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Scaling energy system optimizations: Techno-economic assessment of energy autonomy in 11 000 German municipalities

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ABSTRACT

Increasing energy autonomy is one of the main reasons for municipalities to invest in renewable energy technologies. In this study, the potential of weather-robust autonomous energy systems is evaluated for 11 003 German municipalities in over one million parallelized techno-economic optimizations utilizing high-performance computing clusters. For this purpose, a holistic municipal-level energy system model (ETHOS.FineRegions) was developed that minimizes annualized system costs in 2045. The completely energy autonomous supply can be established in around 90% of German municipalities corresponding to 50% of the country‘s population. Especially highly populated municipalities often do not have the capacity to meet their own energy demands due to low wind and open-field PV potentials. Large rooftop PV capacities account for 40% of installed capacity in the autonomous municipalities. Seasonal storage needs are met by large underground thermal storage tanks and batteries provide intraday storage. Furthermore, huge capacity increases are often required for the final 20% of energy demand to be met in order to achieve a degree of autonomy of 100%. The large storage and rooftop PV capacities lead to high specific system costs in the autonomous municipalities with between 144 €/MWh and 174 €/MWh on average, depending on legislation and opposition towards onshore wind installations. By paying a premium of up to 50% compared to the grid-dependent system, 3945 municipalities with 17.2 million inhabitants could become completely autonomous by 2045. For regions that could achieve an autonomous energy supply at moderate costs, however, lost revenues through energy exports could be a decisive argument against autonomy efforts.

1. Introduction

Countries around the world are shifting towards low-carbon energy sources to reduce carbon emissions from energy supply activities. In 2021, the energy sector in Germany contributed the largest share to national greenhouse gas emissions, at 32%. The German Climate Protection Act 2021 [1], has set the goal of decarbonizing Germany's energy supply by 2045, particularly through the expansion of renewable energy sources [2]. In 2022, the share of energy supplied using renewable sources reached 46%, 17%, and 7% for electricity, heating, and transport sectors, respectively [3]. The adoption and deployment of new renewable technologies is mainly distributed, which is evident in Germany with more than 4.4 million solar power plants spread throughout the country [4]. The large number of distributed generators in the electricity system has led to various local producers generating their own electricity.

There are many motivating factors for local electricity generation. In surveys, economic incentives, environmental protection, as well as self-sufficiency efforts are cited as reasons why ever larger segments of the population are generating their own electricity [5]. Many of these local energy systems operate at the collective level of communities or municipalities. In German municipalities, the striving for energy autonomy or self-sufficiency in so-called energy regions is becoming increasingly prevalent. The motives of the actors to formulate such goals

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Nomenclature

Parameters and Variables

$C_{OffshoreWind}$	Capacity of offshore wind turbines [MW]
$C_{OnshoreWind}$	Capacity of onshore wind turbines [MW]
C_{PV}	Capacity of photovoltaic plants [MW]
$CF_{OffshoreWind}$	Capacity factor of offshore wind turbines [–]
$CF_{OnshoreWind}$	Capacity factor of onshore wind turbines [–]
CF_{PV}	Capacity factor of photovoltaic plants [–]
CF_{RE}	Normalized generation by renewable energy sources [MW]
D	Energy Demand [MWh]
D_E	Electricity demand [MWh]
$D_{E,eq}$	Electricity-equivalent demand [MWh]
D_H	Heat demand [MWh]
D_{H_2}	Hydrogen demand [MWh]
$D_{PH,HT}$	High-temperature process heat demand [MWh]
$D_{PH,LT}$	Low-temperature process heat demand [MWh]
$D_{PH,MT}$	Medium-temperature process heat demand [MWh]
$Export$	Energy exports [MWh]
$Grid_{cap}$	Grid connection capacity [MWh]
$Import$	Energy imports [MWh]
p	Electricity price [€/MWh]
TAC_{Spec}	Specific system costs [€/MWh]
TAC_{Sys}	Total annual system costs [€]
ϵ_{HP}	Heat pump coefficient of performance [–]
ζ	Degree of energy autonomy [–]
$\eta_{electrolyzer}$	Electrolyzer efficiency [–]
$\eta_{E-boiler}$	Electric boiler efficiency [–]
$\eta_{E-furnace}$	Electric furnace efficiency [–]

are manifold. However, the main drivers are environmental awareness, tax revenues and the desire for independence from superordinate structures [6]. Furthermore, if municipalities involve the population in participatory projects, the acceptance of local renewable energy projects may be increased [7].

With recent increases in energy prices and concerns about energy security in Germany, the topic of local energy autonomy has gathered additional interest. Municipal energy systems employing decentralized local generation can also be economically attractive compared to centralized energy supply, which requires higher grid expansion costs [8]. For individual municipalities aiming for energy autonomy, the required investment depends on the type of energy autonomy it strives for. In the case of complete energy autonomy, the municipal system strives for no energetic interaction with the overarching grid and locally balances generation and demand. Systems with balanced energy autonomy, where the municipal system retains its grid connection, enable energy exchange with other regions [9]. Therefore, for future grid planning and the design of future energy systems, it is important to know the techno-economic feasibility of municipal energy autonomy based on different scenarios.

1.1. Literature review

Energy system models used for determining the cost-optimal regional energy systems can be divided into simulation and optimization models (see Table 1). However, only Locherer [10] used a simulation model to evaluate regional energy systems. The majority of studies use optimization approaches, which can be distinguished between solving linear optimization problems (LPs), or mixed-integer linear problems (MILPs). The selection of the method must be weighted between computational time and model accuracy. MILPs have the advantage that binary variables can be considered, for example, to account for binary investment decisions, but this increases computation time [11]. For this reason, LPs are often applied for municipality- and county-level analyses. Only a few energy system models such as RE^{3}ASON [12] employ a MILP approach.

In addition, the spatial scope of the analyses varies. Most of the literature examines single municipalities (e.g., Brodecki et al. [32]) and case studies with up to 72 municipalities [10]. Weinand [19] employs a regression analysis to project optimization results from 15 representative municipalities to the entirety of municipalities in Germany. In addition, municipalities that host large industries are excluded a priori from the over 10,000 German municipalities, which is why the number of municipalities studied is 15 with the MILP model and 6314 with the regression analysis. Yazdanie et al. [29] adopts a similar approach for Switzerland and models 20 archetypical municipalities to quantify the role of decentralized generation in all Swiss municipalities in 2050.

Table 2 provides an overview of the energy sources, sectors, and infrastructures considered in the energy system models. The considered energy carriers vary in the analyzed literature. While electricity and heat are considered in almost all of the models, hydrogen in particular is often neglected – only Brodecki and Blesl [20] and Gabrielli et al. [27] implement it as an energy carrier. Studies that explore the transformation of the national energy systems (e.g., Stolten et al. [33]), conclude that hydrogen will play a significant role in the future energy system. Consequently, the neglect of hydrogen as an energy carrier in the regional energy system models represents a shortcoming. The exploitation of power-to-X potentials can help reduce the curtailment of renewable energy technologies. Accordingly, the comprehensive modeling of these, including the necessary energy forms, is of corresponding importance in order to be able to fully evaluate regional energy concepts.

One possibility for flexibilization through power-to-X is the use of central, electricity-based heat generators in combination with district heating networks and underground heat storage, as is already common in Denmark [34]. Mainzer [18] utilized Open-Street-Map data [35] to map the heat exchange between municipal districts through existing district heating networks in the RE^3ASON model. Based on this, Weinand et al. [36] implemented the costs of district heating networks in municipalities by taking into account the specific heat distribution costs within settlement areas, as well as the distance to possible deep geothermal sites. Eggers [16] accounted for district heating network expansion by cost per meter of pipeline within a node and estimated pipeline lengths based on the existing gas network.

The residential, commercial, industrial, and transportation sectors are included in most of the energy system models considered. However, in some works such as Moeller [13], Mainzer [18], or Weinand [19], individual sectors are modeled based on simplified consumption increases, which means that the associated generation portfolio, as well as power-to-X technologies, are not optimized as well (see Table 2). Weinand [19], for example, excludes the energy-intensive part of the industrial sector a-priori for the analyses of energy autonomous municipalities.

In addition to the sectoral resolution of energy demand, the spatial resolution requires sophisticated approaches for regional energy systems. As the literature is based on case studies for individual regions and the only analysis for all municipalities in Germany [37] is based on a regression analysis, the demand modeling approaches draw on region-specific estimates. Moeller [13] incorporates the electricity requirements of the regional master plan for this purpose and employs standard load profiles as a temporal resolution. Other articles such

Table 1
Regional energy system models in the literature.

Source	Model	Purpose	Method[a]	Resolution[b]			Scope
				C	M	D	
Moeller [13]	oemof [14]	Storage requirements and system costs for energy autonomous regions	LP	x	x	x	24 municipalities
Locherer [10]	PROMET [15]	Simulation of a sustainable regional energy system	Sim	100 m × 100 m			72 municipalities
Eggers [16]	KomMod [17]	Techno-economic municipal energy transition plan	LP	–	x	–	1 municipality
Mainzer [18]	RE[3]ASON [12]	Optimization of urban energy systems	MILP	x	x	x	6 municipalities
Weinand [19]	RE[3]ASON [12]	Energy system analysis of autonomous municipalities	MILP + RA	–	x	–	6314 municipalities
Brodecki and Blesl [20]	TIMES Local [21]	Implementing autonomy in energy system models	LP	–	x	x	1 municipality
Alhamwi et al. [22]	FlexiGis [23] & urbs [24]	Storage/cellular structures in urban energy systems	LP	–	x	x	1 municipality
Scheller et al. [25]	IRPopt [26]	Competition between residential flexibility options	MILP	–	x	x	6 households community
Gabrielli et al. [27]	D-MES model	Seasonal storage in multi-energy systems	MILP	–	x	x	1 city district
Jalil-Vega and Hawkes [28]	HIT	Trade-offs between heat supply technologies and network infrastructure	MILP	–	x	x	1 city
Yazdanie et al. [29]	community TIMES [30]	Decentralized generation potential in municipal energy systems	LP + RA	–	x	–	20 archetypical municipalities
This study	ETHOS. FineRegions [31]	Energy system analysis of autonomous municipalities	LP	x	x	–	11 003 municipalities

[a] LP: linear problem, MILP: mixed-integer linear problem, RA: regression analysis, Sim: simulation.
[b] C: county, M: municipalities and cities, D: city districts.

as [18], Weinand et al. [37], or Alhamwi et al. [22] utilize data about the buildings (e.g., Census [38] or OpenStreetMap [35]) in a region to estimate the energy demand.

The generation technologies considered vary depending on the purpose of the analysis and scope of the model applied (see Table 2): while rooftop PV is included in all models and wind, biomass and biogas in almost all, open-field PV is only covered by Brodecki and Blesl [20], although it makes up a large share of the electricity supply in national energy system analyses, e.g., in Ref. [33].

In energy system models, the expansion of renewable energy sources is limited by regional potential. The decisive factor is the potential limit, as well as the regional distribution of the potentials, especially for energy autonomy considerations. Moeller [13] and Eggers [16] use the master plans from the regions of Osnabrück [39,40] and Steinfurt [41] or Frankfurt [42], respectively. Locherer [10] also applies a region-specific analysis to estimate the renewable potentials in a Bavarian region. Alhamwi et al. [22] and Mainzer [18] utilize Open Street Map data to designate sites for wind turbines. While Alhamwi et al. [22] make further use of Open Street Map data to estimate rooftop PV potential, Mainzer [18] developed a new machine learning methodology for this purpose based on satellite image recognition [43]. Weinand et al. [44] also use hydrothermal temperature data [45] and have extended the RE[3]ASON model [12] to include deep geothermal energy. The study concludes that deep geothermal plants could have a significant impact on the costs of autonomous municipal energy systems. Many regional energy system models only use potential analyses for individual regions. This approach is not sufficient to answer the research questions of the present study. For this reason, this work utilizes the site-specific resolved renewable energy data from Risch et al. [46]. Table 2 presents an overview of considered conversion and storage technologies, as well as grid considerations within the regional energy systems. Heat pumps are implemented for converting electricity into heat in nearly all publications. Only Moeller [13] does not consider these, as the heat supply is only simplistically modeled by an increase in consumption and is therefore not optimized. As can be deduced from the lack of consideration of hydrogen, the possibility of converting electricity into gaseous energy carriers is not considered in the majority of the models examined. Consequently, chemical energy storage using hydrogen is only deemed to be possible by Gabrielli et al. [27]. While direct electricity storage is considered in almost all of the models, heat storage is only represented in five of the energy system models (Locherer [10], Eggers [16], Brodecki and Blesl [20], Gabrielli et al. [27] and Yazdanie et al. [29]). When considering the network, all models except that in Jalil-Vega and Hawkes [28] apply a simplified approach without considering network topology. Also in Jalil-Vega and Hawkes [28], only a simplified greenfield approach is considered and existing network topologies are ignored. Alternatively, in other models costs and losses are approximated in a simplified way without knowledge of the physically correct network. Most of the literature on regional energy autonomy examines individual regions in order to make statements regarding the potential for energy autonomy. All studies conclude that certain degrees of autonomy are techno-economically feasible to achieve, but that extreme storage sizes lead to sharply increasing system costs if these degrees are exceeded. Moeller [13] finds for the Osnabrück–Steinfurt combined region that degrees of energy autonomy above 80% are possible under increased system costs in 18 of the 24 municipalities studied, but complete autonomy is not investigated. Möller et al. [47] also find that complete self-sufficiency would be theoretically possible for the combined region under extreme storage expansion. For the Berlin–Brandenburg region, Moeller et al. [48] come to the similar conclusion that complete autonomy can be achieved with increased storage expenditures (gas and battery storage). Alhamwi et al. [22] draw on the concept of energy cells and show that for the Oldenburg region that autonomous operation does not make economic sense. Ranalli and Alhamwi [49] also apply the model to Philadelphia (USA) and use a residual load analysis to show that accurate planning of the generation mix on a regional level can lead to strongly reduced load residuals and thus lower grid requirements. Weinand et al. [37] conclude with a combined cluster and regression analysis that 56% of German municipalities could operate in an off-grid system without imports.

Table 2
Energy sources, sectors, generation technologies, as well as conversion, storage and grid considerations in regional energy system models.

	Source by reference number											
	[13]	[10]	[16]	[18]	[19]	[20]	[22]	[25]	[27]	[28]	[29]	This study
Energy source												
Electricity	x	x	x	x	x	x	x	x	x	x	x	x
Heat	x^a	x	x	x	x	x	–	x	x	x	x	x
H_2	–	–	–	–	–	x	n.a.	–	–	–	–	x
Gas/Biogas	–	x	x	x	x	x	n.a.	x	x	x	x	x
Biomass	–	–	x	x	x	x	–	–	–	–	x	x
Sector												
Residential	x	x	x	x	x	x	n.a.	x	x	x	x	x
Commercial	x^b	x	–	x^s	x^s	x	n.a.	–	x^s	x^s	x	x
Industry	x^b	x	–	x^s	x^s	x	n.a.	–	–	–	x	x
Transport	x^b	–	x^b	x^s	x^s	x	n.a.	–	–	–	–	x
Generation technology												
Wind turbines	x	x	x	x	x	x	x	–	–	–	–	x
Rooftop PV	x	x	x	x	x	x	x	x	x	x	x	x
Open-field PV	–	–	–	–	–	x	–	–	–	–	–	x
Deep geothermal	–	–	–	–	x	–	–	–	–	–	–	–
Waste-to-energy	–	–	–	x	x	x	–	–	–	–	x	x
Biomass	–	x	x	x	x	x	x	–	–	x	x	x
Biogas	x	–	x	x	x	x	x	–	–	–	x	x
Hydropower	–	x	–	–	–	x	x	–	–	–	x	–
Conversion technology												
Heat pumps	–	x	x	x	x	x	–	x	x	x	x	x
Large heat pumps	–	–	–	–	–	x	–	–	–	x	–	x
Direct heaters	–	–	–	–	–	x	–	–	–	x	–	x
Power-to-gas	–	–	–	–	–	x	–	–	x	–	–	x
Storage technology												
Electricity storage	x	x	x	x	x	x	x	x	x	–	x	x
Heat storage	–	x	x	x	x	x	–	–	x	–	x	x
Hydrogen storage	–	–	–	–	–	–	–	–	x	–	–	x
Grid infrastructure												
Electricity grid	x^s	x^s	x^s	x^s	x^s	x^s	x	x^s	x^s	x	x^s	x^s
Heat grid	–	x^s	x^s	x^s	x^s	n.a.	–	–	–	x	x^s	x^s
Gas/hydrogen grid	–	x^s	x^s	x^s	x^s	n.a.	–	–	x^s	x	x^s	x^s

'x' indicates inclusion in the study, '–' indicates exclusion, 'n.a.' not available, 'x^a' modeled by increasing electricity demand , 'x^b' only electricity demand considered, 'x^s' simplified implementation.

1.2. Contribution

Based on the reviewed literature, the conclusion is that energy autonomy is technically possible in many regions, but does not appear to be economically efficient above certain degrees of autonomy. However, the findings presented come from individual case studies and are not based on an examination of a representative number of regions. In addition, some models show shortcomings in the modeling of energy carriers, generation and conversion technologies (power-to-X), which could be, however, of great importance for achieving energy autonomy in the regions.

To fill the identified gaps this study presents a regional energy system model with the most comprehensive combination of considered energy sources, sectors, generation technologies as well as conversion, storage and grid considerations. This study aims to analyze the techno-economic potential of all German municipalities, with a focus on the following research questions:

1. How many German municipalities can technically reach a completely energy autonomous supply based on renewable energy technologies?
2. What are the implications of municipalities' energy autonomy efforts for optimal technology choices and costs in the energy system?
3. Is it economically viable for municipalities to achieve energy autonomy as opposed to remaining connected to the existing grid?

The developed regional energy system optimization model ETHOS.FineRegions can evaluate the cost-optimal composition of future energy systems, from districts to the municipal level. In addition, various autonomy boundary conditions are modeled in order to represent the different objectives of the municipalities.

This paper is structured as follows: first, Section 2 illustrates the methodology by introducing the energy system model ETHOS.FineRegions and explains the modeling approach adopted to analyze the energy autonomy of German municipalities. Section 3 presents the results obtained for the techno-economic potential of autonomy in German municipalities and the implications of energy autonomy for the optimal technology choices and cost in the energy system. Section 4 provides a discussion of the results obtained in relation to the other relevant work from the literature. Finally Section 5 presents a summary and conclusions.

2. Methods

In the following, the methodology of this study is presented. First, in Section 2.1, the general energy system optimization framework is described. Subsequently, Section 2.2 introduces the regional energy system model ETHOS.FineRegions, before Section 2.3 explains the calculation of specific system costs and Section 2.4 the modeling of autonomy. In Section 2.5 the procedure for single-node optimization of all German municipalities is presented and Section 2.6 discusses the scenarios considered in this work.

2.1. Energy system optimization framework

To model the regional energy systems, this study extends the open-source Framework for Integrated Energy System Assessment

(ETHOS.FINE) [50]. The Python-based framework simplifies the formulation of optimization problems for the modeling of energy systems. The optimization objective function of ETHOS.FINE is to minimize the annualized system cost, which is for the target year of 2045 in the present study. To this end, five component classes are included in ETHOS.FINE, namely: source, sink, conversion, storage, and transmission components. For each required technology, an instance of these component classes can be created, which is then used to define the contribution to the optimization objective function. The initialization of each component specifies which commodity is converted, consumed or generated by its operation. For example, a commodity can be an energy flow or a fuel. ETHOS.FINE transforms the input parameters such as the capacity constraints or modes of operation of the components into corresponding constraints of the optimization. In addition, the contribution to the energy or material balance of the energy system is initialized for each component. The optimization model is implemented in ETHOS.FINE using Pyomo [51] and then solved with a solver such as Gurobi [52] or GLPK [53]. In the context of this study Gurobi is utilized.

In general, both linear (LP) and mixed integer (MILP) problems can be initialized in ETHOS.FINE. As all 11 003 municipalities in Germany are considered as individual single nodes in over one million optimizations, the application of a and a calculation number of this size in MILP model would exceed computational limits. Therefore, a linear model was used in this work, which allows the research questions defined at the beginning to be answered in a reasonable computing time, despite the high number of individual nodes and the resulting model size. Furthermore, the number of optimized time steps is reduced by the open-source tsam package [54], which aggregates time steps based on similarities with cluster methods. In this study, 40 typical days and 12 segments within typical days are employed, thereby reducing the optimized time steps from 8760 to 480. The impact of time series aggregation on the results of this study is examined in sensitivity analyses (see Supplementary Material).

For the wind turbines, an additional approach was developed to be able to consider a minimum turbine size, despite the linear optimization approach employed. For this purpose, after optimization a check was made as to whether built wind turbines reach a minimum size of 2 MW. If this is not the case and the built capacity is at the same time not equal to zero (tolerance: 1 kW), two further optimizations are commenced: the target values of an optimization without wind turbines and an optimization with wind turbines that are at least 2 MW in size are compared. Based on this comparison, the optimization model with the lower annualized system cost is taken as the result for the associated power system.

A hardware configuration with 2 TB RAM memory and two CPUs Intel Xeon Gold 6334 (3.6 GHz base clock frequency) was used to optimize the model.

2.2. Energy system optimization model

In this section, the ETHOS.FineRegions [31] regional energy system model is presented. Fig. 1 shows a block diagram containing the interconnections of the model components. To this end, the available technologies are based on the scientific consensus for relevant technologies in the future German energy system, e.g., from Stolten et al. [33] and Sensfuß et al. [55]. All techno-economic parameters (capital costs, interest rate, operational costs, lifetime, and efficiencies) are based on the study by Stolten et al. [33]. The most important input parameters are depicted in Table 3.

ETHOS.FineRegions includes ten commodities that can be generated by source technologies or converted from other commodities by means of conversion technologies. The demands are modeled by sink technologies with fixed profiles, the derivation of which is presented in the Supplementary Material. A fixed profile must be met by the model at each time step, meaning that the operation of the component cannot be reduced or increased. Electricity can be generated or imported from the electricity sources of wind (wind onshore) and solar energy (rooftop and open-field PV). The maximum generation from renewable energy plants is constrained by potential limits. For onshore wind and PV, the site-specific potential determination from Risch et al. [46] is used as an input in the model. The Supplementary Material shows how the potential for biomass and waste is modeled. Furthermore, electricity imports can be limited by any autonomy constraints (see Section 2.4).

Table 3
Most important techno-economic input parameters based on the study by Stolten et al. [33].

Technology	CAPEX	OPEX	Economic lifetime
Wind turbines	1025 €/kW	2.5% of CAPEX	20 a
Rooftop PV	528 €/kW	2.1% of CAPEX	20 a
Open-field PV	345 €/kW	1.7% of CAPEX	20 a
Heat pumps (decentral)	I1111 €/kW	2.5% of CAPEX	20 a
Heat pumps (central)	760 €/kW	0.9% of CAPEX	20 a
Batteries (decentral)	311 €/kWh	2.5% of CAPEX	15 a
Batteries (central)	142 €/kWh	2.5% of CAPEX	15 a
Heat storages (decentral)	30 €/kWh	4.0% of CAPEX	20 a
Heat storages (central)	0.67 €/kWh	3.0% of CAPEX	20 a

Table 4
Overview of time series used in ETHOS.FineRegions. The maximum time series means an upper bound for the operation of the respective component, whereas a fixed time series must be met at all time steps.

Technology	Maximum/fixed time series	Number of time series per region
Wind turbines	Maximum	7
Rooftop PV	Maximum	9
Open-field PV	Maximum	1
Electricity demand	Fixed	1
Heat demand	Fixed	1
Hydrogen demand	Fixed	1
Process heat demand	Fixed	5

Table 4 summarizes the time series used in the model. For onshore wind turbines, seven generation time series are employed for each region. To this end, the generation profile of the location specific sites of Risch et al. [46] are simulated using the open-source tool RESKit [56]. Afterwards, if more than seven time series are available in a region, the time series of all turbines are reduced to seven based on the ETHOS.Spagat [57] tool for the spatial aggregation of technologies, to reduce the complexity of the model. The rooftop PV modules are modeled with nine time series to accommodate different orientations. Here, an additional distinction is made between potential and existing installations. As all open-field PV systems are placed in a southerly direction and can thus be assumed to have nearly the same generation profile across all systems within a municipality, they are modeled with one time series. As the renewable technologies described are subject to curtailment, e.g. due to insufficient demand, they are modeled with maximum operation time series, i.e. the model can choose to generate between zero and the values of the time series at any given time step. In addition, electricity from other commodities can be converted: for example, biomass, biogas and waste can be converted into electricity in power plants or heat and electricity in CHP plants.

The intranodal network for distributing electricity within the node is represented by a conversion, with network expansion costs based on Stolten et al. [33]. In addition, as assumed by Stolten et al. [33], 40% of rooftop PV generation is provided close to the point of consumption without any necessary distribution infrastructure. Other generation, as well as electricity from centralized battery storage, must first be distributed through the grid.

The hydrogen demand arising in industrial settings or via conversion technologies can be covered by hydrogen production in proton exchange membrane (PEM) electrolysers, which internally induce an additional electricity demand in the model. A conversion component

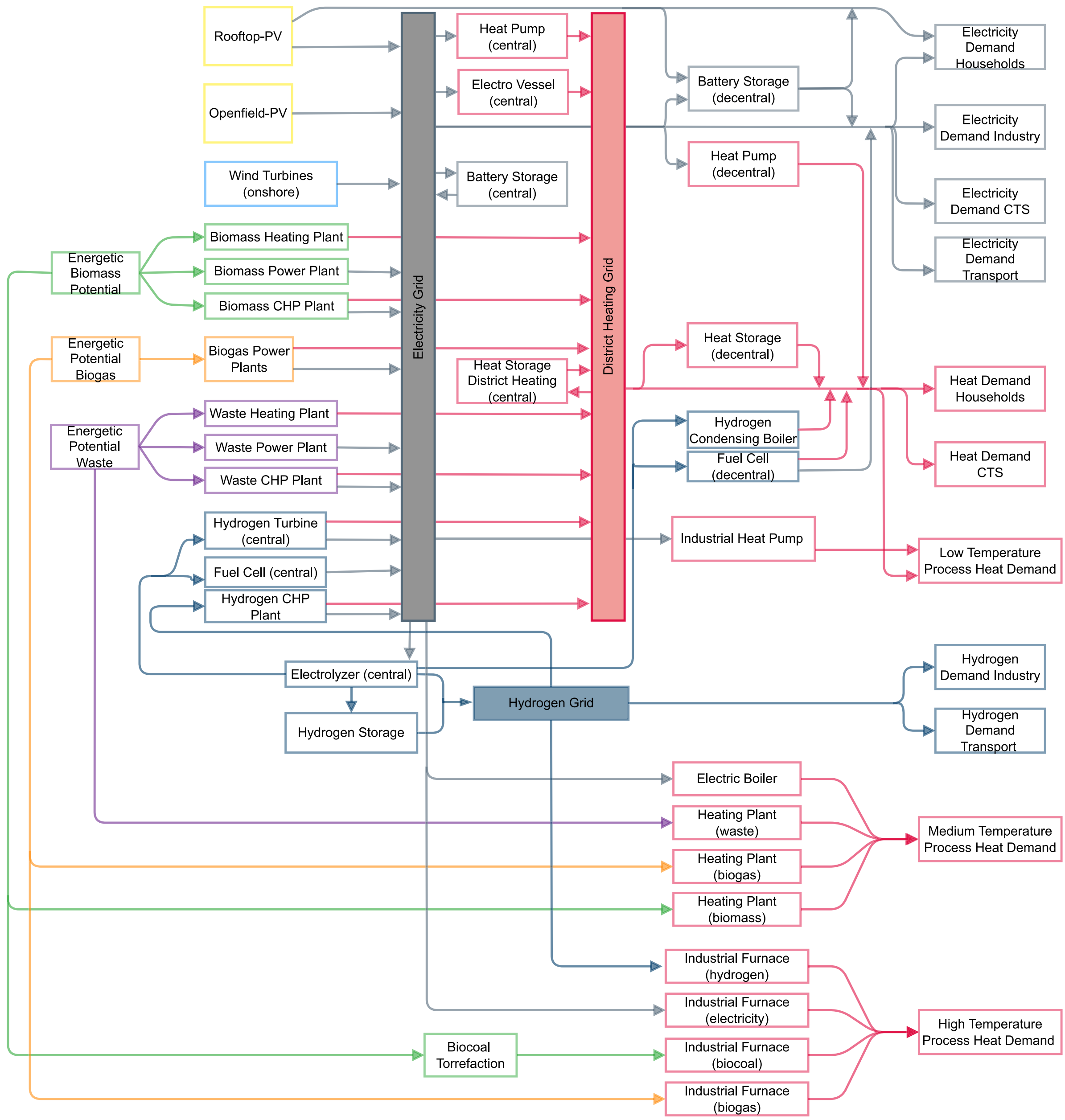

Fig. 1. Block diagram of the components of the optimization model ETHOS.FineRegions. Electricity flows and technologies are depicted in gray, heat flows and technologies in red, hydrogen flows and technologies in blue, waste flows and technologies in purple, biogas flows and technologies in orange, and biomass flows and technologies in green. PV technologies are shown in yellow and wind turbines in light blue.

is initialized to distribute the hydrogen within a node, which must be expanded to supply the decentralized consumption components. The hydrogen can then be stored centrally, without prior distribution, in above-ground pressure tanks. Through subsequent reconversion in central hydrogen turbines or fuel cells, an indirect possibility for electricity storage is provided. Hydrogen imports are not considered in this study, which means that the hydrogen is produced inside the municipalities, e.g., by electrolyzers in conjunction with electricity generated inside the municipal borders or electricity imports.

The industrial sector is usually greatly simplified in regional optimization models, for example, and is only modeled in the form of an increase in energy demand (see Section 1.1). However, this methodology does not allow any conclusions to be drawn regarding technology selection in the industrial sector. In ETHOS.FineRegions on the one hand, the hydrogen and electricity demand of the industry is considered. On the other, the process heat demand of the industry is represented by three additional commodities: the low-temperature process heat represents the heat demand that occurs at temperatures lower than 100 °C; the medium-temperature range is defined as being between 100 °C and 500 °C; and the high-temperature range starts at 500 °C. Table 5 shows which technologies are available in the model for generating process heat.

Low-temperature heat can be provided by all technologies connected to the district heating network. Alternatively, in regions where a district heating network is not part of the cost-optimal system, an industrial heat pump can be directly installed on-site. Medium-temperature process heat demand can be met by heating plants that can generate heat from biogas, biomass, or waste. In addition, an industrial electric boiler can be used, which can convert electricity into medium-temperature process heat. High temperature process heat is provided by industrial furnaces using biocoal, biogas, hydrogen, or electricity as energy sources. However, as not all industrial processes can be

Table 5
Generation technologies for process heat in the ETHOS.FineRegions model.

Process heat	Technology	Energy source
Low-temperature	Technologies connected to the district heating network and industrial heat pump	
Medium temperature	Heating plant Industrial electric boiler	Biogas, biomass or waste Electricity
High-temperature	Industrial furnaces	Biomass (biocoal), electricity, biogas or hydrogen

electrified, a non-electrifiable portion of the demand is defined: firstly, in ETHOS.FineRegions the process heat demand for steel production can only be covered by gaseous energy carriers (biogas and hydrogen) by means of direct reduction [58] comparable to the modeling in Kullmann et al. [59]. Secondly, cement production cannot be electrified in the model, and so only biocoal, biogas or hydrogen may be used [59].

The ETHOS.FineRegions model includes several flexibility options. In addition to biomass, biogas and waste-to-energy plants, hydrogen-fueled flexibility options are considered, such as hydrogen turbines. Furthermore, flexibility is provided internally in the model through sector coupling options, such as power-to-heat-technologies combined with heat storage.

2.3. Calculating specific system costs

Municipalities differ significantly by area, population, demand structure, and supply potentials. In order to facilitate a comparison of costs between different systems with different conditions, specific system costs (TAC_{Spec}) are introduced with Eq. (1).

$$TAC_{Spec} = \frac{TAC_{Sys}}{D_{E,eq}} \tag{1}$$

The total annual system costs (TAC_{Sys}) for meeting the municipal demands are set in relation to an electricity-equivalent demand ($D_{E,eq}$). The latter is the sum of all energy demands (electricity demand D_E, heat demand D_H hydrogen demand D_{H_2}, low-temperature process heat demand $D_{PH,LT}$, medium-temperature process heat demand $D_{PH,MT}$, and high-temperature process heat demand $D_{PH,HT}$), which are converted into electricity demand equivalents using the efficiencies (electrolyzer efficiency $\eta_{electrolyzer}$, electric boiler efficiency $\eta_{E-boiler}$, electric furnace efficiency $\eta_{E-furnace}$) and coefficients of performance (heat pump coefficient of performance ε_{HP}) of the technologies used for meeting these demands (see Eq. (2)). A representative technology is defined for each type of demand and used for the calculation. For example, the conversion of heat demand into electricity demand is performed by the average coefficient of performance of the heat pump used in the model.

$$D_{E,eq} = D_E + \frac{D_H}{\varepsilon_{HP}} + \frac{D_{H_2}}{\eta_{electrolyzer}} + \frac{D_{PH,LT}}{\varepsilon_{HP}} + \frac{D_{PH,MT}}{\eta_{E-boiler}} + \frac{D_{PH,HT}}{\eta_{E-furnace}} \tag{2}$$

Although the annual demands and conversion factors are input variables of the model, the total annual system cost (TAC_{Sys}) represents the objective function of the optimization. The detailed formulation of the objective function for minimizing costs can be found in Welder et al. [50]. The specific system costs were calculated after the optimization.

2.4. Modeling of energy autonomy

A necessary scenario dimension for examining the research questions of the present work are the energy autonomy constraints. In the case of a grid connected system with balanced energy autonomy, a region generates at least the sum of its own demand over the period of one year by means of its own plants. The degree of energy autonomy (ζ) is defined using the annual integral of energy imports ($Import$) and the annual integral of demand D (see Eq. (3)).

$$\zeta = 1 - \frac{\int Import(t)dt}{\int D(t)dt} \tag{3}$$

In the case of complete autonomy, i.e., off-grid operation, the degree of autonomy is 1. Measures for the operation of the power grid, e.g., for frequency conservation, are not considered. For the final evaluation of autonomy, the grid connection capacity ($Grid_{cap}$) of the region must be considered for imports and exports ($Export$, Eq. (4)).

$$Import(t) \leq Grid_{cap} \geq Export(t) \;\; \forall\, t \,in\, T \tag{4}$$

From a grid perspective, grid connection capacity is the most meaningful indicator, as infrastructure costs can only be reduced by including the time dimension in exchange limits. For example, high transmission power peaks at a few points in the year can still lead to high degrees of autonomy. Accordingly, from a network perspective, a capacity-based exchange limitation may have advantages over a generation-based one. McKenna [60] also highlights that limiting generation-based network interactions by considering the degree of autonomy can lead to macroeconomic disadvantages.

In order to consider the degree of autonomy in energy system modeling, an additional constraint is implemented, namely the flow outgoing through the transmission component ($Export$) is omitted (Eq. (5)).

$$\sum_t Import \leq (1-\zeta) \cdot \sum_t D \tag{5}$$

2.5. Optimizing a large number of municipalities

For each of the 11 003 municipalities, a separate optimization problem was formulated and solved. This has the advantage that the problems can be solved in parallel. The disadvantage of this approach is that no exchange of information between the individual municipalities is possible during the optimization. Therefore, conclusions regarding exchange possibilities between individual municipalities are only possible to a limited extent. In order to nevertheless model an exchange, an import and export are implemented as source and sink, respectively. To maximize autonomy in the scenarios with complete autonomy, the purchase price is set to 100 000 €/MWh. Under the objective of minimizing the system cost, this leads to using a power purchase only as a last option to ensure that the optimization problem remains solvable.

In the grid-connected scenarios, an electricity price time series is considered that takes into account the generation potentials from renewable energy sources, so that high electricity prices result in times of low generation potentials and low electricity prices in times of high generation potentials. This allows modeling that, for example, a high supply of PV electricity in the summer depresses the price of electricity on the stock exchange. Thus, it is assumed that renewable generation is the main price driver in the electricity market. First, normalized generation by renewable energy sources (CF_{RE}) is defined as follows (see Eq. (6) which is given in Box I). The capacities of PV plants (C_{PV}), onshore wind plants ($C_{OnshoreWind}$) and offshore wind plants ($C_{OffshoreWind}$) are chosen in such a way that they correspond to the values of a national transformation scenario as in Stolten et al. [33]. The capacity factors of the respective technologies (CF_{PV}, $CF_{OnshoreWind}$ and $CF_{OffshoreWind}$) are defined by the averaged capacity factors of the potentials used by Risch et al. [46]. The price time series is calculated by the relative deviation of the weighted renewable capacity factors CF_{RE} from the mean value. In addition, an exponent X

$$CF_{RE}(t) = \frac{C_{PV} \cdot CF_{PV}(t) + C_{OnshoreWind} \cdot CF_{OnshoreWind}(t) + C_{OffshoreWind} \cdot CF_{OffshoreWind}(t)}{C_{PV} + C_{OnshoreWind} + C_{OffshoreWind}} \quad (6)$$

Box I.

is introduced to weight the fluctuations in the price (p, see Eq. (7a-b)).

$$p(t) = \begin{cases} \overline{p} + \left(\frac{\overline{CF_{RE}} - CF_{RE}(t)}{\overline{CF_{RE}} - CF_{RE,min}} \right)^X \cdot (p_{max} - \overline{p}), & \text{for } CF_{RE}(t) \leq \overline{CF_{RE}} \quad \text{(a)} \\ \overline{p} - \left(\frac{CF_{RE}(t) - \overline{CF_{RE}}}{CF_{RE,max} - \overline{CF_{RE}}} \right)^X \cdot (\overline{p} - p_{min}), & \text{for } CF_{RE}(t) > \overline{CF_{RE}} \quad \text{(b)} \end{cases} \quad (7)$$

Through this approach, the electricity price is low when the simultaneously available capacity of renewable energy is high and expensive when the available capacity is low. Fig. 2 hypothetically illustrates the price-time series for a spread between 0 €/MWh and 100 €/MWh and $X = 2$. In the following, the described price time series will be referred to as the *PriceTimeSeries*^{X}, although in this paper only a price time series with $X = 2$ is considered, i.e., *PriceTimeSeries*^{2}.

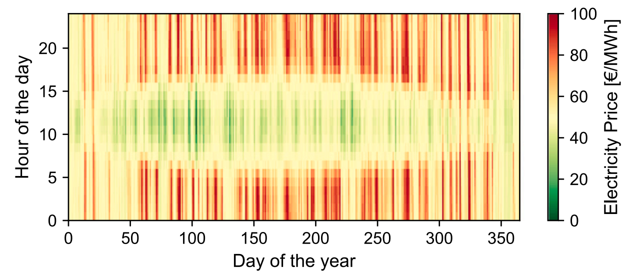

Fig. 2. Electricity prices in the *PriceTimeSeries*^{2} (0–100 €/MWh) over the course of a year.

2.6. Considered scenarios

In order to analyze the regional energy systems, various scenarios are defined that depict possible future developments. For this purpose, different scenario groups are formed in order to investigate different influencing variables. Table 6 provides an overview of the defined scenarios. First, a baseline autonomy scenario ($NoGrid_{ref}$) is defined, from which various specifications are varied in the subsequent scenarios. In the $NoGrid_{ref}$ scenario, the degree of energy autonomy in the municipalities is maximized, i.e., if possible, complete autonomy is achieved (purchase price of 100 000 €/MWh, see Section 2.5). For wind development, the upper limit is given by an expansive scenario (see Risch et al. [46]), i.e., minimum distances to inner settlement areas are 1000 m, and to outer areas (e.g., single buildings outside settlements) the minimum distances are three time the turbine height. Turbine installations in forests are allowed. For open-field PV development, the upper limit is a scenario in which potential is also available on marginal strips along highways and railways, as well as agriculturally disadvantaged land. For rooftop PV, all roofs are made available to the model, so that the choice of orientation is the result of the optimization. In the first scenario group ($NoGrid_{acceptance}$, $NoGrid_{legislation}$, $NoGrid_{rooftopPV}$), the boundary conditions of the renewable energy sources are varied compared to the $NoGrid_{ref}$ scenario. Furthermore the degree of energy autonomy is maximized in this scenario group, i.e., complete autonomy is achieved. The scenarios have the following characteristics:

- **NoGrid$_{\text{acceptance}}$**: Unlike the $NoGrid_{ref}$ scenario, the expansion of onshore wind is dictated by a restrictive scenario with minimum distances of 1000 m each to inner and outer residential areas in order to estimate the maximum impact of social acceptance towards onshore wind on cost-optimal autonomous energy systems. This scenario is defined to reflect the public opposition towards onshore wind [61] and the resulting decrease in expansion numbers in Germany [62,63].
- **NoGrid$_{\text{legislation}}$**: Unlike the $NoGrid_{Ref}$ scenario, the wind potentials are based on current legislation in the federal states, i.e., with individual distance restrictions. The permitting of turbines in forests is also individualized per state.
- **NoGrid$_{\text{rooftopPV}}$**: The CAPEX for rooftop PV are reduced by 50%, to 264 €/kW, to favor rooftop PV development. Such a development can be triggered, for example, by increasing subsidies for rooftop PV. To still reflect the total costs from a macroeconomic perspective, the reduced share of costs is added to the total system costs after the optimization. In the Result Section, only these total costs from a macroeconomic perspective are discussed.

The influence of the autonomy conditions described in Section 2.4 is examined using the $Grid_{balanced}$ scenario.

- **Grid$_{\text{balanced}}$**: The generation in the municipalities must be at least equal to their demand over the year, and the price signal is given by the *PriceTimeSeries*^{2}. This allows a comparison of completely autonomous systems with balanced-autonomous systems.

In addition, the influence of the possibility of buying and selling electricity for the municipalities is examined:

- **Grid$_{\text{ref}}$**: Imports and exports are allowed with the prices of the *PriceTimeSeries*^{2}. With the help of this scenario, the cost-optimal autonomous systems can be compared with the cost-optimal regular energy systems.

For the $NoGrid_{ref}$ scenario, the sensitivity of the results to the following influencing factors is also investigated:

- **Weather years**: to account for the variability of renewable generation over different years and to measure their impact on the results, these are simulated for 40 weather years and the time series are used as inputs to the optimization model. This means that all of the 11 003 municipalities were optimized 40 times. Next, the worst weather year was determined for each municipality (critical weather year): first, the year in which the municipality reaches the lowest degree of energy autonomy was chosen. If the municipality achieves a degree of autonomy of 1 in all of 40 years, the specific system costs are used as a second criterion.
- **Cost assumptions**: for a variation in cost of ±5%, ±10%, ±20% and −50% (halving), or +100% (doubling), the impact of the capital costs of wind, open-field PV, rooftop PV, battery storage, thermal storage, and H_2 storage is examined. Halving and doubling of the component costs are considered in order to analyze potential extreme developments.
- **Time series aggregation**: the influence of time series aggregation is assessed by optimizing without using *tsam* [54].

In all 95 scenarios and sensitivity calculations, all 11 003 municipalities are optimized, i.e., more than one million optimizations are performed in this work. An automated workflow is employed to carry out all optimizations. This involves providing a parameter file (JSON file) to the model, which then adjusts the relevant parameters to the desired values or triggers the relevant logic within the model.

Table 6
Considered scenarios.

Scenario	Autonomy	Electricity price	Description
$NoGrid_{ref}$	Complete	–	Expansive wind turbine scenario
$NoGrid_{acceptance}$	Complete	–	Restrictive wind turbine scenario
$NoGrid_{legislation}$	Complete	–	Wind turbine scenario based on current legislation
$NoGrid_{rooftopPV}$	Complete	–	CAPEX for rooftop PV are reduced by 50%
$Grid_{balanced}$	Balanced	*PriceTimeSeries*[2]	–
$Grid_{ref}$	–	*PriceTimeSeries*[2]	Imports and exports are allowed

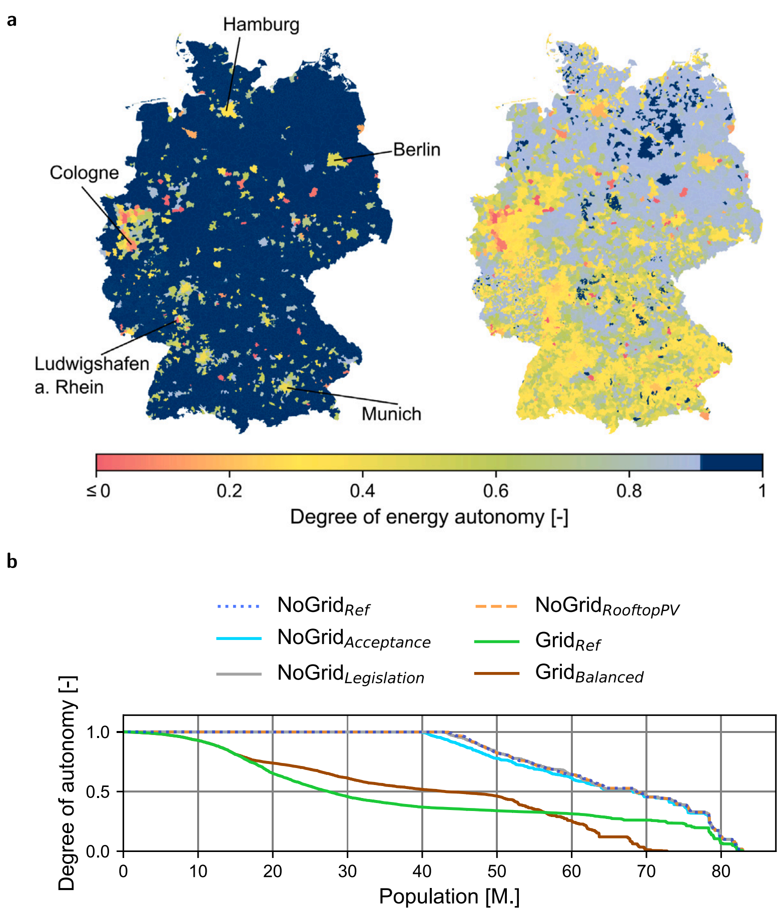

Fig. 3. Maps with the degree of energy autonomy in German municipalities for the $NoGrid_{ref}$ scenario (a, left) and the $Grid_{Ref}$ scenario (a, right); (b) illustrates the degree of autonomy for all scenarios in relation to the population.

For instance, to analyze the sensitivity of the cost assumptions, the JSON file specifies the cost data points. These files are automatically generated for each municipality and each observation, and for each JSON file a parallel process is initiated and a result file is written. In all scenarios, energy systems are determined for 2045, all of which must be greenhouse gas-neutral.

3. Results

The following section compares the results of the scenarios at the municipality level. For this purpose, all municipalities are optimized as single node models in parallel and without interconnection. First, in Section 3.1, an overview of the feasibility and cost of energy autonomy in all municipalities is given. Subsequently, Section 3.2 compares the optimal energy systems in the scenarios with complete energy autonomy and addresses the impact of legislation and social acceptance on the autonomous systems. This is followed by a comparison of the results for different autonomy conditions, i.e., complete and balanced autonomy (Section 3.3). In Section 3.4, the sensitivity of the results to the use of various weather years and different cost assumptions is examined. While the results are described at a high level throughout this section, in the Supplementary Material, the results for two individual municipalities are described in detail as case studies.

3.1. Techno-economic potential of energy autonomy

In the $NoGrid_{ref}$ scenario, completely autonomous energy systems are developed in 10 231 (93%) of the German municipalities, with a total of 43.4 million inhabitants (52%) and an average population of 4240 (see Fig. 3). In total, 7884 of these municipalities have fewer than 5000 inhabitants, which classifies them as rural [64]. Similarly, according to the classification by Dornbusch et al. [65], 7298 of the autonomous municipalities are categorized as rural (<150 inhabitants/km^2) and 2764 as rural dense (<750 inhabitants/km^2) (see Fig. 4a). For example, in sparsely-populated areas in Mecklenburg–Vorpommern and Brandenburg, an autonomous energy system is achievable for many municipalities in the $NoGrid_{ref}$ scenario, due to the large renewable potentials and lower energy demand in these regions. On the other hand, there are 39.8 million inhabitants in 772 municipalities (on average 51 500 inhabitants per municipality), for which an autonomous energy supply is not

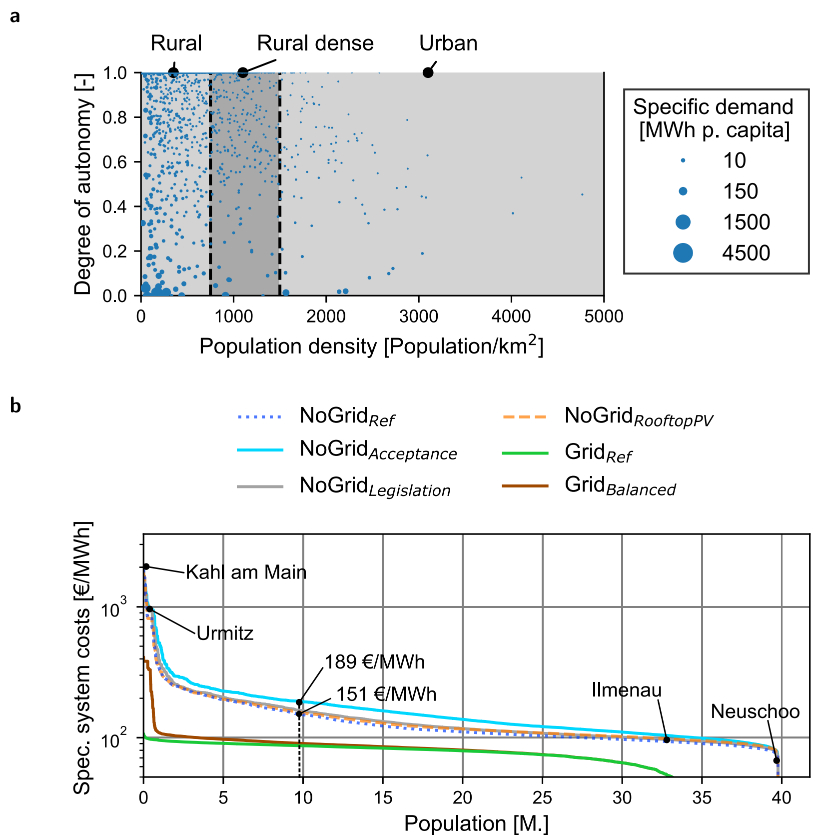

Fig. 4. Degree of autonomy of municipalities in the $NoGrid_{ref}$ scenario over population density (a); as well as specific system costs over population in different scenarios on a logarithmic axis (b). In (a), the specific demand is represented by the size of the points.

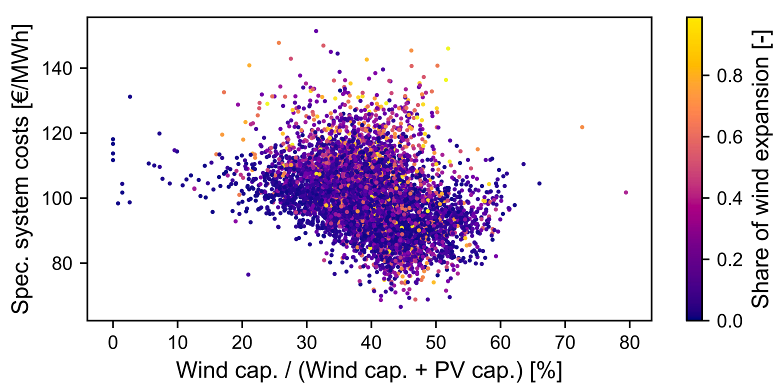

Fig. 5. Scatter plot of system costs versus installed wind capacity as a percentage of total renewable capacity for all municipalities that are not fully exploiting their wind potential.

possible. First, the municipalities with larger populations have higher final energy demands, and second, the potential for the expansion of open-field PV and onshore wind is lower due to land use competition. For example, major cities such as Hamburg, Berlin, Munich, or the metropolitan areas in North Rhine–Westphalia (e.g. Cologne) cannot achieve an energy autonomous supply (see Fig. 3a). Furthermore, Fig. 4a demonstrates that even sparsely-populated municipalities with high specific demands, for example due to industrial sites, cannot achieve complete energy autonomy. One example of a municipality with high energy demand from industry and a low degree of energy autonomy (0.002) is "Ludwigshafen am Rhein".

Without the requirement of complete autonomy and with the possibility to import and export electricity at the prices of the PriceTimeSeries[2] in the $Grid_{Ref}$ scenario, the degree of autonomy decreases for the majority of the municipalities (see Fig. 3). Especially in southern Germany and North Rhine-Westphalia, optimal degrees of autonomy are between 0.3 and 0.7 for many regions. On the other hand, northern Germany has a large share of municipalities with degrees of autonomy higher than 0.8. In the case of the latter municipalities, this can be explained by their large, cost effective wind potentials. This leads to significant overcapacities in order to obtain revenues from the generated electricity. As a side effect, the renewable capacity built is so large that the municipalities' electricity needs can be met almost entirely from their own generation. For 486 municipalities, this even results in an autonomous supply structure, despite the possibility of importing electricity. 204 of these regions are unpopulated areas and so do not import electricity. In the remaining 282 municipalities, the excess capacities are so large that even in the cost-optimal case no imports are needed. By comparing the *Grid* scenarios with the $NoGrid_{ref}$ scenario, the economic disadvantages of autonomous supply structures become apparent: while autonomous supply in the $NoGrid_{ref}$ scenario results in population-weighted average costs of 144 €/MWh, the costs for the same municipalities in the $Grid_{balanced}$ scenario with 70 €/MWh and $Grid_{Ref}$ scenario with 55 €/MWh are much more favorable (see Fig. 4b). However, for 12.3 million residents in the $NoGrid_{ref}$ scenario, energy autonomy at the municipal level is possible for costs below 100 €/MWh. In addition, by paying a premium of up to 50% compared to the $Grid_{Ref}$ scenario (referred to as extended economic potential – see Kleinebrahm et al. [66]), 3945 municipalities with 17.2 million inhabitants could become completely autonomous. Nevertheless, the untapped source of revenue in the $NoGrid_{ref}$ scenario through energy exports possible in the $Grid_{Ref}$ scenario represents a significant disadvantage from a municipal perspective.

3.2. Impact of legislation and social acceptance

In the $NoGrid_{rooftopPV}$ scenario, a similar distribution of the degree of energy autonomy is evident compared to the $NoGrid_{ref}$ scenario (see Fig. 3b), as only the cost of rooftop photovoltaics is reduced. In contrast, in the $NoGrid_{acceptance}$ and $NoGrid_{Legislation}$ scenarios, other onshore wind power potentials are altered, thereby reducing the maximum population in energy autonomous municipalities from 43.4 million to 42.6 million in the $NoGrid_{Legislation}$ scenario and to 39.8 million in the $NoGrid_{acceptance}$ scenario. For 540 municipalities with 22.6 million inhabitants, the degree of autonomy changes by an average of 12% from $NoGrid_{ref}$ to the $NoGrid_{acceptance}$ scenario. Relative to all 11 003 municipalities, the mean deviation of the degree of autonomy is only 0.6%. There are three reasons for the low impact of the wind potential scenario on the autonomy distribution: first, 3826 municipalities in the $NoGrid_{ref}$ and $NoGrid_{acceptance}$ scenarios have identical wind potential. Second, in 2496 municipalities, despite the reduced potential, the capacity of wind turbines needed for the cost-optimal configuration of the energy system can still be built in the $NoGrid_{acceptance}$ scenario. Third, the remaining 4141 municipalities must reduce the wind capacity built compared to the cost optimum in the $NoGrid_{ref}$ scenario, but continue to achieve the same degree of autonomy despite the adjusted energy system design. In the following, the impact of legislation and social acceptance on system costs (Section 3.2.1), installed renewable energy capacity (Section 3.2.2), storage capacity (Section 3.2.3), low-temperature heat supply (Section 3.2.4), process heat supply (Section 3.2.5) and curtailment (Section 3.2.6) is presented.

3.2.1. System costs

The adaption of autonomous energy systems can lead to significantly higher costs. Fig. 4b depicts the specific system costs of the municipalities in the four scenarios with complete energy autonomy. The costs vary widely across all municipalities: for example, in the $NoGrid_{ref}$ scenario, the specific costs in Neuschoo in Lower Saxony are 67 €/MWh, whereas in Kahl am Main in Bavaria with 2042 €/MWh, the highest costs occur. The costs in Kahl am Main are about twice as high as in Urmitz, whose cost-optimal autonomous energy system is shown in detail in the Supplementary Material. These municipalities can only achieve an autonomous energy system with extreme and very expensive measures.

For municipalities with a total population of 30 million, an autonomous energy system can be achieved in the $NoGrid_{ref}$ scenario with costs below 151 €/MWh, with an average cost of 122 €/MWh per municipality, whereas the population-weighted average is higher with 144 €/MWh. This demonstrates that highly populated municipalities face higher specific costs on average. The $NoGrid_{acceptance}$ scenario, due to reduced wind capacity, exhibits the highest costs of all scenarios. First, possible overcapacities that lead to the cost-optimal system in the $NoGrid_{ref}$ scenario cannot be built. Second, PV-heavy systems are more often deployed, in which the battery storage must be larger in order to ensure an optimal system integration of PV. This translates into an average cost in the $NoGrid_{acceptance}$ scenario of 138 €/MWh per municipality, and a population-weighted average cost of 174 €/MWh. For a population of 30 million, specific system costs are below 189 €/MWh in the $NoGrid_{acceptance}$ scenario.

The reduced costs for rooftop PV systems in the $NoGrid_{rooftopPV}$ scenario, which are added to the system costs after the optimization, also lead to higher system costs compared to the $NoGrid_{ref}$ scenario. The lack of information in the model about the actual cost of rooftop PV systems leads to a deviation from the overall macroeconomic cost optimum. Accordingly, the population-weighted average is 149 €/MWh, which is slightly above the $NoGrid_{ref}$ scenario but significantly below the $NoGrid_{acceptance}$ scenario.

Fig. 5 displays a scatter plot of specific system costs versus wind capacity share in renewable generation capacity for all 5948 (54%) municipalities in the $NoGrid_{ref}$ scenario in which the wind potential is not fully exploited in the cost-optimized systems. This means that the 5948 depicted municipalities could theoretically add more wind capacity. 99% of the considered municipalities are above 12% and below 59% wind share in renewable capacity at specific system costs below 151 €/MWh. On average, the specific system costs of municipalities are 100 €/MWh. Compared to the entirety of autonomous municipalities in the $NoGrid_{ref}$ scenario, the specific system costs are therefore 18% or 44% lower, respectively. Thus, a diversified generation mix and the flexibility to choose renewable technologies is crucial for attaining moderate system costs in the municipalities.

3.2.2. Installed renewable energy capacity

Fig. 6a presents the installed renewable generation technologies for the municipalities that achieve a completely autonomous supply structure in all four scenarios. The installed capacity is predominated by rooftop PV systems in the scenarios. For example, in the $NoGrid_{ref}$ scenario, rooftop PV systems account for 108 GW, which is about 40% of the installed capacity. In the $NoGrid_{acceptance}$ scenario, the share of rooftop PV increases to 162 GW and 51%, respectively, due to reduced wind capacity. In the $NoGrid_{rooftopPV}$ scenario, the built rooftop PV capacity increases even more to 208 GW and 69% of the total capacity. However, due to the simultaneity in PV generation, the open-field PV capacity is mainly reduced in this scenario (-59%), whereas the wind capacity only decreases by 10% compared to the $NoGrid_{ref}$ scenario.

The reasons for the dominance of rooftop PV capacity in the scenarios are manifold: first, the full-load hours of PV plants are lower than those of onshore wind plants, so that for the $NoGrid_{ref}$ scenario, generation by onshore wind plants (135 TWh) is larger than by rooftop PV plants (98 TWh) at smaller capacity. Second, the proximity of rooftop PV to consumption is of great importance in autonomy considerations and is a major advantage of the technology. The greater expansion of rooftop PV in the autonomous municipalities can also be explained by urban municipalities, which can barely reach a degree of energy autonomy of 1. In these municipalities, the full renewable potential is exploited snd there is a lack of flexibility to compose the system in a cost-optimal way. This is expressed, for example, by the fact that rooftop PV modules are also built in a northern orientation in these municipalities (see detailed results for Urmitz in the Supplementary Material).

3.2.3. Installed storage capacity

Fig. 7a illustrates the storage capacities in the autonomous municipalities. In addition, the normalized storage levels in all municipalities are shown over one year in Fig. 7b for the $NoGrid_{ref}$ scenario. The seasonal storage demand in the energy autonomous municipalities is mainly met by a thermal storage capacity of 54 TWh in the $NoGrid_{ref}$ scenario with two charging cycles[2] (capacity-weighted average). In addition, hydrogen tanks are used, but these are sized one order of magnitude smaller in all scenarios. For example, in the $NoGrid_{ref}$ sce-

[2] The charging cycles are defined as complete discharges and charges over the year. Partial cycles are summed up and thus also taken into account.

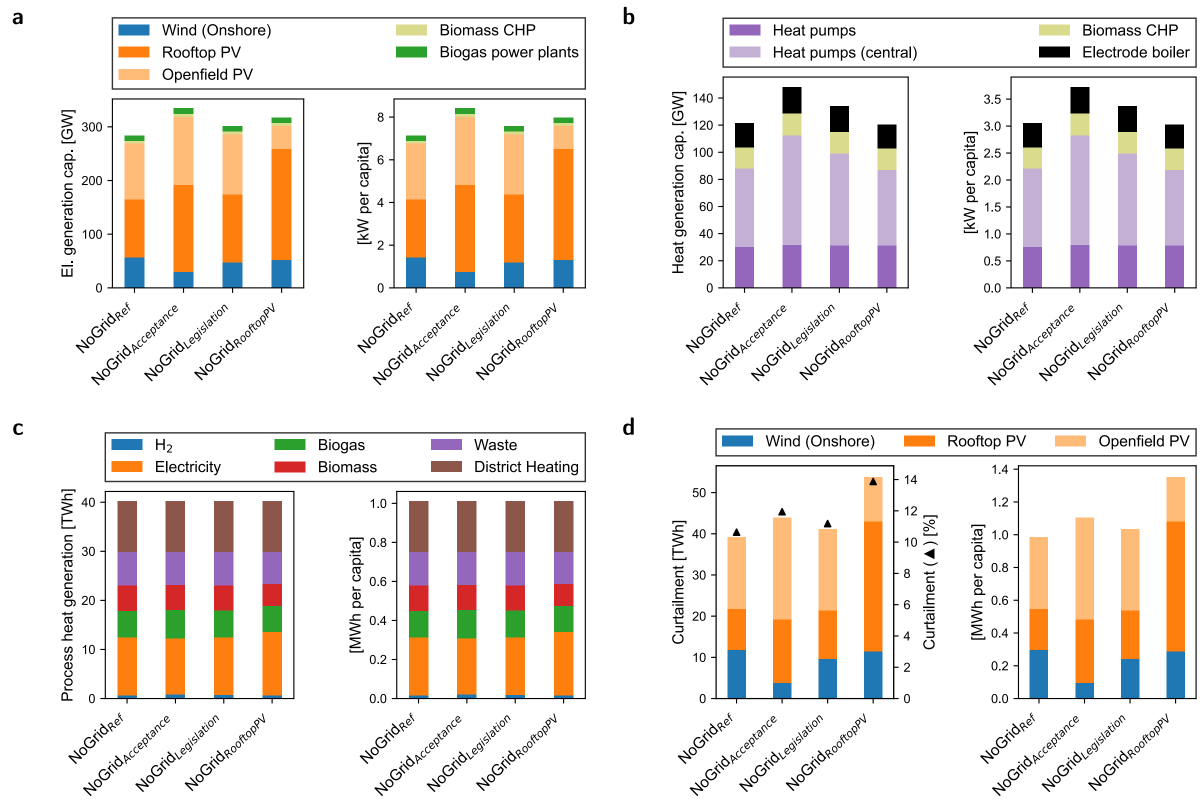

Fig. 6. Electricity generation capacities (a), low-temperature heat generation capacities (b), process heat generation (c) and renewable generation curtailment (d) in the energy autonomous municipalities.

nario, 1.6 TWh are installed (14 charge cycles in the capacity-weighted average). Centralized battery storage is used as inter-day storage, with correspondingly smaller sizes due to this use case and higher capacity-specific costs ($NoGrid_{ref}$ scenario: 285 GWh with 179 charge cycles in the capacity-weighted average). In the $NoGrid_{acceptance}$ scenario, the seasonal and interday storage is significantly larger. The battery storage, hydrogen storage, and thermal storage have higher capacities by 58%, 69%, and 54%, respectively, compared to the $NoGrid_{ref}$ scenario. One reason for this is the seasonal and intra-day variation in PV-driven power generation in the $NoGrid_{acceptance}$ scenario, which requires more storage for optimal system integration than wind.

3.2.4. Low-temperature heat supply

Fig. 6b shows the capacities for supplying low-temperature heat in the autonomous municipalities. Through the use of power-to-heat technologies, the electricity and heat systems are coupled. In conjunction with the large heat storage facilities, this also makes the electricity system more flexible. Accordingly, in the $NoGrid_{acceptance}$ scenario, the largest large-scale heat pump capacities (81 GW) and electrode boiler capacities (19 GW) are built in combination with the large-scale heat storage systems. In the $NoGrid_{ref}$ scenario (large-scale heat pumps: 58 GW, electrode boilers: 18 GW), $NoGrid_{Legislation}$ scenario (large heat pumps: 68 GW, electrode boilers: 19 GW) and $NoGrid_{RooftopPV}$ scenario (large-scale heat pumps: 56 GW, electrode boilers: 18 GW), the capacities are correspondingly smaller.

3.2.5. Process heat supply

The configuration of process heat generation in the autonomous municipalities is shown in Fig. 6c. There is little difference in the generation of process heat in the scenario comparison. While the district heating network takes the largest share for the low temperature sector in the $NoGrid_{ref}$ scenario, waste with 66% and biomass with 11% are used as energy sources for the medium temperature sector. The high-temperature demand is met by using biogas (27%) and biochar (21%) obtained from biomass by means of torrefaction. As the availability of biomass and biogas in the municipalities is limited, there is a regional discrepancy between the emergence of bioenergy sources and the demand for process heat generation. Due to this, a significant portion of medium- (23%) and high-temperature heat generation (49%) is electrified. Hydrogen is used only at 3% for high temperature process heat generation. It should be noted that the material hydrogen demand of industry is not included in these quantities.

3.2.6. Curtailment

Despite the large-scale storage, about 39 TWh of possible generation is curtailed in the $NoGrid_{ref}$ scenario (see Fig. 6d). In a fully renewable energy system, a comparatively higher level of curtailment can be expected, but the curtailment of an average of 11% must still be considered large. This fact highlights the trade-off between storage sizing, further flexibility in the system, and curtailment at the cost optimum: the larger the storage capacity is, the smaller the curtailment may be. On the other hand, extreme storage sizes lead to high costs, such that curtailment can be cost-optimal in case of high renewable generation, especially in autonomous municipalities. The curtailment reduces the need for storage capacities for peak generation, such as electrolyzers for H_2 storage. In some municipalities, virtually every kilowatt-hour must be utilized, meaning that no curtailment occurs in any of the scenarios in these municipalities (cf. Supplementary Material).

Although the PV capacities in the $NoGrid_{acceptance}$ scenario are proportionally larger than in the $NoGrid_{ref}$ scenario with 91% of the installed renewable capacity and so there is a higher simultaneity of generation, the curtailment is only slightly higher by 12%. However, the storage facilities are significantly larger, as described above, which explains the moderate increase in curtailment due to a shift within the trade-off between flexibility and curtailment. In contrast, in the $NoGrid_{rooftopPV}$ scenario, the curtailment increases more

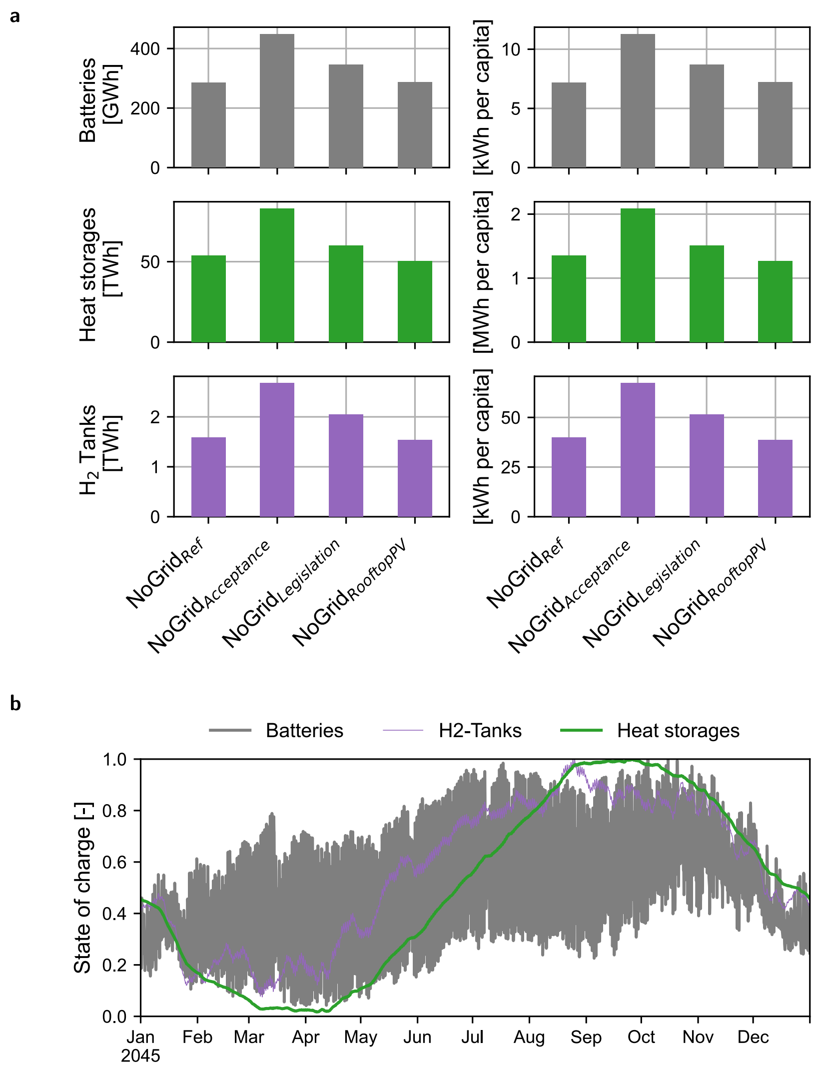

Fig. 7. Storage capacities in the energy autonomous municipalities in the scenario comparison (a). Normalized state of charge in all municipalities in the $NoGrid_{ref}$ scenario over the year (b).

significantly to 14% because the additional rooftop PV capacity built is cost-optimal, despite the increased curtailment due to artificially-reduced costs. This is also reflected in the large share of rooftop PV systems in the curtailment (see Fig. 6d).

3.3. Impact of autonomy type on system composition

While in the $NoGrid_{ref}$ scenario a total of 306 GW renewable capacity is installed, grid connection and the external price signal in the $Grid_{balanced}$ scenario increase the capacity significantly to a total of 738 GW due to the potential revenues (see Fig. 8a). The scenario comparison in this section is limited to the 10 231 municipalities that can establish an autonomous supply structure in the $NoGrid_{ref}$ scenario (see Fig. 3). These autonomous municipalities tend to be regions with large revenue opportunities due to extensive renewable resources. Due to the autonomy constraint, the total capacities in the $Grid_{balanced}$ scenario are 82 GW (11%) larger than in the $Grid_{ref}$ scenario. However, for 6019 of the 10 231 municipalities and 46% of the population, respectively, an identical energy system results for both scenarios. The remaining municipalities are forced to build capacity that deviates from the cost optimum, most of which is rooftop PV. Therefore, rooftop PV capacity is 73 GW higher in the $Grid_{balanced}$ scenario, which explains 89% of the deviation in capacity. Accordingly, the objective of balanced autonomy or targets for demand-related minimum generation from renewable energy sources at the regional level is not a problem, as long as the region manages to meet these targets while respecting national expansion plans. Otherwise, there is a risk that uneconomic or unneeded capacities are developed, which in turn can have a negative impact on the overall system through required grid extensions or energy justice considerations (see the discussion of network charges in McKenna [60]).

Considering the other generation capacities, it is evident that the largest flexibility options are needed for achieving complete autonomy: the capacity of biogas power plants is the largest at 10 GW in the $NoGrid_{Ref}$ scenario, followed by the capacity of biomass CHP plants (6 GW_{el}). On the other side of the spectrum is the $Grid_{Ref}$ scenario, in which no biomass or biogas power plant capacity is built.

Despite the fact that flexible generators can help reduce the need to build excess capacity, the curtailment is still highest in the $NoGrid_{Ref}$ scenario (see Fig. 8b). In addition, the results indicate that non-southern-facing PV systems are deployed in energy systems with greater flexibility needs, despite the lower full load hours, due to their divergent generation profiles. Accordingly, support instruments should be developed in the future that do not remunerate renewable generation across the board, but help to provide targeted incentives, taking into account the regional and temporal dimension, to increase flexibility and thus integrate renewables into 100% renewable energy systems and reduce their curtailment.

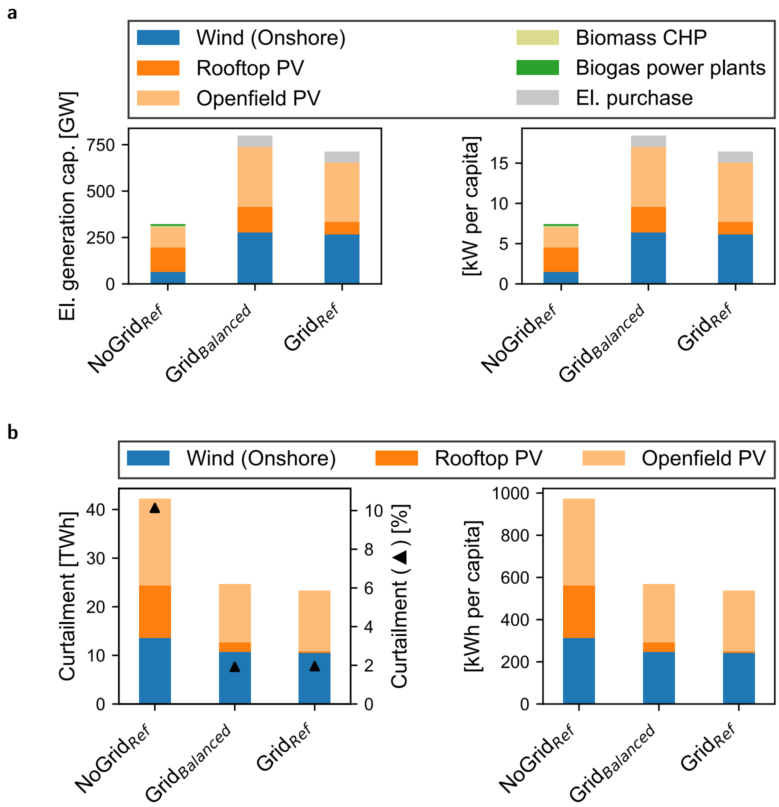

Fig. 8. Total electricity generation capacities (a) and curtailment (b) under different autonomy conditions, for the 10 231 municipalities that can establish an autonomous supply structure in the $NoGrid_{ref}$ scenario. These 10 231 municipalities can satisfy the autonomy requirements in all scenarios.

3.4. Sensitivity analyses

This section focuses on the impact of weather years and techno-economic assumptions on the techno-economic potential of all municipalities for complete energy autonomy. The influence of the time series aggregation approach on the results is not significant and hence is described in the Supplementary Material.

3.4.1. Impact of weather years

To evaluate the impact of different weather years on the results, the renewable generation in the $NoGrid_{ref}$ scenario was varied by using 40 different weather years. In addition to the results for the different years, a scenario with the worst weather year was chosen for each municipality: first, the weather year leading to the lowest degree of energy autonomy was selected for each municipality. In municipalities for which autonomous supply is possible for all weather years, the maximum specific system costs were used as an evaluation criterion. This scenario is referred to as the *critical weather year* in the following.

The weather year of the $NoGrid_{ref}$ scenario (2014) is associated with medium degrees of autonomy in the optimized municipalities compared to the other weather years (see Fig. 9a). By definition, the critical weather year represents the lower limit of the degree of autonomy. Compared to the weather year of the $NoGrid_{ref}$ scenario, the critical year leads to a decrease of the population in municipalities in which energy autonomy is technically feasible by 2.4 million. As the demand must be met regardless of weather conditions, the critical year represents a more robust estimate of potential degrees of autonomy in German municipalities. In terms of the specific system costs, however, there are no significant deviations between the critical year and the $NoGrid_{ref}$ scenario (see Fig. 9b) for much of the population. Thus, on average, the specific system costs in the municipalities increase on average by 8% to 127 €/MWh, or if population-weighted by 18% to 150 €/MWh. For 30 million inhabitants, the costs only increase by up to 7%. For the remaining municipalities, stronger deviations between the weather years result. These deviations are due to the fact that systems with increased costs can only barely realize a completely autonomous supply in the $NoGrid_{ref}$ scenario. For these municipalities, changes in generation therefore have a particularly large impact on system costs. Accordingly, the cost for about one million residents in the critical year is 797 €/MWh and on average (population-weighted) 2.75 –fold higher than in the $NoGrid_{ref}$ scenario.

The share of the population in potentially energy autonomous municipalities decreases at most from 52% to 49% when considering several weather years. The overall results regarding autonomous supply in German municipalities can thus be considered relatively robust, as mainly municipalities achieve autonomy that can mobilize further potential for energy supply in unfavorable weather years. With regard to the costs and built capacities in the municipalities, it can be stated that the systems display a medium sensitivity to the weather year used. The stability of these systems may also be questioned, as this section only examines sensitivity to historical weather conditions. Potentially more significant generation lulls in the future could lead to the emergence of even more expensive systems or unmet demand.

3.4.2. Impact of cost assumptions

Fig. 10 shows the sensitivity of the $NoGrid_{ref}$ scenario to capital cost assumptions. For ±20% deviations in investment, moderate deviations in installed capacity of about ±5% can be seen for thermal storage and open-field PV systems. For battery storage, rooftop PV systems, hydrogen tanks, and wind systems, the deviations are slightly higher at approximately 10%. For the mean specific system costs, the largest variation of -3% results from a change in the capital costs of the wind turbines. The influence of the costs in the investment variation range of ±20% on the results of the $NoGrid_{ref}$ scenario can thus be classified

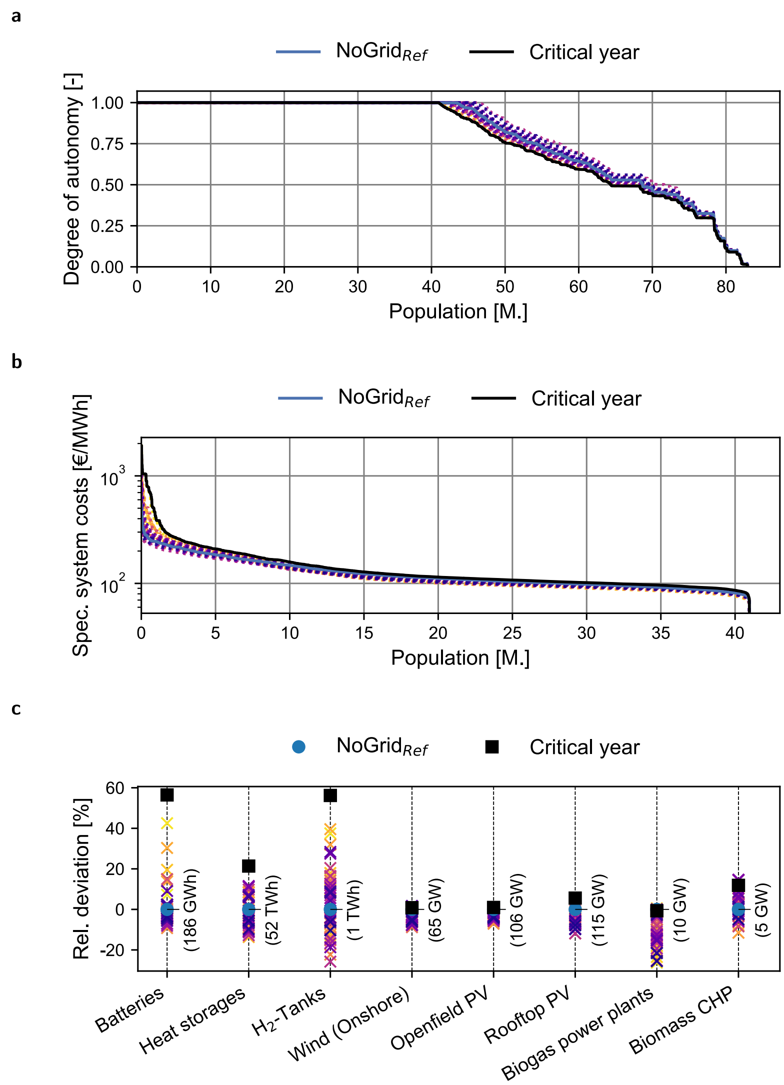

Fig. 9. (a) Population-weighted distribution of the degree of energy autonomy for different weather years. (b) Population-weighted distribution of specific system costs of completely autonomous municipalities for different weather years. (c) Relative change in selected capacities compared to the $NoGrid_{ref}$ scenario.

as moderate. If costs are halved (−50%) or doubled (+100%), the largest impact on specific system costs comes from the capital costs of rooftop PV and onshore wind. For these technologies, the lowest amount of substitution opportunities exist for municipal systems. For rooftop PV, the behavior can be explained by the full exploitation of open-field PV potential in the municipalities, which leaves no alternative for the use of rooftop PV in many municipalities. For wind turbines, the effect results from the beneficial generation profile. The impact due to battery and thermal storage on system costs is somewhat smaller due to existing substitution options. Halving or doubling battery capital costs symmetrically varies battery capacity by ±31% compared to the $NoGrid_{ref}$ scenario. The interaction with the $CAPEX$ variations of the other technologies turns out to be comparatively small, with the maximum capacity increase when doubling the capital costs for wind turbines (8%). The positive correlation can be attributed to the decrease in wind turbine capacity and the accompanying increase in PV capacity in the systems, which necessitates higher battery storage capacity for evening and nighttime hours.

Doubling or halving the capital costs of thermal storage results in a change in capacity of −21% and +22%, respectively. The absolute deviation is significant due to the large heat storage capacities in the $NoGrid_{ref}$ scenario with −14 TWh and +14 TWh, respectively. In addition, the heat storage capacities are found to interact especially with the capital costs of the rooftop PV systems and the capital costs of the hydrogen tanks. In the case of hydrogen tanks, this is due to the seasonal use of both storage technologies in the energy system models (see Section 3.1). This effect is particularly measurable when the capital cost of hydrogen storage is reduced. If hydrogen storage costs are halved, 11% less thermal storage is built. This interaction can also be observed for the capacity of the hydrogen tanks: doubling the capital costs of the heat storage tanks results in an increase in the capacity of the hydrogen tanks by 25%. For the hydrogen tanks' capital costs, an asymmetrical outcome occurs: halving the cost leads to an increase in the capacity of 71%, whereas doubling the cost leads to a reduction of 27%.

For the rooftop PV plants, there is also a larger impact due to a reduction than an increase in capital costs. Two reasons account for this: first, municipal energy systems only have limited flexibility to reduce rooftop PV capacity due to the lack of substitution options. A doubling of costs only leads to a reduction of capacity by 21%. Second, there is a large interaction with open-field PV plants due to the similar generation profiles. Thus, when costs are halved, a system change occurs in which large shares of the open-field PV capacity are replaced with rooftop PV capacity. Increasing rooftop PV capacity by 102 GW (46%) is matched by a reduction in open-field PV capacity by 61 GW. The effects of changing open-field PV capital costs to rooftop PV

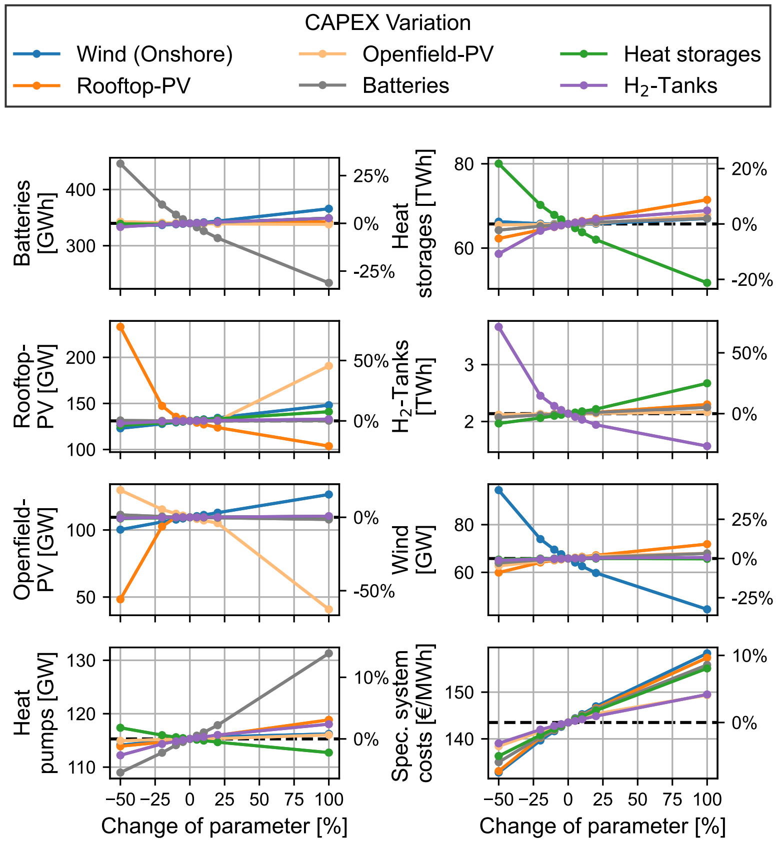

Fig. 10. Sensitivity of the results in the $NoGrid_{ref}$ scenario to $CAPEX$ assumptions for ±5%, ±10%, ±20%, and halving or doubling of the costs.

capacity are also asymmetrical: doubling the cost leads to an increase in rooftop PV capacity to 191 GW on the one hand, while decreasing the cost leads to no measurable change in rooftop PV capacity, on the other. This can be explained by the already low costs for open-field PV in the $NoGrid_{ref}$ scenario, which leads to a preference for open-field PV over rooftop PV in the municipalities. Nonetheless, an increased open-field PV capacity of 19% results through a halving of capital costs, which primarily substitutes wind capacity. Accordingly, an increase in wind turbine capital costs also leads to an increase in open-field PV capacity of 16%, and wind capacity is reduced by 32%. Halving the capital cost of wind turbines leads to an increase in wind capacity by 44%.

For the heat pump capacities, a positive correlation with the capital costs of the battery storage system can be identified: for a doubling of the battery storage costs, an increase in the heat pump‘s capacity by 14% arises. For a halving of the battery cost, the capacity decreases by 6%. This demonstrates that the heat pump, in conjunction with the heat storage capacities, is an alternative to make the power system more flexible. In particular, excess heat pump capacity can be understood as an alternative measure to intraday storage in batteries. Consequently, a negative correlation of heat pump capacity towards the capital costs of heat storage can also be seen as the technologies are deployed in combination.

In the $Grid_{ref}$ scenario, the impact of cost changes on the results is greater than in the $NoGrid_{ref}$ scenario because the constraint that electricity must be generated and used within the region no longer applies. With import and export options, technologies and measures must now withstand cost pressures from additional substitution options, meaning that cost changes lead to larger deviations compared to the $NoGrid_{ref}$ scenario. At the same time, the interactions between technologies are smaller, as they do not necessarily have to interact in the energy system. For more details on the impact of cost changes in the $Grid_{ref}$ scenario, see the Supplementary Material.

4. Discussion

In this section, the results obtained are placed in the context of the literature and critically discussed. To this end, Section 4.1 first discusses the impacts of energy autonomy at different spatial scales and Section 4.2 the socio-economic effects of autonomous energy systems. Subsequently, the results are compared with the findings from previous literature (Section 4.3) and the limitations of this study (Section 4.4) are discussed.

4.1. Economies of scale

In larger energy systems, economies of scale and temporal smoothing contribute to enhanced economic efficiency [60]. The optimal scale of energy autonomy is discussed in multiple studies using different perspectives and modeling approaches (e.g., for buildings in Kleinebrahm et al. [66] or larger regions and countries in Tröndle et al. [67]). Studies on the European scale conclude that widespread, highly interconnected systems result in the lowest costs by exploiting the best renewable resources and balancing local supply and demand fluctuations through spatial smoothing over large areas [67]. Kleinebrahm et al. [66], on the other hand, investigate the techno-economic potential of energy autonomy of freestanding single-family buildings within the European building stock under framework conditions in 2020 and 2050. In comparison to large-scale electricity systems, the spatial proximity of rooftop PV and electricity and heat demand requires integrated systems that allow the efficient use of small-scale co-generation technologies. While energy transport losses are minimized, high marginal costs for achieving the final degrees of self-sufficiency prevent economic operation as long as no fixed grid charges are introduced [66]. In contrast to energy autonomous supply concepts at the building level, the high marginal costs at high degrees of self-sufficiency can be significantly reduced at the municipal level through the combination of wind turbines and PV in combination with large scale heat storage and distribution systems. However, especially in the planning and implementation of municipal energy systems, purely techno-economic analyses must be expanded to include the expectations and interests of stakeholders such as local authorities, citizens, utilities, and companies [68]. Therefore, the question arises as to which degree different stakeholder groups are willing to pay additionally for energy autonomy. The design of residential energy supply systems is a decision based on the homeowner's personal preferences, increasing the likelihood of deviation from purely economically-driven investments.

4.2. Socio-economic impacts of regional energy autonomy

While complete energy autonomy is hardly understood as an objective in real world energy regions, balanced energy autonomy is often considered desirable for various stakeholders, such as in the projects 100ee-Region [69] and bioenergy villages [70]. Engelken et al. [6] highlight that decision-makers often strive for energy autonomy out of ecological conviction, because of tax revenues, and to achieve independence from private companies. Furthermore, Ecker et al. [71] show that individuals in autonomous supply structures have a higher willingness to pay. Especially at the household level but also at the urban one, the endowment effect [72] occurs, which means that individuals attribute a higher value to goods simply because they own them [71]. From an economic perspective, regional value creation can be further strengthened and jobs created in a region [73]. In addition to economic effects, energy regions can help increase public acceptance of the energy transition by increasing the involvement and participation of the region's residents [74]. Furthermore, end-use energy savings can be achieved by engaging the public and making consumers more aware of the energy use [75]. Accordingly, the Easter package of the German Federal Ministry for Economic Affairs and Climate Action (BMWK) states that the financial participation of local authorities should be further developed in the interest of local acceptance [2].

Despite the positive influences of regional energy concepts mentioned, the macroeconomic effect, as well as the influence on the superordinate energy system of autonomous energy regions is hardly explored [19,60]. The pursuit of balanced energy autonomy potentially leads to high peaks in transmission output but low utilization of transmission infrastructure. McKenna [60] highlights that balanced energy autonomous regions may contribute little to network costs as a result, leading to macroeconomic disadvantages.

4.3. Comparison with previous studies

With the exception of Weinand et al. [37], existing studies (see Section 1.1) on the energy autonomy potential of municipalities only evaluate individual regions. Weinand et al. [37] project the results from 15 representative municipalities to the entirety of German municipalities, with the result that 56% of German municipalities and 14% of the population, respectively, could become autonomous. The results differ compared to the $NoGrid_{ref}$ scenario of the present study, in which 93% of German municipalities, encompassing 51% of the population could become autonomous. There are several reasons for these discrepancies, such as the consideration of additional technologies including open-field PV plants or seasonal storage highlighted in the present study, which are shown here to be significant for achieving energy autonomy. Furthermore, in contrast to this article, Weinand et al. [37] consider four extreme days per year, during which demand peaks and no solar irradiation or wind is present.

Beyond that, Moeller [13] shows for the municipality of Greven that a degree of energy autonomy of 80 % is associated with a specific system cost of 122 €/MWh, but higher degrees of autonomy are not investigated. Electricity not generated within the municipality can be imported at a cost of 67 €/MWh. Taking over this electricity price in the present work and under the assumptions of the $NoGrid_{ref}$ scenario, a degree of autonomy of 80% results in a cost of 141 €/MWh for the autonomous system in Greven, which is comparable to the costs outlined in Moeller [13].

4.4. Limitations

Most of the studies modeling regional energy systems (listed in Section 1.1), including this study, follow a greenfield approach which assumes all of the energy technologies are installed anew. In reality, the already installed energy technologies which are yet to complete their operational lifetime will have an impact on the optimum design of the municipal energy systems. These existing energy technologies can lead to path dependencies. For example, an older district heating system which is still operational might impact investment in new, more efficient and carbon-neutral district heating technologies [76]. Another aspect which can impact the optimal design of municipal energy systems is the hosting capacity related constraints of the existing grid infrastructure. Integration of renewable energy technologies can cause voltage imbalance and thermal overload in the electrical network [77,78]. Mitigation of these operational challenges requires grid reinforcement which can be expensive. Therefore, it is important to consider the grid capacity and grid-related constraints in decentralized energy system modeling [79]. The current optimization model used in this study considers grid capacity-related constraints for the import and export of energy. Further constraints related to hosting capacity and the costs of grid reinforcement can be added in the future.

As observed within the results, local energy supply potential plays a major role in the possible autonomous operation of the municipalities. For smaller municipalities lacking wind and open-field PV supply potential, autonomous power supply is not possible. If several smaller municipalities are merged together, they can share their supply resources. This can benefit in terms of added complementarity in the aggregated demand as well as supply profiles of merged municipalities. This can make autonomous operation possible for the group of these municipalities which would not have been possible individually. The smoothing of demand and supply as a result of merging the municipalities will also result in a lower residual load which will lead to lower flexibility and cost requirements for autonomous operation. This aspect requires further investigation to analyze what is the optimal scale of spatial aggregation for autonomous operation [80]. The results obtained also show that the autonomous operation of the municipalities heavily relies on the deployment of hydrogen-based seasonal storage. It is assumed that the hydrogen is produced locally in the off-grid scenarios and can be easily imported in the scenario considering the grid supply. The availability of hydrogen infrastructure as well as the land use constraints related to its deployment need to be further analyzed in future studies.

When looking at the technologies used in the autonomous municipalities in this work, it is noticeable that a large portion of the flexibilization of the energy supply is provided on the heating side. By combining underground heat storage with central heat pumps within the district heating network, surplus electricity can be used flexibly to supply heat. The use of this combination of technologies is also evident in the scenarios in which electricity may be imported and exported. The sensitivity analysis (Section 3.4.2) also shows that central heat storage remains in the cost-optimal system in both the $Grid_{ref}$ scenario and the $NoGrid_{ref}$ scenario, even when the capital cost assumption is doubled. The utilization of so-called Carnot batteries [81] could make heat-side flexibilization even more attractive in future studies. Regenerative power generation could be investigated, for example, using steam turbines in an Organic Rankine Cycle.

Given the first-time consideration of all municipalities in Germany and the associated computation times, this work refrained from formulating a mixed-integer linear optimization problem, as was done, for example, by Weinand et al. [37]. By employing larger computational capabilities in future work, the results of this work could be made more precise by using a mixed-integer linear problem formulation. Furthermore, the spatial resolution within municipalities could be improved through a multi-node implementation that would allow the network infrastructure within a region to be represented in greater detail. In addition, further base-load capable technologies such as deep geothermal plants for heat [36] and power [82] supply could be beneficial in future autonomous municipal energy systems [44], but were not included in the present work. This technology has great potential in Europe and Germany in particular, can supply electricity and heat, and caries further opportunities for revenue generation such as direct lithium from hydrothermal water [83].

5. Conclusions

The results demonstrate that 10 231 (93%) German municipalities are capable of establishing a completely energy autonomous supply. Furthermore, the calculated system costs for the autonomous energy systems are partly lower than the mean electricity prices of around 155 €/MWh for household consumers excluding taxes and adjusted for inflation in the European Union for 2023 [84]. However, the comparison of the autonomous municipalities in the reference scenario with a scenario with grid connection, in which the purchase and sale of electricity is allowed, shows that no economic potential exists for energy autonomous municipalities. For regions that could achieve an autonomous energy supply at moderate costs, lost revenues constitute a decisive argument against autonomy efforts. Autonomous regions with high energy demands are associated with very high system costs; other regions cannot meet their demands at all autonomously. However, by paying a premium of up to 50% compared to the grid-dependent system, 3945 municipalities with 17.2 million inhabitants could become completely autonomous by 2045. Appropriate political instruments should be developed or expanded to give regions a greater share of revenues in order to curb the pursuit of complete autonomy in municipalities where energy autonomy is not the optimum from a macroeconomic perspective.

The results of this study on the techno-economic feasibility of energy autonomy in municipalities can be transferred to other countries with similar conditions in terms of renewable potentials or demand patterns, such as in Central Europe. The methodology demonstrated here can be transferred to any municipalities in other countries with similar data availability using the open-source energy system framework presented.

CRediT authorship contribution statement

Stanley Risch: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jann Michael Weinand:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Kai Schulze:** Writing – review & editing, Methodology, Investigation. **Sammit Vartak:** Writing – review & editing, Writing – original draft. **Max Kleinebrahm:** Writing – review & editing, Writing – original draft. **Noah Pflugradt:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Felix Kullmann:** Writing – review & editing. **Leander Kotzur:** Supervision, Conceptualization. **Russell McKenna:** Writing – review & editing, Writing – original draft. **Detlef Stolten:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.enconman.2024.118422.

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