - | - | - | Covariate | Reject |
| PV knowledge | Of respondent | 2.32 | 1.011 | | ~ | ~ | ~ | .052 | 0.036 | ~ | ~ | Mediator | Support | Mediator | Support |
| Att | Of respondent | 4.0362 | 0.73501 | ~ | | ~ | .433 | .225 | ~ | ~ | -.91 | Mediator | Support | Mediator | Support |
| SN | Social pressure on the respondent | 3.7193 | 0.90327 | ~ | .405 | | .300 | ~ | ~ | ~ | ~ | Mediator | Reject | Mediator | Reject |
| PBC | Of respondent | 3.7601 | 0.74888 | ~ | ~ | ~ | | .195 | 0.028 | 1.593 | ~ | Mediator | Support | Mediator | Support |
| SA | Of respondent | 3.7692 | 0.64658 | | | | | | | ~ | ~ | Output | | Mediator | Reject |
| AMC | Zero-centred variable | 0 | 0.585 | ~ | -.082 | .072 | ~ | .086 | - | | | Covariate | Support | Covariate | Reject |
| SN & PBC | Interaction | | | | | | | | -0.005 | | | Mediated | | | |
| SN & Att | Interaction | | | | | | | | -0.008 | | | Mediated | | | |
| Att & PBC | Interaction | | | | | | | | 0.009 | | | Mediated | | | |
| SN& Att & PBC | Interaction | | | | | | | | -0.003 | | | Mediated | | | |
| PBC x Income | Interaction | | | | | | | | | - | -0.376 | | | Moderated | |
| PVK x Age | Interaction | | | | | | | | | - | 0.286 | | | Moderated | |
| PVK x Income | Interaction | | | | | | | | | - | -0.154 | | | Moderated | |
| SN x Income | Interaction | | | | | | | | | - | 0.220 | | | Moderated | |
| SN x Age | Interaction | | | | | | | | | - | -0.244 | | | Moderated | |

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