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Modeling the Baltic countries' Green Transition and Desynchronization from the Russian Electricity Grid

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ABSTRACT

In the next ten years, the Baltic countries — Estonia, Latvia, and Lithuania — are planning large investments in renewable power generation and transfer capacity, substantial phase-out of fossil-based power generation, and desynchronization from the Russian electricity grid. In this article, the operational impacts of these changes on the Baltic energy system from 2017 to 2030 are studied with an open-source Backbone energy system model. The operation of Estonian, Latvian and Lithuanian power and heat, transport, and building sectors are optimized simultaneously on an hourly level, and results are analysed with operational, environmental, economic, and security indicators.

Results suggest that the planned transition would support Baltic targets in renewable generation (from 45% to 92%) and self-reliance (2.3 TWh increase in domestic power generation and 5.5 TWh decrease in natural gas imports) with a moderate impact on system costs. However, an increase in transport CO2 emissions could risk national non-ETS targets. The hourly operation of the system, with a high share of wind and solar, is based on active use of storages and interconnectors. Model results raise concerns about the amount of Estonian dispatchable capacity, the commercial feasibility of Latvian natural gas CHP's, and the high ramping rates of Lithuanian interconnectors.

Keywords

Energy system model;
Baltic countries;
Renewable energy;
Emission reductions;
Wind power

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1. Introduction

The Baltic countries — Estonia, Latvia, and Lithuania — are committed to significantly reducing their greenhouse gas (GHG) emissions. The countries have ambitious 2030 targets as a part of the EU's emission reduction target of 55% by 2030 [1]. In addition to rapid emission reductions, the Baltic countries' near-term focus is on improving energy security by increasing domestic generation and synchronizing with the Continental European electricity grid instead of the synchronous grid of Russia by 2025 [2, 3].

The planned targets require considerable investments in variable renewable energy (VRE) and transmission capacity. According to the Baltic national plans, the VRE generation capacity would increase by 460% from 1.0 GW in 2017 to 5.6 GW by 2030, and this would raise the capacity share of intermittent sources in power generation from 13% up to 50% [4–6]. The Baltic countries are planning to balance the high VRE shares with hydropower in Latvia, pumped hydro storage in Lithuania, and cross-border transmission capacity. Denmark will reach a 70% VRE share by the end of 2022 [7] with

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Abbreviations

BRELL	Belarus, Russia, Estonia, Latvia Lithuania
CHP	Combined heat and power
DH / dh	District heat
Elec / e	Electricity
ETS	Emissions trading system
EV	Electric vehicle
GAMS	General Algebraic Modeling System
GHG	Greenhouse gas
LPG	Liquefied petroleum gas
OPEX	Operating expenses
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaics
RetGas	Retort gas (from oil shale)
VRE	Variable renewable energy

similar enablers: high transmission capacity and hydro storages in other Nordic countries [8].

In order to join the synchronous grid of Continental Europe, the plans include building new interconnectors between Lithuania and Poland (1.2 GW), Lithuania and Latvia (0.3 GW), and Latvia and Estonia (0.6 GW), while disconnecting up to 1.8 GW of the current capacity from Russia, Belarus, and the Kaliningrad region [9]. For scale, the current cross-border transmission capacity to the Baltic region is approximately 3.8 GW [10].

Nearly one-fifth (18%) of the existing thermal electrical capacity is planned to be decommissioned within the decade [11–13]. The majority of decommissionings concern the Estonian shale oil plants in Narva, and this would convert Estonia from electricity net exporter to net importer. In order to successfully implement the Baltic green energy transition in the challenging circumstances listed above, the operation of the planned system must be studied in detail.

Recurring themes in Baltic energy research include energy security assessments (e.g. [14, 15]) as well as evaluating the prerequisites and impacts of the renewable transition (e.g. [3, 16]). Several studies assess the transition from the energy policy perspective, highlighting the challenge of translating the plans to implementable policies and strategies [17, 18]. High-quality modeling studies in the Baltic region, also those using model-optimized investments, show capacity changes in the same direction and order of magnitude as the national plans reported above [19, 20]. However, depending on the assumptions and modeling methodology, they predict different speeds of fossil generation phase-out and share of electricity imports. Several studies agree that a highly renewable system seems feasible without major energy security challenges [21, 22]. The strong transfer connections, combined with the goal to boost domestic capacity, offer opportunities for fast VRE deployment, but create sensitivity to changes outside the Baltic region [3, 23]. Studies emphasize the need for investments in not only VRE, but also flexibility, storages, and interconnectors [16, 21].

While these examples show that the future of the Baltic energy system has been studied with various approaches, it is still less comprehensively covered than many North and Central European regions. The modeling studies [19, 20, 22, 24] have used a range of methods to simulate and optimize the possible futures of the Baltic system. However, they have not focused on analysing the intra-year operation of the highly renewable energy system, nor evaluated policy plans with techno-economic indicators.

The wind and solar integration studies focusing on modeling energy systems with VRE shares, up to 50% and more, highlight the need to model the operational impacts with full-year, high-temporal resolution and with multiple sources of flexibility [25]. Including these features in modeling the Baltic energy system offers operational detail that may have been overlooked in previous modeling using only annual energy balances [20] or representative time periods [19, 22, 24].

The value of the Baltic Backbone model presented in this paper is in improving the operational accuracy of the energy system modeling applied to the region. Further, the model is applied to the most recent policy targets, addressing the national plans with policy goal indicators. The aim of our study is to find out impacts, opportunities, and operational challenges the planned Baltic green transition holds.

Chapter 2 documents the Baltic Backbone model alongside the used input data. Chapter 3 summarizes the model validation. Chapter 4 presents the modeled impacts of the planned transition on emissions, renewable energy shares, energy security, system balancing, operation of different types of units, and costs of the system. Chapter 5 discusses the results and methods, and Chapter 6 summarizes the conclusions.

2. Methods and Data

The Baltic energy system is studied using the Baltic Backbone model, consisting of power and heat, building, and transport sectors in Estonia, Latvia, and

Lithuania. This chapter presents the model's modular structure and describes each module and data sources.

2.1. Overview of the Baltic Backbone model

The Baltic Backbone model is built with a Backbone modeling framework. The Backbone framework is a well-established, highly flexible, and open-source energy systems modeling tool. It can be used to create models for studying the development and operation of a particular energy system. Due to framework adaptability, the models may include multiple energy sectors and simulate a large-scale system or a high-detail area. The Backbone framework developed in GAMS (General Algebraic Modeling System) is fully described in [26] by Helistö et al. It has been applied and validated in many peer-reviewed studies, e.g. [27–29]. Both the Backbone framework and the Baltic Backbone model are openly available in GitLab[1].

Figure 1 presents a scheme of the Baltic Backbone model structured into three modules: system, buildings, and transport. The built structure allows running the system module separately, or all three modules can be optimized simultaneously.

A. *System module* describes electricity and district heating systems. It also includes electricity reserves, transmission, storages, and conversions between grids, such as large heat pumps. The system module can be used to study a wide range of issues including the impacts of new generation capacity, sources of flexibility, the role of interconnections, and reserves.

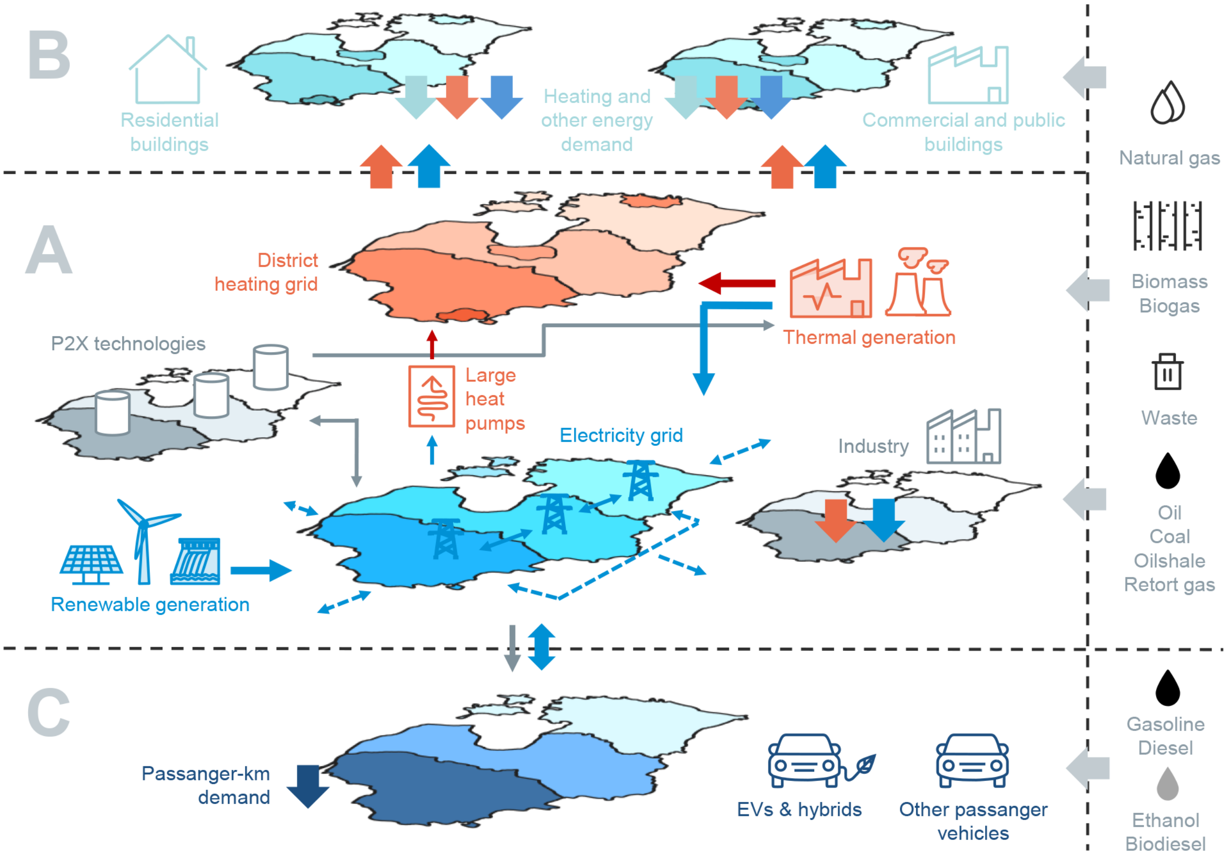

Figure 1. Illustration of the Baltic Backbone energy system model. The model consists of electricity and district heat grids, energy conversions (Module A); buildings energy use (Module B); and personal vehicles (Module C).

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[1] https://gitlab.vtt.fi/backbone/projects/fasten-model

B. *Buildings module* represents the residential, commercial, and public building sectors. This module allows studying the impacts of improved energy efficiency, electrification, and flexibility in buildings.

C. *Transport module* describes the energy use of personal vehicles in each country to investigate transport electrification, charging patterns, flexibility options, and their impacts on the system.

The electricity grid consists of Estonian, Latvian, and Lithuanian power networks and cross-border connections to Finland, Sweden, Poland, Russia, and Belarus. The district heating network and building energy use of each country are divided between the capital and the aggregate of all other regions. This allows the detailed study of building heating in the capital regions. Transport energy use is modeled at a national level.

The model runs a full year in hourly time steps with a rolling horizon, using linear optimization. It takes units as given assets and optimizes their annual and hourly use in order to minimize overall annual system costs while maintaining a supply and demand balance, reserve requirements, and other given constraints.

2.2. System module (Module A)

The system module (Module A) includes power and heat generation and demand, storage, and transmission of electricity and district heating. Electricity units are modeled at unit-level detail, while heat-only units are aggregated by fuels. Table 1 summarizes the generation unit data.

Table 1. Summary of modeled electrical and district heat capacity by source and by country in 2017 and change to 2030.

	Estonia				**Latvia**				**Lithuania**			
	Electrical capacity [MWe]		**District heat capacity [MWdh]**		**Electrical capacity [MWe]**		**District heat capacity [MWdh]**		**Electrical capacity [MWe]**		**District heat capacity [MWdh]**	
	2017	**2030**	**2017**	**2030**	**2017**	**2030**	**2017**	**2030**	**2017**	**2030**	**2017**	**2030**
Renewables & waste	**429**	**+1312**	**1493**		**1798**	**+945**	**1972**	**+353**	**853**	**+2608**	**1980**	**+373**
..wind onshore	303	**+397**			77	**+319**			521	**+985**		
..wind offshore	0	**+500**			0	**+396**			0	**+700**		
..PV decentralized	0.1	**+405**			1.2	**+97**			82	**+803**		
..PV centralized	0.1	**+10**			0.1	**+10**			0.1	**+10**		
..Hydro run-of-river	8				28	**+1**			27			
..Hydro reservoir	0				1536	**+44**			101			
..Biomass	95		1436		95	**+41**	1909	**+278**	66	**+69**	1866	**+188**
..Biogas	6		7		60	**+31**	64	**+32**	37		52	
..Waste	17		50		0	**+7**	0	**+28**	20	**+41**	63	**+185**
..Solar collectors			0				0	**+15**			0	
Natural gas	96		4027		1168	**-74**	3651	**-765**	1676	**-52**	7730	**-298**
Oil shale	1879	**-1609**	360	**-50**	0		0		0		0	
Retort gas	10				0		0		0		0	
Oil	0		1092		0		17	**-9**	186		434	
Coal	0		0		3	**-3**	66	**-33**	0		0	
Excess heat			0				0				390	
Heat pumps			0				0	**+115**			0	
Storages	**0**	**0**	**0**		**0**	**+30**	**0**	**+184**	**900**	**+310**	**0**	
..Hydro pumped	0				0				900	**+110**		
..Batteries	0	**+200**			0	**+30**			0	**+200**		
..Heat storage			0				0	**+184**			0	

The majority of Estonia's electrical capacity consists of condensing (1.6 GW_e) and cogenerating (0.3 GW_e) oil shale plants located in the Narva region [30]. A total of 1.7 GWe of Narva units' electrical capacity is planned for decommissioning before 2031 [11], but in our modeling for 2030, the two most recent units are kept as backup capacity due to lack of reserve capacity with current plans.

In Latvia, the major units include three Daugava hydropower plants in cascade (1.5 GW_e) with 3–6 hours' storage, depending on the season, and two large gas-fired CHP plants in Riga (1.0 GW_e) [31].

In Lithuania, the installed electrical capacity (3.6 GWh_e) is modest compared to consumption, and mainly based on natural gas. A significant electrical resource is the Kruonis pumped hydro storage, with 0.9 GW_e of capacity and 11 GWh_e of storage. To balance the substantial increase in variable generation Lithuania plans to expand the Kruonis station by 0.11 GWh_e, and introduce 0.2 GWh_e of grid-scale batteries.

All countries are planning a significant increase of VRE capacity by 2030 [4, 12, 13]. In the district heating capacity, the fuel selection is diverse and increasingly renewable, but the majority of the current capacity is gas-fired in all three countries [30–32].

Unit operating parameters (variable and fixed operating costs, operating constraints, etc.), are from the previously mentioned national sources when available. Missing parameters are supplemented with data from the Baltic Energy Technology Scenarios study [19] and technology catalogue data by the Danish Energy Agency [33].

Baltic countries are part of the BRELL (Belarus, Russia, Estonia, Latvia, and Lithuania) grid, where electricity is transferred from Belarus through the Baltic countries to the St. Petersburg region in Russia. This is because of Russia's geographical layout of generation and demand. Because Russia and Belarus are not included in the model, the net transfer capacities of interconnectors in 2017 are estimated based on typical historical flows from ENTSO-E transmission system operator power flow data [34] (Table 2). Major changes are foreseen for the Baltic countries due to the planned disconnection of all transfer capacities with Russia and Belarus, and strengthening Polish and inter-Baltic connections in 2025 as a part of ongoing integration with the synchronous grid of Continental Europe [9].

Annual demand data of electricity and district heating for 2017 is from national statistics (Table 3) [30–32]. National estimates project a 12 to 25% increase in total electricity demand and an 8 to 19% decrease in district heating demand in 2030 [5, 6, 11]. Transmission and distribution losses (9–16% depending on the power or district heating grid) are subtracted between production and consumption [30–32]. End-use electrification and economic development are estimated to increase electricity demand, while the impact is countered by population decline and efficiency improvements. District heating demand will decrease towards 2030 due to

Table 2. Summary of modeled electrical cross-border transfer capacities in 2017 (actual and modeled), and change from 2017 modeled to 2030.

	Cross-border electricity transfer capacity [MW]					
	[1] → [2]			**[1] ← [2]**		
	2017, actual	**2017, modeled**	**2030**	**2017, actual**	**2017, modeled**	**2030**
[Estonia] - [Finland]	1000	1000		1000	1000	
[Estonia] - [Latvia]	800	800	**+600**	800	400	**+1000**
[Estonia] - [Russia]	600	600	**-600**	600	25	**-25**
[Latvia] - [Lithuania]	1000	1000	**+300**	1000	550	**+750**
[Latvia] - [Russia]	400	100	**-100**	400	200	**-200**
[Lithuania] - [Sweden]	700	700		700	700	
[Lithuania] - [Poland]	500	350	**+650**	500	350	**+650**
[Lithuania] - [Belarus]	1000	1000	**-1000**	500	500	**-500**
[Lithuania] - [Kaliningrad]	300	0		300	300	**-300**

Table 3. Summary of modeled electricity and district heating demands by country in 2017 and change to 2030.

	Annual demand [GWh]					
	Estonia		**Latvia**		**Lithuania**	
	2017	**2030**	**2017**	**2030**	**2017**	**2030**
Electricity	**7736**	**+7 %**	**6485**	**+9 %**	**10730**	**+6 %**
..Transport	46	**+168 %**	104	**+67 %**	74	**+209 %**
..Buildings	4656	**0 %**	4423	**0 %**	6145	**0 %**
..Other	3034	**+16 %**	1958	**+26 %**	4511	**+11 %**
District heat	**4602**	**-10 %**	**7034**	**-10 %**	**10817**	**-19 %**
..Buildings	3812	**-10 %**	5986	**-10 %**	7873	**-22 %**
..Other	790	**-10 %**	1048	**-10 %**	2944	**-11 %**

improvements in energy efficiency and investments to alternative heating technologies.

Hourly historical electricity demand data from Nordpool [35] is divided by sectors according to national statistics [30–32]. The sectoral development is according to national estimates [5, 6, 11], and transport and building assumptions (see 2.3 & 2.4). The district heating demand curve is based on historical temperatures and demand variation.

The modeled power system reserve requirements include aggregated upward regulation of primary control reserves for each Baltic country. The reserve demand equals the largest producing unit or interconnector (N-1 condition). Thermal units are assumed to be able to provide 7%, hydropower 10%, curtailed wind power 20%, and batteries 90% of their online capacity as reserve capacity. Variable generation can produce reserves in situations where the capacity is not fully generating [36]. The curtailed share of wind capacity can ramp up the generation quickly, but we used a lower value (20%) due to intermittency and uncertainty of the available capacity. Generating VRE capacity increases the need for operating reserves due to forecast errors [37]. For this reserve increase, we used 5% of generation, which might be too conservative of an assumption.

Variable renewable datasets from MERRA-2 are combined with technology data [33] and used as a deterministic time series for wind and solar generation [38]. The average capacity factor of onshore wind is estimated to increase from 0.25-0.30 in 2017 to 0.37 in 2030 [33]. Hourly variation for hydro inflow is based on previous studies [19].

Modeled fuels include biogas, biomass, waste, natural gas, coal, oil, oil shale, and retort gas, modeled as commodities with annual prices [39, 40]. Sensitivity to changes in natural gas price and availability is reduced by the Latvian Inčukalns' underground gas storage facility. Imported electricity is also modeled as a commodity with an hourly price time series [35].

National taxes, like fuel and excise taxes, are included in the model [41, 42]. Power transmission and distribution costs are included for all end-use sectors, and EU emission trading system (ETS) prices are estimated to increase from 5 €/tCO_2 in 2017 to 50 €/tCO_2 in 2030 [24].

For the power and heat sector, investment costs are calculated outside the model. Investment annuities are based on technology data [33] and use a 5% interest rate and 20 years payback time. Decommissioning costs are estimated as 10% of building costs.

2.3. Buildings module (Module B)

The buildings module simulates the energy use in buildings for space and hot water heating, as well as electricity demand for other purposes, like lighting and cooking (Table 4). Historical energy data is built on Eurostat energy balances [43], Eurostat Questionnaire for statistics on final energy use in households [44], and national district heating statistics presented in the previous section.

Eurostat energy balances provide total final energy use by fuel for residential and commercial sectors, but does not specify the type of end use. The questionnaire for households provides data of final energy use by type of end use, but only for the residential sector. The same split is used for the commercial sector. Energy use data is supplemented with heat pump data from the Eur'Observer heat pump barometer [45]. The split between buildings' energy demand in the capital area and other regions is based on the population of these regions in each

Table 4. Summary of modeled buildings energy demand by fuel, type of end use, and region in 2017.

	Energy use for heating and hot water, 2017 (GWh)								**Other energy use, 2017 (GWh)**
	Coal	**Oil**	**Natural gas**	**Biomass**	**DH**	**HP, ambient**	**HP, electricity**	**Electricity, direct**	**Electricity, other**
Estonia	**24**	**101**	**1264**	**4507**	**3558**	**348**	**174**	**1008**	**3473**
…Tallinn	7	28	352	1294	1552	100	50	279	1158
…Other	17	73	912	3213	2006	248	124	730	2315
Latvia	**156**	**603**	**1754**	**6476**	**5986**	**14**	**7**	**1052**	**3363**
…Riga	27	105	304	1137	3427	3	1	181	1087
…Other	129	498	1450	5339	2559	12	6	871	2277
Lithuania	**1039**	**260**	**1978**	**5709**	**7873**	**22**	**11**	**634**	**5500**
…Vilnius	204	52	389	1134	1719	4	2	124	1139
…Other	835	208	1589	4575	6154	18	9	511	4361

Baltic country. National district heating statistics provide the amount of district heat supplied in each modeled region (capital and other), while other fuels are split between the remaining demand of each region.

National estimates and other forecasts project a 10% decrease of heating and hot water demand in buildings from 2017 to 2030 [4–6]. This would reduce the use of fossil fuels and district heating. The amount of heat pumps is assumed to increase from 160,000 units in 2017 (0.6 TWh) to 300,000 units in 2030 (1.1 TWh). Together, these result in the reduced use of fossil fuels, biomass, and district heat in the buildings sector. The assumed changes in the use of fossil fuels are based on [19].

2.4. Transport module (Module C)

The transport module simulates the energy use by passenger vehicles. The module includes the main fuels (gasoline, diesel) and the main alternative energy sources (electricity, biodiesel, ethanol). Additionally, Lithuania and Latvia have a notable share of liquefied petrolium gas (LPG) passenger vehicles (10% of total passenger vehicle energy use) [46], but they are summed up with gasoline vehicles. In Estonia, the share of LPG vehicles is considerable smaller.

The transport module requires that the hourly passenger demand (vehicle-km) is fulfilled. National total demands for vehicle-km are from Eurostat [47] and the hourly curve is from Lithuanian road traffic measurements [48]. The contribution of different vehicle types is based on the total amount of vehicles per fuel type [49] and annual fuel consumption [46] that allows for the calculation of the average annual distance driven by vehicles per fuel type (Table 5). The total fuel demand and emissions are calculated bottom-up, based on previous assumptions and average annual efficiency of each vehicle type [50] in 10-year age group intervals. The module is calibrated by slight national adjustments to driven distance and efficiency of vehicles that reflect national differences in car stock and typical journeys.

Renewable fuels are blended to fossil fuels. The historical biofuel shares are from national energy statistics [46], and 2030 shares are based on national legislation or targets (Estonia 6%, Latvia 2%, Lithuania 6% ethanol in gasoline and 10% of biodiesel in diesel).

Development from 2017 to 2030 is based on national projections where the total national transport demand continues the historical growth trend, leading to a larger number of vehicles. Efficiency of the future car fleet is based on the published technology catalogues [50].

Two types of charging technologies for PHEVs and EVs are included. For 2030, 50% of the fleet is assumed to be charged with fast charging through-out the day with little given flexibility in the charging pattern. The rest would be charged overnight with slower chargers, allowing the model to partially optimize the charging pattern during the night.

3. Model Validation

The model is validated by comparing the results of the historical model run of 2017 with statistical data (Figures 2 and 3).

Table 5. Summary of modeled passenger vehicle stock by country in 2017 and 2030.

		2017			2030		
		Amount	**Avg. Distance driven**	**Efficiency**	**Amount**	**Avg. Distance driven**	**Efficiency**
		1000 vehicles	**1000 vkm**	**1000 vkm / MWh**	**1000 vehicles**	**1000 vkm**	**1000 vkm / MWh**
Estonia	Gasoline	450	9.5	1.46	573	9.75	1.61
	Diesel	275	16.2	1.55	378	14.4	1.70
	PHEV	0	-	-	12	9.25	3.09
	EV	1.2	9	4.47	25	9.25	4.72
Latvia	Gasoline	301	13.3	1.42	313	12.5	1.58
	Diesel	388	16	1.53	558	14.2	1.69
	PHEV	0.1	12.8	2.92	11	12.8	3.09
	EV	0.3	12.8	4.47	23	12.8	4.72
Lithuania	Gasoline	441	13	1.46	456	12.3	1.60
	Diesel	907	15.6	1.57	1337	14	1.70
	PHEV	9	12.3	2.92	23	12.3	3.05
	EV	0.6	12.3	4.47	47	12.3	4.72

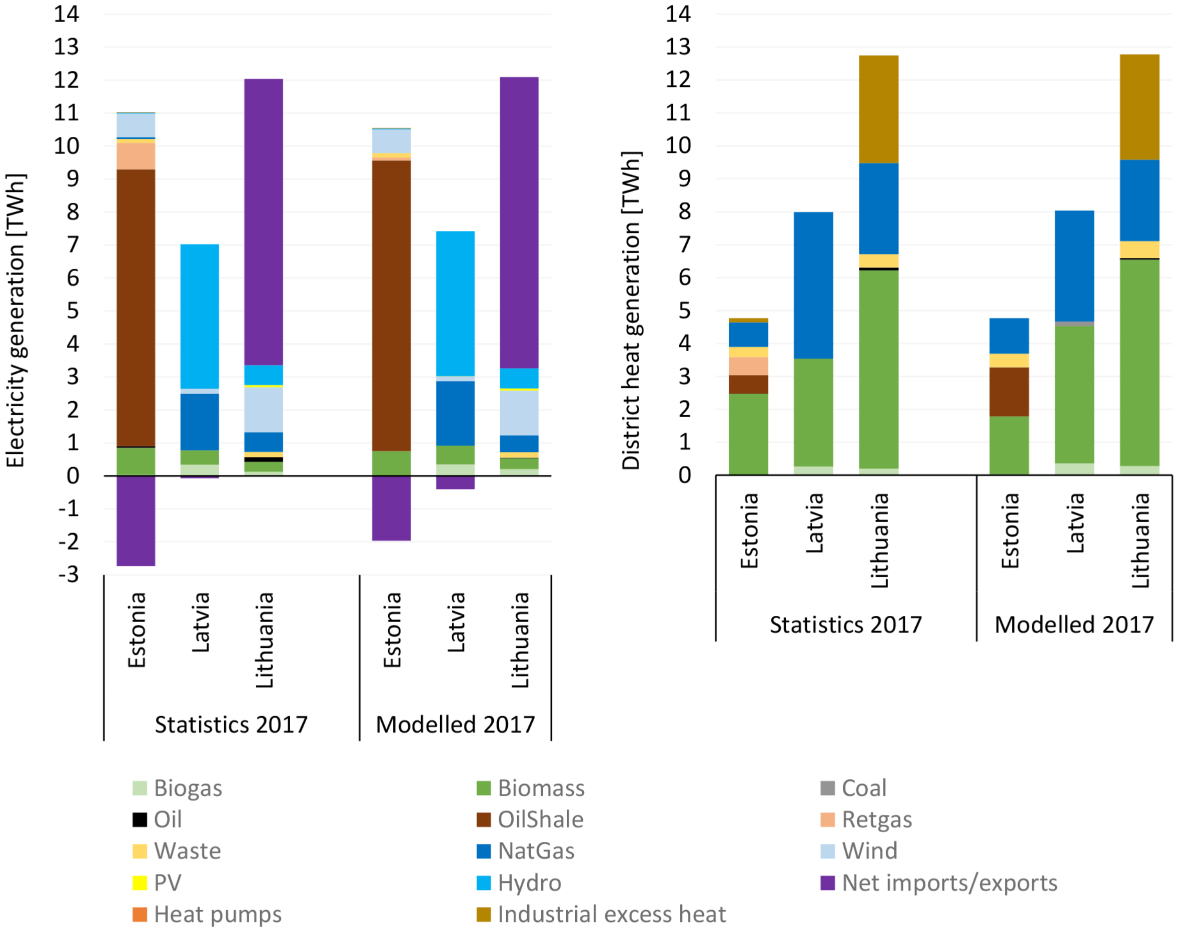
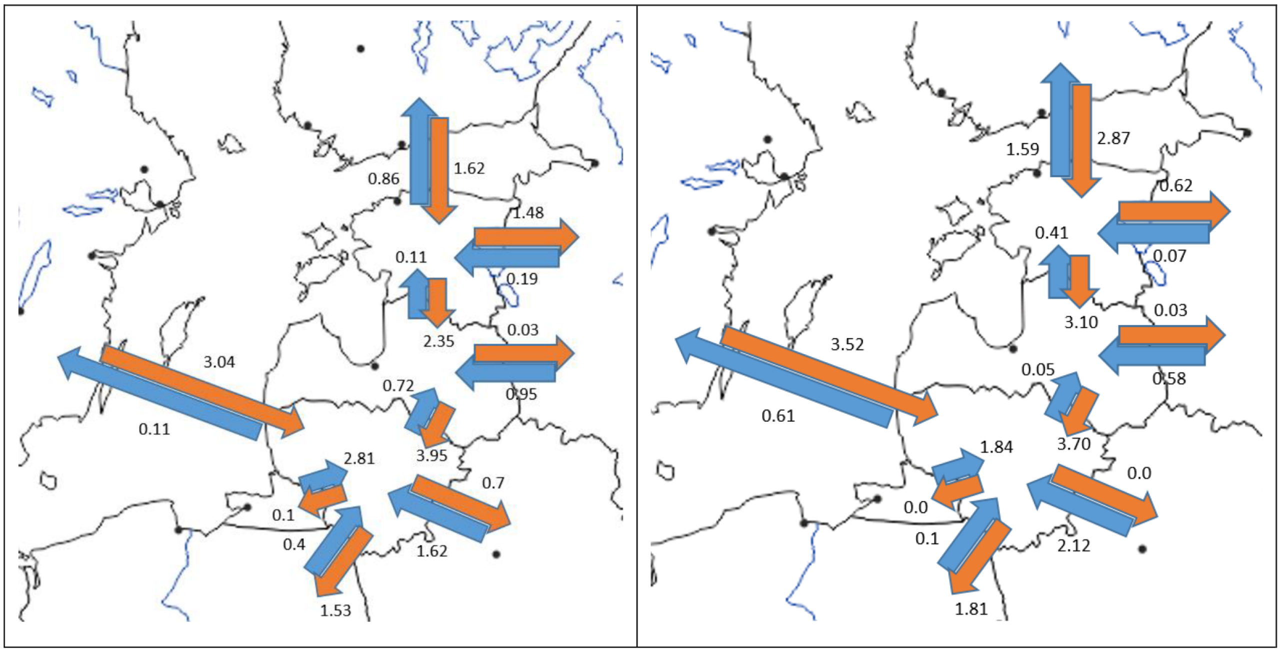


Figure 2. Statistical and modeled electricity and district heating supply by source and by country in 2017.



(a) Statistics 2017

(b) Modeled 2017

Figure 3. Statistical and modeled electricity imports and exports in 2017 (TWh).

As shown in Figure 2, the modeled and statistical electricity generation is well aligned in all three countries. In Estonia, the generation shares by oil shale and oil-shale-derived retort gas differ slightly from historical, but their combined generation nearly matches the statistics (8.9 vs. 9.2 TWh). Also, the actual electricity net exports in 2017 were somewhat higher than modeled (2.0 vs. 2.7 TWh). In Latvia, the model generates slightly more (0.3 TWh) electricity by natural gas and net exports compared to historical data. In Lithuania, the model results correlate highly to statistical values.

The results for district heating supply by source are similar to statistical data, especially for Lithuania. However, for Estonia the model generates too little heat by biomass (1.8 vs. 2.5 TWh), and too much by oil shale (1.5 vs. 1.1 TWh) and by natural gas (1.1 vs. 0.7 TWh). Also in Latvia, the generation shares by biomass (4.2 vs. 3.3 TWh) and natural gas (3.4 vs. 4.4 TWh) do not match exactly.

The total net imports and exports in the model results are close to historical data. However, as shown by Figure 3, the import and export flows by connection are somewhat different. As the power systems of Sweden, Finland, Russia, Belarus, and Poland are not included in the model, the imports and exports from and to these countries are only limited by the interconnector capacity and hourly electricity trade prices. In addition to the impact of modeling simplifications, the actual BRELL transit flows from the Moscow region to the St. Petersburg region, via the Baltic counties, result in differencies in modeled and statistical flows.

4. Results

The modeling according to national plans shows a fast transition in power and heat generation towards renewable sources in all three Baltic countries. The highest VRE share is reached in Lithuania, up to 82% of domestic power generation. Electrification of transport and heating seem to have only a limited role within the next ten years. The modeled development would lead to a significant reduction in power and heat sector emissions as well as an increase in renewable and domestic electricity shares between 2017 and 2030. The model is able to balance the operation of the highly renewable system with active use of storage and interconnectors. However, a need for additional flexible capacity in Estonia is indicated. In the modeling results, six key outcomes are identified.

4.1. Fast transition of power generation towards high VRE shares

The Baltic power system shifts from 53% fossil-based electricity generation in 2017 to only 4% in the ‘2030 reference’ (Figure 4). Simultaneously, the annual share of electricity by wind and PV increases from 11% to

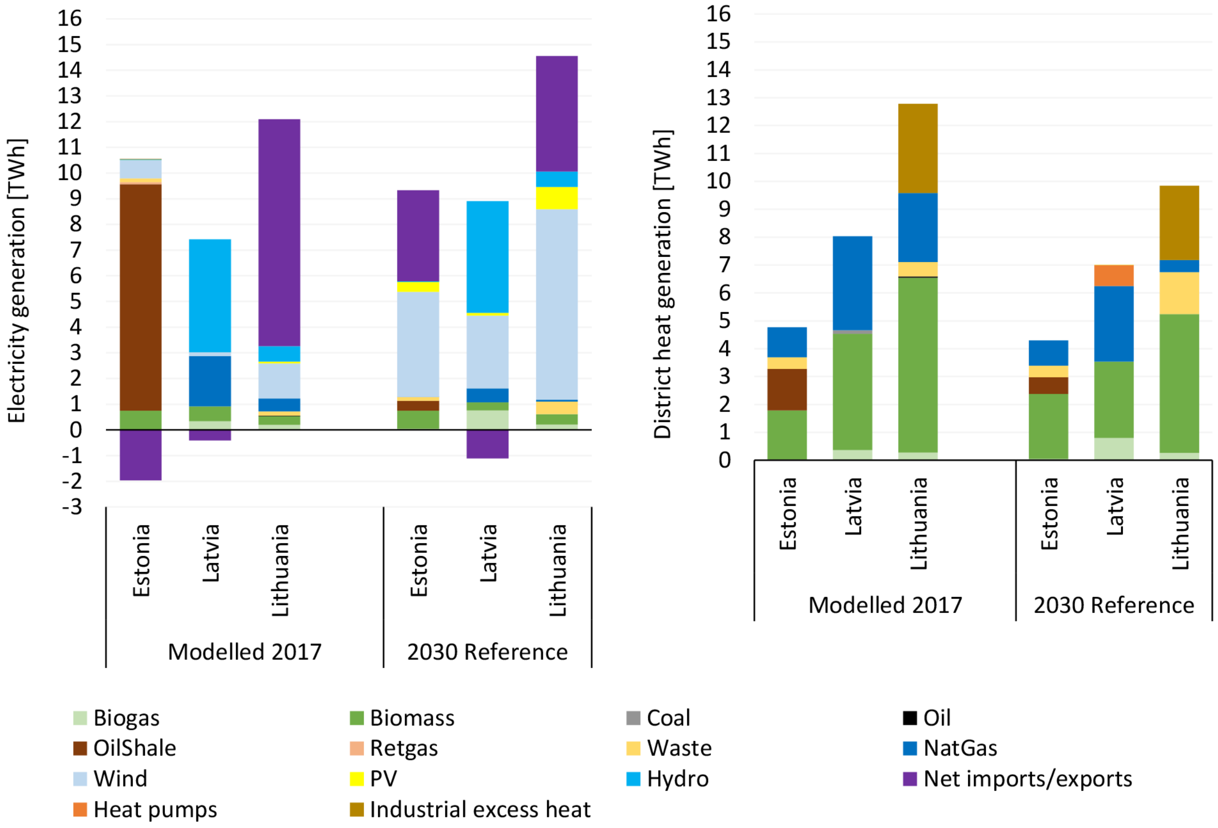


Figure 4. Annual electricity and district heat generation by source and by country in 2017 and the '2030 reference' scenario.

63%. The fast transition is a result of large investments in wind power and PV, decommissioning of Estonian oil-shale-based generation and an increase in fossil generation operational costs, mainly due to an increase in EU emission trading prices.

The change is the most pronounced in Estonia, where oil-shale-based generation decreases from 8.9 to 0.4 TWh, and the import-export balace shifts from 2.0 TWh net export in 2017 to 3.5 TWh net import in the '2030 reference'. In Lithuania, the share of electricity generation by wind increases from 42% to 74%, reducing net imports from 8.8 to 4.5 TWh. Latvia faces more subtle, yet significant changes: 1.4 TWh reduction in natural gas based generation, 2.7 TWh increase in wind generation, and 0.7 TWh increase in net exports. In district heating generation, fossil phase-out is balanced with decreasing demand and existing biomass capacity, leading to a slower transition.

4.2. Increased need for balancing capacity and reduced online hours of thermal plants

The results indicate that energy self-sufficiency in the three modeled countries will develop differently (Table 6). While the total Baltic domestic electricity generation slightly increases (by 2.3 TWh) and both electricity and natural gas import dependency decrease (by 1.4 and 5.5 TWh correspondingly), the phase-out of dispatchable thermal capacity, increase in VRE, and desyncronization from BRELL impact operational security.

In Estonia, the '2030 reference' scenario, without added dispatchcable capacity to replace phased-out oil shale units, leads to volatility and frequent peaks in Estonian electricity marginal prices. This points to challenges in operational balancing. To correct the model stability and provide reserves, new flexible capacity needs to be introduced. A comparison between gas turbines, biomass CHPs, batteries, new interconnectors, and leaving oil shale units as backup capacity, results in grid-level battery storages being the most cost-efficient option. A 200-MW battery unit is introduced, and the two most recent Narva oil shale units (270 MW) are left as backup for the Estonian '2030 reference' scenario.

In Latvia, planned wind power investment levels in the '2030 reference' reduce the operational hours of

Table 6. Summary of self-sufficiency indicators by country including annual domestic generation, imports and exports, and domestic share in 2017 and the '2030 reference' scenario.

	Estonia		**Latvia**		**Lithuania**	
	2017	**2030 reference**	**2017**	**2030 reference**	**2017**	**2030 reference**
Domestic generation (TWh)	10.54	5.47	7.43	8.88	3.19	9.20
Total imports (TWh)	3.35	5.65	3.74	2.33	11.37	7.60
Total exports (TWh)	5.31	2.10	4.14	3.44	2.54	3.11
Domestic share (%)	123 %	60 %	106 %	114 %	25 %	63 %

strategically important CHP units, namely Riga's large natural gas CHPs, to less than 1,000 h/a. The model substitutes CHP generation with wind power and heat boilers, challenging the unsubsidised commercial feasibility of CHP units, especially during warm weather years.

In the Lithuanian '2030 reference' scenario, up to 82% of domestic electricity, and 57% of electricity demand, would be generated by VRE. The transition to a highly variable system coincides with planned changes in interconnectors. While the model is able to support the high variability by the active use of pumped-hydro storage and interconnectors, the resulting high ramp rates in interconnectors may be an indication of issues.

4.3. Slow changes in transport and buildings

In the transport sector, transport volumes increase faster than alternative fuel sources. As a result, fossil fuel demand increases even though the share of electricity and bioliquids increase (Figure 5). The share of battery electric and hybrid electric vehicles reaches 3% of passenger kms by 2030, and the share of biofuels increases from 3.4% in 2017 to 6.5% in 2030. The Baltic countries have different target levels for bioliquids, ranging from 2% in Latvia to 10% in diesel in Lithuania by 2030. The modeled results include only passenger vehicles.

Buildings consume a very small direct share of fossil fuels in the Baltic countries, and the projected change in fuel mix towards 2030 is relatively small (Figure 6). Therefore, decarbonization of the residential and commercial sectors will happen mostly through decarbonization of the power and heat sector. Modeling of energy efficiency measures and building level heat pumps reduce fossil fuel use in buildings only slightly (from 12.6 to 11.2%).

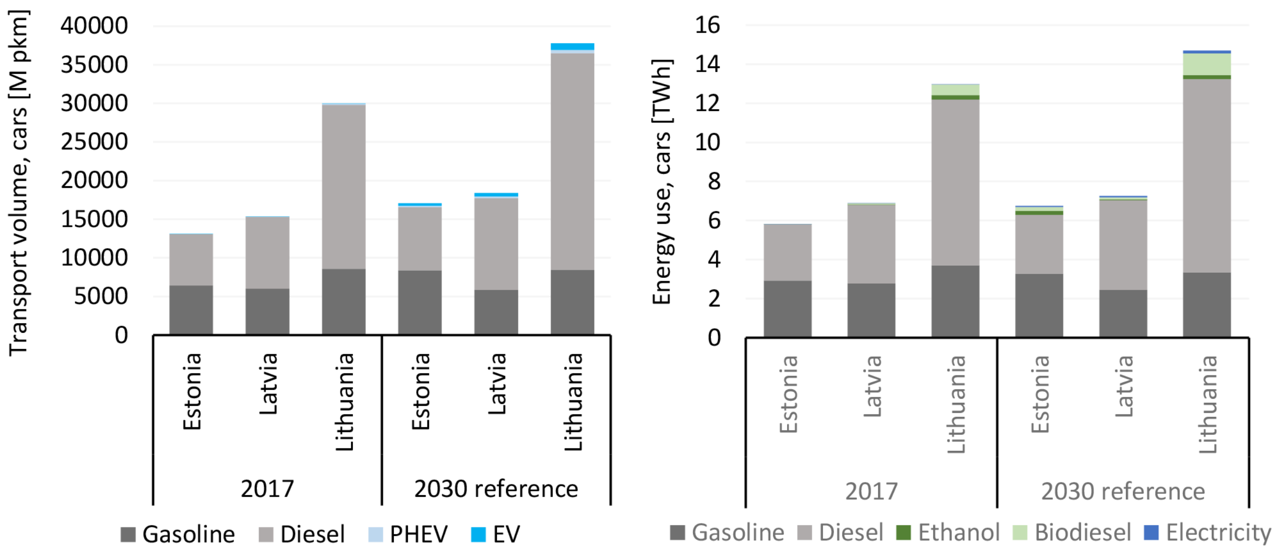


Figure 5. Annual transport volume and energy use of cars by country in 2017 and the '2030 reference' scenario.

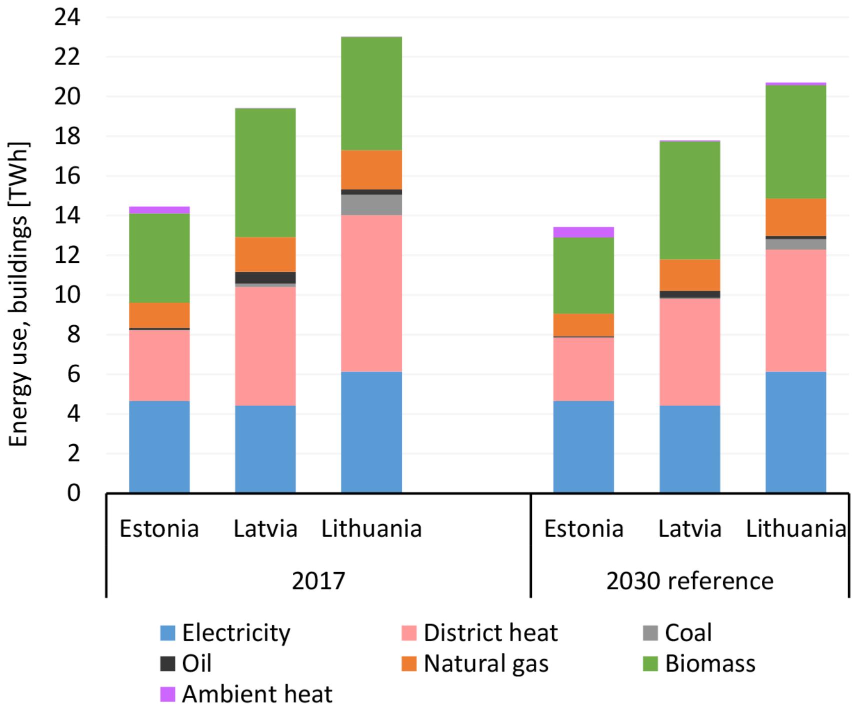


Figure 6. Annual energy use in buildings by country in 2017 and '2030 reference' scenario.

4.4. Increase in renewable shares and reduction in emissions

As shown in Table 7, the share of power generation by renewables and waste exceeds 90% in all three countries in the '2030 reference'. The renewable shares in district heat generation remain lower, but vary significantly by region.

CO_2 emission reductions are substantial in power and heat generation, and the total modeled Baltic CO_2 emissions halve from 21.0 $MtCO_2$ in 2017 to 10.1 $MtCO_2$ in the '2030 reference' (Figure 7). The majority of the remaining emissions are due to oil use in the transport sector. Due to an increase in volumes, transport emissions increase slightly, from 6.5 to 6.9 $MtCO_2$.

4.5. Moderate increase in power and heat sector costs

The total modeled annual cost in the power and heat sector increase between 2017 and the '2030 reference' in all three countries (from 501 to 602 M€/a in Estonia, 275 to 407 M€/a in Latvia, and 529 M€/a to 814 in Lithuania) as shown in Figure 8. This is mainly due to investment costs in new generation capacity and changes in import costs and export profits.

Table 7. Annual share of renewable electricity and district heat generation by country in 2017 and the '2030 reference' scenario.

	Estonia		**Latvia**		**Lithuania**	
	2017	**2030 reference**	**2017**	**2030 reference**	**2017**	**2030 reference**
ELECTRICITY						
'Renewable and waste' share of domestic generation (%)	16%	92%	74%	94%	69%	91%
VRE share of domestic generation (%)	7%	77%	2%	33%	44%	82%
DISTRICT HEAT						
'Renewable, heat pump and waste' share, capital regions (%)	48%	52%	25%	32%	18%	82%
'Renewable, heat pump and waste' share, non-capital regions (%)	44%	75%	96%	99%	66%	65%

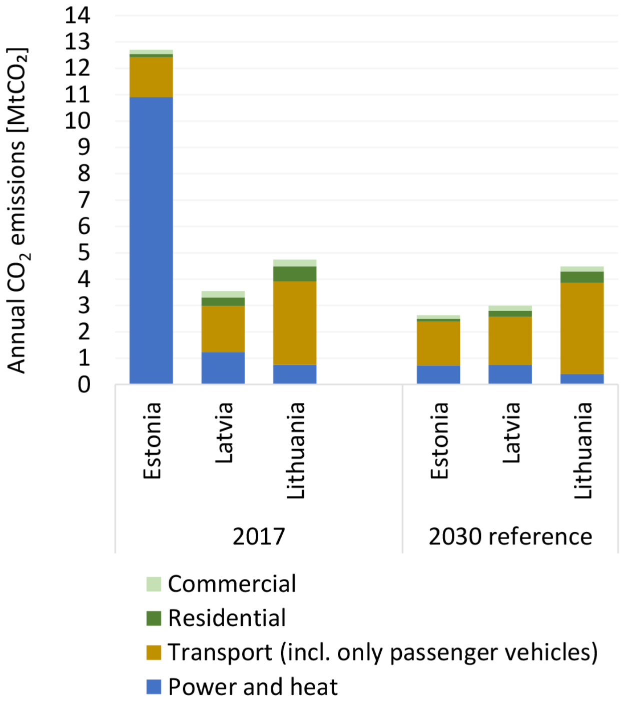


Figure 7. Modeled annual CO2 emissions by direct primary energy use in sectors by country in 2017 and the ‘2030 reference’ scenario. Non-CO2 emissions are not included in the modeling.

In Estonia, power generation operational costs lower due to a change in source; and in Lithuania, operational costs increase due to increased domestic generation. Between 2017 and the ‘2030 reference’, the average marginal price of electricity increases from 35 to 41 €/MWh, and the marginal price of district heat from 18 to 26 €/MWh. Despite the overall cost increase, sensitivity scenarios show that fewer investments in wind power would lead to even higher total annual Baltic power and heat sector costs.

For the transport sector, the model predicts an operational cost rise of roughly 10%, mainly due to an increase in fuel prices. For the building sector, an operational cost decline of roughly 10% is estimated due to energy efficiency measures and electrification. Investment costs in transport and buildings are not accounted for.

4.6. Deployment of onshore and offshore wind power cost-effectively reduces emissions

A sensitivity analysis of the ‘2030 reference’ with different wind capacities (Figure 9) displays the correlation of the annual power generation mix with different wind power capacities. The wind power capacities range from

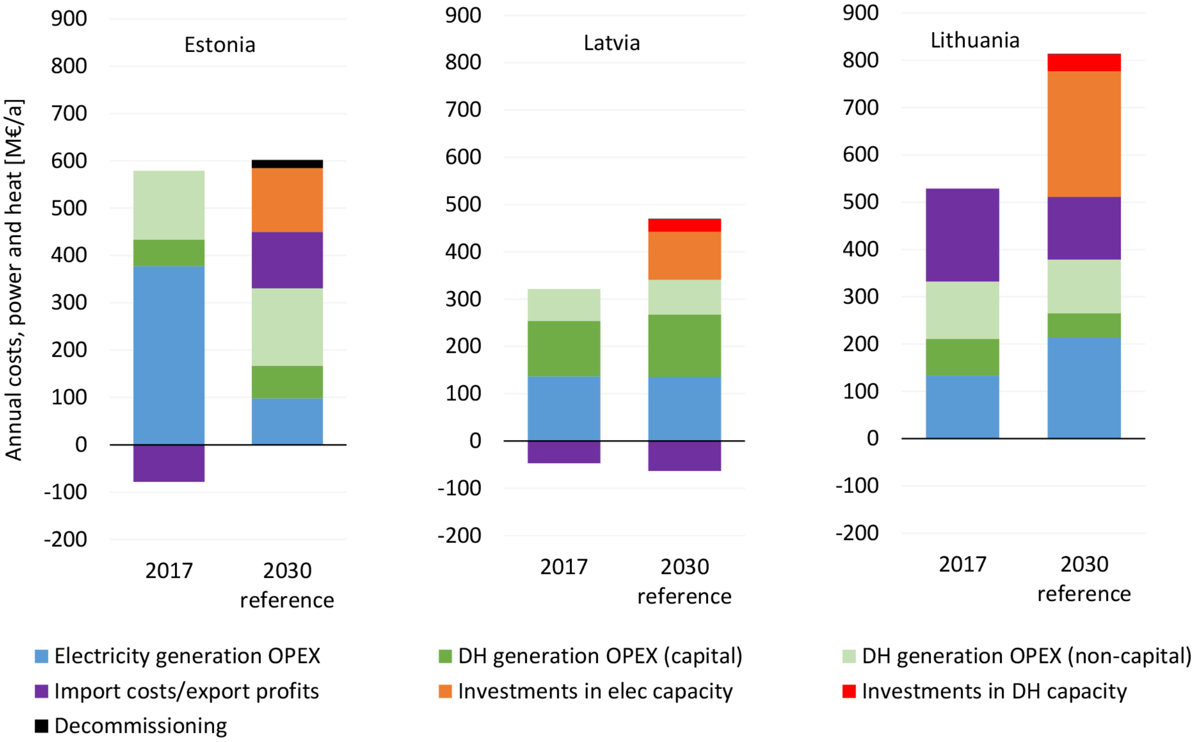


Figure 8. Annual modeled system costs for power and heat by country in 2017 and the ‘2030 reference’ scenario.

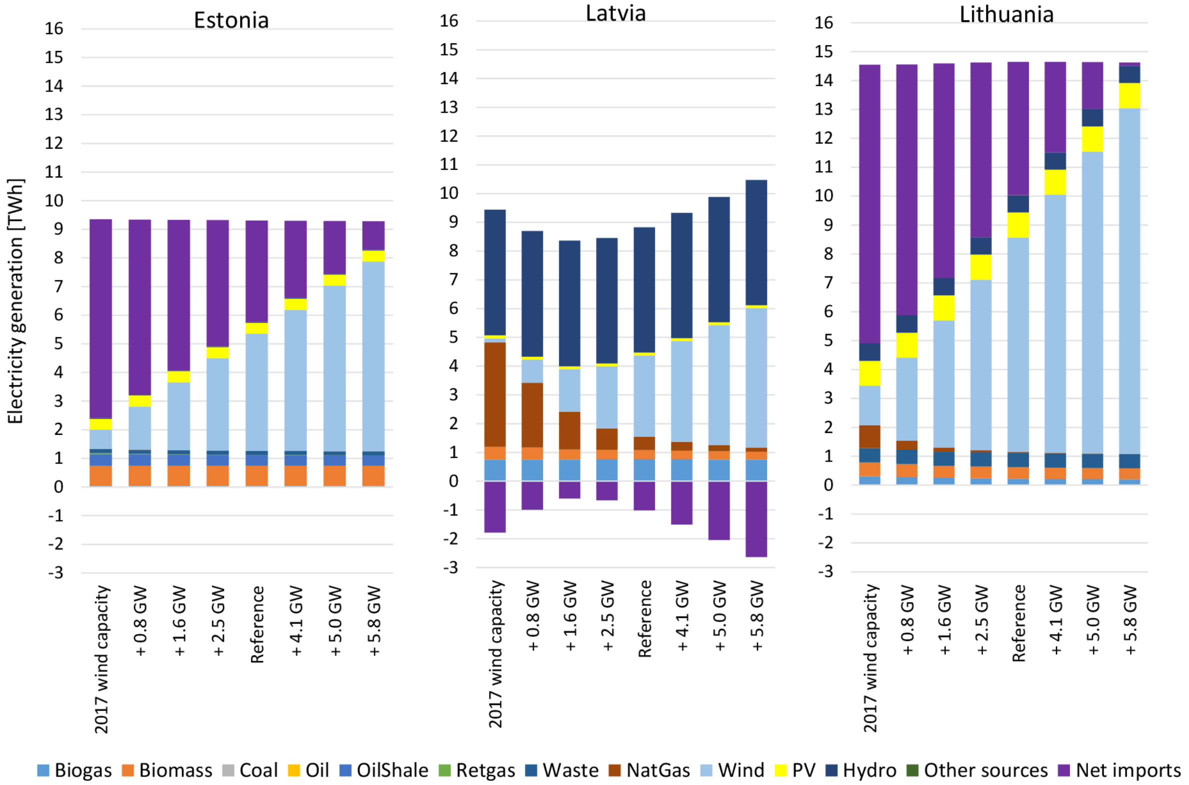


Figure 9. Annual electricity supply in 2030 with different wind power capacities by country. Reference assumes +3.3 GW compared to 2017 capacity.

only 2017 capacity to nearly double the capacity of the '2030 reference'.

In Estonia and Lithuania, additional wind capacity decreases annual electricity imports nearly linearly. In Latvia, additional wind power capacity replaces natural gas generation between the '2017 capacity' and the '2030 reference'. Beyond reference, wind deployment increases electricity exports.

With the given assumptions, the Baltic cost minimum is found at the level of reference scenario (-75 M€/a from the '2017 capacity' to the '2030 reference'). Between the lowest wind sensitivity scenario and the reference, the addition of wind power increases the Baltic renewable generation share from 66 to 92%, domestic generation share from 50 to 74%, and reduces emissions by 1.2 $MtCO_2$. Beyond the reference scenario, additional wind power deployment primarily benefits domestic generation share.

5. Discussion

In general, the results of the Baltic Backbone modeling are well-aligned with Baltic modeling studies in literature [20, 24, 29]. Modeled national policy targets lead to a slightly faster fossil generation phase-out and higher VRE share than in comparative studies. However, neither this nor the increased operational accuracy of the modeling reveal any serious operational challenges or discrepancies with previous studies. Overall, the results support the planned Baltic green transition and syncronization plans toward 2030. The widely recognized opportunities in the planned transition — namely emission reductions and increased self-sufficiency — are replicated in our modeling.

The reliability of the Baltic Backbone model is supported by the good results in validating the 2017 model against statistics. The modeled annual generation outputs in power and heat are very similar to historical data. The largest differencies concern the cross-border electricity flows. The simplified electricity trade and operating reserve modeling in neighboring countries are unable to represent all actual operations, and improved accuracy in flows would require expansion of the regional scope to neighboring regions.

One of the most important energy security findings is the shortage of Estonian balancing capacity in 2030 unless new flexible capacity is introduced. The finding builds on the study by Lehtveer et al. [15] in 2016, where concerns were raised about the need for additional capacity beoynd oil shale. While the planned wind power answers the concern of annual generation, a new concern for the capacity adequacy and the amount of flexible capacity is raised. The addition of 200 MW battery capacity corrected the situation in the '2030 reference' in our modeling, but the real amount of necessary flexible capacity addition should be further investigated with the inclusion of extreme conditions in both variable generation availability and demand. Additionally, the war in Ukraine has raised new energy security considerations; and, for example, the energy security impacts of low natural gas availability to the system operation should be evaluated.

In addition to energy security, the model allows for the investigation of the roles of specific technologies in the green transition setting. For example, cost-efficiency of wind power is clearly demonstrated in comparison of the 2030 situation with and without planned wind capacity. Many electrification techonologies, like heat pumps, perform better when combined with the conditions of the '2030 reference' than that of 2017. Some sector coupling opportunities are already indicated, like deployment of additional electrification technologies supporting the value of electricity and feasibility of important thermal units. However, most sector coupling opportunities are not yet visible in the 2030 setting, and many of the results presented relate to power system changes alone. The role of other energy sectors will grow as the timescale is extended closer to carbon neutrality.

6. Conclusions

The ambitious green transition plans and simultanous desyncronization project from the Russian electricity grid impact the Baltic countries' energy system operation profoundly. The most pronounced impact is the shift from mostly dispatchable and centralized power generation towards highly intermittent generation dominated by wind power already in the 2020s. This transition increases the demand for flexible capacity. The strong interconnectors to the Nordic and Continental European countries, as well as existing reservoir hydro power in Latvia and pumped-hydro storage in Lithuania are important resources in the planned VRE integration. However, additional flexibility needs to be provided by storages, interconnectors, generation units, and sector coupling. This issue is especially important for Estonia, which does not have existing large scale electricity storage. A moderate increase in power and heat sector costs is expected due to fuel and emission price increases and investments in new capacity.

The opportunities of the green transition include power and heat CO_2 emission reductions and an increase in the renewable generation share. With the addition of domestic generation capacity, the annual self-sufficiency improves and reliance on net imports deminishes. However, the overall impacts on energy security require further study. The supply of low-cost electricity provides opportunities for the expansion of end-use electrification that is capable of utilizing the intermittent inexpensive hours. The key challenges arrise from providing enough flexibility, maintaining the feasibility of strategically important thermal units, and in providing enough policy support to also reduce the non-ETS emissions.

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