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Urban-Rural Cooperation for an Economy with 100% Renewable Energy and Climate Protection towards 2030: the Region Berlin-Brandenburg

Thure Traber[a*], Hans-Josef Fell[b] and Christian Breyer[c]

[a]*Ansvar2030 Holding GmbH, Plauener Straße 21, 44139 Dortmund, Germany.*
[b]*Energy Watch Group Berlin, Albrechtstraße 22, 10117 Berlin, Germany.*
[c]*LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finland.*

ABSTRACT

The German federal states of Berlin and Brandenburg are committed to the Paris Agreement with its goal of keeping global warming safely below 2 degrees in order to protect the earth system from uncontrollable warming. This demand means that 1.5 degrees must be targeted in order to maintain a reasonable chance of realisation. Renewable energy is the only resource that can be scaled up with the required time horizon. We use a linear cost minimisation model for the Berlin-Brandenburg region to show how a 100% renewable energy target is possible without relying on contributions from other regions. We conclude that a 100% renewable energy system based predominantly on photovoltaics on buildings and on green hydrogen production, as well as a transition to electricity use for all purposes, is feasible in time and at a reasonable cost below that of fossil-nuclear energy. Hydrogen storage technology seems to be one of the main cost drivers, while a sensible integration of German and European transition systems could further limit costs.

Keywords

sector coupling;
power-to-gas;
hydrogen;
renewable energy;
climate policy.

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1. Introduction

The Federal Republic of Germany has signed the Paris climate protection agreement, which is binding under international law. Limiting global warming to 1.5°C above pre-industrial levels with acceptable probability requires an end to all greenhouse gas (GHG) emissions by around 2030 [1], [2], while a further delay would question the capability for action in general [3], [4].

Today, the energy sector is still based on the use of fossil oil, fossil gas, and coal, accounting for 55% of all anthropogenic greenhouse gas emissions [5]. We lay out the switch to 100% zero-emission renewable energies for all consumption sectors which forms the most important contribution to necessary climate measures that could serve also as starting point for the conversion of agriculture and forestry, organic farming and he realization of a waste- and emission-free circular economy [6]. Accompanying the creation of a zero-emission economy, the development of carbon sinks must be accelerated.

Further developments of fossil and nuclear energy technologies are, according to current cost calculations, in any case energetically inefficient, too expensive and too slow in expansion and hinder a consistent strategy by postponing a profound transformation [4]. Historic deployment clearly shows that nuclear energy and carbon capture, transport, and storage are too slow to be effective in this decade, which is critical to achieving climate goals.

Fossil gas technologies are similarly not an option due to methane emissions during extraction, transport

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*Corresponding author e-mail: thure.traber@ansvar.com and distribution chain [7], [8], but also due to fundamental risks to energy supply in the case of Germany due to heavy dependence on imports particularly from Russia. Against the background of cost-effective renewable energy alternatives, conventional fossil and nuclear technologies are no longer tenable overall.

For the accomplishment of the German commitments, all regions must deliver their contribution without delay. Not only for economic reasons, but also for further climate protection, all energy supply must be converted immediately to 100% renewable energy with sector coupling. Fossil fuels, with or without carbon capture and storage and nuclear energy, are not only more expensive [9], [10], as recently also clearly confirmed by the IEA in the World Energy Outlook 2021 [11], but also incompatible with a timely transition to a climate-friendly economy. To be able to achieve compliance with the Paris Agreement in Germany, the Berlin-Brandenburg capital region must develop a clear plan for the use of renewables. This is envisaged by legislation and declarations of the state governments [12], [13] summarised in Appendix A.

Complying with the Paris Agreement, however, means that energy-related emissions must be phased out by 2030, rather than discussing so-called scenarios of climate neutrality by 2050 or 2045 that involve further investment in fossil fuels. Literature that shows pathways for a transition in a less demanding timeframe and yet provide important insights for the for Germany's compliance with the Paris Agreement is manifold.

Noteworthy, the coverage of industrial heat demand is exemplified in [14] for the German example. A comprehensive assessment of influential reports for the German case is given by [15] with a comparison particularly of [16], [17], and [18]. Renewable energies can provide a viable and fast answer how to reduce emissions as has been shown most often in research on the national level. In total, about 40 studies on 100% renewable energy are known for Germany [19]. The four most cited articles on 100% renewable energy system analyses for Germany on a national level are Weitemeyer et al. [20], Palzer and Henning [21], [22], Hansen et al. [23], and Robinius et al. [24]. More discussion is provided on future perspectives on urban-rural optimization and complementarity as referred to in section 4.5 below.

Some studies show the technological feasibility of a climate-protective supply based on 100% renewables by 2050 on higher geographical level representing large areas of nations or continents. Other studies investigate 100% renewables for less population and related consumption. The following studies provide European examples investigating 100% renewable energy in increasing order of covered population.

In a fairly detailed fashion Pina et al. [25] explore a smart energy system at urban level for the roughly 20,000 people of Bressanone-Brixen in Northern Italy elaborating the case specific for urban people particularly in a mountainous environment. For the comparative size of about 34,000 inhabitants in Zwolle community of in The Netherlands Leeuwen et al. [26] show a geographically distinct example is given for Northwestern Europe with an objective that maximises self-sufficiency. For the case of the city of Osnabrück and adjacent regions in Germany the study of Möller et al. [27] emphasise the synergy by the integration of regional city-hinterland energy systems combining around 160,000 inhabitants of the city of Osnabrück with its hinterland given by Kreis Steinburg and rural Kreis Osnabrück with a total investigated region of about 950,000 inhabitants.

Amer et al. [28] optimise a low-carbon energy system for the case of Greater Copenhagen with its roughly 1.8 million inhabitants in a framework that includes the Danish and wider European electricity grids and find a substantial renewable energy sourcing of the dense urban area of Copenhagen by the surrounding rural area of the island of Zealand. Noteworthy, they include heavy duty transport demand and lay out climate neutrality by 2050. Kienberger et al. [29] optimise various scenarios for the future of Oberösterreich, an Austrian Federal State with an energy consumption of around 35 TWh and 1.5 million inhabitants. They demonstrate that the existing infrastructure in the region is almost sufficient for a transition of the energy system towards full renewable energy supply if sector coupling is facilitated by conversion technologies such as heat pumps and power-to-gas are applied to deliver overall energy efficiency as well as flexibility. Connolly et al. [30] optimise an energy system based on solely renewable energy for the then about 4.5 million inhabitants of the Republic of Ireland matching roughly the population of the 6.2 million people covered in this study.

There is only limited research which describes the urban-rural interaction in detail, such as for the case of Osnabrück in Germany [27], but also for the case of Delhi in India [31]. Two studies analyse the rural-urban transition synergy, on the case of Osnabrück and Berlin-Brandenburg [27], [32] while the latter was limited to the power sector. Möller et al. [32] conducted an early transition study for the Berlin-Brandenburg region, which is the so far only known journal publication showing the possibilities for a complete conversion to 100% renewables in Berlin and Brandenburg in the power sector in time steps up to the year 2020 and 2030. However, that study could not fully consider the meanwhile shortened timeframe for the required implementation to meet the climate targets, the further cost reductions for the crucial technologies, nor the possibility and economic necessity of coupling the power sector with the heat and the transport sector via sector coupling.

To meet climate targets, an earlier transition by about 2030 is needed for Germany, and Berlin- Brandenburg. Kobiela et al. [33] outline elements of the challenge for Germany and examine all major greenhouse gas emitting sectors even beyond the energy system studied here, but not in an integrated optimised system with sector coupling.

This work aims to find a cost minimal renewables-based energy system for the Berlin-Brandenburg region that could be potentially established in the necessary timeframe to 2030 and features a first scenario which is consistent with the climate targets of the Paris Agreement despite a start of accelerated renewable energy deployment as late as the early 2020s. The scenario also provides a first scenario that adopts and models latest costs of hydrogen transport and storage infrastructure options as competitive measures particularly to provide energy in extended periods of low wind and solar yield.

The study demonstrates a techno-economic feasible solution for 100% renewable energy supply for all energy demand including industrial heat and electricity with a full electrification of the transport sector for the metropolitan region Berlin-Brandenburg. The model and methods open a general perspective to other regional cases with a comprehensive yet parsimonious energy source, energy storage, and energy transport infrastructure representation.

2. Methods and Data

In this section we describe the method and the data used to represent the supply options and consumption of heat and electricity for current and additional transport end use.

2.1. Method

This study uses the linear model Mira-Mod, a model which is documented in its previous version in [34] and also considers the option of a hydrogen pipeline network here.

The modelled problem's objective is the minimisation of the total levelised cost of energy TLCoE including electricity and heat exchange across regions r. Denoting the capital recovery factor CRF and technology-wise cost C^n, and frequencies freq(t) of the load and supply events in t the objective function for cost minimization by the choice of generation q and investment k is the total levelized cost of the energy system, TLCoE expressed as follows

$$min_{\mathrm{q,k}}\ TLCoE = \sum_T^R \sum_n^N CRF^{\mathrm{n}} k^{\mathrm{n,r}} + \sum_t^T freq(t)\ C^{\mathrm{n}} q^{\mathrm{n,t,r}}\ , \tag{1}$$

where CRF denotes the capital remuneration factor, F denotes the fixed costs of the technologies denoted n, freq denotes the frequency of the time step t, C denotes the variable costs of energy provision.

Restrictions of the optimisation are the maximum investments, the energy balances at each hour and between time steps taking into account the conversion efficiencies and the meteorological conditions that limit the generation with the installed renewable energy capacities. In the chosen approach, hourly demand can be used based on historical or estimated loads and in principle also in combination with observed or estimated prices. In this paper, the historical load of three weeks of an extreme meteorological event in 2017 is supplemented with average load and availability events of renewable energies for the four weeks which are also represented, as adopted in [31].

The time sequences chosen here to represent events of system stress are three weeks with 504 consecutive

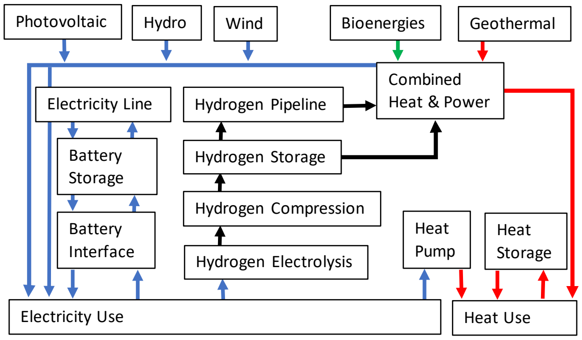

Figure 1: Energy sources solar PV, hydro and wind at the top and flows of electricity (blue), bioenergy (green) heat (red) and hydrogen in the middle (black) to energy use below. The five combined heat and power technologies are listed in Appendix B, and are denoted technologies 5-9.

hours of an extraordinary long situation of particularly low wind and solar availability from January to February 2017. Further five weeks are chosen for the representation of more moderate load situations. Notably, the choice of representative years and weeks for the design of fully renewable energy systems under weeks of challenging meteorological conditions is a topic under research [35], [36], [37] [38] [39].

The technological details of the costs and efficiencies of the technologies outlined in their relationship in Figure 1 are set out in the next section following the description of consumption data.

2.2 Energy consumption and supply data

Currently, the aggregated final energy supply in Berlin with its 3.7 million inhabitants and in Brandenburg with its 2.5 million inhabitants is based mainly on fossil gas (22%), fossil oil (36%) and 8% specified renewable energies according to the most recently available data of the statistical offices of the two states for 2017. The remainder consists of hard coal (4%), lignite coal (1%), about 18% of not further specified electricity and some 11% of heat from CHP. Final energy consumption including industrial heat demand of the region totaled around 154 TWh and is assumed to be kept constant through 2030 by efficiency gains.

For the estimation of the status quo of the energy mix we weight the regionally specific shares of renewables in primary energy with the final energy shares of Berlin and Brandenburg in total regional final energy [42]. We find a share of renewable energy of 16.4% for 2020 and a corresponding share of 83.6% fossil-fuel in the Berlin-Brandenburg region. In addition, from 2020 to 2021 the growing renewable energy supply suggests that the respective share is currently above 17% implying a share of fossil fuels of around 83%. This estimation does not include any transport between German states and international transport as far as these quantities are not accounted for in the cited statistics of Berlin and Brandenburg.

The assigned ambitious potentials for renewables are shown in Table 1 and are estimated in view of the fulfilment of the challenge of transforming a system largely dominated by fossil fuels in the region to one that is fundamentally more decentralised and entirely based on renewable energy within barely ten years. Comparable transformations have historically been related only to partial areas of energy demand and hence assume far reaching changes of the regulation and economics of energy [43]–[45].

Ambitious possibilities are assumed for the construction particularly of solar photovoltaic (PV) systems and heat pumps, but also the utilisation of geothermal electricity, the use of bioenergy (BE) and hydrogen storages necessary for system balancing.

The bioenergy potential includes both solid and gaseous sources estimated at a total of 4.5 TWh input energy as reported in the latest official documents [46], [47]. This restriction effectively limits the expansion of CHP plants fired with bioenergies, while the installed capacity that may utilise bioenergy is assumed to be non-binding (open). Similarly fuel cells are assumed to be restricted not by capacity, but the generation of hydrogen that is endogenously modelled. The potential for geothermal energy was set in accordance with analysis for the European and German cases [48], [49].The power line capacity between Berlin and Brandenburg has currently about 1.2 GW of capacity and is assumed to be expandable to 1.8 GW by 2030. All hourly load and availability data used in this study are taken from Traber et al. [34].

Table 1: Final energy demand of electricity and heat for Berlin-Brandenburg (BB) by 2030. More than half of the expected final consumption of electricity in Berlin is required for the transport sector.

EWG 100% BB TWh	Berlin	Brandenburg	Total BB
Electricity	29	42	71
Thereof Electricity	14	22	36
Thereof transport	15	20	35
Heat	22	40	62
Final energy	51	82	133

Table 2: Installed renewable energy generation capacities in 2020 and potentials in GW of electrical power in BB. *The potential use of bioenergy in CHP plants is limited to 4.5 TWh primary energy input to CHP plants.

	Berlin		Brandenburg	
Potential GW electric	Used 2020	Total 2030	Used 2020	Total 2030
PV ground-mounted	-	0	3	15.4
PV buildings	0.1	12	1	30.0
Wind onshore	-	0	9	11.9
Bioenergy CHP*	-	0	-	0
Bioenergy Small CHP*	0.5	open	1	open
Geothermal energy	-	0.2	-	0.5
Hydrogen CCGT	-	0.3	-	0.7
Fuel cell	-	open	-	open

3 Scenarios for 100% Renewable Energy in Berlin and Brandenburg

We derive results based on the cost assumption for the reference year 2025. The EWG Scenario uses a central cost assumption and is complemented by the scenarios Conservative and Progressive assuming higher and lower future costs for the green hydrogen route. In the central EWG scenario, a medium cost development is assumed for storage, transport and conversion of hydrogen to electricity in fuel cells. Two other scenarios assume higher costs on the one hand and more favourable costs on the other.

Scenario 1 (Conservative Scenario): High costs for hydrogen storage, hydrogen pipeline transport and fuel cell technology.

Scenario 2 (EWG scenario): Medium costs for hydrogen storage, hydrogen pipeline transport and fuel cell technology

Scenario 3 (Progressive Scenario): Low costs for hydrogen storage, hydrogen pipeline transport and fuel cell technology

These scenarios were chosen to capture the sensitivity of the results to uncertainty in the costs of the major components of the hydrogen process. This uncertainty concerns in particular the costs of stationary hydrogen conversion, the development of salt caverns for large-scale hydrogen storage and the costs of hydrogen pipelines.

For stationary applications and especially the conversion of hydrogen to electricity using fuel cells, there is a lack of experience in mass production due to the limited application to date. However, these technologies are considered to have a high learning potential [50], [51], which leads to the expectation of decreasing unit costs with high expansion rates. Furthermore, fuel cells and water electrolysis can be designed as reversible processes, which offers the potential for further cost savings [52]. The Conservative Scenario assumes fuel cell costs per installed electric kilowatt of 3,000 EUR, while the Progressive Scenario assumes 2,000 EUR per kilowatt. The central assumption of the EWG Scenario assumes 2,500 EUR per kilowatt of installed electrical capacity.

The usable hydrogen storage potential in Germany is estimated at about 4,400 TWh [53]. Assuming the average German area density of suitable caverns, we find a potential hydrogen storage of 376 TWh for the Berlin-Brandenburg area representing no constraint for our scenarios. Regarding the costs of building and operating hydrogen storage capacity, 0.24 € per kWh storage capacity is assumed for the Progressive Scenario representing salt caverns used in Brandenburg following the assumption of Fasihi and Breyer [54]. This contrasts with an assumed cost of small-scale hydrogen storage of 30 € per kWh which is used for the case of Berlin in the conservative scenario. The assumed costs for all scenarios and both states are summarised in Table 3.

Costs for hydrogen line capacities are assumed to be 110, 137 and 164 €/(kW·100 km) for the scenarios EWG, Progressive and Conservative respectively. Energy consumed for pipelines is represented by a loss factor of 2% per input energy and 2% for output from the lines. Fuel costs of bioenergy in Brandenburg is set at 5 €-cent/kWh and transport to Berlin is considered by an additional 1 €-cent per kWh. The remaining cost and efficiency assumptions are shown in Tables 4 and 5 below.

Table 3: CAPEX of hydrogen storage by state.

H_2-Storage Capex (€/kWh)	Berlin	Brandenburg
Conservative	30.00	9.00
EWG	13.08	4.62
Progressive	9.00	0.24

Table 4: Capital expenditures (CAPEX) per kW in 2025 for technologies with costs invariant across scenarios. An asterisk denotes storage costs per kWh.

	Capex [€/kW; €/kWh*]
PV ground-mounted	333
PV buildings	737
Wind onshore	1060
H2 Compressor	220
H2 Electrolyzer	380
Hydrogen CCGT	975
Fuel cell	2500
H2 pipeline	4470
H2 pipeline	137
Power transmission	437
Bioenergy CHP	577
Bioenergy CHP	3000
Battery storage*	163
Battery Power	91
Heat pump	768
Heat storage*	16
Electric heating	30

Table 5: The energetic efficiencies for injection (generation), withdrawal (extraction) and over an average storage cycle (storage). The results outline the target system that can succeed economically based on a specific mix of generation and storage technologies enabling 100% renewable energy supply in all energy sectors. This ensures a fast climate protection while maintaining energy supply security with energy demand coverage at every hour of the year and taking into account reasonable energy imports of Berlin from Brandenburg.

	Generation	Extraction	Storage
H2 Compressor	0.98	1.00	-
H2 Electrolyzer	0.62	1.00	-
Hydrogen CCGT	1.00	0.60	-
Fuel cell	1.00	0.50	-
Bioenergy CHP	1.00	0.35	-
Bioenergy small CHP	1.00	0.30	-
Battery Power	1.00	1.00	-
Heat pump	1.00	3.57	-
Battery storage	0.98	0.98	1.00
Hydrogen storage	0.99	0.99	0.98
Heat storage	0.95	0.95	0.90
H2 pipeline	0.98	0.98	-
Power transmission	0.99	0.99	-

In the following the optimised mix of power plants is presented, focussing the central EWG scenario. The electrical performance of the capacity mix is highlighted, as well as the load coverage during the most challenging periods of the year, which is crucial for the system design. These are mapped using three meteorologically challenging weeks in January 2017. This is followed by an illustration of electricity generation and heat supply. Subsequently, the levelised cost of the entire energy system are presented, as well as the necessary annual investments of the EWG scenario in comparison with the Conservative and Progressive scenarios for varying the costs of hydrogen storage and transport.

4 Results and Discussion

In this section the optimised capacities for electricity conversion and storage, for heat and hydrogen, and for storage are introduced followed by their utilisation, resulting cost and investment. A discussion of the results in light of findings from the literature on quantitative analysis of possible urban-rural systems based on renewable energies concludes.

4.1 Capacities for generation, for energy transport and for storage and year-round supply through 100% renewable energy

The electrical capacities of required conversion plants in the central EWG scenario total just under 128.5 GW. Around half of the capacity in Berlin and a bit more than a third in Brandenburg are required for storage, transport and conversion of electricity into heat (Figure 3). Around 14 GW of capacity is permanently available for the time of maximum residual load.

The most prominent features of this capacity expansion are the construction of almost 16 GW of electrolyser capacity and 5.3 GW of battery capacity with a storage capacity of 26 GWhel. As it turns out, in the scenario results (Appendix C, Figures C1-C3), hydrogen storage is not used in Berlin even under the progressive assumptions for non-cavern storage reported by a dedicated hydrogen and fuel cell project supported by the EU [55].

In the EWG scenario fuel cells are to be expanded by about 4 GW and combined cycle gas power plants (H2-CCGT) by 1 GW for hydrogen use, which together are to be provided with a hydrogen storage capacity of 4.8 TWhH2. PV ground-mounted plants, wind plants, the CHPs for bioenergy, and hydrogen fully utilise the expansion potentials assumed here by 2030. PV on buildings, though more expensive, fill the apparent PV gap. This is due to a conservative assumption on planned land-use for ground-mounted PV of only 0.5% of the region's land area in conventional design. The land requirement of ground-mounted PV can be further reduced by sharing land for PV systems with simultaneous agricultural use via Agri-PV [56], [57], floating PV [58], the integration of PV systems into the transport and parking infrastructure, or applied as vehicle-integrated PV [59].

The share of land used for onshore wind energy in 2030 consisting of about 4.5 GW of wind turbines already installed in 2020 and 7.7 GW new built and repowered sites requires roughly 2% of the area estimated based on a study for Germany published by the Federal Environment Agency [60] and restricts agricultural land use accordingly only by a small fraction of below one percent.

The use of bioenergy in small CHPs and large CHPs together uses the entire energetic potential of 4.5 TWh assumed in this study. CHP expansion is effectively limited by bioenergy availability to around 2.7 GW electric installed capacity.

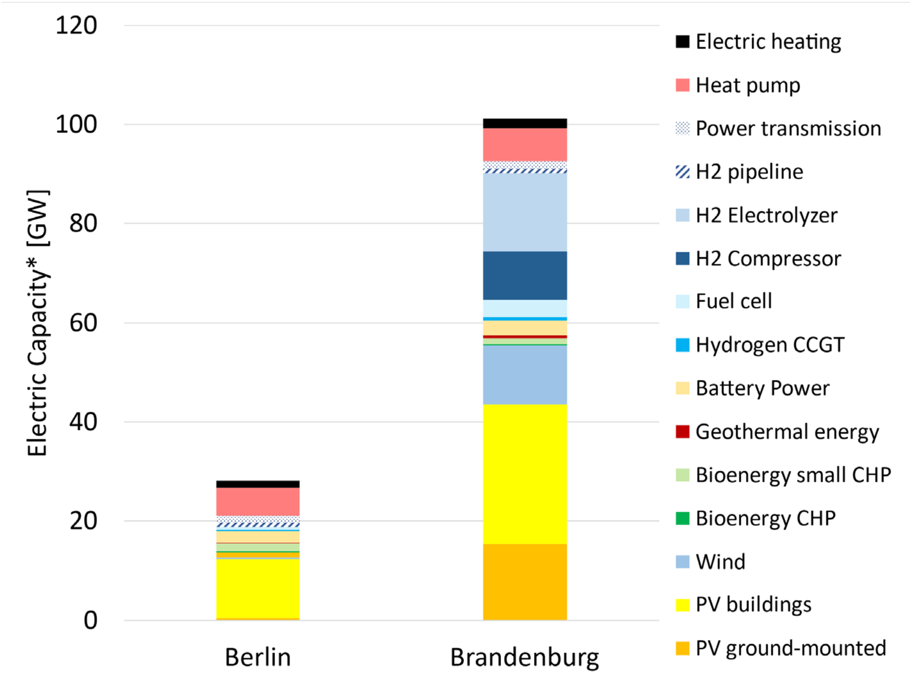

Figure 2: Capacity* for electricity generation, electric input to heat, and for transmission towards 100% renewable energy supply in the EWG scenario in 2030.

The load coverage in the winter period shows how the system can absorb the almost complete outage of solar PV between January 12 and 15 in Berlin (Figure 3; hours 181 to 221) and the outage of wind power during the week of January 21 to 24 in Brandenburg (Figure 4; hours 401 to 481), the reference year 2017 is used here, as an example of the EWG scenario.

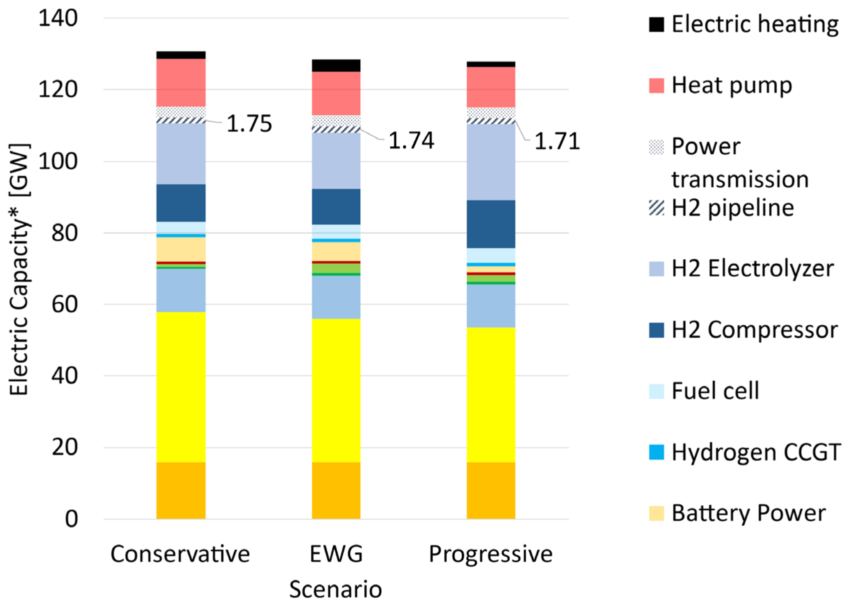

Figure 3: Capacity* for generation (76–82 GW), of electric input to heat, and of transmission facilitating 100% renewable energy supply in Berlin and Brandenburg in the EWG scenario by 2030.

Capacities of the whole BB region across scenarios are laid out in Figure 3. The EWG scenario uses 1.74 GW of hydrogen transport capacity and 4 GW of batteries, and comparatively pronounced electric heating. The Progressive scenario utilises substantially the hydrogen storage options, which leads to a smaller total of installed capacity.

Different technologies play specific roles under the various meteorological conditions. The hourly generation and electricity exchange under extreme meteorological conditions in the EWG scenario are visualized for Brandenburg and Berlin by Figures 4 and 5 respectively.

The regional energy system in Brandenburg shown in Figure 4 above, is based on the substantial regional wind power potential, so that longer lulls as in the first and last week of the dark lull mapped here are crucial for the system design. At the beginning of the mapped dark slack period, however, the energy demand of this period is still comparatively low. The highest residual load peak is reached in Brandenburg towards the end of the dark slack period in hour 455 (January 24) is absorbed by a mix of electricity supply from batteries, hydrogen, bioenergy, and geothermal energy.

In the event of lack of PV yield due to low solar radiation, up to 95% of the required energy is partly provided for Berlin via a total of 3 GW of high-voltage power lines consisting of 1.2 GW of existing alternating current (AC) transmission lines and 1.8 GW of additional high-voltage direct current (DC) transmission lines with underground cabling from Brandenburg to Berlin as represented by the red areas in Figure 5. Energy input for 0.9 GW of electric power installed in fuel cells (FC) and combined cycle gas turbines (CCGT) are fuelled by a further 1.7 GW of hydrogen pipeline capacity from Brandenburg to Berlin.

In addition to hours with a comparatively high proportion of hydrogen power generation (hours 261 to 281), Bioenergy power generation supported by battery power is crucial over longer calm wind periods. At the time of the highest residual load considered here, between hours 441 and 481, all thermal plants, fuel cells, and batteries are fully utilised.

In an integrated 100% renewable energy system in Europe, it is expectable that less hydrogen and battery storage would be needed as the intermixing of consumption peaks and availability of renewables balances out geographically. In addition, hydroelectric power from southern Germany and the Alpine countries, as well as offshore wind from northern Europe, would add significant power that is available almost year-round.

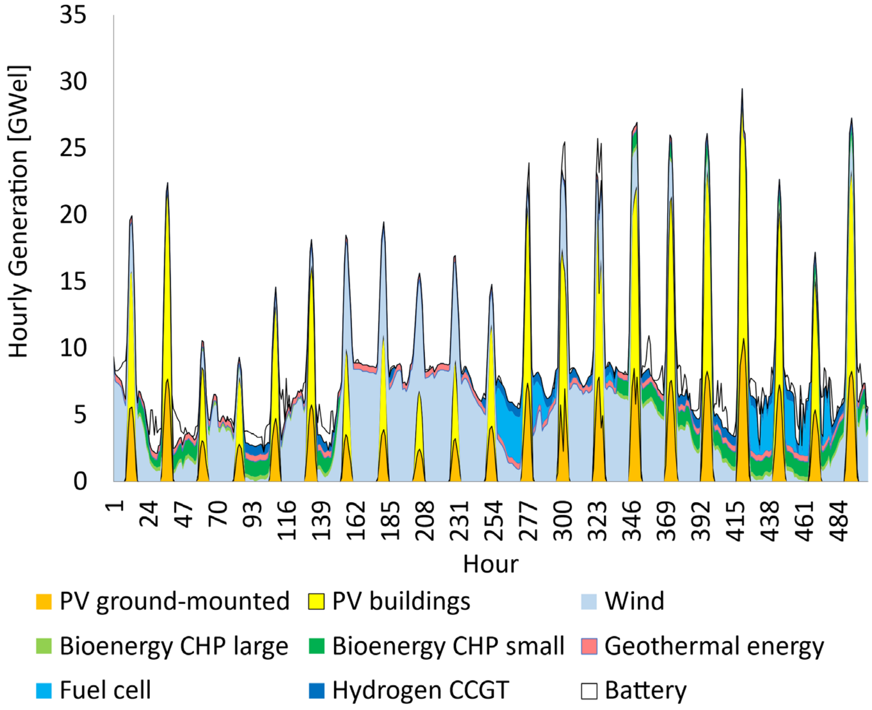

Figure 4: Electricity generation in Brandenburg under extreme meteorological conditions in the EWG scenario.

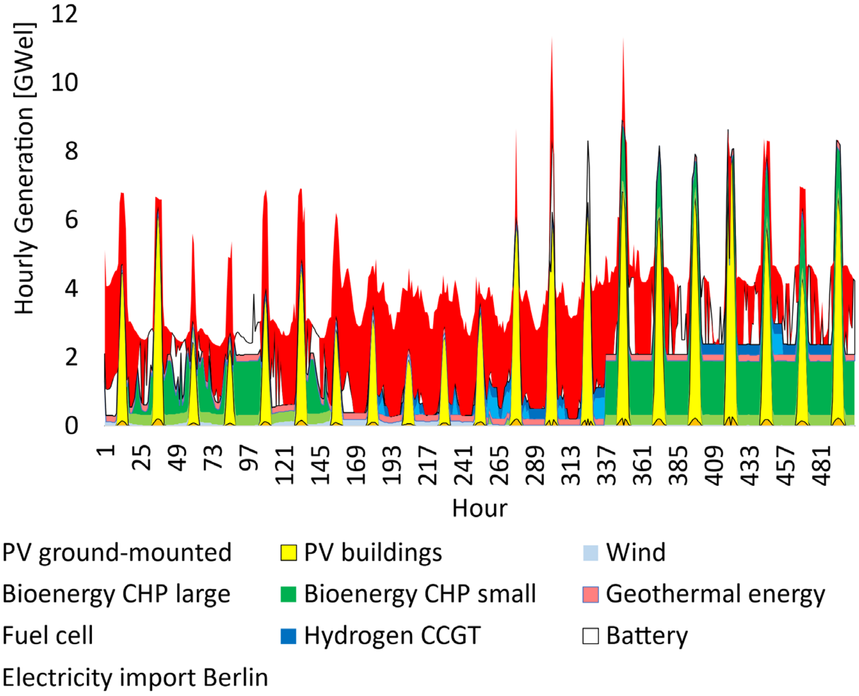

Figure 5: Electricity generation of Berlin and electricity import from Brandenburg under extreme meteorological conditions in the EWG scenario.

4.2 Electricity generation and energy exchange Berlin-Brandenburg

Over the entire year, the total final energy demand for heat, conventional electricity use and electromobility of 133 TWh is enabled in the EWG scenario by 109 TWh of electricity and coupled heat generation (Figure 6). Brandenburg's wind power, ground-mounted PV systems, and PV rooftop systems in both states dominate the generation of electricity.

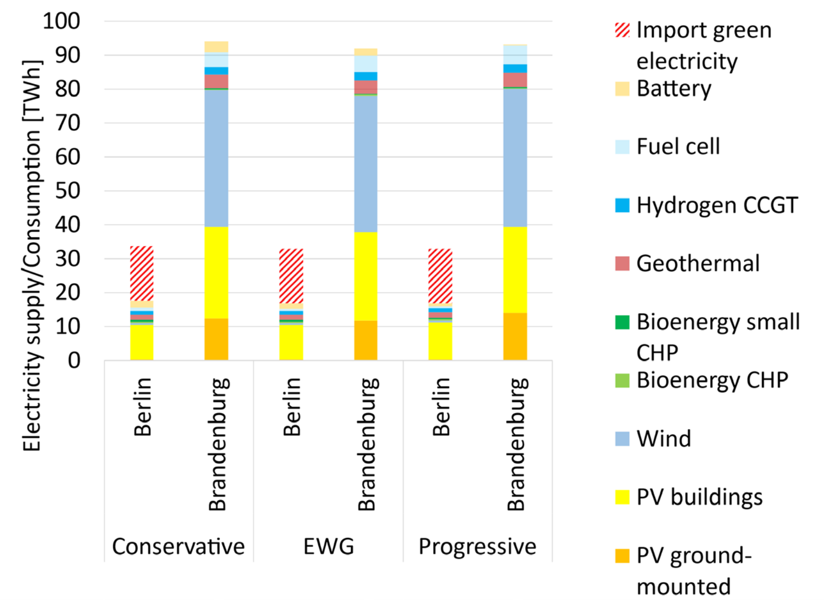

Figure 6: Electricity generation mix for the three scenarios for the energy system in 2030.

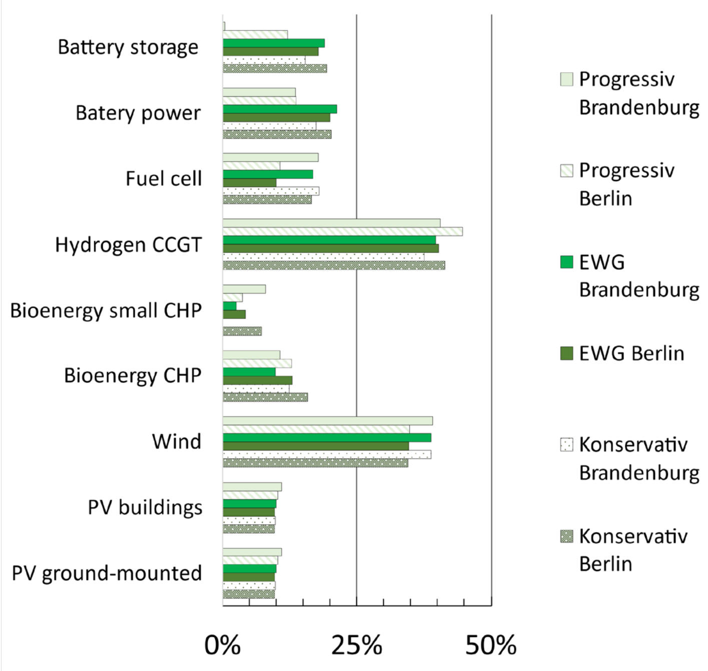

Figure 7: Utilisation of installed capacities as percentage to their maximum theoretical output by technology in the three scenarios.

About 50% of Berlin's annual electricity demand is provided by imports from Brandenburg. In the power sector, hydrogen-based power generation contributes nine TWh, while battery discharge covers four TWh in the EWG scenario. Brandenburg provides further the bioenergies for generating 1.6 TWh of electricity in CHPs.

By contrast, in the Conservative scenario more battery storage is utilised, while in the Progressive scenario, more hydrogen storage is built (Figure 5). Battery storage utilisation in Berlin is reduced by 20-30% in the Progressive scenario compared to the Conservative scenario and not used in Brandenburg (Figure 7).

Figure 7 also shows a substantial sensitivity of the utilisation of CHP and particularly small CHP that is moreover lower compared to the utilisation of larger counterparts with higher efficiency. The generally low utilisation of technologies appears as a major issue for investment incentives

4.3 Heat for Berlin and Brandenburg

The power supply with 100% renewable energy also enables a complete heat supply without greenhouse gas emissions. A large part of the heat is generated directly from electricity by heat pumps and by heating rods for direct electric heating. In Berlin, conversion of electricity to heat accounts for almost four-fifths of total heat generation of 28 TWh in the EWG scenario shown in Figure 8. Moreover, we find in Brandenburg almost three-quarters of the total generation of 41 TWh sourced by electricity. The remaining heat is generated in thermal plants with cogeneration (CHP), which is assumed to use the existing district heating networks.

To bridge periods of low availability of renewable energy, large parts of the primary heat are temporarily stored in heat storage facilities. In the EWG scenario withdrawal from heat storage amounts to 12 TWh in Berlin and about 15 TWh in Brandenburg (extraction, Figure 8).

4.4 100% renewable energy with lower costs and zero emissions

The EWG scenario represents a climate-compatible pathway, and in addition also a low-cost 100% renewable energy supply through the optimised use of the existing potentials of renewable energy. At an average of 76 €/MWh, the costs are substantially lower than the national average energy costs of over 90 €/MWh in 2017 and only slightly higher than in an energy system optimised on the national level [34]. Noteworthy, these costs are significantly lower than current costs of energy of hard coal, fossil gas or nuclear power plants [61].

In total, 112 b€ have to be invested in the EWG scenario until 2030 for the complete switch to 100%

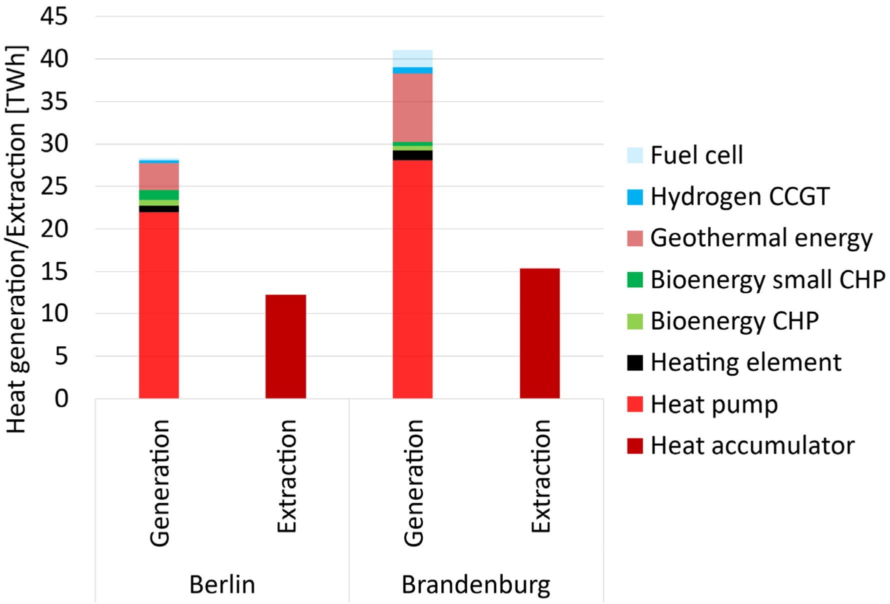

Figure 8: Heat generation (Generation bars to the left of each region) and withdrawals from the storage (Extraction to the right of each region) in Berlin and Brandenburg in the EWG scenario in 2030. Heat pumps dominate the optimal EWG scenario generation mix, which is shown in the lower part of each bar.

renewables. This corresponds to an average financing requirement of about 18,400 EUR per capita and compares to per capita financial assets averaging around 61,760 EUR in 2020 [62]. In the EWG scenario, a total of 9.3 b€ in annual average costs must be covered (Figure 10). About half of these costs are used for PV plants, wind turbines, bioenergy and geothermal plants. This cost block is also largely constant across the scenarios.

Significant differences between the scenarios result from the hydrogen process, which is used more in the

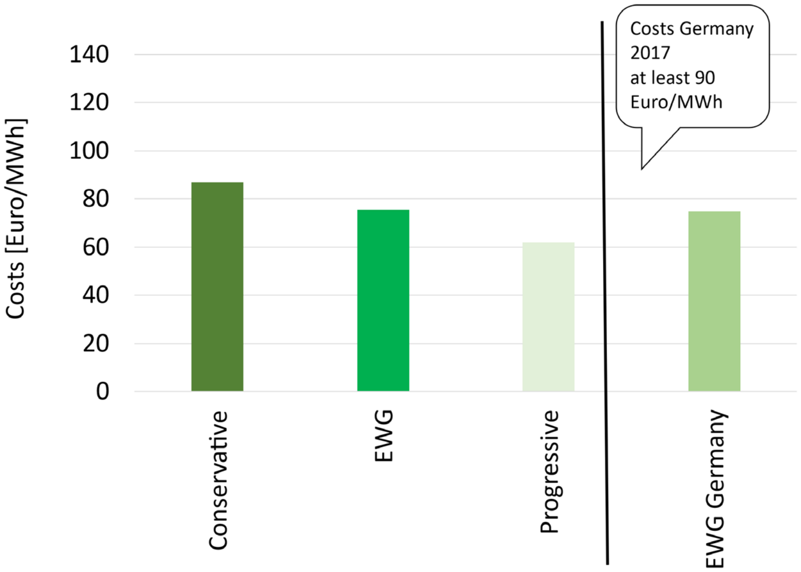

Figure 9: Average energy costs in the Conservative, EWG and Progressive scenario in comparison to the EWG Germany scenario for 100% renewable energy supply. The average cost from the parent optimisation of Germany is slightly lower than for the case of Berlin-Brandenburg.

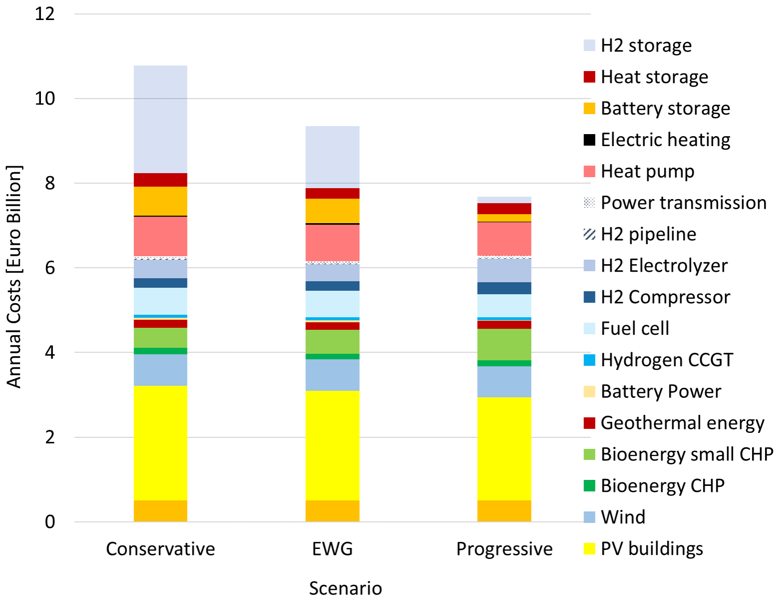

Figure 10: Annualised total system cost for the scenarios calculated for the estimated cost by 2025.

Progressive scenario, so that higher cost shares are incurred for electrolysis, hydrogen compression, and hydrogen-based power generation. However, the decisive factor for the cost difference between the scenarios are the different costs for the construction and operation of hydrogen and battery storage systems. The scenario comparison for different costs of hydrogen storage and pipeline transport reveals 18% lower costs (Progressive) and 16% higher costs (Conservative) compared to the EWG scenario result.

The annualised costs that must be spent on generation and conversion technologies are around 7 b€ in all three scenarios of this research and are predominantly influenced by the costs of the storage technologies as shown in Figure 10. The costs for the three storage technologies range widely between 0.6 and 3.5 b€, with 2.3 billion € for the EWG scenario.

It can be seen that there are considerable technological and planning uncertainties for the costs, especially for hydrogen-related technologies for year-round security of energy supply. For given feasibility of salt cavern storage and transport of hydrogen and its industrial use in fuel cells, the energy transition gets another effective lever through sector coupling via green hydrogen, which can strengthen the coupling of the power, heat, and transport sectors, as also found in other research [63].

However, even without progress in technological development and respective cost breakthroughs, the EWG scenario shows significant use of hydrogen technologies and infrastructures. Further, the use of hydrogen as an energy carrier might pave the way for the use of green hydrogen also for materials applications for emissions abatement in related industries, such as the packaging, chemicals [64], ammonia [65], steel [66], copper [67] , and cement and wood [68], [69] to solve technological and cost challenges in the industry [70]. Synergies from this can provide in turn sustainability of the industrial production of renewable energy technology, particularly through the provision of materials management and infrastructures.

From a climate perspective the similarity of unburned hydrogen [71] to the warming impact of methane leakages has to be stressed. Both leakages must be minimised and more than compensated by climate sinks to reach the target set in the international climate agreement of Paris.

4.4 Complementarity of urban and surrounding rural region in 100% renewable energy systems

This research tries to provide a prototype of urban-rural regional optimisation for a decentralised system sourced by 100% renewables on the premise off self-supply. Key element of such an urban-rural interaction is the high density of energy demand in the urban region, which can hardly be covered within that area.[72]. Typically, rooftop PV and waste-to-energy are the main, resources available today for urban energy demand coverage [31] while the local energy demand exceeds the supply potential by factors. The example of Berlin and Brandenburg shows, that 17 TWh or about 50% of the electricity demand and about 1.5 TWh of bioenergy needs to be imported for the EWG scenario as presented in this study. In addition, imports are required for all aviation fuel for the international airport which serves both states. The following research designs should receive further research attention:

- Weitemeyer et al. [20] use a simplified power sector model and focus mainly on the ratio between solar PV and wind. Here the trade-off between types of PV like ground- mounted and rooftop PV like in the differentiation used in this study and furthermore the assessment of PV systems integrated in infrastructure and agriculture deserves emphasis [73].
- Palzer and Henning [22] introduced a detailed sector-coupled energy system for Germany in hourly resolution with diversified storage options and detailed power and heat sector considerations. A more thorough representation of thermal use and generation differentiated into temperature levels and in addition by solar thermal applications including concentrated solar power remains a task for future research. Similarly, adiabatic and other compressed air energy storage (A-CAES) [74], redox flow batteries [75] , off-river hydro power [76], ice storage [77] and other storage concepts may play a role when considered more in detail. and a broader more decentral participation is no longer hindered by regulatory hurdles as in Germany [78].
- Hansen et al. [23] investigate different energy system design options with more detailed transport sector considerations comparing different policy and technology options. The papers insights on the trade-off between energy efficiency and heat technology has importance for the optimal planning in spatial dimension particularly when climate policy necessities provide only a narrow window for successful action.
- Robinius et al. [24] focus the interaction of the power and transport sector with detailed considerations of hydrogen options and a more detailed regional representation of hydrogen transport and distribution compared to the only two locations compared in this study.

5 Limitations

The energy system presented in this research does not fully exploit the possibilities arising from the integration of

1. international and European interconnected electricity systems with existing pumped hydro energy storage, and hydropower reservoirs, especially in the neighbouring Alps and in Scandinavia [79]–[81],
2. bidirectional storage of electricity in the transport sector [82]–[84],
3. other electricity storage technologies with fast technology improvements as outlined in the previous section,
4. solar thermal energy and concentrated solar power,
5. excess heat recovery from electrolysis,
6. PV applications in combination with hydro power and with farming.

In this analysis, the storage segment is simplified and in effect considers only two reasonably efficient seasonal storage solutions: hydrogen and heat storage. Furthermore, heat storage and use are considered in a simplified way. For instance, heat recovery from electrolysis could increase the efficiency of electrolysis by up to about forty percent. The rational for the simplification of heat representation is that the costs of meeting heat demand are about an order of magnitude lower than the costs of electricity applications and seem to deserve less focus from a fist sight economic perspective. However, there seem comparable planning issues when heat networks are considered.

Our results find a major role for bioenergy for the provision of flexible energy. But bioenergy comes from many different sources and it is important to assess its sustainability. For time consistent planning of heat networks, a clear definition and estimation of the potential of sustainable bioenergy has to be developed. To improve consistency of planning of heat networks a more thorough representation of thermal use and generation differentiated into temperature levels would contribute to the efficient coverage of industrial energy demand. A further uncertaintiy concerns the potential of feasible geothermal energy roll-out and the use of geothermal energy electrically that is assumed here based on Aghahosseini and Breyer [74] - This still needs to be demonstrated for Germany on a time horizon to 2030.

Finally, important sectors such as cement production and the metals and chemicals industries, which can also provide flexibility and limit storage needs, are assumed to be inflexible in this study. In addition, to the need for greenhouse gas abatement by the power and industrial sectors, agriculture and forestry must also contribute to climate change mitigation, not only by providing bioenergy to the power system, but also by storing carbon and plant available nitrogen by biochar in the soil [85]. Subsequent studies should also improve the choice of critical meteorological conditions to be represented to optimise reliability and costs [86], [87], to show if the probability weighting of the meteorologic events that are used here are supported by long term time series data. It remains important to note that policy recommendations should also consider the possibilities for expanding public transport, cycling and pedestrian traffic.

This work another example where competitive cost of fully renewable energy-based systems are technically feasible. However, market implementation has to deliver answers to several questions on how these costs are transferred into prices. The future application of the model therefore aims at helping design prices and pricing mechanisms that transfer the cost results into contracts between customers and investors in the field of fully renewable energy systems. Thus, further research is required to study how to optimise such locally coupled systems to identify the urban-rural synergetic interdependencies of costs of fully renewable energy sourced systems. The most pressing problems for swift transformations to year-around renewable energy systems appear with a) large areas of uniform pricing b) cost coverage of technologies mainly necessary for the security of supply under challenging meteorological conditions and c) path dependencies.

Germany is the prime example where a) uniform pricing causes a structural problem on the system development. On the background of renewable energy planning from the 90ies with its substantial cost advantage of wind power over solar power, high electricity exports from Northern to Southern Germany were planned. However, a uniform price regime is further maintained for reasons of social cohesion between the two parts. Two decades later the costs of an about 98% regionally supplied Southern German system allows competitive costs as calculated in [34].

Therefore, social aspects of regionally uniform prices can be addressed on the customer level with small and decreasing budget for socially justified purposes that can be financed on the federal level. Rather, differences in the regional technology mix appear more important for the design of pricing for both, the industrial deploy of renewable energy facilities and high-density consumption of industrial and urban areas.

The ability to coordinate fair long-term contracts without excess profits between investors and customers for small energy cells appears as a remedy for the deficiencies of uniform pricing and deserves more research attention. In particular, the potential efficiency gains of novel approaches that support the feasibility of more local solution for instance by dynamic frequency stirred pricing [88] that can provide remuneration for technologies with a high share of investment in costs and are utilised only a small fraction of the year. AI supported energy security planning [89] suggests another promising complementary technology that may identify the necessary target capacities and frequencies of remuneration.

Finally, a related topic of interest is the timing of investments in fully renewable energy systems on the background of their rapidly decreasing costs against sharply increasing costs of fossil fuelled energy as shown lately in [90]. The increase of damages from more greenhouse gas emissions further reduces their value [91] so that the benefit of renewable energy deploy increases over time. This gives rise to a continued readjustment of renewable energy targets and additional risks for planning and investments. The introduced model framework lends itself for the analysis of both regulatory and meteorological risks for investors and planners.

6 Conclusions

This study shows an energy system transition pathway for the Berlin-Brandenburg region to jointly achieve its contribution to meeting the climate targets agreed in the Paris Agreement in the current decade and at competitive costs, without relying on integration into the German and European interconnected high-voltage transmission grid. For the EWG scenario, it is shown that a power line expansion from the existing 1.2 GW capacity by 1.8 GW to 3 GW of transmission capacity is built and complemented by the construction of hydrogen transport pipelines with a transport capacity of another 1.7 GW is sufficient to compensate for the comparatively low land availability in Berlin due to energy surpluses of Brandenburg.

The system presented here as EWG scenario envisages a substantial storage expansion of 4.8 TWh of hydrogen storage as well as about 4 GW of electrical capacity from fuel cells. Batteries, which are projected to reach a power interface capacity of 5.3 GW and an energy storage capacity of 26 GWhel, will also play a significant role. Compared, for example, with the Copenhagen metropolitan region, which already envisages a Paris compatible transition of the energy system, Southwest Ireland, or Osnabrück and its energy system, we obtain a far more solar-driven energy system by using updated PV, battery, and electrolysis costs. On the generation side, the first priority is to massively expand PV systems on buildings both in Berlin (11.9 GW) and Brandenburg (27 GW), and additionally to further expand the already well- developed wind energy systems in Brandenburg from nearly 9 GW today by about 3 GW to nearly 12 GW to enable the complete conversion of all energy sectors in the Berlin- Brandenburg region.

The EWG scenario for Berlin-Brandenburg enables the combination of reducing energy-related GHG emissions to zero with affordable costs, which at 76 €/MWh are significantly lower than the current energy costs of more than 90 €/MWh that are additionally posing a substantial supply risk. A total of 112 b€ will be needed to build the capital-intensive power plants, storage facilities and related infrastructure for a secure and sustainable energy system.

Appendix A

Climate policy in Berlin and Brandenburg

The associated reduction of GHG emissions towards net zero was brought forward to 2045 by the states of Brandenburg and Berlin as a result of the amendment to the Federal Climate Protection Act [83]. The so-called climate neutrality in Brandenburg is to be achieved through a cross-sectoral, binding climate protection strategy as well as a corresponding package of measures, which are based on a state-specific climate plan. This climate plan has been developed since the summer of 2021 by a consortium of various research organisations in cooperation with the state of Brandenburg with citizen participation and will be implemented from the first quarter of 2022 [93].

In Brandenburg, the Energy Strategy 2030 [94] which sets an interim target of reducing energy-related CO emissions to 25 million metric tons (MtCO) by 2030, is also being revised as part of the climate protection strategy process. Acceleration of the net-zero goal from 2050 to 2045 means also achieving 100% renewable energy supply by 2045. In addition, the resolution of the state parliament of June 2020 includes the submission of a climate report on the development of GHG emissions based on scientifically accompanied monitoring, which will be updated every two years, as well as a procedure according to which a climate check can be introduced into all laws [12].

Berlin's government aims to support its targets with similar measures on the basis of the lawfor climate protection and energy transition [13] . The goal of climate neutrality in Berlin by 2045 is being pursued through a reduction target of 70 percent for the year 2030 and is to be supported by a sectoral quantity control system accompanied by transparent scientific monitoring.

Appendix B

List of Technologies

Name	Description	#
PV ground-mounted	Photovoltaic ground-mounted	1
PV buildings	Photovoltaic facade, streets, parking, etc.	2
Wind	Wind onshore	3
Hydro RoR	Run of river hydro power	4
Hydrogen CCGT	Hydrogen combined cycle gas turbine	5
Geothermal	Geothermal heat and power	6
Bioenergy CHP	Bioenergy large combined heat and power	7
Bioenergy CHP small	Bioenergy small combined heat and power	8
Fuel cell	Stationary fuel cell	9
H2 storage	Hydrogen storage	10
H2 compressor	Hydrogen compression	11
H2 electrolyzer	Hydrogen electrolysis	12
Battery storage	Battery storage	13
Battery power	Battery interface	14
Heat pump	Heat pump	15
Electric heating	Electric heating	16
Heat storage	Heat storage	17
H2 pipeline	Hydrogen transport pipeline	18
Power transmission	High voltage direct current line	19

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