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The Baltic Sea Region: Storage, grid exchange and flexible electricity generation for the transition to a 100% renewable energy system

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Abstract

The Baltic Sea Region could become the first area of Europe to reach a 100% renewable energy (RE) power sector. Simulations of the system transition from 2015 to 2050 were performed using an hourly resolved model that defines the roles of storage technologies in a least cost system configuration. Investigated technologies are batteries, pumped hydro storage, adiabatic compressed air energy storage, thermal energy storage, and power-to-gas. Modelling proceeds in five-year time steps, and considers current energy system assets and projected demands to determine the optimal technology mix needed to achieve 100% RE electricity by 2050. This optimization is carried out under the assumed cost and status of all technologies involved. Results indicate the levelised cost of electricity (LCOE) falls from 60 €/MWh$_e$ to 45 €/MWh$_e$ over time through adoption of low cost RE power generation and from inter-regional grid interconnection. Additionally, power system flexibility and stability are provided by ample resources of storable bioenergy, hydropower, inter-regional power transmission, and increasing shares of energy storage, together with expected price decreases in storage technologies. Total storage requirements include 0-238 GWh$_e$ of batteries, 19 GWh$_e$ of pumped hydro storage, and 0-16,652 GWh$_{gas}$ of gas storage. The cost share of storage in total LCOE increases from under 1 €/MWh to up to 10 €/MWh over time. Outputs of power-to-gas begin in 2040 when RE generation approaches a share of 100% in the power system, and total no more than 2 GWh$_{gas}$ due to the relatively large roles of bioenergy and hydropower in the system, which preclude the need for high amounts of additional seasonal storage. A 100% RE system can be an economical and efficient solution for the Baltic Sea Region, one that is also compatible with climate change mitigation targets set out at COP21. Concurrently, effective policy and planning is needed to facilitate such a transition.

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1. Introduction

The need for global, coordinated efforts to mitigate the threat of climate change seems obvious in the context of the landmark Paris Agreement. Such efforts include limiting "global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C" through low greenhouse gas (GHG) emissions [1]. As approximately 80% of GHG emissions originate from the energy sector, a great deal of attention is directed towards creating climate-friendly energy, as recently witnessed by the establishment of a European Energy Union in 2015. In doing so, the European Commission adopted "A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy" [2], which highlighted the need for cooperation among member states and implied that strong regional ties could aid in achieving objectives. The Baltic Sea Region (BSR) was identified as one such "natural" region [3], as energy cooperation and trade among BSR countries is already well developed, particularly in the Nordics [4]. In addition, strong trade of electricity is expected to continue amongst the Nordics, and between the Nordics and several Baltic countries (Estonia, Latvia and Lithuania) [5].

Nomenclature

A-CAES	adiabatic compressed energy storage
BSR	Baltic Sea Region
CCGT	combined cycle gas turbine
CHP	combined heat and power
CSP	concentrating solar thermal power
ESS	energy storage solutions
GHG	greenhouse gas
G	giga
h	hour
HHB	hot heat burner
HVAC/HVDC	high voltage alternating current/direct current
ICE	internal combustion engine
k	kilo
LCOE	levelised cost of electricity
M	mega
OCGT	open cycle gas turbine
PP	power plant
PHS	pumped hydro storage
PtH	power-to-heat
PtG	power-to-gas
PV	photovoltaics
RE	renewable energy
SNG	synthetic natural gas
ST	steam turbine
t	ton
T	tera
TES	thermal energy storage
WACC	weighted average cost of capital
$_e$	electric units
$_{gas}$	gas units
$_{th}$	thermal units

In political and economic circles, interest is high in investigating whether BSR countries can develop energy cooperation and become "stronger together" on the way to a 100% renewable energy (RE) system [6]. And recent scientific investigations of global and regional energy systems indicate that interconnected energy systems can result in greater cost savings while also achieving high levels of RE, resilience and sustainability [7]–[13]. Such benefits of interconnections as well as sector integration have also been seen for Europe in general [14]–[16], and for the Nordic region [17], but a systematic analysis of a potential energy transition for the BSR is lacking. In addition, the roles of various energy storage solutions (ESS) have not been well defined even though they are generally accepted as being important to the transition towards sustainability and for security of supply [18].

One of the reasons that fossil fuels were so widely adopted in global energy systems was the high level of flexibility they offered. They could be stored for long periods of time, and used when needed to maintain the balance between supply and demand over both the short and long terms. Therefore, making the transition towards renewables, particularly the intermittent resources of the sun and wind, necessitates identifying and harnessing new sources of flexibility in energy systems. Several studies show the importance of introducing flexibility to energy systems with high shares of intermittent renewable supply [19]–[21]. And both ESS and interconnections are mentioned as important sources of flexibility. However, there are still further measures that merit investigation. In particular, the intermittency of renewable supply may not be as significant when viewed over larger geographic areas. Additionally, there may be temporal, even seasonal complements between various resources that result in much lower intermittency when examining the sum of resource contributions rather than the individual contribution of a single resource. This seems highly relevant for the BSR as it possesses an abundance of natural resources such as biomass (Sweden, Finland and Lithuania), hydropower (Norway, Sweden and Finland), wind (Norway, Sweden and Denmark) and solar (good everywhere, but better in Denmark, Southern Sweden, Estonia, Latvia and Lithuania).

For these reasons, this work seeks to investigate the roles of energy storage, grid exchange and flexible electricity generation in a transition towards 100% RE for the electricity sector of the BSR. Excluded from the BSR will be Poland and Germany due to the fact that interconnections between those countries and so many others would necessitate a much broader analysis that goes well beyond the "natural" regional cooperation mentioned above. Including Poland would mean including Germany, the Czech Republic, Slovakia and Hungary. Including Germany would mean further including Austria, Belgium, France, Luxembourg, Netherlands and Switzerland. Therefore, for the purposes of this work the BSR is defined as being composed of Norway (NO), Denmark (DE), Sweden (SE), Finland (FI), Estonia, Latvia and Lithuania. Additionally, for the purposes of modelling the final three countries are joined as a single Baltics region (BLT) in order to establish balance between investigated areas in terms of both population and geographic area, and to reduce modelling complexity. A transition towards 100% RE for the BSR is modelled from 2015 to 2050 in five-year time steps using the Lappeenranta University of Technology (LUT) Energy System Transition Model [8], [12]. Two scenarios are investigated: Regions, whereby each region has an independent energy system; and Area, whereby regions are interconnected with high voltage transmission lines.

2. Methods

The BSR power system was modelled with the LUT Energy System Transition Model described in [8], [12]. Two scenarios were modelled for the transition period of 2015 to 2050: Regions and Area. The modelling tool is based on linear optimization of energy system parameters under a set of applied constraints. A visualisation of the model is found in Figures 1 and 2.

2.1. Model summary

In order to minimize the energy system cost, the target function of the model is to optimize calculating the sum of the annual costs of the installed capacities of each technology, costs of energy generation, and costs of generation ramping. Additionally, distributed generation and self-consumption is included in the system in the form of residential, commercial and industrial prosumers through installations of respective capacities of rooftop PV systems and batteries. Prosumers have the target function of minimizing the cost of consumed electricity, which is the sum of self-generation cost, annual cost, and cost of electricity consumed from the grid. The cost of selling excess generation to the grid is subtracted from this total. The target functions of the model were applied in five-year time steps from 2015 to 2050, concurrently with two important constraints that were built into the model. The first was that a maximum of 20% growth in RE installed capacities compared to total power generation capacities could be achieved for each five-year time step. This constraint was an attempt to avoid excessive disruption to the power system. The second constraint was that no new nuclear or fossil-based power plants could be installed after 2015. An exception to this was allowed for gas turbines, a technology that can efficiently utilise sustainably produced synthetic natural gas (methane) and biomethane as a fuel.

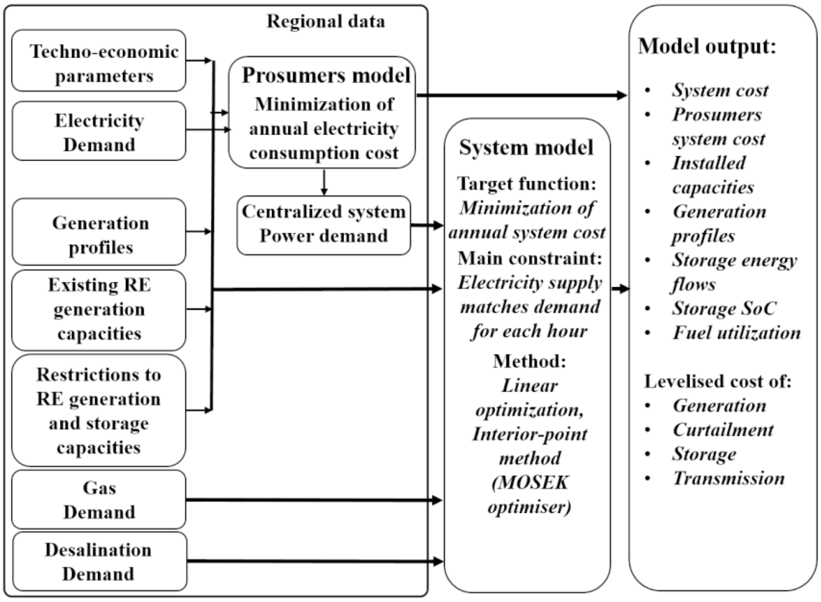

Figure 1. Main inputs and outputs of the LUT Energy System model

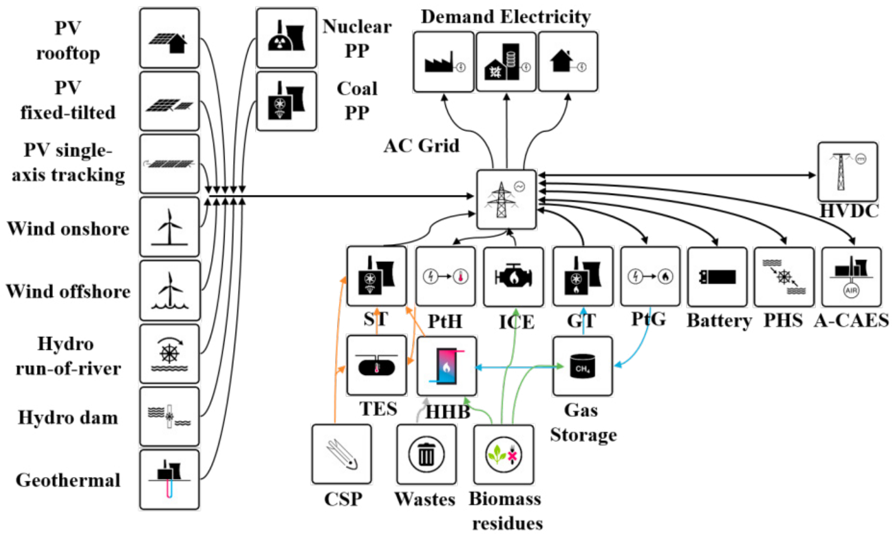

Figure 2. Block diagram of the LUT Energy System model. Acronyms not introduced elsewhere include: PP - power plant, ST - steam turbine, PtH - power-to-heat, ICE - internal combustion engine, GT - gas turbine, PtG - power-to-gas, PHS - pumped hydro storage, A-CAES - adiabatic compressed air energy storage, TES - thermal energy storage, HHB - hot heat burner, CSP – concentrating solar thermal power

2.2. Applied technologies

Four categories of technologies are introduced to the model: electricity generation, energy storage, energy sector bridging, and electricity transmission (Figure 2). Interconnections with neighbouring countries in the Area scenario were based on information derived from the European Network of Transmission System Operators for Electricity [5]. This included the current status and future potentials of HVAC and HVDC interconnections.

2.3. Financial and technical assumptions

Financial assumptions are made for all energy system components in five-year time steps. A full list of financial and technical assumptions can be found in the Supplementary Material. For the residential, commercial and industrial sectors, electricity prices were calculated using the same method as [22] and extended to 2050. For all scenarios, the weighted average cost of capital (WACC) is set at 7%. However, WACC is set at 4% for residential PV prosumers because of lower financial return expectations. Excess electricity generated by prosumers is fed into the national grid and is assumed to be sold for a transfer price of 0.02 €/kWh. The model ensures that prosumers satisfy their own demand for electricity before such transfer. No other financial incentives for solar PV production are assumed.

Current installed capacities of all technologies were provided by [23]. Upper limits for all the RE technologies and for pumped hydro storage were calculated according to Bogdanov and Breyer [12]. Upper limits for all other technologies are not specified. Due to energy efficiency reasons, it is assumed that available biomass, waste and biogas fuels are available throughout the year evenly. A synthetic electricity demand profile was created based on data from [24], [25].

2.4. Renewable resource potentials

Resource potentials for renewable energy categories were derived from a number of sources. First, generation profiles for solar CSP, solar PV (optimally tilted and single-axis tracking), wind power (onshore and offshore) were calculated according to [12]. Capacity factors for onshore wind generation and solar PV can be seen at [26]. Second, a hydropower feed-in profile was based on precipitation data for the year 2005 as a normalised sum of precipitation throughout the country. Third, biomass and waste potentials were divided into four main categories: solid waste, including used wood; solid biomass waste, including industrial residues; solid biomass residues, including straw, agricultural residues and forestry residues; and biogas, including gas produced from municipal bio-waste, animal excrement, landfill gas and sewage gas. Biomass and waste potentials are derived from [27] for all countries but Norway. Potentials for Norway are derived from [28]. Costs for biomass were based on data provided by [28]. For solid wastes, a gate fee of 100 €/t was assumed for all regions and years except BLT, where a gate fee of 85 €/t was assumed for 2015, raising to 100 €/t in 2035 and remaining at 100 €/t thereafter. Finally, geothermal energy potential was calculated according to the method described in [9].

3. Results

Main modelling results are compiled in Figures 3-9. Further results and analysis can be found from the Supplementary Material.

Figure 3 shows how installed capacities for all technologies were developed by the model. Due to the high age of current coal-fired power plants in the region, capacities decrease rapidly by 2020, essentially disappearing by 2035. Likewise, nuclear power is eliminated by 2030. Both coal and nuclear power are primarily replaced by wind power up to 2025, and then by solar PV thereafter. Installed capacities appear to increase at a greater rate in 2030, but develop rather evenly throughout the period of 2025 to 2050. The somewhat exaggerated increase in installed capacity from 2030 onwards can be explained by the lower number of full load hours for solar PV systems compared to thermal power plants. The role of biomass expands from 2020 onwards, as sustainable biogas and biomethane replace fossil natural gas in the energy system, and as available biomass resources are utilized. Total installed capacities are higher in the Regions scenario, most notably with relation to a lack of system-level solar PV. In both scenarios, there is a noticeable role of solar PV prosumers. Figure 4 shows electricity generation increasing steadily to supply the growing demands of the BSR. In 2050, the share of hydropower is 35%, followed by wind at 30% and solar PV at 22% for the Area scenario. A virtually 100% renewable energy system is achieved in the BSR by 2035 in the Area scenario (Figure 8), with only minute quantities of coal in the system from 2035 onwards due to remaining assets that had not yet reached their lifetimes.

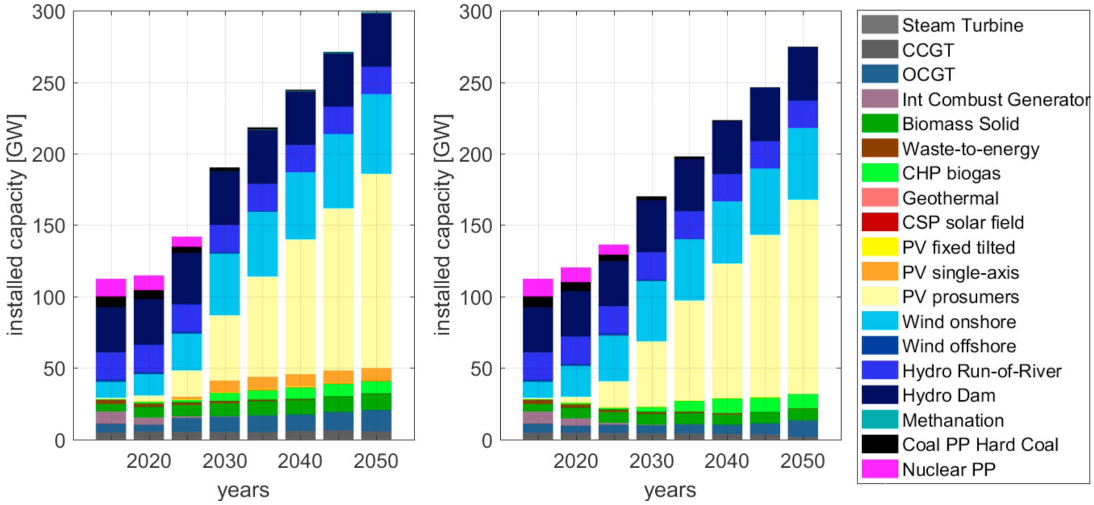

Figure 3. Cumulative installed capacity for all generation technologies from 2015 to 2050 for the Regions (left) and Area (right) scenarios.

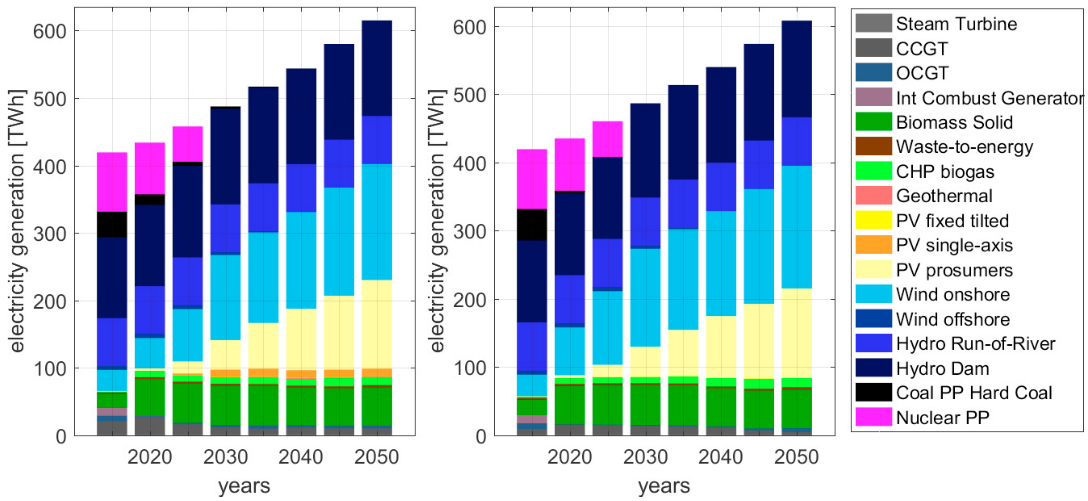

Figure 4. Total electricity generation by generation technology from 2015 to 2050 for the Regions (left) and Area (right) scenarios.

The role of storage technologies increases with the share of renewable energy, especially solar PV and wind (Figure 5). Traditional PHS provides most of the needed storage for the system in 2020. Thereafter, batteries cover the shorter term storage demands from 2025 onwards. The share of renewable energy generation in the system reaches 81% in 2020, when battery storage appears in the system. The shares of renewables are 89% and 86% in 2035 in the Regions and Area scenarios, respectively, and an increase in battery storage is evident. In 2040, renewables increase to virtually 100%, and battery storage continues to increase, most notably for solar PV prosumers. Seasonal gas storage and TES become noticeable parts of the energy system in the Regions scenario only after 2040. There is also a noticeable role for PHS in both scenarios throughout the transition, although slightly more so for the Regions scenario.

Table 1. Total installed capacities (GWh except for PtG in GW) of storage technologies in the Regions and Area scenarios for the period of 2015 to 2050 in the BSR.

Storage technology	Unit	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
Gas	GWh	Regions	0	962	3582	6191	9927	12370	14996	16380
		Area	0	1195	3737	4941	6985	9735	12220	16651
System batteries	GWh	Regions	0	0	2	9	21	29	42	60
		Area	0	0	0	0	3	16	39	50
Prosumer batteries	GWh	Regions	0	1	16	58	97	129	154	178
		Area	0	1	16	58	97	129	154	178
PHS	GWh	Regions	19	19	19	19	19	19	19	19
		Area	19	19	19	19	19	19	19	19
TES	GWh	Regions	0	1	1	2	16	16	16	16
		Area	0	0	0	0	0	0	1	1
A-CAES	GWh	Regions	0	1	1	1	10	10	11	11
		Area	0	0	0	0	0	0	1	1
PtG	GW_e input	Regions	0	0	0	0	1	1	1	1
		Area	0	0	0	0	0	0	0	0

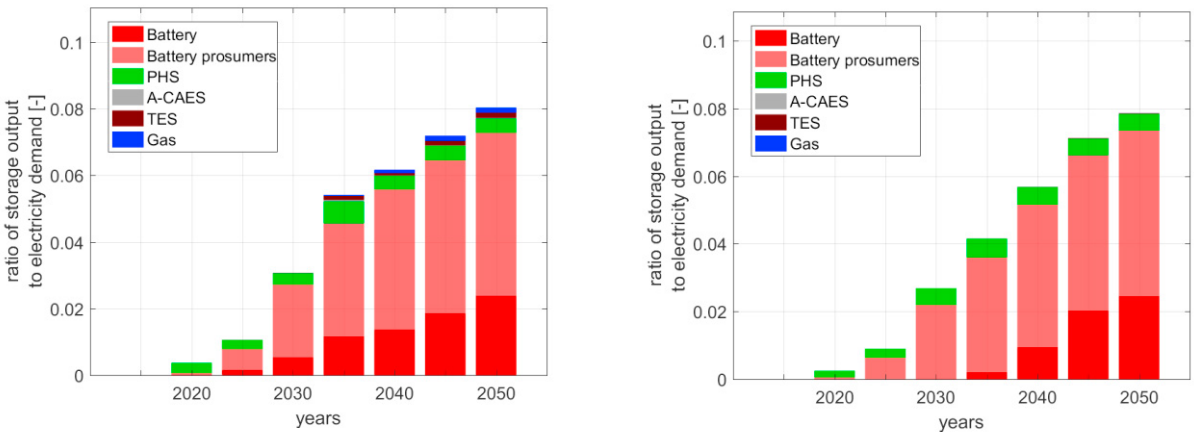

Figure 5. Relative contribution of storage technologies to end-user electricity demand from 2015 to 2050 for the Regions (left) and Area (right) scenarios

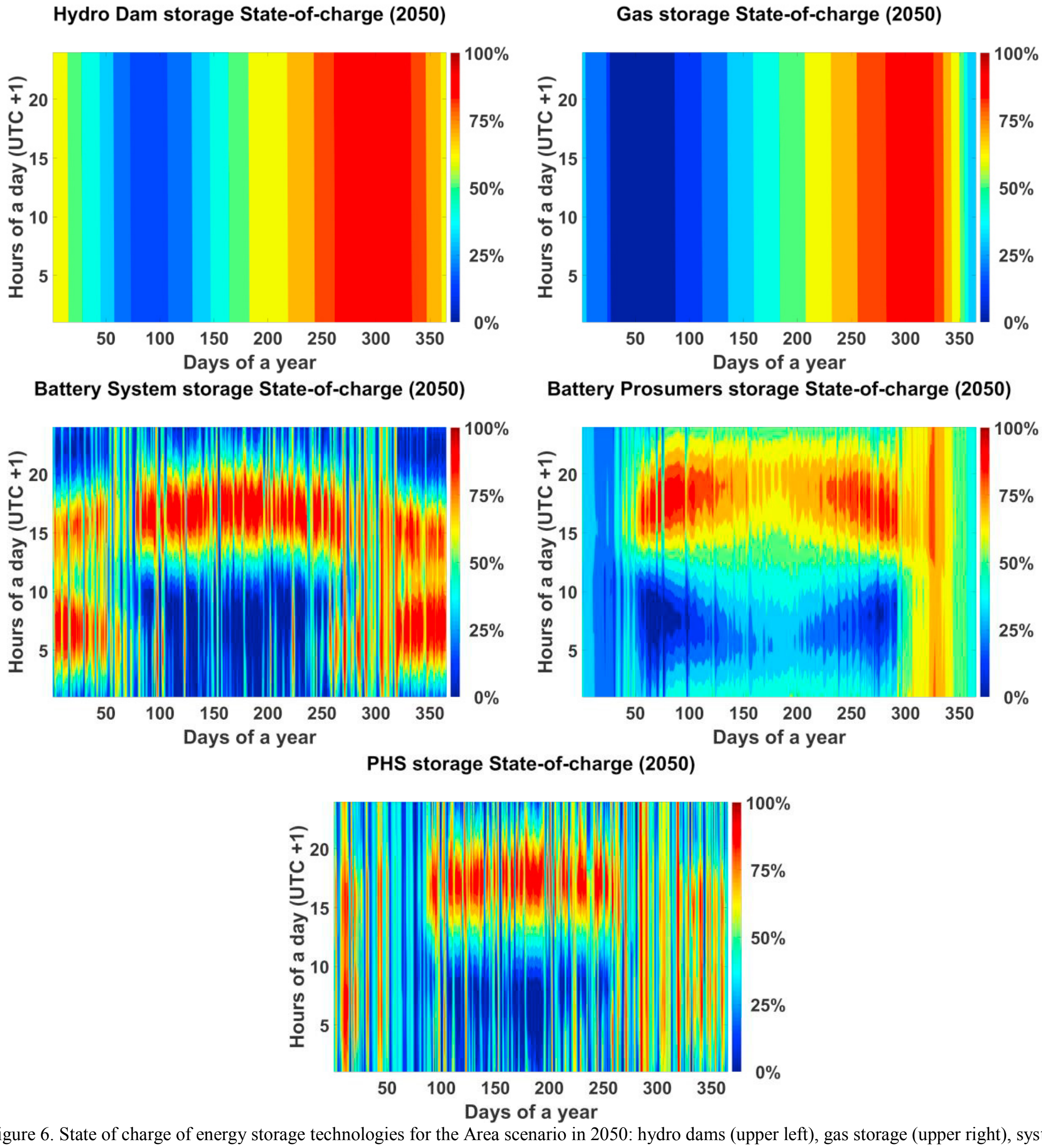

Figure 6. State of charge of energy storage technologies for the Area scenario in 2050: hydro dams (upper left), gas storage (upper right), system batteries (middle left), prosumer batteries (middle right), pumped hydro storage (lower)

Figure 6 shows the state of charge of selected energy storage technologies for the Area scenario. Hydro dams are charged by melting snow in the late spring and by rain in the summer and autumn periods. Gas storage is charged beginning in summer by excess amounts of solar PV energy, and in autumn, normally a time of high wind in the BSR (also see Figure 7 right). These storage technologies show net discharging throughout the winter months, when electricity consumption is highest in the BSR. The longer term and seasonal nature of these storage technologies is noticeable, and contrasts between the shorter term and more diurnal patterns that are shown by batteries (Figure 6 middle left and right). Pumped hydro storage (Figure 6 lower) shows a mix of diurnal storage in the summer months and longer term (over days and weeks but not seasons) storage during colder months. Diurnal patterns of afternoon charging from solar PV during warmer months (days 100-250) are evident, followed by evening discharge of batteries and PHS. In winter months, battery charging is associated with wind energy generation in general. Charging occurs from early morning to early evening, with a similar pattern of evening discharge as is seen during warmer months. During winter, peak demand for electricity occurs in two periods of the day, roughly 8:00 to 12:00 and 16:00 to 19:00. At these times, general trends of battery discharging are observed. PHS also shows a similar winter effect, albeit to a lesser extent. The use of system level batteries in this regard appears to prevent unnecessary and costly ramping up and down of biomass power plants. This effect is seen for system level batteries only, and not for prosumer batteries, which see little use during winter months. In total, storage technology capacities are lower for the Area scenario than the Regions scenario, as shown in Table 1. At the same time, installed storage capacities increase throughout the transition, as higher shares of RE are seen in the energy system.

Figure 7 (left) shows the grid utilisation profile for the Area scenario. Noticeable is the seasonal nature of grid use, with greater transfer of power during colder months, and during periods of high wind energy generation (Figure 7 right) in contrast to the solar PV dominated summer months with more local electricity generation.

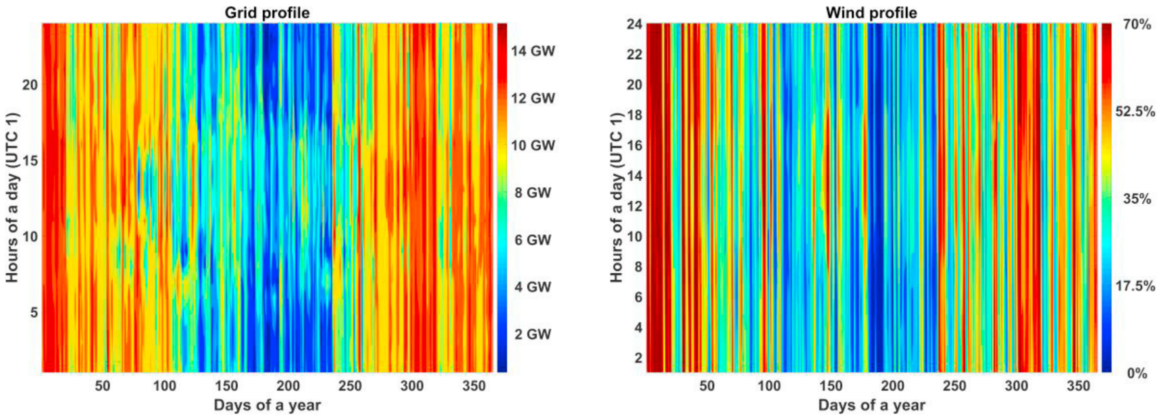

Figure 7. Grid utilisation profile for the Area scenario (left) and wind energy capacity factor profile (right) for the BSR region in 2050.

Figure 8 shows carbon emissions falling significantly after the phase out of coal power after 2020. Further reductions occur as imported natural gas is replaced by domestically-produced methane. By 2035, the BSR energy system is virtually decarbonised. Decarbonisation occurs a decade earlier in the Area scenario.

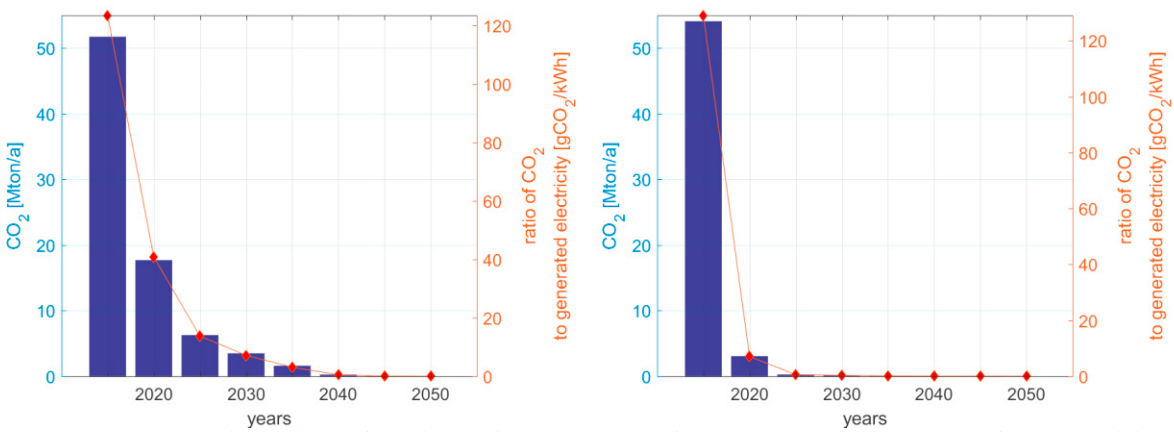

Figure 8. Total carbon emissions and ratio of emissions to electricity generation from 2015 to 2050 for the Regions (left) and Area (right) scenarios.

Figure 9 shows the trend of decreasing levelised cost of electricity (LCOE) over the years 2015 to 2050. Higher cost nuclear and coal-based generation is replaced by lower cost wind, solar PV and biomass-based power production. Lower capital expenditures, operational costs, fuel costs and emissions costs contribute to lower LCOE over time. Higher transmission costs in the Area scenario are more than offset by reduced primary generation, storage and curtailment costs. Cost reductions occur more quickly in the Area scenario due to lower costs of GHG emissions related to faster decarbonisation.

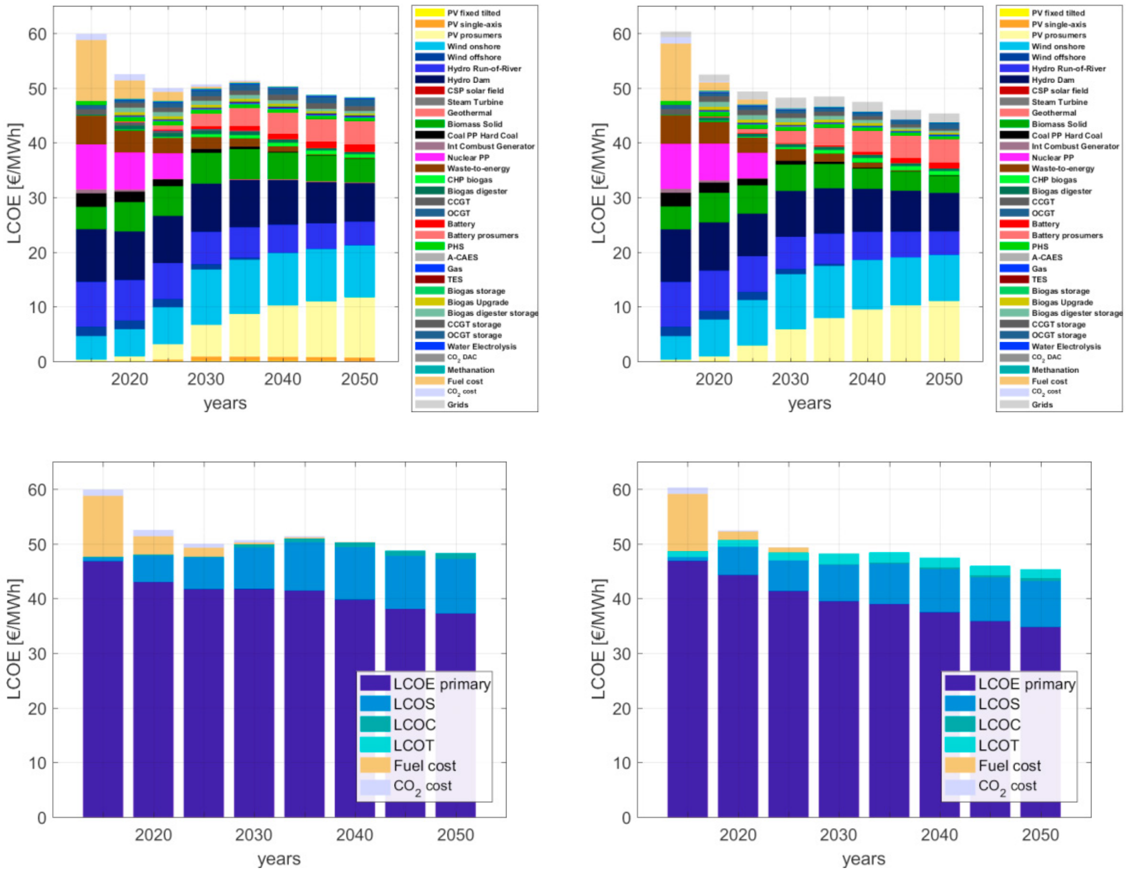

Figure 9. Levelised cost of electricity and the contribution of technologies (above) and breakdown in cost categories (below) for the Regions (left) and Area (right) scenarios. Levelised cost of electricity and the contribution of levelised costs of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), fuel cost, and carbon emission cost. Transmission costs (LCOT) are zero as interconnections with neighbouring countries were not utilized in this study.

4. Discussion

Results from modelling show that a 100% renewable power system is achievable for the BSR well before 2050. What is more, this represents a least cost solution for the region based on the assumptions used in this study. For the first time, it is also possible to visualise the transition towards a 100% renewable BSR power system. This transition is enabled by low-cost renewable and flexible energy generation, storage technologies, and intra-regional interconnections.

The LCOE values obtained in this work indicate that the cost of electricity could decrease from 60 €/kWh in 2015 to 48 €/kWh in 2050 for the Regions scenario and to 45 €/kWh in 2050 for the Area scenario. Results for the transition of the BSR towards 100% RE in terms of LCOE are consistent with several other similar transition studies using the LUT Energy System Transition model, which show a range of about 50-70 €/MWh for 2030 [9]–[13], [29]–[32].

Other similar energy transition studies also suggest that least cost power systems for 2050 can be achieved with 100% RE [26], [33]–[37]. These studies also suggest that further integration of desalination and non-energy gas demands into the energy system model could result in further LCOE savings, suggesting an interesting area of further research for the BSR.

Much of the cost savings can be attributed to the decreasing costs of renewable energy generation expected over the transition period, especially for solar PV and wind energy. It is clear that these technologies have strong roles in the future energy system, especially with regards to PV prosumers, who are set to play an active role in the energy transition as they seek to find the lowest options for electricity supply. Hydropower also continues to be important in regions where the resource is plentiful. Together with biomass, these flexible and dispatchable resources have important functions in providing system balance and in complementing the intermittent nature of the solar and wind resource in the short term and over seasons. At the same time, the total biomass resource has not been exploited, leaving ample supplies (up to 133 TWh) for biofuel production if necessary in the transport sector, or for the heating sector. Further seasonal complementarity and flexibility could be expected from utilising this biomass resource in the combined heat and power plants that may be increasingly common in Europe [38].

Cost savings and increased flexibility are also seen through the use of interconnections in the Area scenario. The sharing of intermittent renewable energy generation over a broader area leads to lower levels of generation, storage and curtailment. Such effects have been seen in other studies conducted both generally [39], and more specifically for Europe [15]. These cost savings are more than enough to compensate for the more modest costs of transmission that are incurred in the Area scenario. Such an effect has also been confirmed in a study of India [39]. Notably, the level of interconnection seen in the Area scenario results is not significantly higher than what is already seen in the BSR region [5]. The current status of 12 GW of interconnection is supplemented by an additional 1 GW connection between Finland and Estonia in the Area scenario. The results suggest that up to 15% of total generation of 587 TWh would be traded to other BSR regions. Such a level of trade is already exceeded in many BSR countries. Moreover, the highly regarded Nord Pool market already ensures ease of electricity trade between the Nordic countries, and expansion to include Estonia, Latvia and Lithuania is at least possible. However, due to the limited scope of this study and the decision to model Estonia, Latvia and Lithuania as a single region, it is unclear if strengthening of interconnections between those countries would be needed. At the same time, current HV interconnections already exist between Estonia and Latvia (750 MW), as well as between Latvia and Lithuania (1300 MW), that have been projected to increase in the future (to 1600 and 2100 MW, respectively) [5]. Therefore, interconnections seen in the results of the Area scenario represent more of a status quo than an unmanageable challenge for the future. It appears that the BSR can indeed be "stronger together" [4], and that an energy union may be of significant benefit.

Cost savings are also the result of different energy storage requirements between the Regions and Area scenarios. While energy storage is increasingly relevant in both scenarios as shares of renewable energy generation approach 100%, the relative importance of various technologies appears to change. Noticeably, the need for additional longer term, seasonal storage capacities such as TES, A-CAES and PtG are greatly reduced in the Area scenario. Instead, existing hydro dams suffice to provide the seasonal storage needed for the interconnected energy system, and as inter-regional balancing of renewable generation, particularly wind energy, occurs. The importance of batteries to provide diurnal storage is highly relevant in both the Regions and Area scenarios.

At the same time, energy storage solutions are increasingly relevant in both scenarios throughout the transition from 2015 to 2050. This result matches several studies which show that increasing shares of intermittent renewable energy generation will result in greater need for storage solutions, especially after the share of RE goes beyond 80% of generation [20], [40], [41]. In absolute terms, gas storage is most prominent (see Table 1), suggesting that the positions of gas-related technology and infrastructure are rather secure, and there is little risk of stranded investments. The results also suggest there would be little technological change in this regard, merely a shift in fuel, away from imported fossil natural gas and towards domestic biogas, biomethane and SNG. Next, the impacts of the expected price declines in solar PV and battery technology are also clearly seen in this study, and match the results of several others. Noticeably, the roles of PV prosumers and prosumer batteries are prominent, suggesting that the general public could have a significant role to play in the climate action demonstrated by the BSR. The strong role of prosumers has been postulated in several recent studies [8], [42], [7]. It remains unclear to what extent battery storage could involve the large amount of battery electric vehicle storage and vehicle-to-grid connections expected in the future. This represents an interesting further area of investigation that would require more detailed modelling of the transport sector. However, important roles of optimal charging and vehicle-to-grid participation has been noted in previous studies to reduce overall costs of energy systems through reduced installed generation and storage capacities [43], [44]. Finally, as high shares of RE in general, and prosumer PV and batteries more specifically, are projected to be seen in the BSR more rapidly than Europe as a whole, the BSR can develop a leadership role in European climate action. Moreover, there may be opportunities to showcase solutions to other European states and globally.

5. Conclusions

A 100% renewable power system is achievable for the BSR by 2050, with much of the decarbonisation achieved by 2035. This also represents a least cost alternative for the BSR, is lower in cost than the current system based on nuclear power and fossil fuels, and can provide for increasing demands for power in the future. Cost savings are seen from harnessing the flexibility of generation by various renewable energy technologies, from the interconnection of regions within the BSR, and by the use of appropriate and low cost energy storage solutions. However, shifts in energy policy are needed at national and regional levels to support the transition needed to reach national goals, as well as to affirm EU and international commitments related to climate change mitigation. The BSR has the ability to lead the EU by becoming the first large region to achieve a 100% renewable energy system.

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Supplementary Material

Further data concerning cost and technical assumptions can be found in the additional information provided in the conference presentation slides. In addition, they can be found from the following link: http://bit.ly/2n7Is7s.

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