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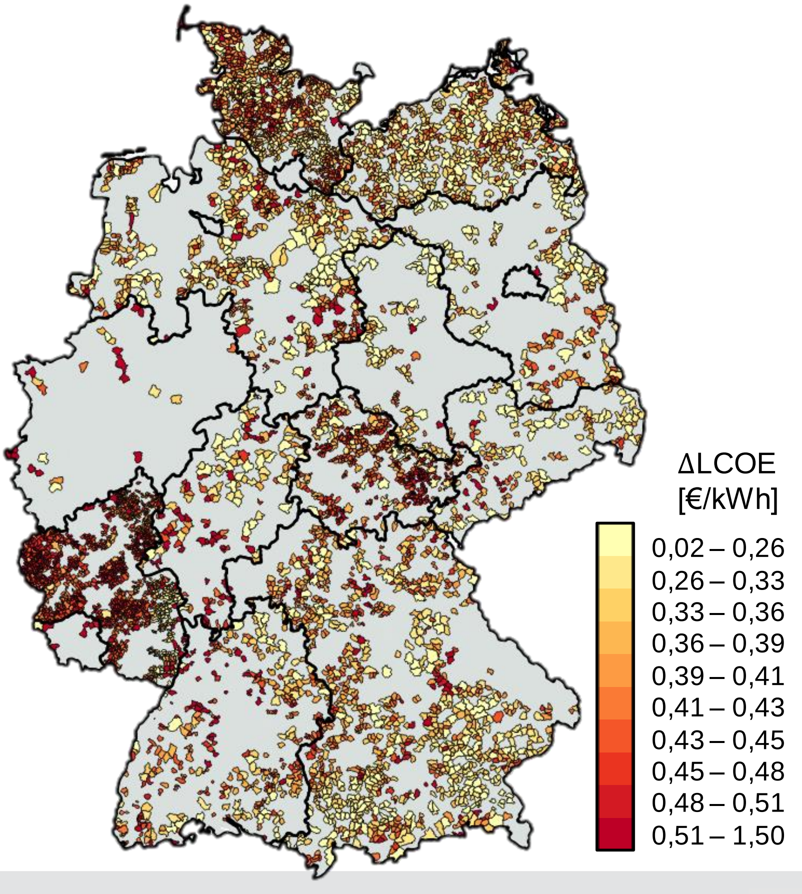
No. 40 | April 2020

WORKING PAPER SERIES IN PRODUCTION AND ENERGY



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***Index Terms*—Energy autonomy, renewable energy, geothermal power generation, electric vehicles, vehicle-to-grid, mixed integer linear programming, regression analysis.**

I. Introduction

The share of renewable energies (RE) in electricity generation has increased steadily in the past years. In 2018, REs already accounted for a third of the worldwide installed electricity capacity [1]. The planning of RE power plants has to be closely coordinated with power grid planning. By simultaneously considering grid and RE expansion, the costs of using local resources can be weighed against the costs of grid expansion to sites with higher RE potential [2]. However, many studies focus on just one of these aspects. For example, [3] and [4] concentrate on large-scale transmission grid planning with fixed generation capacities. At the same time, studies on transmission grid planning are often based on centralized RE generation [5-7].

However, [8] finds that a decentralised RE expansion could be economically favourable, largely due to higher required grid expansion costs in the centralized case. In fact, the expansion of RE resources is mainly decentralized due to their characteristics. Thus, the vast majority of the installed capacity of RE plants is connected to the distribution grid [9]. Related to this, in many countries, the owner structure of energy plants is changing: for example, the majority of German RE plants are actually owned and operated by private individuals, farmers and communities [10]. In this context, an increasing number of municipalities are striving for energy autonomy due to drivers like tax revenues and environmental awareness [11]. These municipalities mainly focus on *annual municipal energy autonomy (AMEA)*, whereby the local RE generation exceeds the annual demand. In addition, some municipalities strive for *complete municipal energy autonomy (CMEA)*, a state in which no energy is imported (i.e. “off-grid”) [12].

For future power grid designs, the questions of whether, which, how many and at what cost municipalities could become completely energy autonomous is of interest. To this end, the whole energy system with all energy consumption sectors - industrial, commercial, residential and transport - should be considered in municipal energy system analyses. Energy autonomy in municipalities has already been examined in [12–16]. Some of these studies are limited to the residential sector [12, 13]. Others also include further sectors. Thereby, the industrial energy demand is determined by surveys [16], interviews [15] or measurements of actual transformer substations [14]. Therefore, the application of these methods to other municipalities would require considerable effort. Since only individual municipalities or regions are considered in the studies, the results cannot be used to develop scenarios for future national energy systems. Furthermore, none of these studies investigates the impact of the flexibility through electric vehicles (EV) on costs.

This paper aims to address the identified shortcomings of the studies on municipal energy autonomy. To this end, the energy systems of 15 municipalities are first analysed in detail with the

The authors gratefully acknowledge the financial support of the PhD College “Energy and Resource Efficiency” (ENRES), from the Federal State of Baden-Wuerttemberg, for funding the first author’s PhD studentship. The contribution of the third author (MK) was supported by the Helmholtz Association under the Joint Initiative “Energy Systems Integration” (funding reference: ZT-0002).

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aid of an optimization model. This model is extended to include the personal transport, industrial and commercial sectors. Thereby, the assumption is made, that all vehicles of the personal transport sector are replaced by EVs. The optimization results are transferred to further municipalities by means of a regression model. Based on the results, energy scenarios could be derived for future planning of electricity grids. At the same time, the following research questions are addressed:

1) How many and which municipalities can become energy autonomous?
2) Which cost increase would be associated with achieving energy autonomy in these municipalities compared to the optimized energy system without energy autonomy?
3) What impact does the consideration of the industrial, commercial and personal transport sector have on costs in off-grid municipalities?

Germany is selected as the case study for this paper since the developments in energy autonomy described in this introduction particularly apply to this country.

The organization of this paper is as follows: In section II, the methodology for optimizing energy systems in municipalities and transferring the results is presented. The results are then explained and discussed in section III and IV respectively, before the study concludes in section V.

II. Methodology

In this section, a method for determining the energy demand of the industrial, commercial and residential sector (cf. section II.A) as well as the RE potential (cf. section II.B) is presented. Section II.C explains how relevant municipalities for this study are identified using these demands and potentials. Subsequently, the RE³ASON model for energy system analysis is explained (cf. section II.D), which is extended by the industrial and commercial sectors (cf. section II.E) as well as personal transport sector (cf. section II.F). Finally, section II.G presents the methodology for transferring results of the RE³ASON model to other municipalities.

A. Demand of Energy Consumption Sectors

The assessment of the electricity demand for the residential, commercial and industrial sector is based on [17]. The assumption is made that the electricity demand of a municipality correlates with selected socio-economic indicators. Since the electricity demand and the corresponding indicators are known on a national level [18], the municipal electricity demand can be downscaled from the national level on the basis of the relative ratio of these indicators ("top-down scaling”). Based on the assumption that the significance of an indicator as a measure of size can be different for each sector, a weight matrix is used to indicate how strongly each indicator is weighted (cf. Table I). The weightings are determined by minimizing the mean square error in comparison to measured consumption values. For this purpose, 17 German municipalities are considered for which the annual electricity consumption is measured and published by sector [19–21].

The non-dimensional parameter *sector size* ($ss_{m,s}$) indicates the size of the respective sector s in the municipality m under consideration in relation to its size in Germany. The sector size is calculated on the basis of the weight matrix $w_{s,i}$, as well as the municipal ($IV_{m,i}$) and national ($IV_{N,i}$) values of all indicators I by means of the weight matrix:

$$ss_{m,s} = \sum_{i \in I} w_{s,i} \cdot \frac{IV_{m,i}}{IV_{N,i}} \tag{1}$$

The electricity demand ED in the municipality m and sector s is thus calculated by applying the sector size as a scaling factor for the corresponding national electricity demand ED_N:

$$ED_{m,s} = ED_{N,s} \cdot ss_{m,s} \tag{2}$$

TABLE I
Weight Matrix $w_{s,i}$, for Assigning a Weight to each Indicator i to Calculate the Size of the Sector s. Sources of Indicators: [22–24].

Indicators	Residential sector	Commercial sector	Industrial sector
Area	0.075	0.000	0.787
Population	0.925	0.958	0.168
Number of industrial companies	0.000	0.000	0.015
Number of industrial employees	0.000	0.000	0.010
Gross salaries in industry	0.000	0.000	0.012
Number of employees with social security contributions	0.000	0.042	0.008

B. Renewable Energy Potential

The determination of the RE potentials in this section serves to select the municipality population to be investigated in this study (cf. section II.C). In [25], the potentials of residential rooftop photovoltaics [26] and wind energy [27] in Germany have been allocated at municipal level. As further potentials, the bioenergy and the deep geothermal energy potential in German municipalities are considered in this study using the methods from [17] and [12]. The bioenergy includes wood combustion plants and biogas plants. The data for forest area and agricultural land in the specific municipalities is taken from [24]. Furthermore, the fraction of the usable area is assumed to be 33% according to [28]. The hydrothermal temperatures for calculating the deep geothermal potential are taken from an open data set [29].

C. Selection of Municipality Population

By means of the methods in sections II.A and II.B, the annual electricity demand and potential RE electricity supply can be determined for each municipality in Germany. If the demand exceeds the supply, the respective municipality cannot achieve AMEA and thus especially not CMEA. Therefore, these municipalities are excluded from the municipality population beforehand. This calculation of AMEA neglects imports from neighbouring municipalities, which would be excluded anyway for CMEA.

The energy consumption patterns in the industrial sector show a high variety (cf. section II.D). Therefore, a standard load profile cannot adequately represent this sector. To minimize the impact on the results when using a standard load profile, only micro and small enterprises as defined by the European Commission [30] are taken into account. Therefore, municipalities with medium-sized and large industries (i.e. enterprises with more than 50 employees) are excluded from the present analysis. When excluding the municipalities, the manufacturing industry serves as a representation for all economic sectors, since this branch accounts for the largest proportion of energy consumption [31] and the employment figures are only available for this sector at municipal level [32]. However, even small enterprises can be energy-intensive. Therefore, municipalities with companies from the *European Pollutant Release and Transfer Register* (PRTR) are additionally excluded. European companies must declare their emissions in this register, if the emission level exceeds certain thresholds [33] (100,000 tCO_2/a for greenhouse gases [34]).

D. RE³ASON Model

After determining the municipality population, the costs for achieving CMEA can be determined for these municipalities. The "Renewable Energies and Energy Efficiency Analysis and System OptimizatioN" (RE³ASON) model is used to calculate these costs, as it can be applied to any municipality in Germany without additional data collection. This is related to the fact that the model uses publicly available data to determine energy demand and potential energy supply. The optimization minimizes the total discounted system costs over the whole model horizon. Thereby, the types, dimensions and dispatch of the energy technologies and measures are optimized. The optimization takes a macroeconomic perspective and optimizes four years with 108 time slices each. The time horizon of the optimizations reaches until 2030 and the years 2015, 2020, 2025 and 2030 are optimized. Except for district heating, no explicit network infrastructure is considered in the model. Detailed information about the actual state of the model can be found in [17] and [13]. In the present study, the model is extended by the electricity demand of the commercial and industrial sector (cf. section II.E). Furthermore, EVs are implemented to represent the personal transport sector (cf. section II.F).

E. Implementation of Industrial and Commercial Sectors

Electricity load profiles enable to scale the calculated energy demand $ED_{m,s}$ to one year. For the commercial sector standard load profiles are used [35]. The electricity demand of the commercial sector *c* in a municipality *m* at hour *t* ($E_{m,c,t}$) is calculated as follows:

$$E_{m,c,t} = E_{c,t} * \frac{ED_{m,c}}{E_{c,sum}} \tag{3}$$

$E_{c,t}$ is the electricity demand at time t and $E_{c,sum}$ the annual electricity demand of the standard load profile. The data set with industrial load profiles used in [36] contains three load profiles for small enterprises, which are used in the present study. The mean profile of the companies for *Shipping, Shaping of sheet* and *Iron casting* is used in this study as load profile for the industrial sector. Equation (3) can then be used to scale the demand profile analogously to the commercial sector.

F. Implementation of the Personal Transport Sector

This study assumes that all vehicles of the personal transport sector in a municipality are replaced by EVs. Thereby, the flexibility potential of the EV fleet is derived as follows. In a first step, flexibility potentials of single vehicles are generated with a model developed in [37]. The model uses representative mobility data of conventional vehicles in Germany [38] and simulates two extreme charging scenarios for each of them, given the assumption that an EV would replace them. The results include one-week time series for an as-soon-as-possible (ASAP) and an as-late-as-possible (ALAP) charging scenario, which can be considered as flexibility potentials for each vehicle. We assume that every vehicle has the possibility to charge both at home and at work, and that it is connected to the charging station throughout the parking duration.

The next step aims at aggregating the single vehicle flexibility potentials to a flexibility potential of one hypothetical battery which represents the municipality's EV fleet (cf. (4)). Therefore, we add the single vehicles' battery capacities C_{EV} to the fleet's battery capacity C_f. $N_{EV,m}$ is the number of EVs in a municipality, available from [39].

$$C_f = C_{EV} \cdot N_{EV,m} \tag{4}$$

In (5), the upper boundary for the fleet's battery state of charge $SoC_t^{max,f}$ in a time slice *t* is derived by totaling the single EVs' $SoC_{t,v}^{max,EV}$ which results when the vehicle is charged according to the ASAP-strategy. The single vehicle *v* is part of the total number of simulated EVs (V). In order to account for the representativeness of the vehicles in the dataset, the time series for $SoC_{t,v}^{max,EV}$ are weighted by the vehicle weightings w_V. By dividing them by the sum of all weightings, the resulting weighted time series represents the average of the fleet. Finally, the flexibility potential is scaled on municipality level with the number of EVs in the municipality.

$$SoC_{t,m}^{max,f} = \sum_{v=1}^{V} \left(SoC_{t,v}^{max,EV} \cdot w_V\right) \cdot \left(\sum_{v=1}^{V} w_V\right)^{-1} \cdot N_{EV,m} \tag{5}$$

$SOC_t^{min,f}$ is calculated accordingly based on the simulated ALAP-strategy. The power discharged from the EV battery by driving $P_t^{dr,f}$ and the available charging power $P_t^{max,f}$ are also determined analogously. The latter depends on the power of the charging station and whether the vehicle is parked at one of its charging locations or not.

As shown in [37], the driving and charging patterns vary for different degrees of urbanization. Since most municipalities from the preselected population are located in rural areas (cf. section III.A), the mobility data is preselected by geographic criteria. The data of vehicles in rural areas with higher and lower density, according to the municipality grouping by BBSR [40], are considered. The resulting flexibility potential pattern of the fleet is used for each municipality and varies by scaling with the number of EVs per municipality. Further assumptions are listed in Table II. The mean value of 3.7 – 22 kW charging power in low-voltage grids is used as available charging power.

Controlled bidirectional charging is selected as charging strategy for the EVs [42]. Therefore, the charging process is controlled by the municipal energy management system with regard to load, time and limitations by the mobility patterns. In addition, the battery can be discharged to feed electricity into the municipal grid, known as *vehicle-to-grid* (V2G). The main modelling aspects of the EVs are listed below, for further information please refer to [42]. The SoC of the EV batteries (SoC_t^f) depends on the previous SoC (SoC_{t-1}^f), the (dis-)charging efficiency (η_{EV}), the charge power ($P_t^{ch,f}$) as well as discharge power ($P_t^{V2G,f}$) and the power required for driving ($P_t^{dr,f}$) [42]:

$$SoC_t^f = SoC_{t-1}^f + \frac{(P_t^{ch,f} \cdot \eta_{EV} - P_t^{V2G,f}/\eta_{EV} - P_t^{dr,f}) \cdot dt}{C_f} \quad \forall t \epsilon T (6)$$

At a SoC above 75%, the charging power reduction ($P_{t,max,red}$) increases linearly according to (7) [41]. P_{SE} is the available charging power of the supply equipment.

$$P_{t,max,red} \geq P_{SE}\left(4 \cdot SoC_t^f - 3\right) \quad (7)$$

Equation (8) ensures that for each day d the EVs are charged with the energy required for driving $P_t^{dr,f}$. This implies that the load shift potential can only be exploited within one day and thus limits the usage of EV flexibility to a more conservative range.

$$\sum_{t=1}^{24}\left(P_t^{ch,f} - P_t^{V2G,f}\right) \cdot dt \geq \sum_{t=1}^{24} P_t^{dr,f} \cdot dt \quad \forall d \epsilon D \quad (8)$$

As in [42], the investment in EVs is assumed to be personal, preference-driven and for mobility reasons only. Therefore, this investment is not considered in the optimizations.

G. Transfer of Results

The RE³ASON model is applied to determine the cost-minimal energy system for preselected municipalities as case studies. On the one hand for the reference case without autonomy and on the other hand for the case with CMEA. In the reference case, the energy system is optimized without restricting imports and exports. Subsequently, the *Levelized Cost of Energy* (*LCOE*) are calculated for both cases and all preselected municipalities (cf. (9), [43]). Thereby the conversion factor for electricity into heat is assumed to be the heat pump`s coefficient of performance (3.5) as in [43], since the heat load is taken into account for the residential sector.

$$LCOE = \frac{\sum_{y=1}^{Y} \frac{CAPEX_y + OPEX_y}{(1+r)^y}}{\sum_{y=1}^{Y} \frac{E_{m,total,y}}{(1+r)^y}} \quad (9)$$

The LCOEs are calculated depending on the investments (*CAPEX*), the operational and maintenance costs (*OPEX*), the total energy demand ($E_{m,total}$) and the year y. The interest rate r is assumed to be 5%.

A regression is used to transfer the results of the case studies to the entire municipality population. The dependent variable is the difference between LCOEs in the autonomous and in the reference case ($\Delta LCOE$). In the selection of the independent variables, those that correlate with other variables are eliminated. Therefore, for all correlations above |0.9| one variable is excluded.

To avoid an overfitting in the regression, a *k-fold cross-validation* is applied [44]. Since our sample is small (n = 15), the *leave-one-out cross-validation* is used, with k = n = 15. 19 different methods are applied, ranging from linear regression models and support vector machines to Gaussian Process Regression models. From these methods, the model that results in the lowest root mean squared error is selected.

TABLE II
Assumptions for Modelling EV Flexibility.

Parameter	Value	Unit	Source
Battery capacity (C_{EV})	50	kWh	[40]
EV energy consumption	10.2	kWh/100 km	[40]
EV battery efficiency (η_{EV})	90	%	[41]
Number of simulated EVs (V)	229		[36, 37]
Available charging power ($P_{t,v}^{max,EV}$)	13	kW	Assumption
SoC-range during operation	5-100	%	Assumption

III. Results

In section III.A, the municipality population examined in this study is presented. In addition, case studies are selected for investigation in the RE³ASON model. Subsequently, the optimization results of these case studies (cf. section III.B) as well as sensitivity analyses (cf. section III.C) are explained. Finally, section III.D presents the results of the regression.

A. Case Studies

The methodology described in section II.C results in an exclusion of 3,120 municipalities that are not suitable for AMEA, 2,656 municipalities with large industries and 616 municipalities from the PRTR Register (grey area in Fig. 4). The remaining 6,314 municipalities correspond to 56% of the municipalities, 14% of the population, 40% of the land area and 23% of the annual electricity consumption of Germany.

As case studies, municipalities which differ particularly with regard to the independent variables from the regression are selected from the municipality population. For each indicator, one municipality is selected that has the maximum or minimum value for this indicator. As for some indicators the municipalities are the same, a total of 15 different municipalities remain for examination, which are geographically distributed across Germany.

B. Energy System Optimization Results

For one of the 15 investigated municipalities, Prinzenmoor, the resulting LCOEs are shown in Fig. 1, for the reference case without CMEA (P1) and with CMEA (P2). Results of other scenarios (P3 to P6) are explained in section III.C.

Prinzenmoor is a small municipality with only 179 inhabitants. The electricity demand in the industrial, commercial and residential sectors is 2.9 GWh/a, 0.3 GWh/a and 0.2 GWh/a respectively.

The value range of the y-axis in Fig. 1 contains negative values (up to -0.1 €/kWh), since exports result in a small negative contribution to the LCOEs in P1. In the autonomy case P2, the energy system of Prinzenmoor changes greatly. Whereas in P1 the energy is provided by wind turbines and power grid, in P2 the entire energy is provided by deep geothermal energy. The geothermal plant is used for base load operation, while the EV batteries in the municipality are discharged to cover peak loads.

For P2, the electricity supply and demand for a typical weekday in 2015 are given in Fig. 2. The high electricity demand of the residential sector at night is remarkable. This is due to the fact that buildings are considered as daily energy storages in RE³ASON. Therefore, during the night hours, when the electricity demand of the other sectors is low, a large part of the heat demand is covered by electric storage heaters and heat pumps. Due to the base load operation of the geothermal plant, electricity surpluses occur in time steps with low electricity demand. Parts of the surpluses are used to charge the batteries of the EVs. A comparison of the power from charging ($P_t^{ch,f}$) and V2G ($P_t^{V2G,f}$) with the maximum available charging or discharging power P_{SE} shows that no more than 60% of the battery flexibility is exploited in the various time steps of the optimization.

CMEA is associated with a high increase in LCOEs in Prinzenmoor (ΔLCOE = 0.45 €/kWh, cf. Fig. 1). In all 15 examined municipalities, the increase in LCOEs range between 82% and 487%, which corresponds to ΔLCOE between 0.19 €/kWh and 0.55 €/kWh. Biomass and additional battery storages are installed in almost every municipality. Geothermal plants are built in 10 of the 15 municipalities, partly supported by biomass, wind and solar energy.

In most municipalities and if CMEA has to be achieved, surplus electricity occurs in hours in which the generation exceeds the demand (cf. Fig. 2 for Prinzenmoor). The surpluses range from 0 to 4 GWh/a. In P2 the surpluses amount to about 50% of the total energy demand of the municipality, which is the highest share among all 15 municipalities. Between 2015 and 2030, the average surpluses are reducing from around 2 GWh to 1 GWh in all municipalities. This is due to the fact that several volatile generation technologies, which are installed in the municipalities in 2015, are replaced over time. The average CO_2 abatement costs for the 15 municipalities are around 3.7 k€/tCO_2. For a detailed discussion of RE³ASON model results, including demand and generation patterns, please refer to [13].

C. Sensitivity Analyses

In the sensitivity analyses (cf. Table III), the reference scenario for the autonomy case P2 is changed in order to examine the influence of model extensions and assumptions (P3, P5 and P6). Secondly, the influence of geothermal plants is investigated, as in many German municipalities no geothermal potential exists (P4).

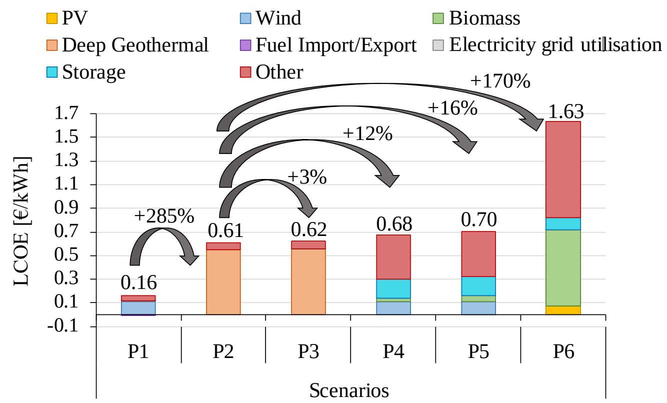

Fig. 1: Technology-specific LCOE contributions for the optimal energy systems in the municipality Prinzenmoor for six different scenarios. The share "Other" includes costs for insulation, heating systems, appliances and lighting in the residential sector.

In order to quantify the uncertainty resulting from the chosen industrial load profiles (cf. section II.E), in scenario P3 the mean profile is replaced by the load profile of the *Iron Casting Company*, which shows higher peaks. The maximum peak is 105% higher than in the mean profile. Consequently, the LCOEs increase by 3% (cf. Fig. 1). In Prinzenmoor, the industrial sector accounts for about 80% of the energy demand. The change in the industrial load profiles therefore has a rather small influence on the results.

If no geothermal plant may be built in scenario P4, the energy is provided by wind and biomass (cf. Fig. 1). Due to the volatile wind energy production, additional storages are required. In addition, more efficiency measures are implemented, such as more efficient household appliances and the insulation of buildings. Especially the efficiency measures and further storages are responsible for the LCOE increase of 12% compared to P2. However, the low increase in costs shows that even municipalities without a large base load potential can become autonomous at comparable costs. Compared to P2, the electricity surpluses are 80% lower. This is because there is less base load in operation in P4 and therefore not so many time

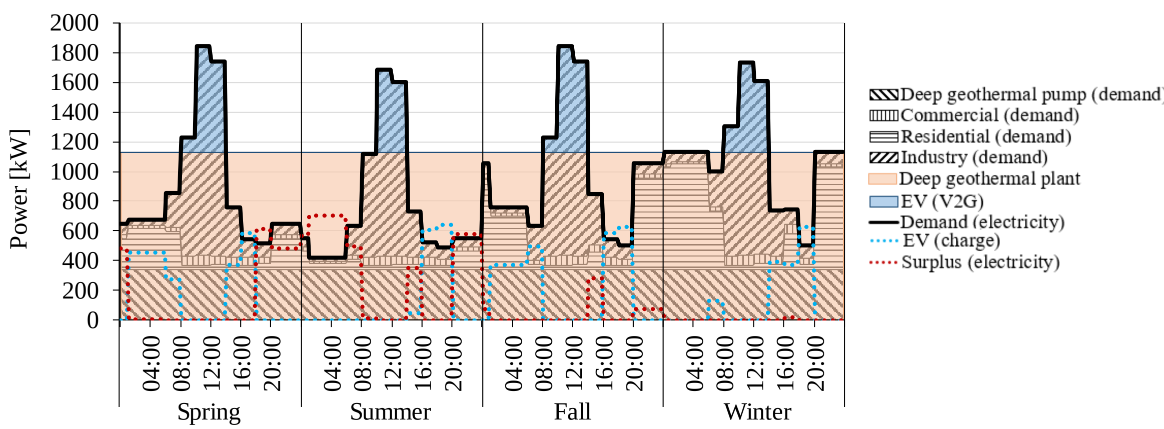

Fig. 2: Electricity generation and demand patterns for a typical weekday in all four seasons in 2015.

steps with surplus electricity as in P2 (cf. Fig. 2).

Due to the electricity surpluses from the geothermal plant in P2, the storage capacities of the EVs are beneficial. However, if a scenario without EVs (P5) is considered, the construction of the geothermal plant is no longer economical. In this case, additional storages have to be installed in order to use much energy from the geothermal plant. Alternatively, the geothermal plant could be dimensioned smaller. However, this type of plant incurs very high fixed costs, and therefore this would not be economical either. This shows that, depending on the conditions of the energy system, the storage capacities of the EVs can moderately reduce costs (by 16% compared to P2). In an energy system without deep geothermal potential, though, the costs would increase only slightly (comparison between P4 and P5).

Due to the consideration of the industrial and commercial sectors in addition to the residential sector, energy autonomy is not feasible in every municipality (cf. section III.A). However, at the same time, the LCOEs for achieving autonomy are greatly reduced (comparison of P2 and P6), since fixed costs of the system are related to a significantly larger amount of energy. Prinzenmoor is an extreme case, due to the small size of the municipality. However, to a lesser extent, this statement can be applied to other municipalities as well.

TABLE III
Scenarios of the Sensitivity Analysis in Prinzenmoor.

Scenario	Differences to reference scenario P2
P3	Load profile of industrial companies (Iron Casting)
P4	Without geothermal plants
P5	Without EVs
P6	Without industrial and commercial sector

D. Regression Results

After the correlation analysis, the following six indicators remained for the regression: industrial electricity demand, residential electricity demand, population density, technical geothermal potential, technical wind energy potential and technical bioenergy potential. From the 19 models of the 15-fold cross validation, *stepwise linear regression* proved to be the best method. The model whose results are shown in Fig. 3 yields the error measures in Table IV.

The technical bioenergy potential and the products of residential electricity demand and population density as well as residential electricity demand and technical geothermal potential are selected as features for the regression. The fact that the industrial electricity demand and the technical wind potential are not used in the regression could be related to the correlation above 0.8 with the technical bioenergy potential.

After applying the regression model to all 6,314 municipalities, 155 outliers downwards (ΔLCOE≤0.02 €/kWh) and 31 upwards (ΔLCOE≥1.50 €/kWh) are eliminated. This is done due to the high R^2 (0.86) as this could indicate a slight overfitting of the model. A lower bound of 0.02 €/kWh was chosen as this corresponds to a cost increase of about 5% in relation to the LCOEs of the 15 investigated municipalities. Fig. 4 shows the 6,128 remaining municipalities and the distribution of ΔLCOE. Among these municipalities, the mean value of ΔLCOE is 0.41 €/kWh. The data of municipalities with ΔLCOE, demand of the sectors and RE potential can be provided upon request.

When distributing the regression results according to the ten German municipality clusters from [26], the results seem plausible: The highest mean ΔLCOE is reached in cluster 2 (0.578 €/kWh), which mainly contains cities with low RE potential. On the other hand, the lowest mean ΔLCOEs are achieved in clusters 3 (0.350 €/kWh), 4 (0.349 €/kWh) and 8 (0.379 €/kWh), which contain mainly rural municipalities with particularly high potential for RE and especially deep geothermal energy.

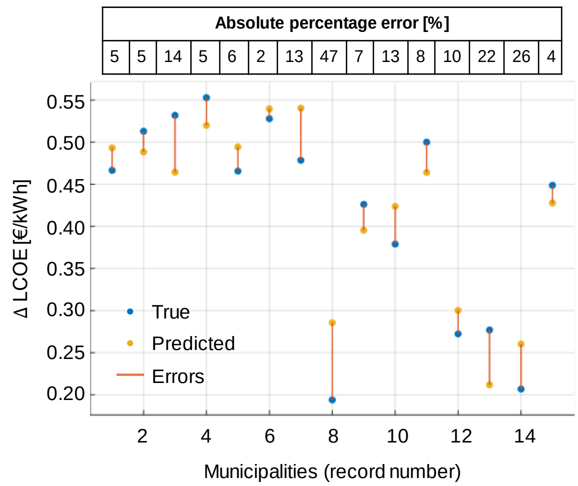

Fig. 3: Results of the stepwise linear regression. The error margins between the results from the optimizations (true) and the predicted values from the regression are shown.

TABLE IV
Resulting Error Measures of the Stepwise Linear Regression.

Root mean squared error	0.047
Mean absolute percentage error	0.125
R-squared	0.860

IV. Discussion and Critical Appraisal

In this study, a methodology for determining LCOEs for achieving energy autonomy in all municipalities of a country was presented. Germany was used as a case study, but the general methodology can also be applied to any other country.

The study has shown that achieving CMEA is associated with large additional costs of 0.41 €/kWh on average. Thus the costs per kWh are more than doubled compared to an optimized energy system without autonomy. Therefore, future studies at a national level should investigate whether and where CMEA is worthwhile if grid expansion is taken into account. Thereby, the results of the present study can serve as a scenario in the design of transmission networks. For example, the assumption could be made that all municipalities with ΔLCOE less than the mean value (0.41 €/kWh) will become autonomous. Then the demand and feed-in from these municipalities could be excluded from the analyses. Furthermore, simultaneous optimization of transmission grid expansion and selection of autonomous municipalities could be performed to determine the optimal future national energy system.

The LCOEs and ΔLCOEs have probably been overestimated in this study. Firstly, due to the separate consideration of individual municipalities. The municipal boundaries represent administrative units that do not necessarily have to represent optimal boundaries for energy systems. In addition, the simultaneous optimization of neighbouring municipalities could lead to lower LCOEs than in individual cases. Instead, the electricity surpluses which could be used in neighbouring municipalities to cover parts of the demand are curtailed. Also, the reference case for the determination of the ΔLCOE is an optimized energy system without autonomy, which in reality does not exist in most municipalities. Furthermore, the expression of these costs in absolute terms, irrespective of the municipality size or energy system structure, could be misleading. An improvement could be to redistribute these costs per final consumer, in order to give a more meaningful and comparable indicator.

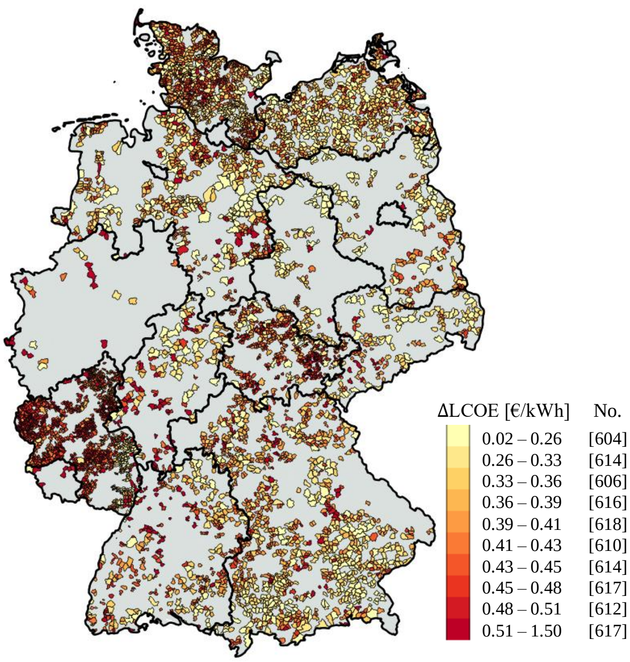

Fig. 4: Illustration of 6,128 [55%] German municipalities that can become completely autonomous and the associated ΔLCOE.

In addition, part of the costs could be underestimated as no grid infrastructures in or outside the municipality were considered. Also, a standard load profile was used to include the electricity demand of the industrial sector. The sensitivity analysis showed that a different structure of the load profile does not have a large influence on the costs. However, the load profiles in individual municipalities could differ greatly from those used in this study. Furthermore, the modelling of EVs could also be improved. Instead of an aggregated driving profile, individual or clustered driving profiles could be used. The computing time of the energy system model would then be a particularly restrictive factor. All of these improvements should be explored in future studies.

Moreover, the regression was used to transfer the results to a large number of municipalities whose individual analysis would not be possible in a single study. However, optimization and subsequent regression do not replace detailed planning of the energy system of a single municipality.

V. Conclusions

In the present study, a methodology was developed to determine the feasibility and costs for complete municipal energy autonomy. First, methods for estimating the energy demand and potential for renewable energies were proposed. On this basis, municipalities in which complete energy autonomy is not feasible could be excluded. Subsequently, an energy system optimization model was extended to include the personal transport, industrial and commercial sectors and applied to a number of municipalities in order to determine the costs for complete energy autonomy. In a final step, the results were transferred to further municipalities using selected indicators in a regression model.

In this paper, Germany has been selected as case study, where 6,314 (56%) municipalities were identified, in which complete energy autonomy could be technically feasible. Of these municipalities, 15 were selected as case studies, which differ greatly in terms of the indicators used in the regression analysis. The results of the optimizations showed the influence of individual technologies and measures on the levelized cost of energy (LCOE). Thereby, it became apparent that complete energy autonomy is always associated with a high cost increase. Furthermore, the integration of the industrial and commercial sectors has a reducing effect on the LCOEs, since fixed costs are distributed across a larger amount of energy. In addition, the flexibility of electric vehicles can moderately reduce LCOEs. Using a stepwise linear regression model (mean absolute percentage error = 12.5%), the results of the optimizations could finally be transferred to the 6,314 municipalities. On average, the additional LCOEs, which have to be paid in the autonomous compared to the reference (minimal cost) case, amount to 0.41 €/kWh. Apart from energy demand, base load capable bioenergy and deep geothermal energy appear to have the greatest influence on the LCOEs.

The main areas for improving the methodology include the consideration of grid infrastructures and surplus electricity from neighbouring municipalities, as well as more detailed modelling of industrial demand. The method of calculating and comparing the costs of energy autonomy should be improved to express these costs per municipal end user. In future studies in which the national energy system or transmission grid expansion is planned, the results of this paper can be used as a possible scenario.

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nationales Forschungszentrum in der Helmholtz-Gemeinschaft

Working Paper Series in Production and Energy
No. 40, April

ISSN 2196-7296