Transitioning to a climate-neutral electricity generation

Deliverable 3 Report: Preliminary results on the development of pathways for reaching climate-neutral electricity generation

Contract details
European Commission – DG Reform
Transitioning to a climate-neutral electricity generation
REFORM/SC2020/068

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Date
November 5, 2021

Acknowledgement
This study was carried out with funding by the European Union via the Structural Reform Support Programme and in cooperation with the Directorate General for Structural Reform Support of the European Commission.

Disclaimer

Rotterdam, November 5, 2021

Client: European Commission – DG Reform.
REFORM/SC2020/068

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1 Introduction

This report presents the methodology and results of modelling conducted for Deliverable 3 of the *Transitioning to a climate-neutral electricity generation* project. **The objectives of Deliverable 3 were to define and analyse potential routes to decarbonised electricity production in Estonia by 2050**. The modelling accounted for relevant market, policy, and physical dynamics in Estonia and considered nine future scenarios: a Business-as-usual (BAU) scenario, a Reference scenario, four technology-focused decarbonisation pathways (each exploring the impacts of investing in a particular low-carbon power technology in Estonia), and three decarbonisation pathways that allow for competition between technologies, given set constraints.[1]

Chapter 2 of the report begins with an overview of the modelling methodology and data inputs used, before providing details on the simulation approach and characteristics of the modelled scenarios. Chapter 3 presents a detailed analysis of the scenarios without a climate neutrality requirement: the BAU and Reference scenarios. Both are projections based on the climate and energy policy framework that existed in 2020, assuming no significant increase in climate change mitigation ambition. In summary, the BAU scenario follows the main lines of the European Union's Reference Scenario 2020 (RS2020)[2], adopting electricity demand, electricity generation and storage capacity, and carbon price projections from that study. The Reference scenario introduces two changes to the BAU to create a more suitable baseline for the decarbonisation modelling: it omits the RS2020 capacity projection and includes electricity demands related to an economically feasible level of power-to-X deployment in Estonia. All of the decarbonisation pathways build on the Reference scenario by adding a requirement for 2050 climate neutrality and assumptions about power-sector investments.

Chapter 4 of the report examines the technology-focused pathways with a climate neutrality requirement: a "Renewables + storage" scenario that assumes 4 GW of offshore wind is installed in Estonia by 2050, a "Nuclear + renewables + storage" scenario that assumes 900 MW of small modular nuclear capacity is built in the country by 2040, a "CCU + renewables + storage" scenario that assumes carbon capture facilities are incorporated into two of

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[1] This report uses the term "pathway" to refer to future scenarios in which Estonia attains climate-neutral electricity production by 2050. As explained in section 2, climate neutral electricity production is defined as production that generates no net emissions of non-biogenic carbon dioxide (CO_2).

[2] Specifically, a draft version of RS2020 that was shared with the project team during the Deliverable 3 modelling.

Estonia’s largest oil shale plants, and a “Renewable gas + renewables + storage” scenario that assumes 1 GW of new biogas generation is implemented in Estonia by 2030. The implications of these assumptions with respect to Estonian electricity production, imports, and prices are discussed in detail.

Chapter 5 of the report examines technology competition pathways with a climate neutrality requirement. Each of these scenarios optimises capacity build-up based on cost. An “All technologies” pathway does not assume any other major restrictions, but an “All technologies + no net electricity imports” pathway requires Estonia to be self-sufficient in electricity, and an “All technologies + 1000 MW” pathway requires that 1000 MW of readily dispatchable capacity be installed in Estonia at all times. These additional scenarios are analysed to explore how high-level regulatory decisions might impact electricity generation levels in an otherwise competitive electricity market.

Core results from all pathways are contrasted and analysed in Chapter 6. Expected capacity build-up, generation, import/export flows, and average electricity prices for 2050 are compared across all scenarios.

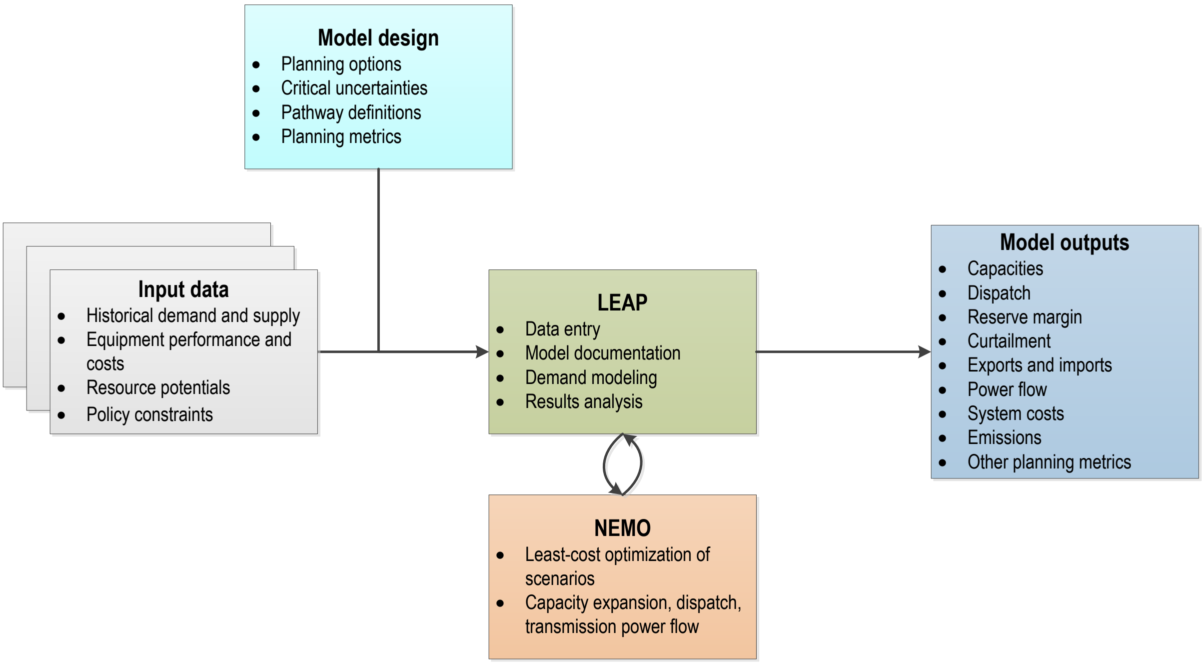
The overall philosophy of the Deliverable 3 modelling was to emphasise inputs and information sourced from Estonia, transparency, and systematic treatment of future uncertainties. The analyses presented in this report are intended to inform policy and planning choices through credible simulations of the long-range future of Estonia’s power system. The modelling seeks to illuminate trade-offs among the decarbonisation pathways, the viability of different options for electricity production, and the implications of planning choices. Results from the Deliverable 3 modelling will feed into the socioeconomic analysis, risk analysis, and policy action plan development planned for upcoming stages of the *Transitioning to a climate-neutral electricity generation* project.

2 Modelling methodology and data inputs

2.1 Modelling software

The Deliverable 3 model was built using the Low Emissions Analysis Platform (LEAP) and the Next Energy Modelling system for Optimisation (NEMO). These modelling tools integrate to provide a flexible, functional, and user-friendly system for electricity sector simulation. LEAP serves as the primary user interface to the model, allowing for model construction and results visualization through its graphical interface. It also carries out the calculations for the electricity demand simulation and provides demand projections to NEMO. The supply side of the electricity system is simulated in NEMO using mixed-integer linear optimisation. NEMO optimises the dispatch and expansion of electricity generation, storage, and transmission capacity, as well as the utilization of selected demand-side measures. The optimisation is conducted within a system of constraints that ensure the reasonableness of the projection (e.g. power flow, reserve margin targets, resource potentials). The figure below presents a schematic of the integrated modelling and shows the respective roles of LEAP and NEMO.

Figure 2-1: Schematic of LEAP-NEMO model



The Deliverable 3 model is being submitted to the Estonian government with this report (Annex A – Deliverable 3 model). It is packaged as a data set that can be opened in LEAP and calculated with LEAP and NEMO. Installation software for LEAP and NEMO is available on the LEAP website at https://leap.sei.org/download/ and is also linked in Annex A – Deliverable 3 model.

2.2 Model scope and structure

The Deliverable 3 model simulates the operation and evolution of the Estonian electricity system and the regional electricity market in which Estonia is embedded. It covers the period from 2015 to 2050, with each year divided into 192 sub-annual time slices. The time slices represent with hourly resolution a typical weekday and a typical weekend day in each of four seasons (winter, spring, summer, and fall). Years from 2015 to 2020 are a historical period in the model; results for this interval are calibrated to known historical data. Projections begin in 2021 and run through 2050.

Geographically, the model distinguishes 21 regions:

- The five NUTS 3 regions of Estonia: Kesk-Eesti, Kirde-Eesti, Lääne-Eesti, Lõuna-Eesti, and Põhja-Eesti (Figure 2-2)
- Nord Pool bidding areas for Denmark, Finland, Germany, Latvia, Lithuania, Norway, and Sweden (Figure 2-3)
- Poland

The geographic disaggregation is greater in Estonia than in other modelled countries to support the calculation of economic impacts by NUTS 3 region under Deliverable 4 of the *Transitioning to a climate-neutral electricity generation* project.

Figure 2-2: NUTS 3 regions in Estonia[3]

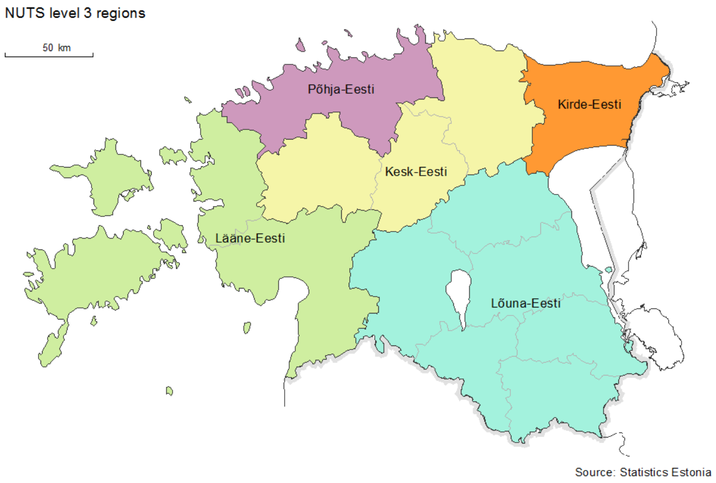


Figure 2-3 Nord Pool bidding areas in modelled countries[4]

The modelling of final electricity demand is broken down by major sector or source within Estonia, including the residential sector, agriculture, mining and manufacturing, construction, other industry, retail and services, and transport. In other regions, total final electricity demand is projected without sectoral detail. Intermediate demands for electricity producers' own-use are represented in all regions, as are losses in the electricity transmission and distribution grids (discussed further below). In Estonia, electricity demand for hydrogen production is also modelled as part of an analysis of economically feasible power-to-X (see section 2.4.2).

On the supply side, the model individually represents significant electricity generation and storage plants and units within Estonia, such as the Auvere oil shale plant and the proposed pumped hydro facility at Paldiski (Annex D – Power plants and technologies included in Deliverable 3 modelling of Estonia). Other electricity generation and storage capacity, both in Estonia and other regions, is aggregated by technology. High-voltage transmission connections among the modelled regions and between third countries (i.e., countries outside the study area) and modelled regions are simulated as well. Transmission capacity is aggregated by pair of trading partners (modelled regions and third countries) rather than representing each transmission line separately.

Electricity demand-side management (DSM) options in Estonia are modelled following information in Elering et al. (2015). Consistent with this source, the DSM options include load

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[3] https://vana.stat.ee/296050.

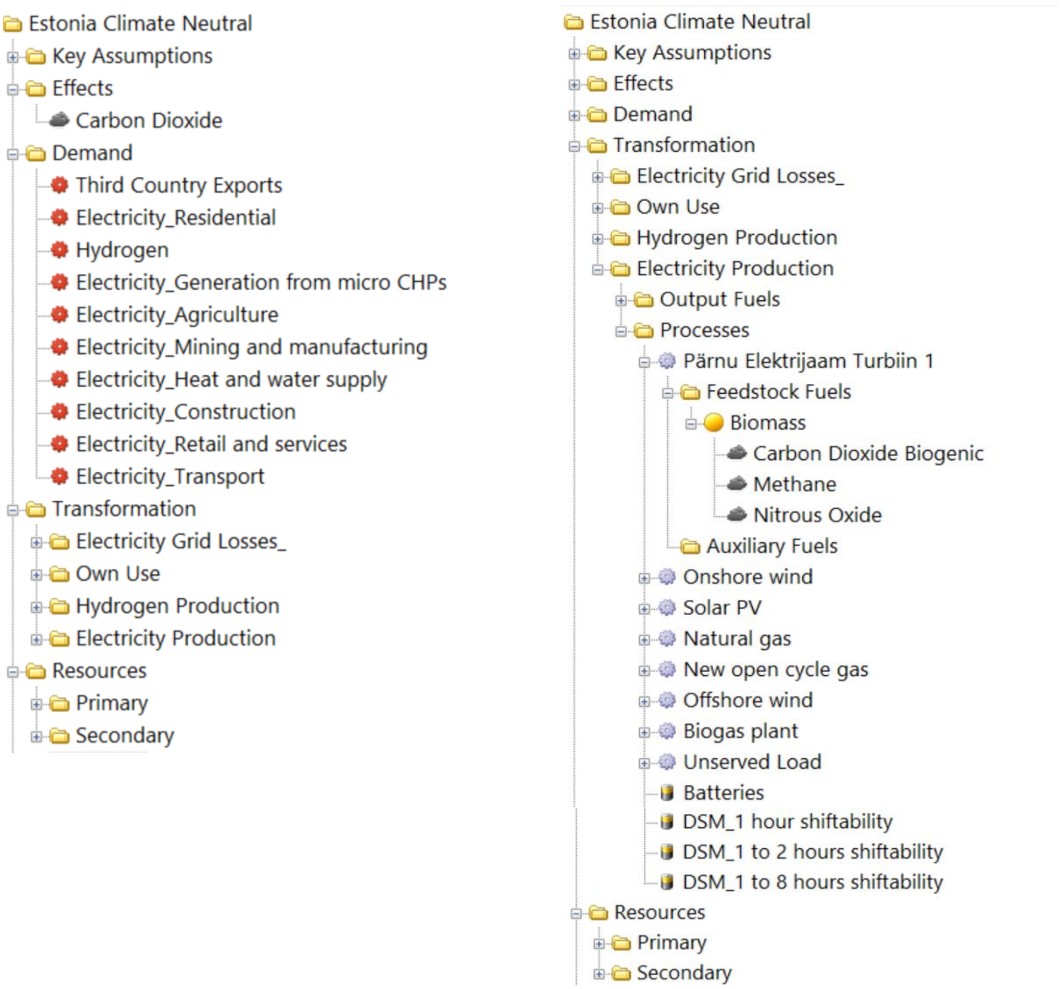
[4] https://www.nordpoolgroup.com/the-power-market/Bidding-areas/.

shifting in three categories: 0-1 hours of load, 1-2 hours of load, and 1-8 hours of load in the industrial, commercial, and residential sectors.

As the main objective of the Deliverable 3 modelling is to analyse pathways to climate-neutral electricity production, the model calculates greenhouse gas (GHG) emissions from electricity generation in all of its regions. Emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) are considered.

Although each modelled region has a unique structure, Figure 2-4 provides an example of the model's internal structure for Lääne-Eesti. The level of disaggregation of the final and intermediate electricity demands for Estonian regions can be observed in the left. The figure at the right shows the structure of the electricity generation sector, which includes storage technologies, DSM options, and individual and aggregated power plants with their associated GHG emissions.

Figure 2-4: Sample model structure for Lääne-Eesti region with focus on demand (left) and electricity production (right)



2.3 Data

The Deliverable 3 model uses a wide variety of data inputs, including historical and projected data on the technical performance and costs of components of the electricity system, market conditions, policy targets, technological improvements, and other factors. Most of the required inputs were collected under Deliverable 2 of the *Transitioning to a climate-neutral electricity generation* project and are documented in the Deliverable 2 report.[5] However, the Deliverable 3 team did need to supplement the Deliverable 2 data collection in some cases. Table 2-1: gives an overview of these cases and the supplemental data sources the team employed.

Table 2-1: Supplemental data sources used for gap-filling in Deliverable 3 model

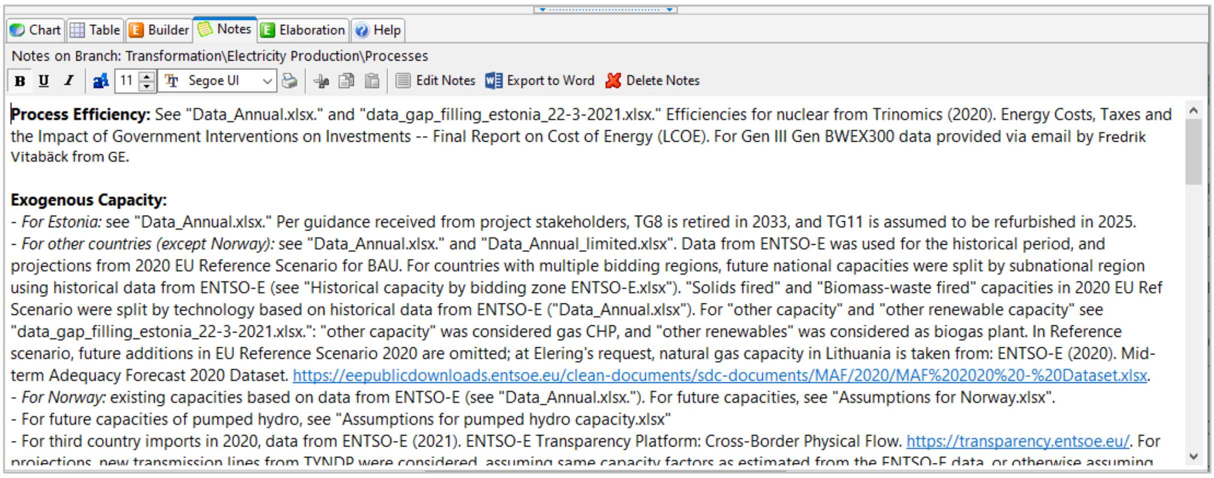
Topic	Data sources
Biogas supply in Estonia	(Eesti Arengufond 2015)
DSM options	(Elering et al. 2015)
Direct air capture of CO_2 performance and cost parameters	(Fasihi et al. 2019)
Emission factors	(European Investment Bank 2020; Republic of Estonia Ministry of the Environment 2020)
Full load hours for pumped hydro storage	(ENTSO-E 2020c)
Historical and projected electricity demand in Estonia, disaggregated by NUTS 3 region and sector	TalTech estimates based on data from Elektrilevi and Statistics Estonia
Historical installed generation and storage capacity by Nord Pool region	(ENTSO-E 2021c; ENTSO-E 2021d; ENTSO-E 2020b)
Historical power generation by Nord Pool region	(ENTSO-E 2021a)
Historical power generation in Estonia	(Elering 2020; Elering 2021)
Hydrogen demand and production in Estonia	(Civitta Eesti AS et al. 2021)
Interest rates for generation and storage investments	(Trinomics 2021)
Load curves	(ENTSO-E 2019a)
Potential electrification of space heating and transport in Estonia	(Knobloch et al. 2020)
Projected electricity demand and generation and storage capacity in Norway	(Statnett 2020; ENTSO-E 2020c)
Reserve margins in Baltic states	(Elering AS et al. 2020)
Selected technical and cost parameters for power production technologies	(Trinomics 2020; DIW 2019; DIW 2020; IRENA 2020a; IRENA 2020b; EASE 2020; Climate Technology Centre & Network 2020; MIT 2020; Energies 2020; Global Energy Monitor 2020; METEC 2015; Vitabäck 2021)
Solar, wind, and hydropower availability profiles	(ENTSO-E 2020c)
Third country electricity imports and exports	(ENTSO-E 2020a; ENTSO-E 2021b)
Transmission expansion costs	(Agency for the Cooperation of Energy Regulators 2015)
Transmission losses	(Council of European Energy Regulators 2020; ENTSO-E 2019b)

[5] Data collected under Deliverable 2 include draft outputs from modelling for RS2020. At the time of the Deliverable 3 modelling, these data were not publicly available.

Topic	Data sources
Wind potential	(Government of Estonia 2019; Enevoldsen et al. 2019; Wind Europe 2019)

Additional details on how the Deliverable 2 and supplemental data inputs were incorporated in the model are provided in the model itself (Annex A – Deliverable 3 model). Inline documentation in the model, entered using LEAP's Notes feature (Figure 2-5), describes the inputs used for each model variable.

Figure 2-5: Inline documentation in LEAP notes



2.4 Modelling methods

2.4.1 Overall simulation approach

The principal simulation method in the Deliverable 3 modelling is cost optimisation. Given a projection of electricity demands, and subject to physical limits and other constraints imposed in scenarios, the model finds a supply solution that minimizes discounted, system-wide electricity production costs. The cost discounting is to 2021 at a 5% real discount rate, and the optimisation is conducted with perfect foresight. In determining a supply solution, the model chooses both capacity dispatch and expansion for electricity generation, storage, transmission, and DSM. It is important to underscore that the simulation is premised on total system-wide costs – not costs in Estonia alone – so results may not always provide the best value from an Estonian perspective. However, basing the modelling on system-wide costs better approximates the operation of the regional electricity system.

2.4.2 Key methods

This section highlights major methodological choices made to localize the Deliverable 3 optimisation model to the study area and capture critical dynamics of the area's electricity system. Additional information about specific methods used in the model is available in Annex A – Deliverable 3 model and the LEAP and NEMO documentation.[6]

Biomass exemption from climate neutrality requirements

As detailed in section 2.5, the model investigates several scenarios of climate-neutral electricity production in Estonia. All of these scenarios assume that GHG emissions from biomass combustion are exempted from climate neutrality requirements.

Biomass supply in Estonia

Consistent with discussions with the Ministry of Economic Affairs and Communications (the Ministry) and other stakeholders, the model does not enforce any limits on the supply of biomass for electricity generation in Estonia. There are, however, restrictions on how much new biomass generation capacity may be added in the country (Table 2-2).

Candidates for endogenous capacity expansion

As explained further below, each scenario in the model contains a projection of exogenously specified electricity generation, storage, and transmission capacity – capacity that is assumed to exist in particular years. These projections include assumptions about anticipated retirements of the exogenously specified capacity. In all scenarios, the model is permitted to complement the exogenous capacity projection with endogenously built capacity if it allows energy, power, and reliability requirements to be met in a more cost-effective way. Candidates for such endogenous capacity expansion are outlined in Table 2-2.

Table 2-2: Candidates for endogenous capacity expansion[7]

Within Estonia	Outside Estonia
• Batteries – all regions • Biogas – all regions • Carbon capture and utilization (CCU) upgrade of Balti Elektrijaam Turbine Generator (TG) 11 and Auvere Elektrijaam – Kirde-Eesti in certain scenarios (see below) • Combined cycle natural gas – all regions • DSM – all regions, up to 61 MW (0-1 hours of load)/149 MW (1-2 hours of load)/52 MW (1-8 hours of load) by 2030	• Batteries – all regions • Biogas – all regions • Combined cycle natural gas – all regions with natural gas capacity in RS2020 • Generation IV nuclear – all regions with new nuclear capacity in RS2020 • Onshore and offshore wind – all regions with onshore/offshore wind

[6] LEAP's documentation is available at https://leap.sei.org/help/leap.html, and NEMO's documentation is at https://sei-international.github.io/NemoMod.jl/.

[7] Unless otherwise noted, an unlimited amount of candidate technologies may be added.

Within Estonia	Outside Estonia
• Generation III+ nuclear (small modular reactor based on GE-Hitachi's BWRX-300 technology) – Kesk-Eesti and Kirde-Eesti, after 2035 in increments of 300 MW • Generation IV nuclear – Kesk-Eesti and Kirde-Eesti, after 2040 in increments of 300 MW • New biomass combined heat and power (CHP) plant – Kirde-Eesti, 22 MW after 2030 • Onshore and offshore wind – all regions with existing capacity or projected capacity in RS2020, limits from supplemental sources (Government of Estonia 2019) • Open cycle natural gas – all regions • Paldiski pumped hydro – Põhja-Eesti, up to 522 MW in increments of 174 MW, starting in 2028 • Solar photovoltaic (PV) – all regions, unlimited potential • Transmission – new connections to Lääne-Eesti: up to 3000 MW to Kesk-Eesti, up to 3000 MW to Latvia, up to 3000 MW to Lõuna-Eesti, up to 3000 MW to Põhja-Eesti	capacity in RS2020, limits from supplemental sources (Government of Estonia 2019; Enevoldsen et al. 2019; Wind Europe 2019) • Solar PV – all regions with solar PV capacity in RS2020, unlimited potential

Carbon border adjustment mechanism (CBAM)

The Deliverable 3 modelling does not consider the implementation of a CBAM as its potential structure, feasibility, and implementation schedule were unclear at the time the model was developed. Possible impacts of a CBAM may be evaluated under Deliverable 5 of the *Transitioning to a climate-neutral electricity generation* project.

Carbon capture limit in Estonia

As indicated in Table 2-2, in certain scenarios the model allows carbon capture in Estonia through CCU retrofits of the TG11 and Auvere oil shale plants. In addition, in scenarios that target climate-neutral electricity production, direct air capture of CO_2 can be deployed (although it is quite expensive, as discussed below). Total captured CO_2 in Estonia (from all sources) is limited to about 700 kt/year, an estimated potential for CO_2 utilization in Estonian industry based on the Deliverable 2 data collection.[8]

Conversion of GHG emissions to CO_2-equivalent

The model can report GHG emissions both in terms of physical quantities of particular GHGs (CO_2, CH_4, and N_2O) and as CO_2-equivalent. Conversions to CO_2-equivalent are carried out using global warming potentials from the Intergovernmental Panel on Climate Change's

[8] The Deliverable 2 data collection provided an estimate of CO_2 utilization potential in Kirde-Eesti in the short term. It was scaled up for the Deliverable 3 modelling to account for other parts of Estonia and longer-term growth.

Second Assessment Report (Houghton and Intergovernmental Panel on Climate Change 1996).

Electricity prices

Wholesale electricity prices are estimated in the model using a levelized cost of electricity (LCOE) approach. Specifically, the estimated price in each region, year, and time slice is calculated as the highest LCOE among resources providing power in the region, year, and time slice, including imports if applicable. Average annual prices are calculated by weighting time-sliced prices by time slice width (i.e., the fraction of the year covered by each time slice). To determine average prices in Estonia, prices for the NUTS 3 regions are weighted by the regions' shares of national electricity production requirements.[9]

Exogenous solar PV projection in Estonia

The model reproduces an exogenous projection of solar PV adoption in Estonia that was developed by TalTech for Deliverable 2. This projection accounts for solar projects that are underway as well as implementation of recent legislation on near zero energy buildings, which is anticipated to require significant additions of rooftop solar. Altogether, exogenously specified solar PV capacity rises from 230 MW in 2020 to nearly 725 MW in 2050.[10] These assumptions apply in all modelled scenarios.

Load curves for electricity demands

The model calculates intra-annual variability in electricity production requirements using region-specific load curves from 2010 (ENTSO-E 2019a). Stakeholders recommended this year as it included a particularly cold heating season. In projections, the future load curve in each region retains the shape from 2010, and its height depends on projected electricity demands.

Oil shale phase-out in Estonia

Following guidance from the Ministry, the model reflects the following prognosis on oil shale generation from Eesti Energia:

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[9] Note that prices in this report do not reflect electricity market prices, but rather represent projections based on LCOE-driven calculations. Marginal price-based results will be considered when comparing pathways in the socioeconomic impact assessment, and when developing policy action plans in upcoming phases of the project.

[10] These figures were verified in consultation with Elering in August, 2021. Data collection methodology sources are further detailed in the Deliverable 2 report for this study, submitted to the Ministry and the Stakeholder Group in March 2021.

- By 2025, all major oil shale generation units except for TG8, TG11, and Auvere are retired, and TG11 is refurbished.
- TG8 retires in 2033.
- By the early 2030s, both TG11 and Auvere switch to using 100% biomass unless retrofitted with carbon capture (in which case, they continue running on a blend of oil shale, retort gas, and biomass as indicated by Eesti Energia).

Power-to-X in Estonia

The Deliverable 3 modelling evaluates several sources that could substantially increase electricity demand in Estonia, potentially absorbing surplus generation. These power-to-X options include electric vehicles, electrified space heating, and hydrogen production. In some scenarios (identified in section 2.5), an economically feasible level of power-to-X deployment is assumed, which adds to electricity production requirements. The economically feasible level of hydrogen production is based on Civitta Eesti AS et al. (2021), a study that conducted stakeholder consultations to identify the feasible uptake of hydrogen in Estonian transportation, buildings, industry, and power generation. Following this source, economically feasible hydrogen demand in Estonia attains about 160 kt per year by 2050. Hydrogen production is simulated in the model as production by polymer electrolyte membrane electrolysis, the most cost-effective method in Civitta Eesti AS et al. (2021). With this technology, producing 160 kt of hydrogen requires about 4.1 TWh of electricity.

For electric vehicles and heating, the economically feasible level of deployment in Estonia is taken from Knobloch et al. (2020). This analysis used economic modelling to simulate the diffusion of electric vehicles and space heating in multiple countries including Estonia. The Deliverable 3 model uses outputs from the study’s 2°C policy scenario, which shows electrification of 69% of residential space heating requirements and 67% of passenger vehicle kilometres travelled in Estonia by 2050 (resulting in an estimated 2.5 TWh and 0.8 TWh of electricity demand, respectively).

Renewable power auctions in Estonia

The model accounts for historical and planned renewable power auctions in Estonia as shown by Ministry of Economic Affairs and Communications (2021). This includes the set-aside for small generators in the 2021 auction (5 GWh should be procured from generators up to 1 MW in size).

Storage duration

Several types of energy storage are represented in the model: batteries, hydropower reservoirs, pumped hydro, and load shifting due to DSM (which is modelled as a kind of storage). Because the model simulates each year with pseudo-hourly resolution – looking at representative days divided into 24 hours per day – storage that operates at sub-hourly timescales (e.g., flywheels for frequency regulation) is not considered. The storage technologies that are modelled cover a variety of applications at hourly and longer timescales. They can be used to meet peak energy and power requirements, absorb surplus generation, and provide required reserves. In addition to ensuring that storage is charged before it discharges, the model imposes some limits on the extent to which different storage technologies can move energy from one part of a year to another. All of the modelled technologies can move energy freely from one hour or day to the next, but only hydropower reservoirs may shift energy from one season to another. None of the technologies are permitted to transfer energy from one year to another. Table 2-3 summarises these restrictions on storage duration.

Table 2-3: Restrictions on storage duration

<table>
<tr><th colspan="2" rowspan="2">Technology</th><th rowspan="2">Key uses</th><th colspan="4">Allowed to move energy from:</th></tr>
<tr><th>One hour to next</th><th>One day to next</th><th>One season to next</th><th>One year to next</th></tr>
<tr><td>Batteries</td><td>Grid-connected lithium ion batteries</td><td rowspan="4">Transferring energy from low demand to high demand periods, contributing to system reserves</td><td rowspan="4">Yes</td><td rowspan="4">Yes</td><td>No</td><td rowspan="4">No</td></tr>
<tr><td>DSM</td><td>Industrial, commercial, and residential load shifting</td><td>No</td></tr>
<tr><td>Hydro reservoirs</td><td>Hydropower reservoirs[11]</td><td>Yes</td></tr>
<tr><td>Pumped hydro</td><td>Pumped hydropower</td><td>No</td></tr>
</table>

[11] This technology is not present in Estonia but exists in other modelled regions.

Transmission and distribution

The transmission system within the study area is simulated as a nodal network in which each modelled region[12] is a separate node. Total high-voltage transmission capacity between any two nodes is aggregated and represented as a single notional line. Power flow is then allowed subject to capacity limits (i.e., a transhipment approach; Krishnan et al. 2016). The model includes average transmission line losses in the power flow calculations.

Transmission connections to third countries are treated in a different fashion as these areas are outside the model's border. Relevant third countries include all countries with which the modelled regions trade or are projected to trade electricity: Austria, Belarus, Belgium, Czechia, France, Luxembourg, Netherlands, Russia, Slovakia, Switzerland, Ukraine, and the United Kingdom. For existing interconnections to third countries, the level of future trade is based on trade observed in 2020[13]; for anticipated new interconnections (Table 2-4)Table 2-4, future trade is based on analogous existing lines, or on a 50-50 split of capacity between imports and exports if no analogous lines exist. Third-country exports from modelled regions are represented as additional demands in the modelled region, while third-country imports are represented as additional supply. Imports are restricted in both energy and power terms, with the power limits determined by the capacity of the associated transmission connection.

Table 2-4: New transmission connections to third countries

Year	Regions connected		Capacity (MW)
2021	DE	NL	300
2021	NO2	GB	1400
2023	DK1	GB	1400
2024	DE	AT	2000
2024	DE	GB	1400
2024	NO2	GB	1400
2025	DE	CZ	150
2025	DE	AT	100

[12] As stated in section 2.2, the 21 modelled regions include the 5 NUTS 3 regions in Estonia.

[13] Third country trade in the Baltics ends with the planned desynchronization from the Russian grid in 2025.

Year		Regions connected	Capacity (MW)
2025	DE	FR	300
2026	DE	LU	1000
2027	DE	AT	600
2028	DE	AT	1500
2028	DE	FR	1500

The model does not explicitly represent the electricity distribution system or transmission lines that do not cross regional boundaries. Average electricity losses in these components of the grid are calculated separately (based on RS2020) and added to electricity production requirements. Additionally, by default the model allows net electricity imports into all Estonian regions. As the model was constructed, stakeholders debated whether net imports should be permitted, and the consensus was ultimately that they should be unless a scenario rules them out.

Wind and solar availability factor improvements

As indicated in Table 2-1:, the model takes baseline availability factor data for wind and solar, including variability during the year, from ENTSO-E's Mid-term Adequacy Forecast 2020 Pan-European Climate Database (ENTSO-E 2020c). These data are region-specific and differentiate between onshore and offshore wind. To derive projected availability factors, the baseline data from ENSTO-E are adjusted using expected improvements in wind and solar availability developed under Deliverable 2. The improvements reflect advances in technology and operational practice, and are in many cases significant – for example, the average onshore wind factor in Estonia is projected to increase nearly 40% by 2050. Full details on projected availability by technology and region are shown in the Deliverable 3 model (Annex A – Deliverable 3 model).

2.5 Modelled scenarios

The project team used the Deliverable 3 model to explore nine future scenarios for Estonian electricity production. Broadly speaking, the modelled scenarios divide into two categories: those with and without a requirement of climate-neutral electricity production. The scenarios without a climate neutrality requirement include a Business-as-usual and a Reference scenario, both of which are based on the existing climate and energy policy framework, assuming no significant increase in climate change mitigation ambition. On the other hand, two categories of climate-neutral scenarios were considered: technology-focused decarbonisation pathways that explore the impacts of investing in a particular low-carbon power technology in Estonia, and technology-competition decarbonisation pathways that allow for competition between technologies, given set constraints. All the decarbonisation pathways build on the Reference scenario by adding a requirement for climate neutrality and assumptions about power-sector investments. Table 2-5 provides an overview of the scenarios' definitions, while sections 2.5.1 and 2.5.2 describe in more depth the main assumptions and key characteristics of each scenario.

Table 2-5: Overview of scenario definitions

	Scenario	Climate neutral[14]	ETS[15] Price	Final electricity demand		Exogenous generation and storage capacity		Endogenous generation and storage capacity	Electricity transmission	Other defining characteristics
				Estonia	Other regions	Estonia	Other regions			
Baseline	**Business as usual (BAU)**	No	RS2020	TalTech estimates based on data from Elektrilevi and Statistics Estonia	- Norway: Statnett (2020), ENTSO-E (2020c) - Other regions: RS2020	Accounts for current projects and plans but does not reflect full results of RS2020 capacity expansion modelling	- Norway: Statnett (2020), ENTSO-E (2020c) - Other regions: RS2020 (full results of capacity expansion modelling)	All options in Table 2-2 except CCU retrofits of Estonian oil shale plants	- Modelled area: Includes planned new lines per ENTSO-E; candidate lines to Lääne-Eesti allowed as an endogenous option - Third country: ENTSO-E (2020a; 2021b)	-
Baseline	**Reference (REF)**	No	(= BAU)	BAU demand + economically feasible levels of power-to-X[16]	(= BAU)	(= BAU)	Current capacity same as BAU but omits planned future capacity additions[17]	(= BAU)	(= BAU)	-
Technology-focused	**Renewables + storage (offshore wind)**	Yes	(= REF)	(= REF)	(= REF)	Reference assumptions + new investments in offshore wind – 1 GW by 2030, 2 GW by 2035, 3 GW by 2040, 4 GW by 2050	(= REF)	All storage, renewable, and DSM technologies in Table 2-2	(= REF)	-
Technology-focused	**Nuclear**	Yes	(= REF)	(= REF)	(= REF)	Reference assumptions + new investments in Generation III+ small modular nuclear – 900 MW by 2040	(= REF)	All storage, renewable, DSM, and nuclear technologies in Table 2-2	(= REF)	-

[14] No net non-biogenic CO_2 emissions from electricity production by 2050 (accounting for direct air capture of CO_2, which is allowed as an endogenous option).

[15] European Union Emissions Trading System.

[16] Includes demand for economically feasible hydrogen production.

[17] For context, exogenous generation and storage capacity outside Estonia is 80 GW lower in the Reference scenario than in the BAU in 2030, and 375 GW lower in 2050. Capacity in these regions in 2020 is about 460 GW.

	Scenario	Climate neutral[14]	ETS[15] Price	Final electricity demand		Exogenous generation and storage capacity		Endogenous generation and storage capacity	Electricity transmission	Other defining characteristics
				Estonia	Other regions	Estonia	Other regions			
	CCU	Yes	(= REF)	(= REF)	(= REF)	Reference assumptions + new investments in carbon capture – TG11 upgraded to CCU on refurbishment in 2025; Auvere upgraded to CCU in 2030	(= REF)	All storage, renewable, and DSM technologies in Table 2-2	(= REF)	-
	Renewable gas	Yes	(= REF)	(= REF)	(= REF)	Reference assumptions + new investments in non-CHP biogas generation – 1 GW by 2030	(= REF)	All storage, renewable, and DSM technologies in Table 2-2	(= REF)	-
Technology competition	**All technologies**	Yes	(= REF)	(= REF)	(= REF)	(= REF)	(= REF)	All low-carbon technologies in Table 2-2 – renewables, CCU, nuclear, storage, DSM	(= REF)	-
	1000 MW dispatchable capacity	Yes	(= REF)	(= REF)	(= REF)	(= REF)	(= REF)	All low-carbon technologies in Table 2-2 – renewables, CCU, nuclear, storage, DSM	(= REF)	Estonia must have at least 1000 MW of dispatchable capacity installed at all times (includes non-CHP fossil fuel, biomass, and biogas; nuclear; landfill gas; and Paldiski pumped hydro)
	No net imports	Yes	(= REF)	(= REF)	(= REF)	(= REF)	(= REF)	All low-carbon technologies in Table 2-2 – renewables, CCU, nuclear, storage, DSM	(= REF)	No net electricity imports into Estonia allowed

2.5.1 Scenarios without a climate neutrality requirement

These two scenarios investigate futures based on the climate and energy policy framework that was in place in 2020. They assume there is no increase in climate change mitigation ambition; in particular, no new climate neutrality requirements are implemented in the study area. The BAU scenario was the first scenario modelled for Deliverable 3. It assesses implications for Estonia if the electricity systems in surrounding regions develop as envisioned in RS2020.[18] Unless otherwise noted, the BAU and all other modelled scenarios use the methods and data described in sections 2.3 and 2.4. Complementing these, the BAU draws several other key assumptions from RS2020 as outlined below.

Defining characteristics of BAU scenario

- Final electricity demand
  - Estonia: TalTech estimates based on data from Elektrilevi and Statistics Estonia
  - Other regions (except Norway): RS2020
  - Norway: Statnett (2020), ENTSO-E (2020c)
- Electricity generation and storage capacity
  - Exogenously specified
    - Estonia: Deliverable 2 data collection (accounts for current projects and plans but does not reflect full results of RS2020 capacity expansion modelling)
    - Other regions (except Norway): RS2020 (full results of capacity expansion modelling)
    - Norway: Statnett (2020), ENTSO-E (2020c)
  - Endogenously built: all options in Table 2-2 except CCU retrofits of Estonian oil shale plants
- Electricity transmission
  - In modelled area: Deliverable 2 data collection (includes planned new lines per ENTSO-E); candidate lines to Lääne-Eesti (Table 2-2) allowed as an endogenous option
  - Third country: ENTSO-E (2020a; 2021b)
- DSM: allowed as an endogenous option in Estonia using assumptions in Elering et al. (2015)
- ETS price projection: RS2020[19]
- Climate neutral electricity production in Estonia: not required

On reviewing results from the BAU scenario, stakeholders observed that it tended to limit new generation investments in Estonia because of the assumption that the RS2020 capacity projection in other countries would be realized. The RS2020 projection includes significant capacity additions in Estonia's neighbours – for example, generation and storage capacity in Latvia and Lithuania increase more than 50% between 2020 and 2050 – that could be used in part to meet future Estonian electricity demands. To respond to this issue, the Deliverable

[18] As mentioned earlier, the Deliverable 3 modelling used draft outputs from RS2020, which were shared by the European Union Directorate-General for Energy (DG Energy). These outputs may differ from the final published outputs for RS2020.

[19] Projected prices in the near term are adjusted so they do not fall below the current (2021) ETS price.

3 team created a second scenario, the Reference scenario. This scenario implements the same assumptions as the BAU except that it omits the RS2020 (and Statnett) generation and storage capacity projection for other countries. In addition, to be a suitable baseline for the scenarios with a climate neutrality requirement, it assumes an economically feasible level of power-to-X deployment in Estonia. This assumption is prescribed by the project's terms of reference.

Defining characteristics of Reference scenario

- Final electricity demand
    - Estonia: BAU demand **plus demand for economically feasible hydrogen production** (+4 TWh by 2050 compared to BAU)[20]**, electric transport** (+0.7 TWh by 2050 compared to BAU)**, and electric residential space heating** (+1.3 TWh by 2050 compared to BAU) (see section 2.4.2)
    - Other regions (except Norway): same as BAU
    - Norway: same as BAU
- Electricity generation and storage capacity
    - Exogenously specified
        - Estonia: same as BAU
        - Other regions (except Norway): **current capacity from RS2020 (planned future capacity additions omitted)**
        - Norway: Statnett (2020), ENTSO-E (2020c) **(planned future capacity additions omitted)**
    - Endogenously built: same as BAU
- Electricity transmission
    - In modelled area: same as BAU
    - Third country: same as BAU
- DSM: same as BAU
- ETS price projection: same as BAU
- Climate neutral electricity production in Estonia: not required

2.5.2 Scenarios with a climate neutrality requirement

These scenarios analyse pathways to climate-neutral electricity production in Estonia by 2050. They include four technology-focused pathways and three pathways premised on technology competition. The technology-focused scenarios explore how particular technology investments could contribute to climate-neutral electricity production. Four technologies are highlighted: offshore wind, nuclear, CCU, and renewable gas. By contrast, the technology competition pathways achieve climate neutrality without presupposing new technology investments (beyond what is planned in the Reference scenario). Instead, all low-carbon technologies compete on cost to realize the decarbonisation goal.

[20] For the sake of simplicity, electricity demand for hydrogen production is classified under final demand in the tables in section 2.5 although it is an input to an energy production activity.

All of the pathway scenarios start with the assumptions in the Reference scenario and add to them the climate neutrality requirement. In addition, as a failsafe measure, the pathways allow direct air capture of CO_2 using cost and energy input assumptions in Fasihi et al. (2019). These assumptions imply that direct air capture is quite costly: its capital cost is 815 $€_{2020}/tCO_2$/year in 2020, decreasing to 222 $€_{2020}/tCO_2$/year in 2050; and it requires an average of 1.4 MWh electricity/tCO_2 captured.

Key assumptions in each climate-neutral scenario are summarised below.

Defining characteristics of Renewables + storage pathway (technology-focused)

- Final electricity demand
  - Estonia: same as Reference
  - Other regions (except Norway): same as Reference
  - Norway: same as Reference
- Electricity generation and storage capacity
  - Exogenously specified
    - Estonia: Reference assumptions **plus new investments in offshore wind – 1 GW by 2030, 2 GW by 2035, 3 GW by 2040, 4 GW by 2050**
    - Other regions (except Norway): same as Reference
    - Norway: same as Reference
  - Endogenously built
    - Estonia: all storage and renewable generation technologies in Table 2-2
    - Other regions: all options in Table 2-2
- Electricity transmission
  - In modelled area: same as Reference
  - Third country: same as Reference
- DSM: same as Reference
- ETS price projection: same as Reference
- Climate neutral electricity production in Estonia: **no net non-biogenic CO_2 emissions from electricity production by 2050 (accounting for direct air capture)**
- Direct air capture of CO_2: allowed as an endogenous option

Defining characteristics of Nuclear + renewables + storage pathway (technology-focused)

- Final electricity demand
  - Estonia: same as Reference
  - Other regions (except Norway): same as Reference
  - Norway: same as Reference
- Electricity generation and storage capacity
  - Exogenously specified
    - Estonia: Reference assumptions **plus new investments in Generation III+ small modular nuclear – 900 MW by 2040**
    - Other regions (except Norway): same as Reference
    - Norway: same as Reference
  - Endogenously built
    - Estonia: all storage, nuclear generation, and renewable generation technologies in Table 2-2
    - Other regions: all options in Table 2-2
- Electricity transmission
  - In modelled area: same as Reference
  - Third country: same as Reference

Defining characteristics of Nuclear + renewables + storage pathway (technology-focused)
• DSM: same as Reference • ETS price projection: same as Reference • Climate neutral electricity production in Estonia: **no net non-biogenic CO_2 emissions from electricity production by 2050 (accounting for direct air capture)** • Direct air capture of CO_2: allowed as an endogenous option

Defining characteristics of CCU + renewables + storage pathway (technology-focused)

- Final electricity demand
  - Estonia: same as Reference
  - Other regions (except Norway): same as Reference
  - Norway: same as Reference
- Electricity generation and storage capacity
  - Exogenously specified
    - Estonia: Reference assumptions **plus new investments in carbon capture – TG11 upgraded to CCU on refurbishment in 2025; Auvere upgraded to CCU in 2030**
    - Other regions (except Norway): same as Reference
    - Norway: same as Reference
  - Endogenously built
    - Estonia: all storage and renewable generation technologies in Table 2-2
    - Other regions: all options in Table 2-2
- Electricity transmission
  - In modelled area: same as Reference
  - Third country: same as Reference
- DSM: same as Reference
- ETS price projection: same as Reference
- Climate neutral electricity production in Estonia: **no net non-biogenic CO_2 emissions from electricity production by 2050 (accounting for direct air capture)**
- Direct air capture of CO_2: allowed as an endogenous option

Defining characteristics of Renewable gas + renewables + storage pathway (technology-focused)

- Final electricity demand
  - Estonia: same as Reference
  - Other regions (except Norway): same as Reference
  - Norway: same as Reference
- Electricity generation and storage capacity
  - Exogenously specified
    - Estonia: Reference assumptions **plus new investments in non-CHP biogas generation – 1 GW by 2030**
    - Other regions (except Norway): same as Reference
    - Norway: same as Reference
  - Endogenously built
    - Estonia: all storage and renewable generation technologies in Table 2-2
    - Other regions: all options in Table 2-2
- Electricity transmission
  - In modelled area: same as Reference
  - Third country: same as Reference
- DSM: same as Reference

Defining characteristics of Renewable gas + renewables + storage pathway (technology-focused)
• ETS price projection: same as Reference • Climate neutral electricity production in Estonia: **no net non-biogenic CO_2 emissions from electricity production by 2050 (accounting for direct air capture)** • Direct air capture of CO_2: allowed as an endogenous option

Defining characteristics of All technologies pathway (technology competition)

- Final electricity demand
  - Estonia: same as Reference
  - Other regions (except Norway): same as Reference
  - Norway: same as Reference
- Electricity generation and storage capacity
  - Exogenously specified
    - Estonia: same as Reference
    - Other regions (except Norway): same as Reference
    - Norway: same as Reference
  - Endogenously built
    - Estonia: **all low-carbon technologies in Table 2-2 – renewables, CCU[21], nuclear, storage**
    - Other regions: all options in Table 2-2
- Electricity transmission
  - In modelled area: same as Reference
  - Third country: same as Reference
- DSM: same as Reference
- ETS price projection: same as Reference
- Climate neutral electricity production in Estonia: **no net non-biogenic CO_2 emissions from electricity production by 2050 (accounting for direct air capture)**
- Direct air capture of CO_2: allowed as an endogenous option

Defining characteristics of All technologies + no net electricity imports pathway (technology competition)
• Assumptions same as All technologies except that **no net electricity imports into Estonia allowed**

Defining characteristics of All technologies + 1000 MW pathway (technology competition)
• Assumptions same as All technologies except that **Estonia must have at least 1000 MW of dispatchable capacity installed at all times** (includes non-CHP fossil fuel, biomass, and biogas; nuclear; landfill gas; and Paldiski pumped hydro)

[21] As noted in Table 2-2, the CCU option applies to the Auvere and TG11 plants. In the technology competition scenarios, the model can choose whether to add carbon capture to these plants, retire them, or continue using them as-is. Continuation of the TG11 plant requires a retrofit in 2025.

2.6 Stakeholder input into modelling

Stakeholders with an interest in Estonia's electricity system were consulted throughout the development of the Deliverable 3 model. The project team solicited stakeholder feedback on the model's design, input data and assumptions, scenario definitions, and simulation results. Consultations with stakeholders extended over a seven-month period (Table 2-6) and included representatives from the following organizations (in addition to the project steering committee from the Ministry and European Commission Directorate-General for Structural Reform Support):

- AS Tootsi Turvas
- Association of Estonian Cities and Municipalities
- Baltic Bioenergy Association
- City of Tallinn
- Cleantech For Estonia
- DG Energy
- Eesti Energia
- Eesti Gaas
- Elering
- Estonia Electrical Industry Association
- Estonian Association of Hydrogen Technologies
- Estonian Cell
- Estonian Electrical Industry Association
- Estonian Environmental Investment Centre
- Estonian Environmental Research Centre
- Estonian Green Movement
- Estonian Heat Pump Union
- Estonian Investment Agency
- Estonian Power Plants and District Heating Association
- Estonian Power Plants and District Heating Association
- Estonian Private Forest Centre
- Estonian Renewable Energy Chamber
- Estonian University of Life Sciences
- Estonian Wind Energy Association
- Fermi Energia
- Fermi Energy
- General Electric
- KPMG
- LHV
- Ministry
- Ministry of Defence
- Ministry of Environment
- Ministry of Finance
- Ministry of Social Affairs
- Ministry of the Interior
- National Audit Office of Estonia
- Nomine Consult
- Permanent Representation of Estonia to the EU
- Port of Tallinn

- PwC
- State Chancellery
- TalTech
- Tartu Regional Energy Agency
- Tavrida Electric
- University of Tartu
- Viru Keemia Grupp
- World Energy Council Estonia

Table 2-6 shows a timeline of the Deliverable 3 stakeholder consultations.

Table 2-6: Stakeholder consultations for Deliverable 3 modelling

Date	Topic
3 December 2020	Stakeholder workshop – Deliverable 3 kick-off and model design. Stakeholders provided feedback on key design questions.
December 2020-January 2021	Stakeholders submitted additional written feedback on key model design questions.
25 January 2021	Modelling team provided responses to feedback on key model design questions. Responses confirmed in a meeting with project steering committee.
February-March 2021	Stakeholders submitted written comments on modelling input data.
18 March 2021	Modelling team provided responses to comments on input data. Responses confirmed in a meeting with project steering committee.
7 April 2021	Stakeholder workshop – draft baseline results. Stakeholders provided feedback on results.
17 May 2021	Stakeholder workshop – revised baseline and initial decarbonisation results. Stakeholders provided feedback on results.
May-June 2021	Stakeholders submitted additional written feedback on baseline and decarbonisation results.
1 July 2021	Modelling team presented updated baseline and decarbonisation results to project steering committee.
July 2021	Modelling team conducted separate consultations on baseline and decarbonisation results with Elering.
July 2021	Stakeholders submitted additional written feedback on baseline and decarbonisation results.
30 July 2021	Modelling team provided consolidated responses to all feedback on baseline and decarbonisation results. Responses shared with full set of stakeholders.
6 August 2021	Modelling team provided draft final materials to the Ministry.
August-September 2021	Modelling team responded to feedback received from the Ministry after discussing their questions and comments in several calls.
21 September 2021	Modelling team circulated final report and executive summary to stakeholder group after Ministry approved materials.
5 October 2021	Feedback received from Elering, Fermi Energia, the Estonian Green Movement, and DG REFORM.
12 October 2021	Modelling team responds to questions and feedback from Elering.
19 October 2021	Modelling team submits revised materials to the Ministry, as well as a compiled file tracking responses to stakeholder comments.
25 October 2021	Modelling team conducted separate consultation with Elering to discuss their comments and next steps.
28 October 2021	Modelling team conducted separate consultation with Fermi Energia to discuss their comments and next steps.

As the project team received input from stakeholders, the Deliverable 3 model was continuously revised to incorporate new information and better reflect conditions in Estonia.

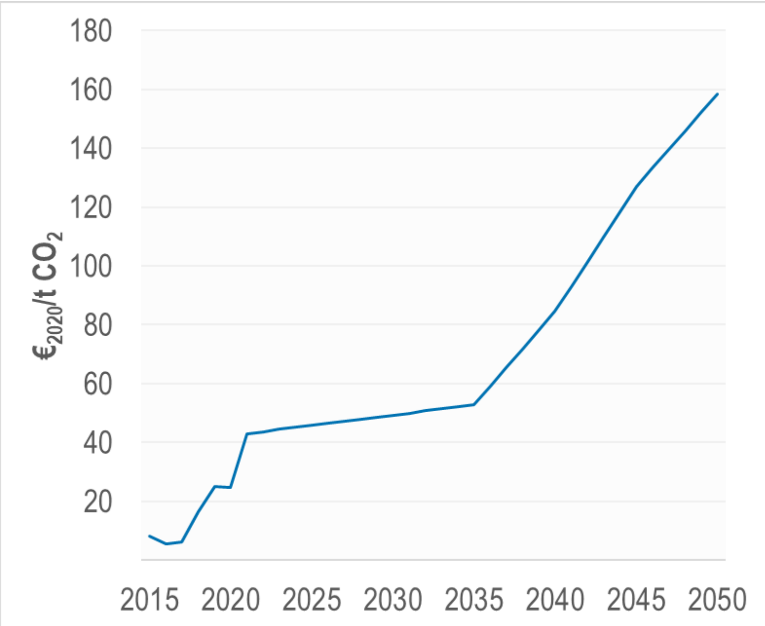
3 Analysis of BAU and Reference pathways

3.1 BAU scenario

Key findings
• Modest growth in final demand coupled with supply-side efficiencies and desynchronization from the Russian grid lead to stable electricity production requirements over time. • High ETS prices and declining technology costs drive substantial system-wide decarbonisation. • Electricity imports continue to increase in Estonia, and domestic generation shifts from oil shale toward wind and solar. • Fluctuations in wind and solar output are balanced by multiple resources: battery storage, DSM, imports, seasonal CHP, and peaking biomass generation.

The BAU scenario is marked by significant changes in the study area's electricity system, driven by planned projects, technological shifts, and a substantial increase in the ETS price (Figure 3-1).

Figure 3-1: BAU – ETS price

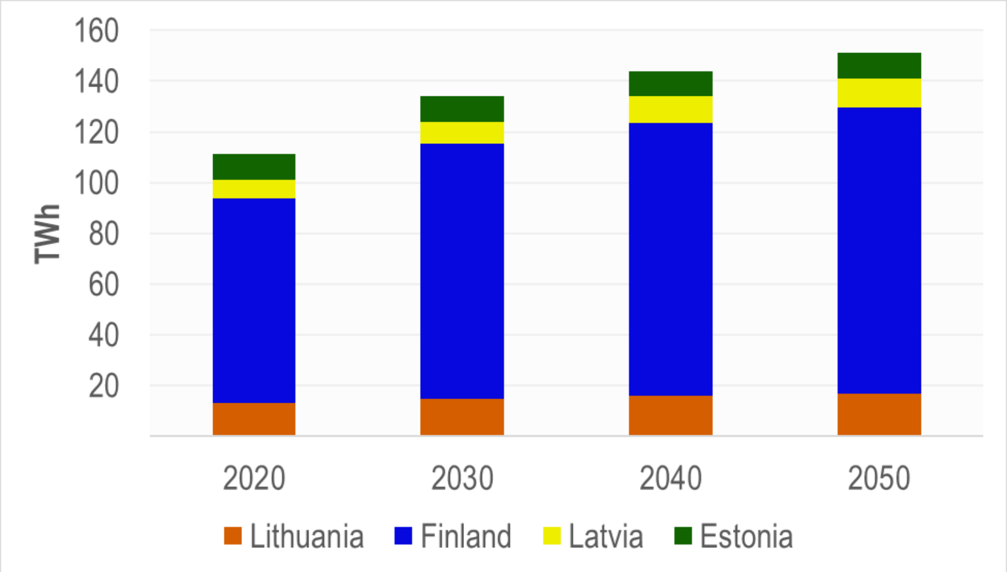


These factors amplify recent trends in Estonia regarding sources of electricity and the country's level of electricity independence.

3.1.1 Electricity demand

The BAU demand projection holds electricity supply requirements[22] in Estonia relatively constant, while demand grows in neighbouring countries (Figure 3-2).

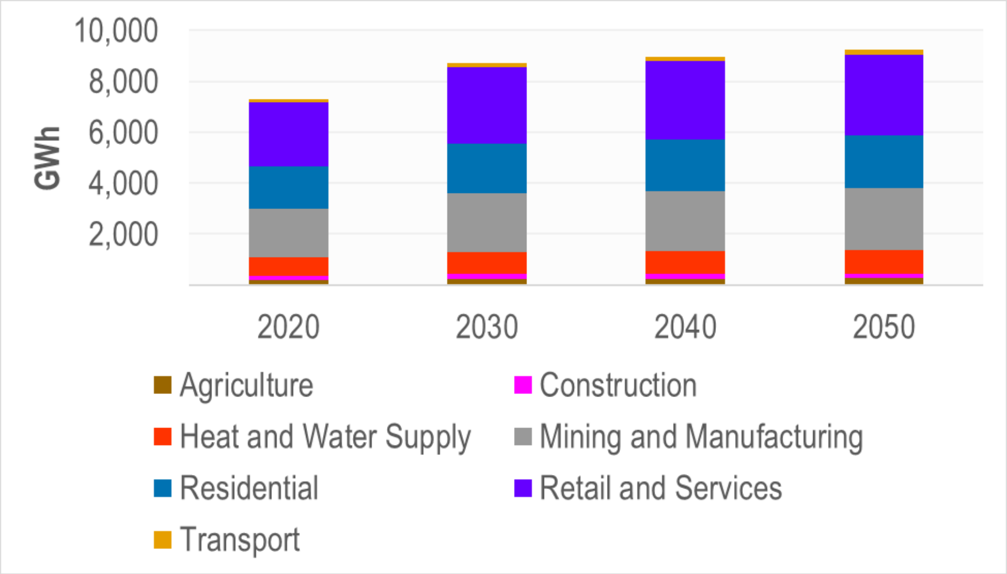
Figure 3-2: BAU – electricity supply requirements



Based on TalTech estimates, final electricity demand in Estonia increases evenly across sectors – about 27% between 2020 and 2050 (Figure 3-3). However, this rise is offset by a decrease in power exports to Russia after desynchronization in 2025, as well as by improving grid loss and own-use rates (assumptions taken from RS2020).

[22] As used in this report, electricity supply or production requirements include all requirements for electricity within a modelled region (or regions): final electricity demand, electricity demand for other energy production (e.g., hydrogen), producer own-use, transmission and distribution losses within the region, and third-country exports from the region (which are modelled as additional final demand; see section 2.4.2).

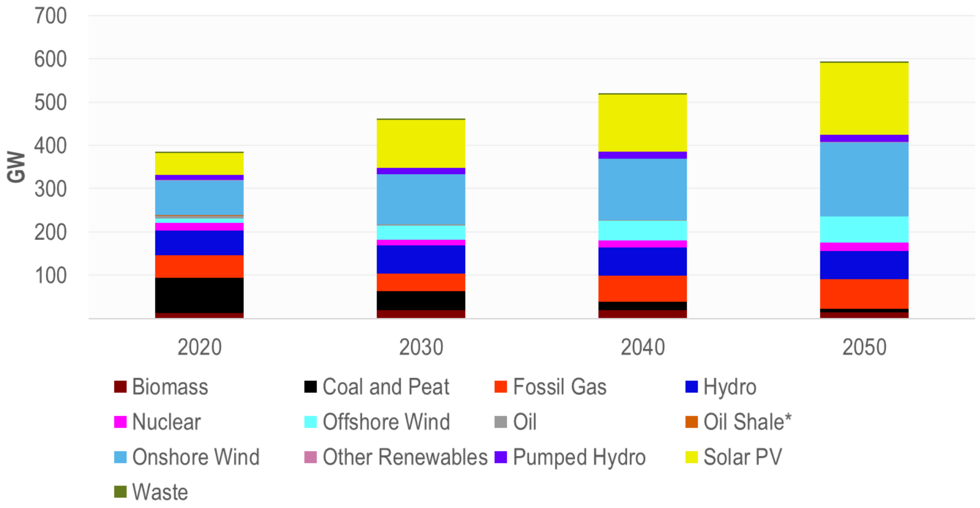
Figure 3-3: BAU – final electricity demand in Estonia



3.1.2 Electricity supply

On the supply side of the BAU scenario, the exogenous projection of generation capacity included in the model, determined principally by RS2020 (see section 0), plays a large role in shaping results. As Figure 3-4 shows, this projection increases area-wide installed capacity by about 50% by 2050. Growth in offshore wind is greatest (545% increase between 2020 and 2050), followed by solar PV (228%) and onshore wind (115%). The additions are spread across regions, including among Estonia's neighbours. For example, the RS2020 projection adds 4 GW of onshore wind and over 3 GW of solar in Latvia and Lithuania between 2020 and 2050.

Figure 3-4: BAU – exogenously specified electricity generation and storage capacity in all regions[23]

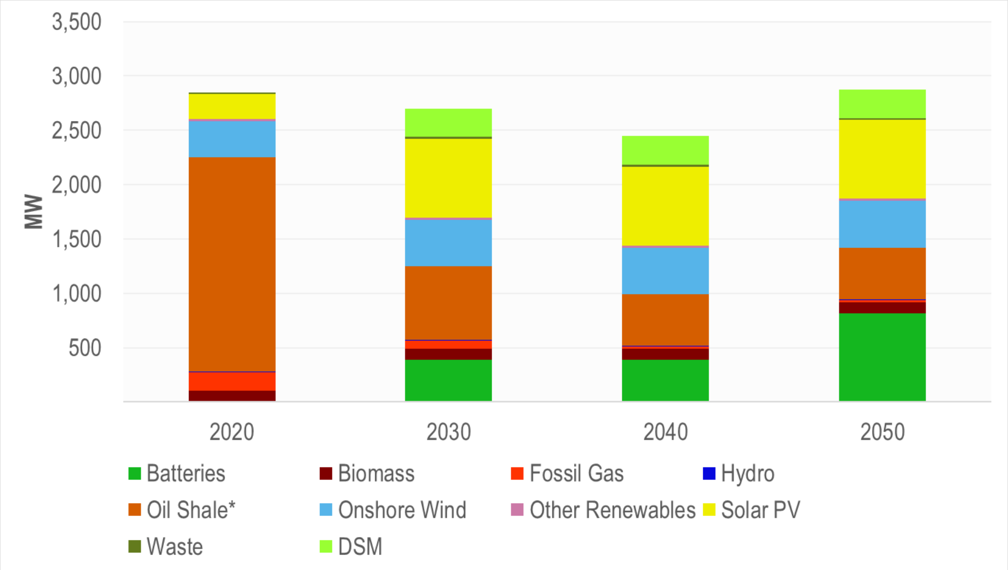


** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

In Estonia, retiring oil shale capacity (including units at Eesti Elektrijaam and Balti Elektrijaam) is replaced by a mix of solar PV, onshore wind, and batteries, complemented by DSM (Figure 3-5). Total capacity in 2050 is about 2.9 GW. Excepting batteries and DSM, most of the capacity is specified exogenously rather than selected by the model. The model chooses to add 100 MW of additional onshore wind but otherwise focuses on developing resources to buffer the variable output of the exogenously prescribed renewables.

[23] The oil shale category in this and subsequent graphs refers to Estonian plants that were originally constructed to burn oil shale. In all of the modelled scenarios, large oil shale plants are converted to use 100% biomass by the early 2030s unless they are retrofitted with carbon capture (see section 2.4.2). Carbon capture retrofits are only allowed in certain cases, however: in the CCU + renewables + storage pathway and the All technologies pathways (see section 2.5). In other scenarios, generation in the oil shale category is essentially all from biomass after 2035.

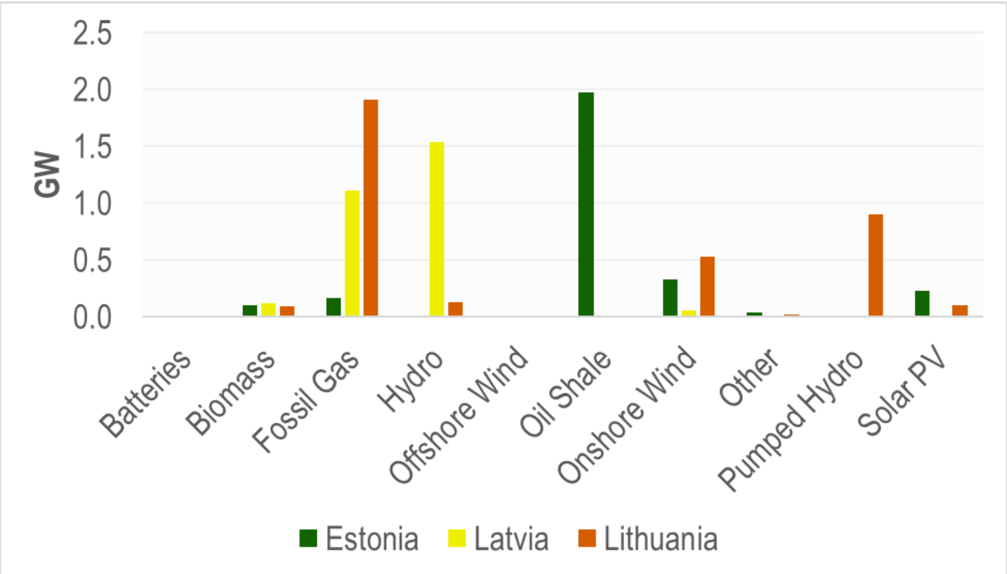
Figure 3-5: BAU – electricity generation and storage capacity in Estonia

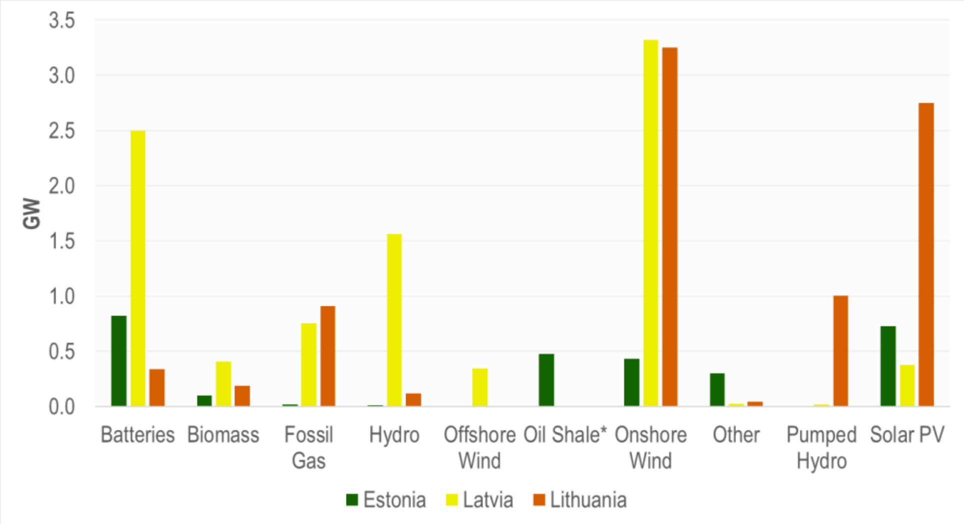


** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Across the Baltic states, capacity is rather unevenly distributed in the long run, as depicted in Figure 3-6. This is a direct consequence of the RS2020 capacity projection for Latvia and Lithuania.

Figure 3-6: BAU – electricity generation and storage capacity in Baltic countries in 2020 (first panel) and 2050 (second panel)

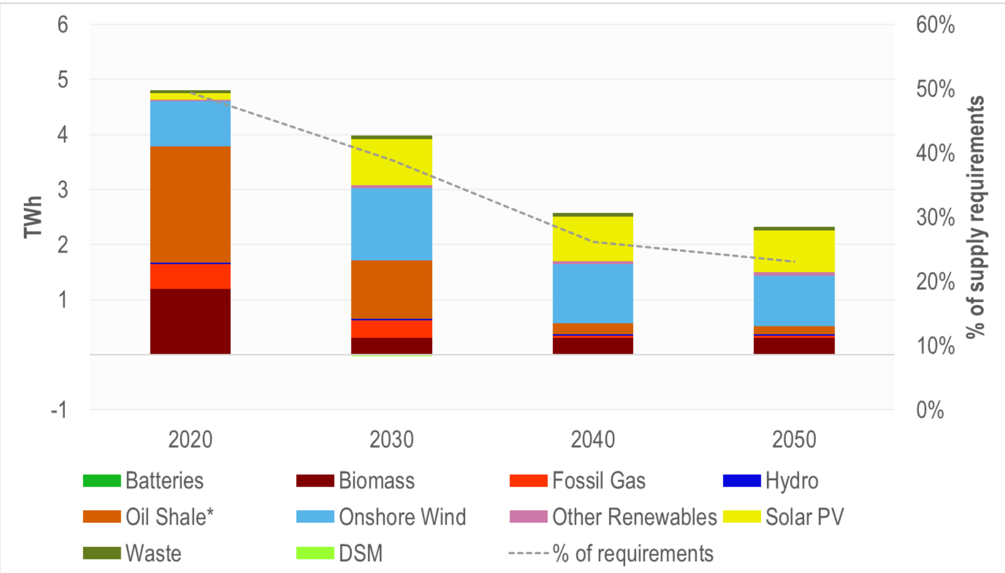




** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

In terms of generation, electricity production in Estonia decreases over time due to pressure on oil shale from the high ETS price and the lower capacity factors associated with wind and solar (Figure 3-7). The share of imports in the national electricity supply rises concomitantly, reaching 77% by 2050. The imports are mainly from Scandinavia via Finland (Figure 3-8); Estonia exports a small amount of power to Latvia in all years of the simulation.

Figure 3-7: BAU – net electricity generation[24] in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

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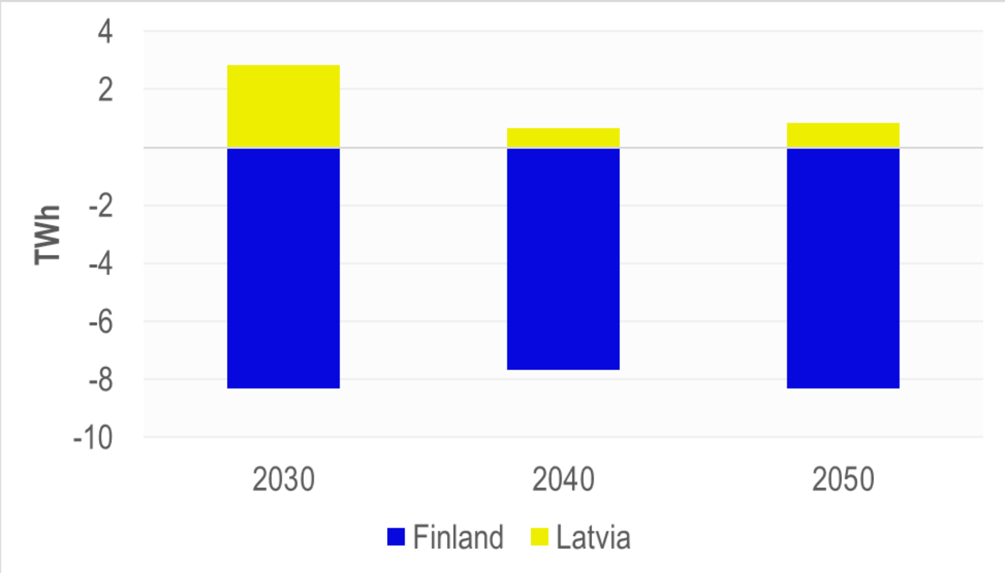
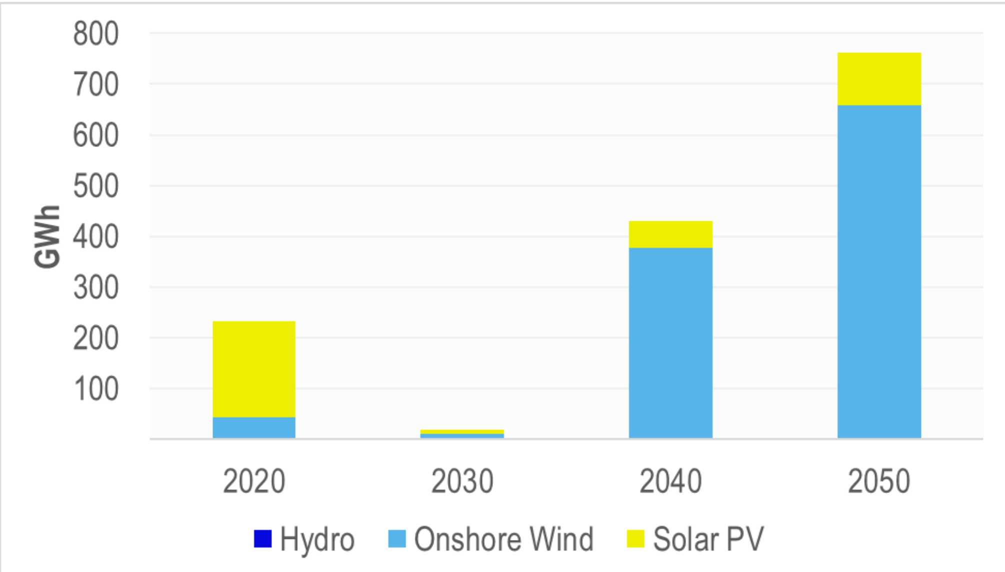
[24] Unless otherwise indicated, net electricity generation in this report refers to generation net of storage charging. Additionally, note that net generation graphs in this report show batteries because they have small negative net generation over the course of a year.

Figure 3-8: BAU – electricity imports to (-) and exports from (+) Estonia



The large build-out of solar power provides a significant amount of electricity in the summer but considerably less in winter. The winter shortfall is made up through a combination of CHP, storage, and DSM, as well as large oil shale plants (running on biomass by 2040) that are used as a peaking resource. In the summer, some curtailment of wind is necessary to accommodate the solar generation (Figure 3-9). The model chooses to curtail wind in this case because it has a small variable cost, while solar does not.

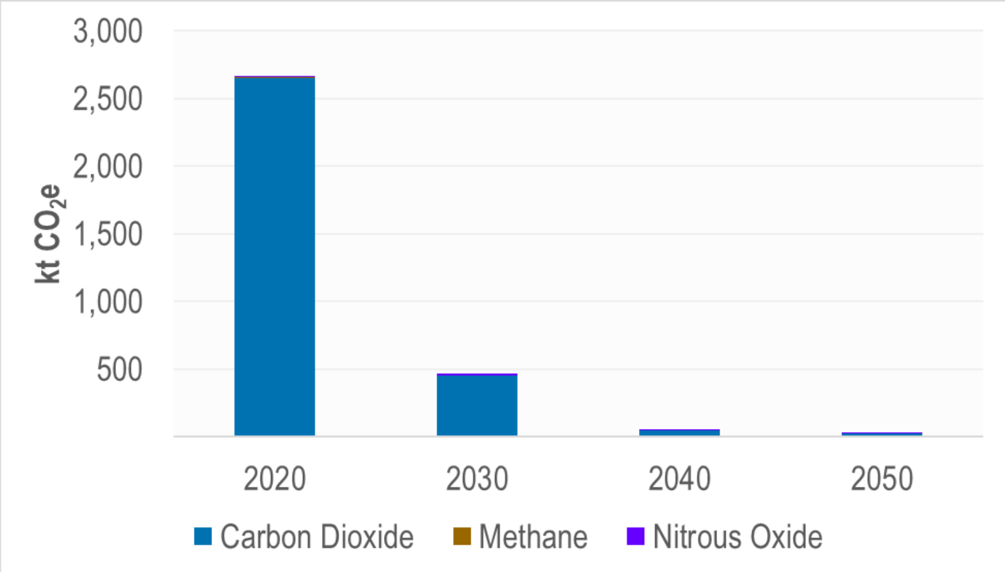
Figure 3-9: BAU – curtailed electricity generation in Estonia



3.1.3 GHG emissions

Figure 3-10 illustrates that in the BAU scenario – which assumes a sharp increase in carbon prices and growth in the availability of low-cost electricity exports from many Nord Pool regions – GHG emissions from power production in Estonia fall to nearly zero by 2050. The remaining emissions in that year (29 kt of CO_2-equivalent) are attributable mainly to fossil-fuelled CHP.

Figure 3-10: BAU – GHG emissions from electricity production in Estonia



3.1.4 Electricity prices

Table 3-1 reports estimated annual average electricity prices in Estonia in the BAU scenario. Overall, prices are projected to rise from current levels but remain relatively stable from 2030 (European Commission DG Energy 2021).

Table 3-1: BAU – annual average electricity prices in Estonia

Year	Price ($€_{2020}$/kWh)
2030	0.1132
2040	0.1120
2050	0.1050

3.2 Reference scenario

Key findings
• Adoption of economically feasible power-to-X increases Estonia's electricity production requirements 55% by 2050. • Higher demand in Estonia and less exogenously specified generation capacity elsewhere in the modelled area mean greater investment in Estonian electricity production is cost-minimizing. • Electricity production capacity in Estonia shifts toward solar PV, onshore and offshore wind, batteries, and DSM, allowing the country to become nearly self-sufficient in electricity by 2050.

Key findings
• The Auvere and TG11 plants, converted to run on biomass, play a major role in balancing wind and solar production. • Estimated wholesale electricity prices in Estonia are about 10% lower than in the BAU scenario.

The Reference scenario implements two changes compared to the BAU:

- It omits the RS2020 projection of future capacity expansion outside Estonia (and the parallel Statnett projection for Norway); and
- It assumes an economically feasible level of power-to-X deployment in Estonia.

These changes cause significant differences in the long-run results for the Estonian power sector. Higher electricity demand in Estonia induces more investment in domestic power generation, leading to a substantial improvement in the import-export balance and better prices for Estonian consumers.

3.2.1 Electricity demand

Demands for economically feasible electric heating, electric transport, and hydrogen raise electricity production requirements in Estonia by more than 50% by 2050 (Figure 3-11 and Table 3-2). In that year, production requirements total 16 TWh. The growth in electricity demand is nonlinear as adoption of power-to-X technologies accelerates in the later years of the projection. By 2050, electric vehicles and heating add about 2 TWh to electricity demand compared to the BAU, while hydrogen production adds almost 4 TWh. The power-to-X demands in 2050 account for 46% of the total projected electricity supply requirements in that year.

Figure 3-11: Reference – electricity supply requirements in Estonia compared to BAU

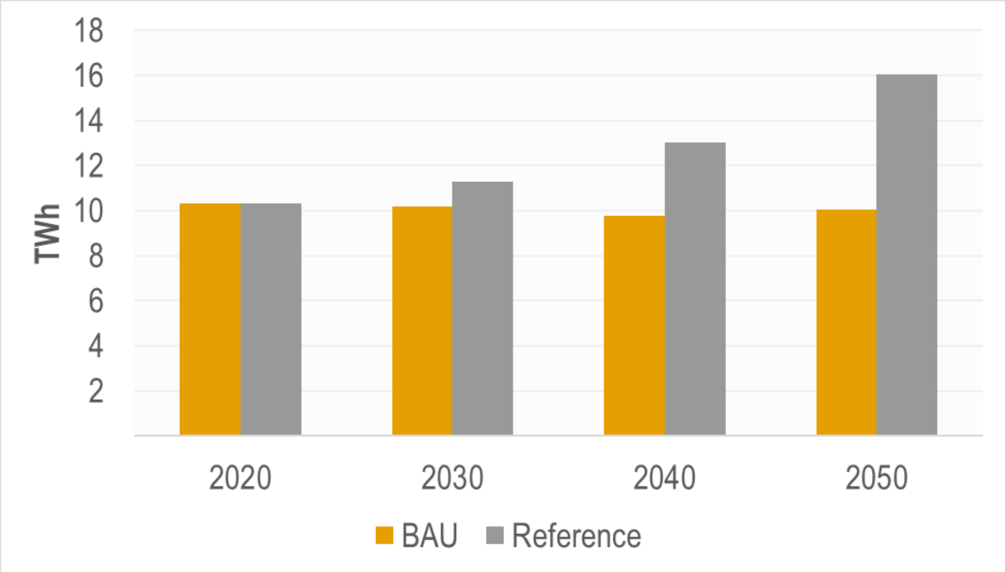


Table 3-2: Power-to-X and total electricity supply requirements in Estonia

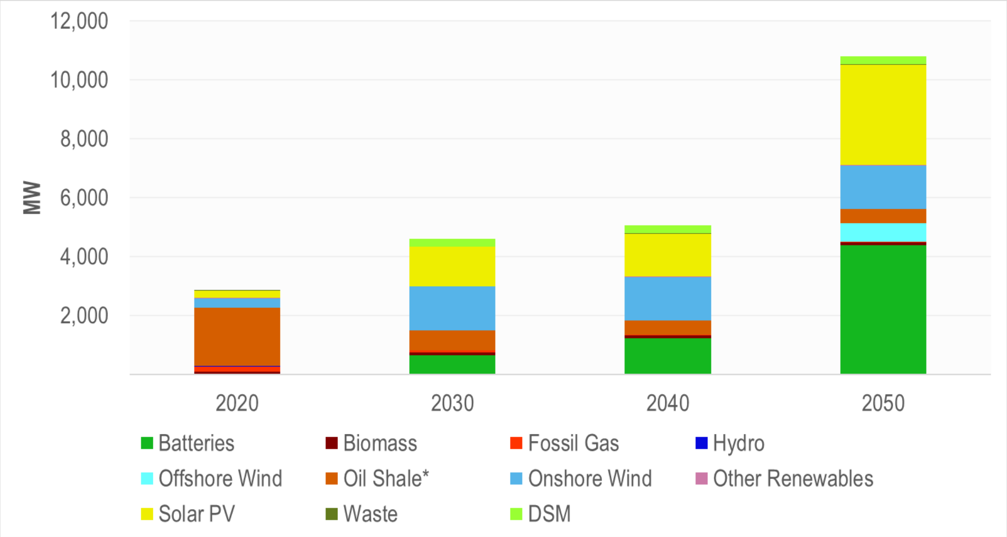
Electricity supply requirements	Unit	2020	2030	2040	2050
Total electricity supply requirements					
BAU	TWh	10.3	10.2	9.8	10
Reference scenario	TWh	10.3	11.3	13	16
Power-to-X requirements in the Reference scenario					
Total power-to-X requirements	TWh	0.7	2.1	4.3	7.4
Hydrogen production	TWh	0	1	2.5	4.1
Electric vehicles	TWh	0.01	0.1	0.2	0.8
Electric heating	TWh	0.7	1.1	1.7	2.5
% of total Reference scenario requirements					
Power-to-X	%	7%	19%	33%	46%
Hydrogen production	%	0%	9%	19%	26%
Electric vehicles	%	0%	1%	1%	5%
Electric heating	%	7%	9%	13%	16%

Along with the increase in production requirements, peak load in the Estonian system also rises, reaching 3.1 GW by 2050. Although mentioned in section 2.4.2, it should be noted again that this load estimate assumes a severe heating season.

3.2.2 Electricity supply

With the increased demand in Estonia and the lower presupposed production capacity in other countries, investments in Estonian generation and storage are considerably higher than in the BAU (Figure 3-12). Rather than remaining level throughout the projection, generation and storage capacity in Estonia about triples by 2050. The technology mix is similar to the BAU, inasmuch as solar PV, onshore wind, and batteries are strongly represented, but the model also builds about 600 MW of offshore wind. Complementing the offshore wind deployment, about 350 MW of new transmission is constructed between Lääne-Eesti and Lõuna-Eesti, and about 325 MW of new transmission between Lääne-Eesti and Latvia.

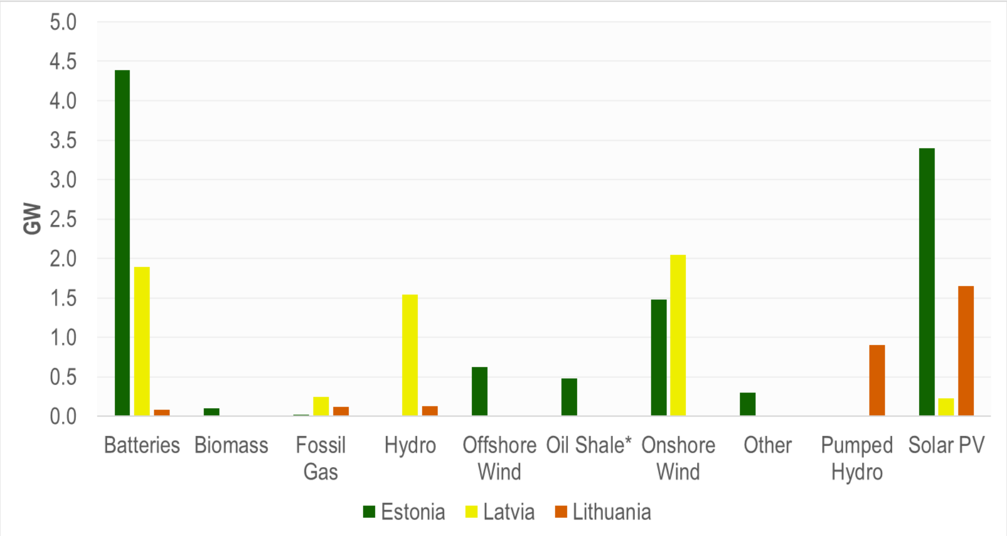
Figure 3-12: Reference – electricity generation and storage capacity in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

The distribution of generation and storage capacity in the Baltic region is slanted toward Estonia in the long run (Figure 3-13). The model chooses to build solar, wind, gas, and storage in Latvia and Lithuania, but these investments are not disproportionately larger than additions in Estonia, as in the BAU scenario.

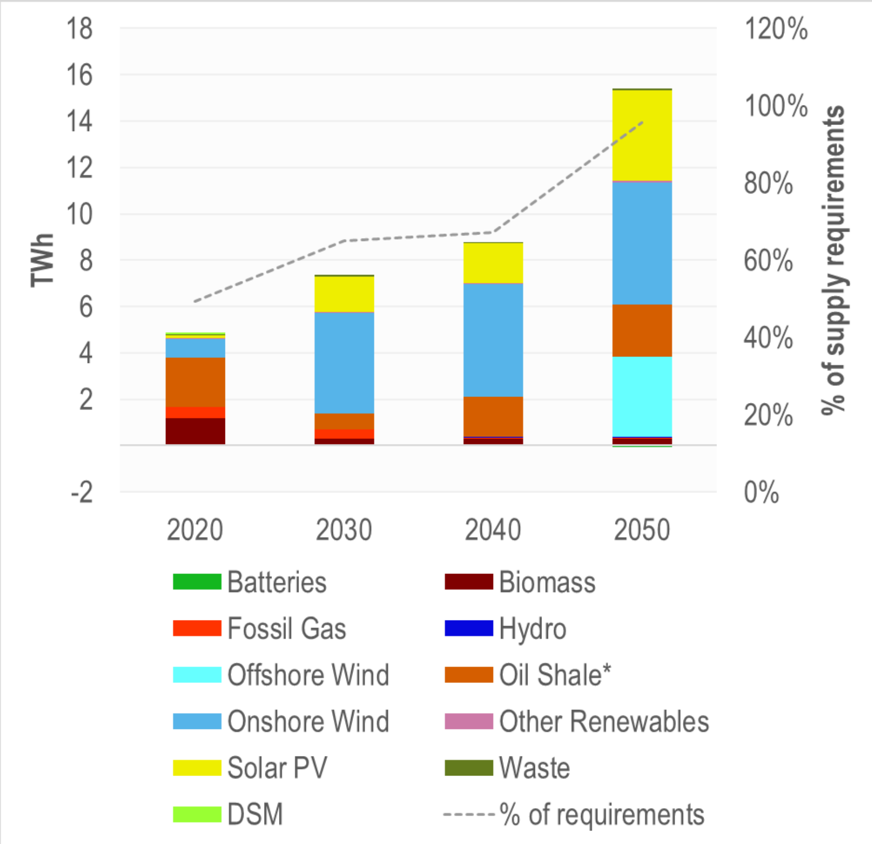
Figure 3-13: Reference – electricity generation and storage capacity in Baltic countries in 2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Significant differences in generation are realized in the Reference scenario as well. As Figure 3-14 shows, generation in Estonia rebounds as demand increases and new power technologies are deployed. By 2050, Estonia essentially attains electricity self-sufficiency, with output equal to 96% of domestic requirements. Solar PV, onshore wind, and biomass (burned in former oil shale plants) all contribute substantially to national production, as does offshore wind that is added in the 2040s.

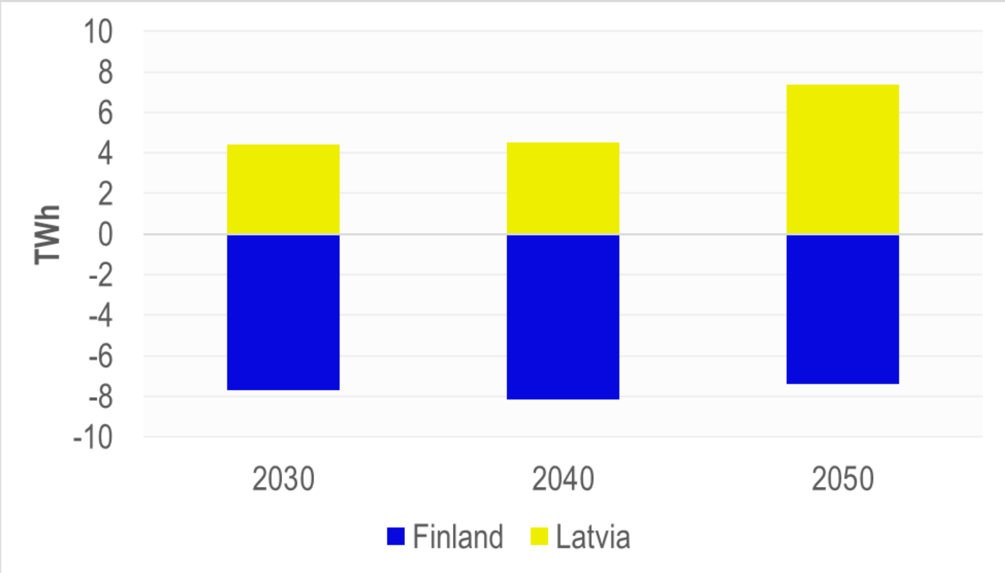
Figure 3-14: Reference – net electricity generation in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

The system shifts to accommodating considerable solar output in the summer, some of which is exported, and to backfilling for reduced solar in the winter using the Auvere and TG11 plants, imports, and CHP. Wind resources contribute in all seasons; and batteries, DSM, the former oil shale plants, and imports are engaged to balance wind and solar variability. Overall, the imports are mainly of Scandinavian power via Finland, while exports flow to other Baltic countries via Latvia (Figure 3-15).

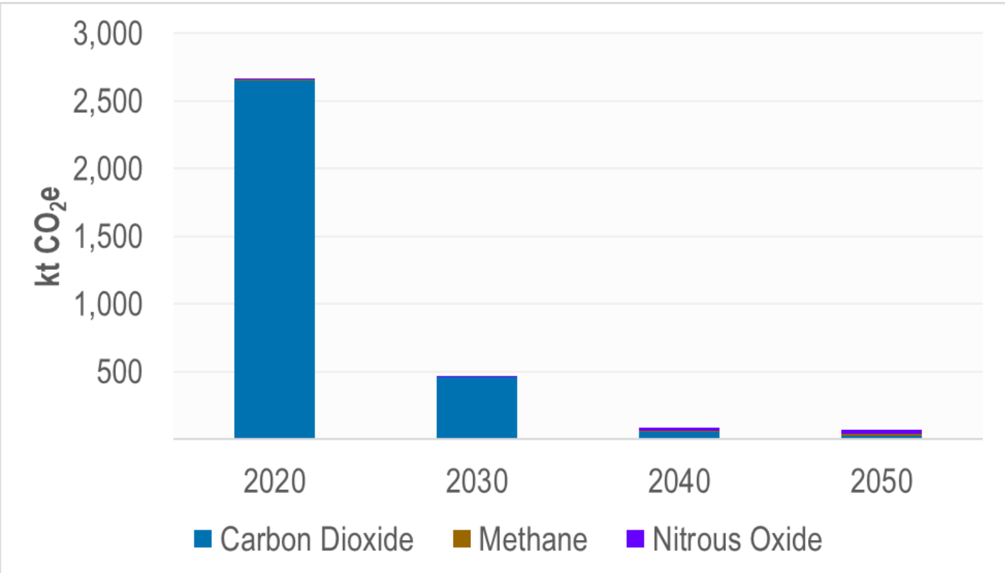
Figure 3-15: Reference – electricity imports to (-) and exports from (+) Estonia



3.2.3 GHG emissions

As in the BAU scenario, electricity production in Estonia is almost fully decarbonised in the Reference scenario (Figure 3-16). The high carbon price and low costs for renewables are again determining factors. They make it cost inefficient to construct new fossil-fuelled plants, while at the same time most existing fossil capacity in Estonia is eventually converted to use biomass. Residual emissions in 2050 are 67 kt of CO_2-equivalent.

Figure 3-16: Reference – GHG emissions from electricity production in Estonia



3.2.4 Electricity prices

Average Estonian electricity prices in the Reference scenario are about one Euro cent per kWh lower than in the BAU scenario (Table 3-3). Prices are still notably higher than historical values, however.

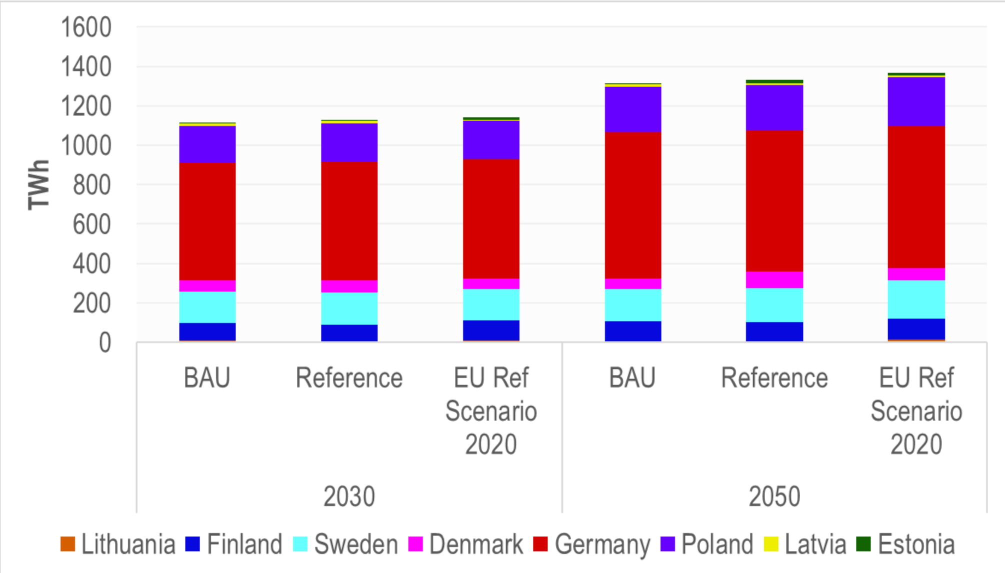
Table 3-3: Reference – annual average electricity prices in Estonia

Year	Price (€$_{2020}$/kWh)
2030	0.1056
2040	0.1025
2050	0.0981

3.3 Comparison with EU Reference Scenario 2020

Since the BAU and Reference scenarios adopt some important assumptions from RS2020 (the draft version shared with the Deliverable 3 team), it is instructive to compare their main outputs. Figure 3-17 shows gross power generation in the three scenarios. Projected generation by region is similar in each case – for example, in 2050, results for the BAU and Reference scenarios are only 3-4% lower than in RS2020. These findings confirm the alignment of regional electricity demands, which, except for Estonia and Norway, are the same in all scenarios and are based on RS2020. Additionally, the comparable results provide evidence of similar treatment of imports and exports in the modelled area.

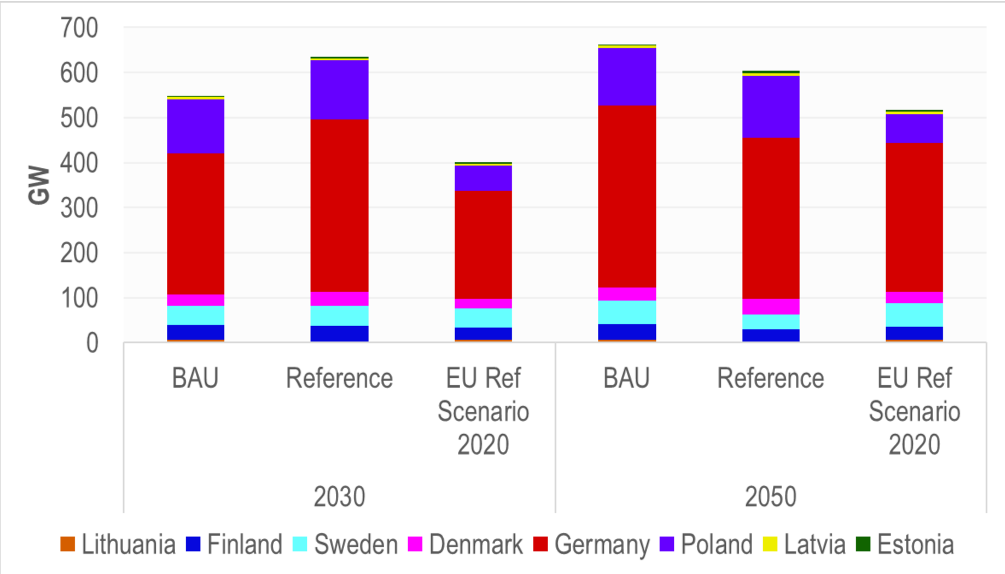
Figure 3-17: Gross electricity generation in BAU, Reference, and RS2020[25]



[25] Norway is excluded from the chart.

Beyond total power generation, however, there are noticeable differences between the scenarios in projected generation capacity, dispatch, and GHG emissions. Looking at generation capacity, Figure 3-18 shows the BAU and Reference scenarios result in an installed capacity that is between 36-58% higher than RS2020 in 2030, and 17-28% higher in 2050. This is due to the Deliverable 3 model selecting more intermittent renewables in response to high ETS prices and competitive wind and solar costs. These technologies are carbon-neutral but have lower capacity factors than fossil alternatives deployed in RS2020, necessitating higher installed capacity for the same electricity output.

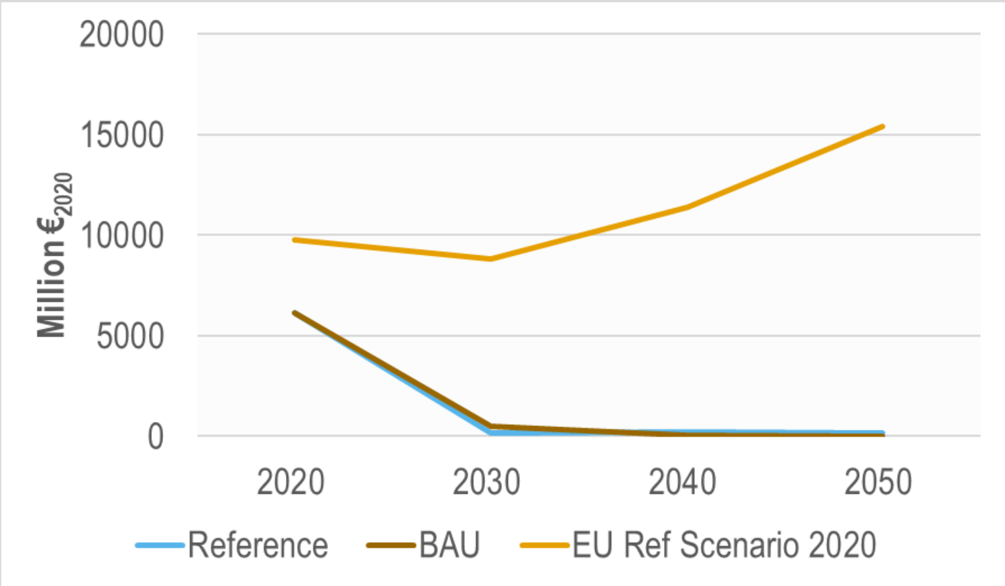
Figure 3-18: Electricity generation capacity in BAU, Reference, and RS2020[26]



Consistent with the capacity projection, RS2020 envisions substantially higher fossil fuel-based electricity generation than in the Deliverable 3 scenarios, and substantially lower solar and wind production. As a result, GHG emissions are markedly higher. In RS2020, a large share of fossil fuels persists in the electricity mix in spite of high ETS prices. Significantly higher carbon costs are incurred compared to the BAU and Reference scenarios, and the costs increase over time instead of dropping as in the Deliverable 3 simulations (Figure 3-19).

[26] Storage capacity and Norway are excluded from the chart.

Figure 3-19: Carbon cost incurred in BAU, Reference, and RS2020



The Deliverable 3 team approached DG Energy to discuss these differences but were not able to obtain enough information to explain them definitively. Likely reasons for the discrepancies include the following:

- The RS2020 model appears to be calibrated to different historical data than the Deliverable 3 model. For example, RS2020 outputs do not match 2020 capacity and generation data from ENTSO-E on which the Deliverable 3 modelling is based.
- RS2020 may rely on different assumptions about technology costs; e.g., wind capital costs in Germany in RS2020 appear to be twice as high as the costs included in the Deliverable 3 model (which were taken from the Deliverable 2 data collection).
- Capacity factors for wind and solar in RS2020 are likely different from those in the Deliverable 3 model (in particular, they may not account for the projected capacity factor improvements developed in the Deliverable 2 data collection; see section 2.4.2).
- Transmission simulations/assumptions may differ between the RS2020 and Deliverable 3 models.
- Assumptions about contracts and power trading with third countries, as well as specific national plans and policies, may diverge between the models.

- Potential errors in either model might contribute to the observed differences. For example, the RS2020 projection of biomass/waste generation in Germany in 2050 implies a capacity factor of 161%.

4 Analysis of technology-focused pathways

As explained in section 2.5.2, all of the climate-neutral pathways evaluated for Deliverable 3 are based on the Reference scenario. They introduce an overall requirement of climate-neutral electricity production in Estonia by 2050 along with selected other changes to test different strategies for reaching the 2050 goal. Because the number of changes is small in each case, the climate-neutral pathways share many basic assumptions and data with the Reference scenario.

This section reports findings from the four climate-neutral pathways with a technology focus – i.e., that explore particular future investments in low-carbon generation in Estonia. It highlights major differences in these scenarios' results as compared to the Reference scenario.

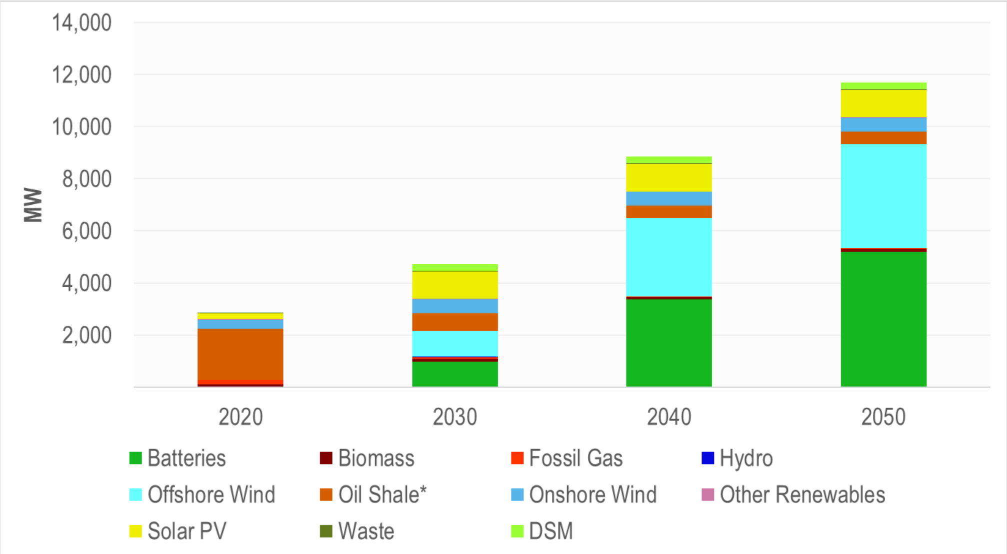
4.1 Renewables + storage scenario

Key findings
• Major investments in offshore wind make available a significant amount of low-variable-cost electricity in Estonia. • Integrating the offshore wind energy into the electricity system requires several complementary changes, including about 1.3 GW of new transmission capacity from Lääne-Eesti. • The offshore build-out enables Estonia to return to its historical position as a net electricity exporter by 2040, providing power mainly to Latvia and Lithuania. • Impacts on annual average electricity prices in Estonia are minimal compared to the Reference scenario.

The Renewables + storage scenario evaluates a large deployment of offshore wind in Estonia: a total of 4 GW by 2050, or about 60% of the country's potential according to the most recent National Energy and Climate Plan (Government of Estonia 2019). The new capacity is constructed in Lääne-Eesti, and as outlined in Table 2-2, the model is allowed to build additional transmission to this region to support it. Endogenous investments in storage and other renewables in Estonia are also permitted.

Figure 4-1 depicts the impact of these assumptions on projected generation and storage capacity in Estonia. By 2050, total capacity is almost 1 GW higher than in the Reference scenario. Offshore wind capacity exceeds the level in the Reference scenario by nearly 3.4 GW, while about 3.3 GW of onshore wind and solar PV is foregone. Battery capacity is 800 MW larger than in the Reference scenario. These results point to seasonal complementarity between solar and wind – solar production is high in summer and low in winter, whereas wind production tends to be greater in winter. When these resources are not added together, storage needs increase. Through 2050, the investment in Estonian offshore wind is about €$_{2020}$ 7.8 billion (not including new transmission, discussed next). Compared to the Reference scenario, total domestic investment in generation and storage is €$_{2020}$ 5.2 billion higher over the modelled period.

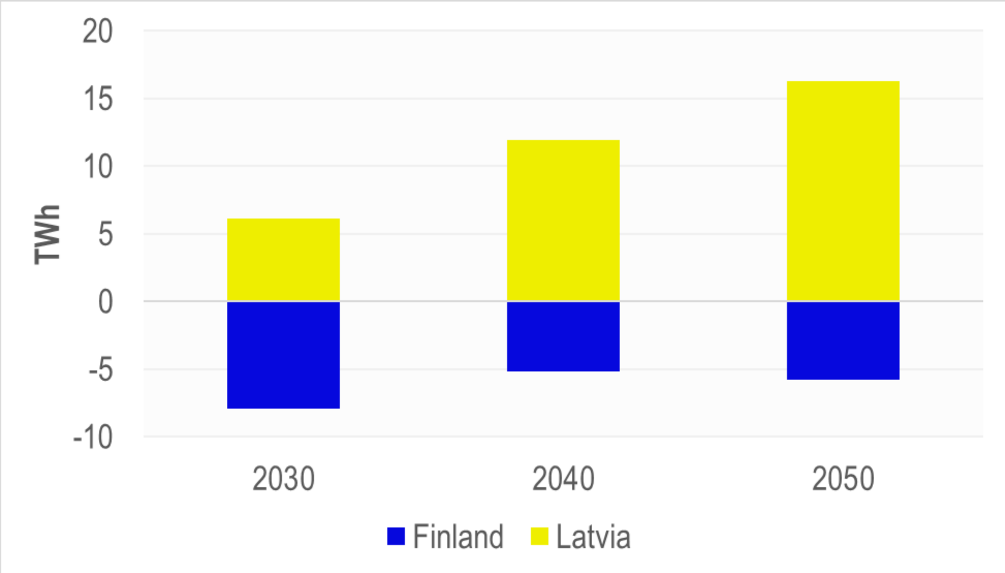
Figure 4-1: Renewables + storage – electricity generation and storage capacity in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

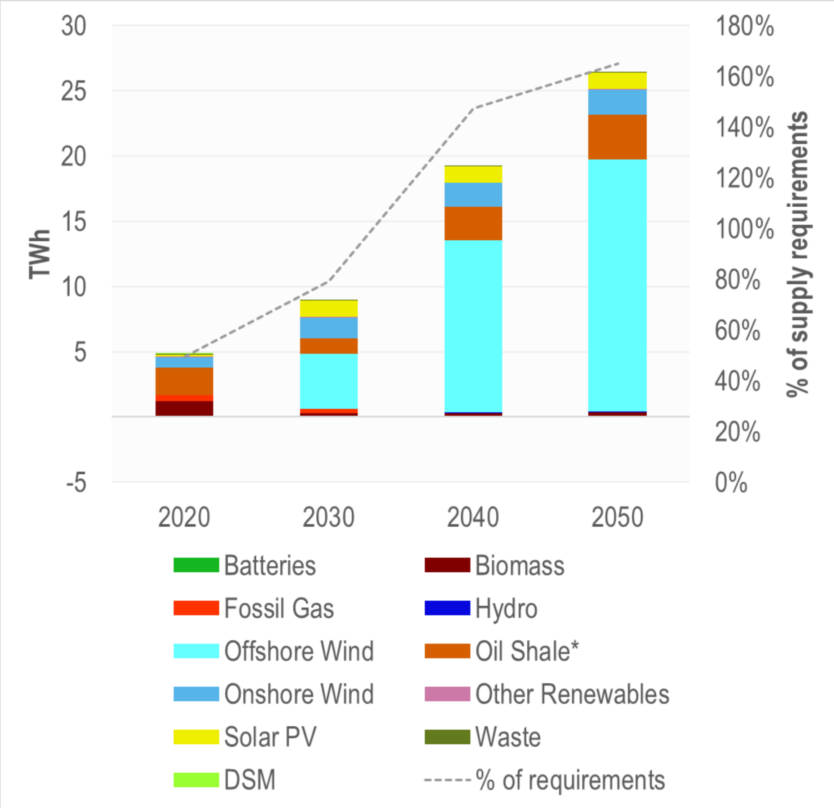
Accompanying the offshore wind, the model elects to build over 1 GW of new transmission from Lääne-Eesti: 150 MW to Lõuna-Eesti and 1180 MW to Latvia, at an estimated cost of €$_{2020}$ 311 million. These connections are essential to utilizing the offshore wind power both domestically and in the wider region. Electricity exports from Estonia rise as the offshore deployment is carried out (1 GW of offshore wind is added by 2030, 2 GW by 2035, 3 GW by 2040, and 4 GW by 2050). As Figure 4-2 illustrates, Estonia continues to import some power throughout the year, but annual imports are overtaken by exports by 2040. At the end of the projection, net exports from Estonia total 10.4 TWh per year. The majority of the exports are to Latvia for use in other Baltic countries.

Figure 4-2: Renewables + storage – electricity imports to (-) and exports from (+) Estonia



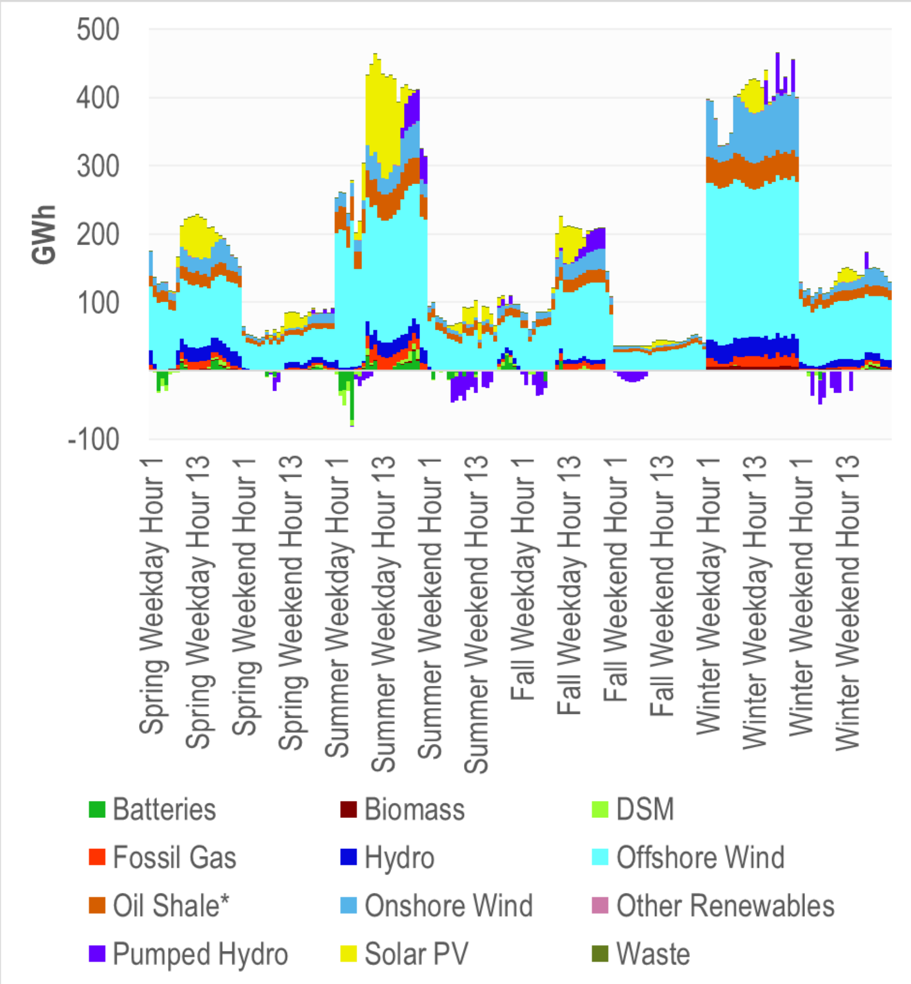
Predictably, electricity generation in Estonia is dominated by offshore wind, but other sources also make key contributions (Figure 4-3). The changes necessary to absorb the offshore production show most clearly at the level of the Baltic region (Figure 4-4). By 2050, variable output from offshore wind, solar, and onshore wind is counterbalanced by storage and dispatchable generation including gas and former oil shale plants. Both pumped hydro (in Lithuania) and batteries (in all Baltic countries) play an important role in moving renewable energy from slack to peak periods. Electricity imports (not shown in Figure 4-4) are also used to fill gaps at certain times.

Figure 4-3: Renewables + storage – net electricity generation in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

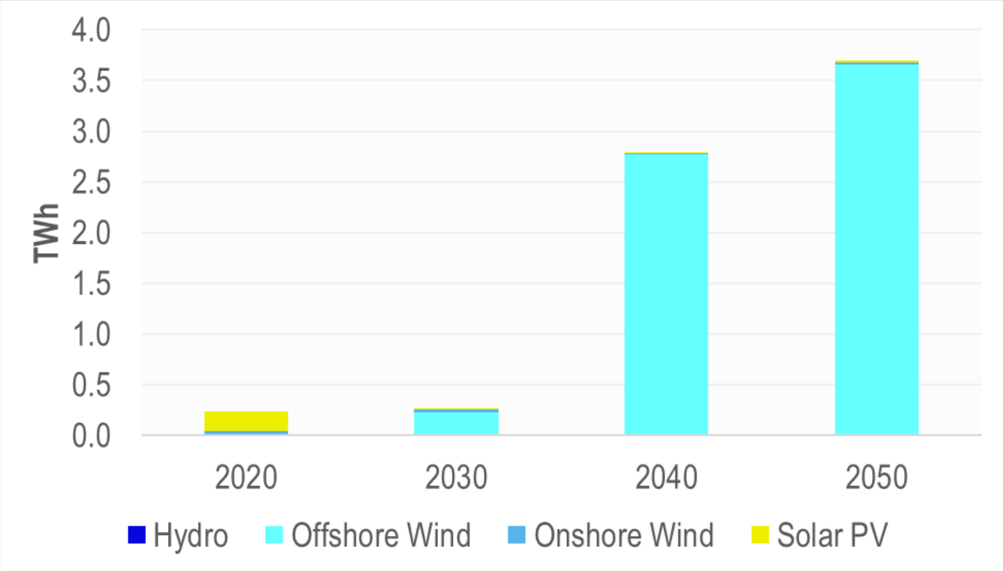
Figure 4-4: Renewables + storage – time-sliced electricity generation in Baltic countries in 2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Although much of the available offshore wind output is utilized, there is some curtailment, amounting to about 16% of the potential offshore production in 2050 (Figure 4-5). This could conceivably be reduced with transmission projects not considered in the modelling (e.g., new connections to Lithuania or the Nordic countries).

Figure 4-5: Renewables + storage – curtailed electricity generation in Estonia



Estimated average electricity prices in Estonia are comparable in the Renewables + storage and Reference scenarios (Table 4-1).

Table 4-1: Renewables + storage – annual average electricity prices in Estonia

Year	Price (€$_{2020}$/kWh)
2030	0.1101
2040	0.0980
2050	0.0967

GHG emissions from Estonian electricity production fall nearly to zero by 2050, though a small amount of CH_4 and N_2O emissions remain from biomass combustion (65.9 kt of CO_2-equivalent). There are also minor residual emissions of CO_2 in 2050 – 15.8 kt, which are offset by direct air capture. The Renewables + storage scenario is the only climate-neutral pathway in which direct air capture is used to meet the decarbonisation target.

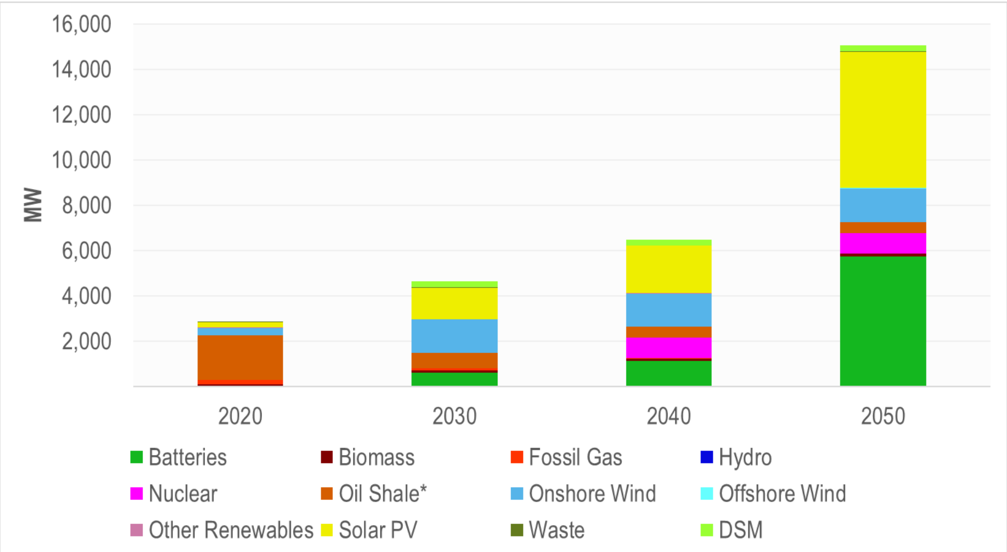
4.2 Nuclear + renewables + storage scenario

Key findings
• Deploying 900 MW of nuclear power in Estonia induces a considerable expansion of solar PV between 2040 and 2050. • The flexibility of nuclear generators is leveraged to integrate solar and wind production, which rises to 70% of national electricity generation by 2050. • Surplus solar and wind power is exported to Latvia and Finland, and imports from Finland help backfill at times of reduced renewable output. • Average electricity prices in Estonia are in line with the Reference scenario.

The Nuclear + renewables + storage pathway simulates climate-neutral electricity production in Estonia given an addition of 900 MW of Generation III+ small modular nuclear capacity by 2040. The nuclear capacity is added in 300 MW increments at a total investment cost of €$_{2020}$ 2.33 billion.[27] Critically, the Generation III+ technology is modelled to have high flexibility, allowing it to ensure grid stability when paired with wind and solar (Wald 2021). Beyond the 900 MW of Generation III+ nuclear, the model is allowed to construct additional Generation III+ and Generation IV nuclear, storage, and renewable generation in Estonia if it contributes to minimizing costs.

The introduction of nuclear power in Estonia causes noteworthy changes in the projection of electricity generation and storage capacity (Figure 4-6). The model does not choose to add more than 900 MW of nuclear, but this capacity enables a substantial expansion of low-cost (and relatively low-capacity-factor) solar power. Compared to the Reference scenario, almost 2.6 GW more solar is built, along with more than 1 GW of additional batteries. These resources substitute for almost all of the offshore wind capacity in the Reference scenario. Overall, domestic investment in generation and storage is about €$_{2020}$ 2 billion higher than in the Reference scenario, and dispatchable capacity (including batteries) is about 2.3 GW higher. By 2050, about half of the country's generation and storage capacity is readily dispatchable (7.4 GW of 15 GW).

Figure 4-6: Nuclear + renewables + storage – electricity generation and storage capacity in Estonia

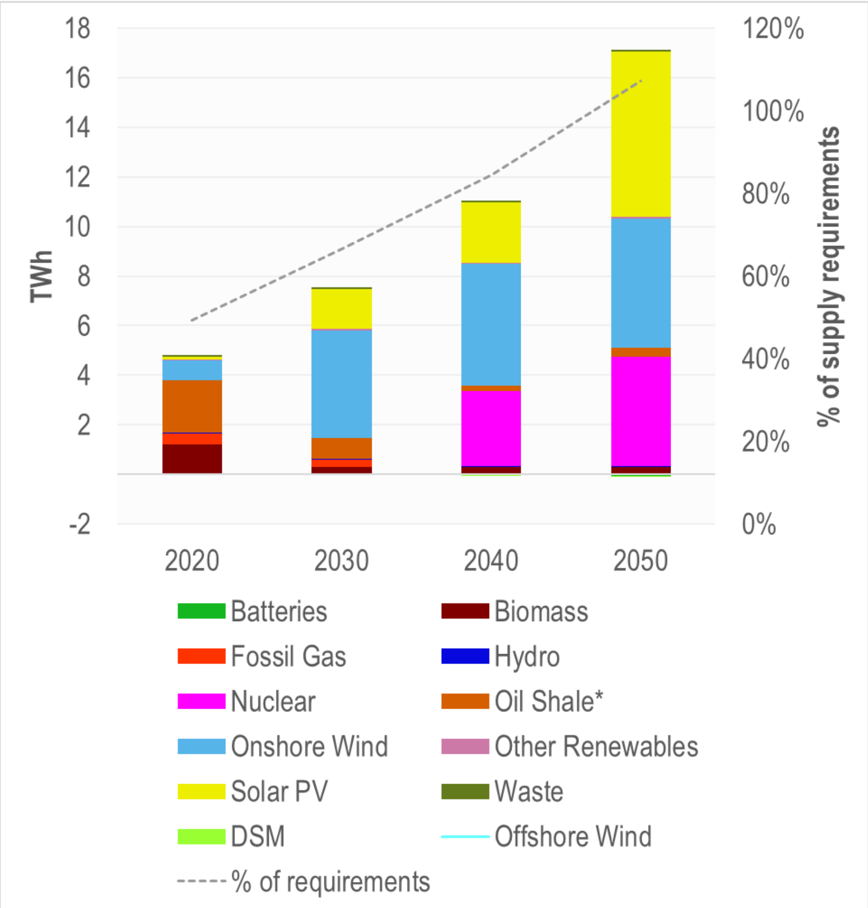


[27] New reactor designs (like the BWRX-300 considered in the model) will be deployed and tested in Canada in upcoming years, which will lead to further clarity on costs and operational profiles associated with the reactor type.

** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Once constructed, the nuclear facilities are used strategically throughout the year to facilitate solar and wind integration (Figure 4-8). They are ramped up especially in overnight periods and in the winter when solar output is lowest. Total nuclear generation in 2050 is about 60% of potential generation accounting for plant downtime.[28] The availability of nuclear leads to less balancing production from the former oil shale plants, whose output drops to 0.4 TWh in 2050 (Figure 4-7). In that year, solar generation is 2.7 TWh higher than in the Reference scenario, offshore wind generation is 3.3 TWh lower, and onshore wind generation is about the same.

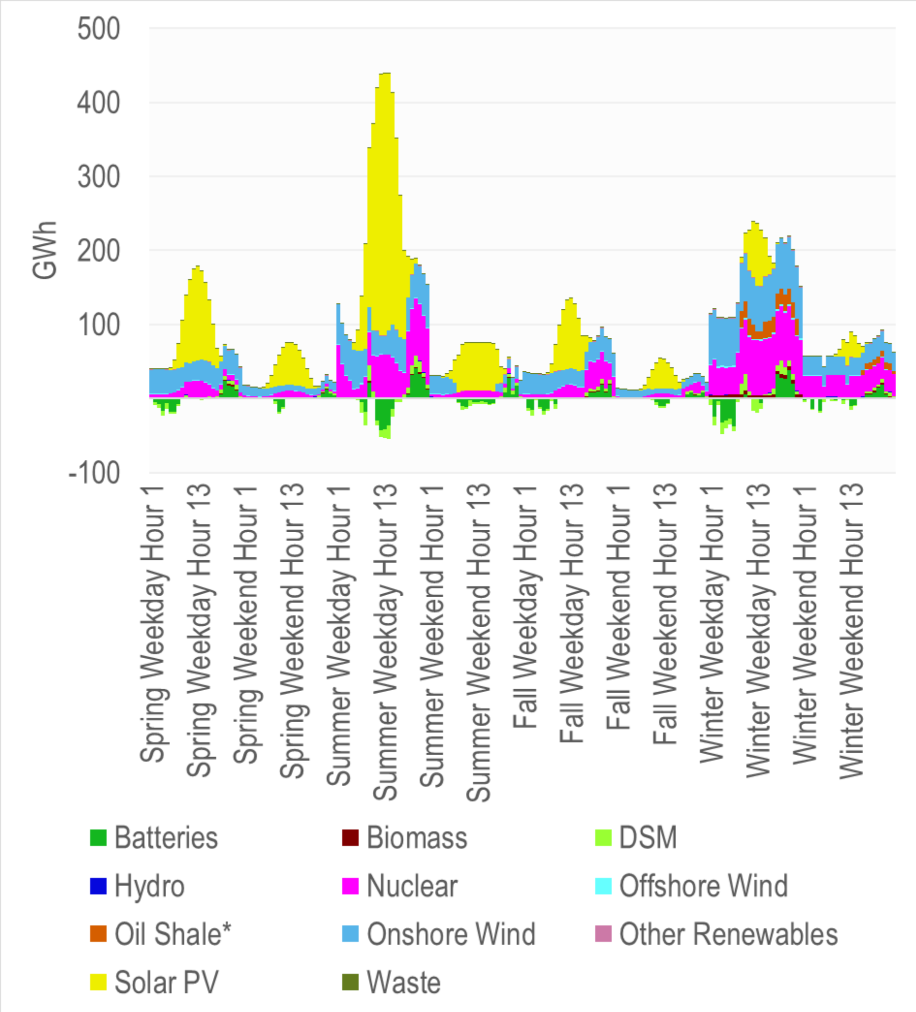
Figure 4-7: Nuclear + renewables + storage – net electricity generation in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

[28] Given feedback from Fermi Energia, it should be noted that the results presented for this scenario reflect how new nuclear plant designs might potentially play a different role in future energy systems (i.e., as a back-up for renewables). 60% dispatch for nuclear plants would be lower than observed rates in traditional plants, which typically fall between 80-90%. The impact of enforcing higher dispatch rates for nuclear plants will be tested in an upcoming sensitivity analysis.

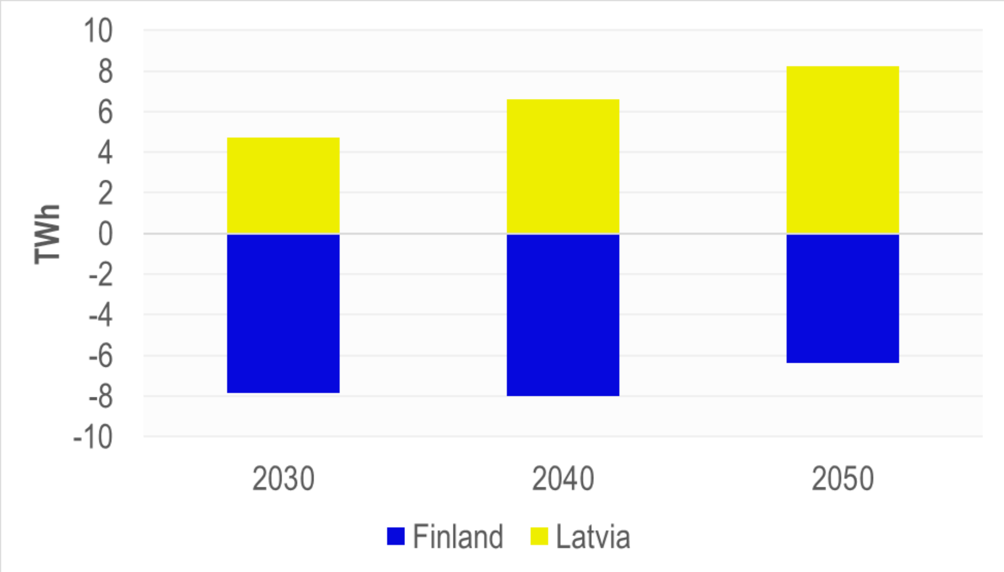
Figure 4-8: Nuclear + renewables + storage – time-sliced electricity generation in Estonia in 2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

As shown in Figure 4-7, the growth in nuclear and solar production yields positive net electricity exports by 2050. At the end of the projection, Estonia is exporting electricity to Latvia throughout the year and to Finland during peak solar production hours (mostly in the summer). Some imports from Finland occur at other times, most significantly in the winter and during overnight hours (Figure 4-9).

Figure 4-9: Nuclear + renewables + storage – electricity imports to (-) and exports from (+) Estonia



Meanwhile, projected average electricity prices in Estonia are within a few percentage points of those in the Reference scenario (Table 4-2). Carbon dioxide emissions from Estonian electricity production decrease to zero by 2050 with no need for direct air capture.

Table 4-2: Nuclear + renewables + storage – annual average electricity prices in Estonia

Year	Price ($€_{2020}$/kWh)
2030	0.1060
2040	0.1061
2050	0.0999

4.3 CCU + renewables + storage scenario

Key findings
• The estimated capacity for CO_2 utilization in Estonia is a binding restriction on the use of power plants with carbon capture. • This restriction leads to decreased output from Auvere and TG11 (compared to the Reference scenario) when these plants are retrofitted with carbon capture technology. • The lower effective availability of Auvere and TG11 inhibits the uptake of wind and solar in Estonia, increasing the need for electricity imports and raising long-run electricity prices.

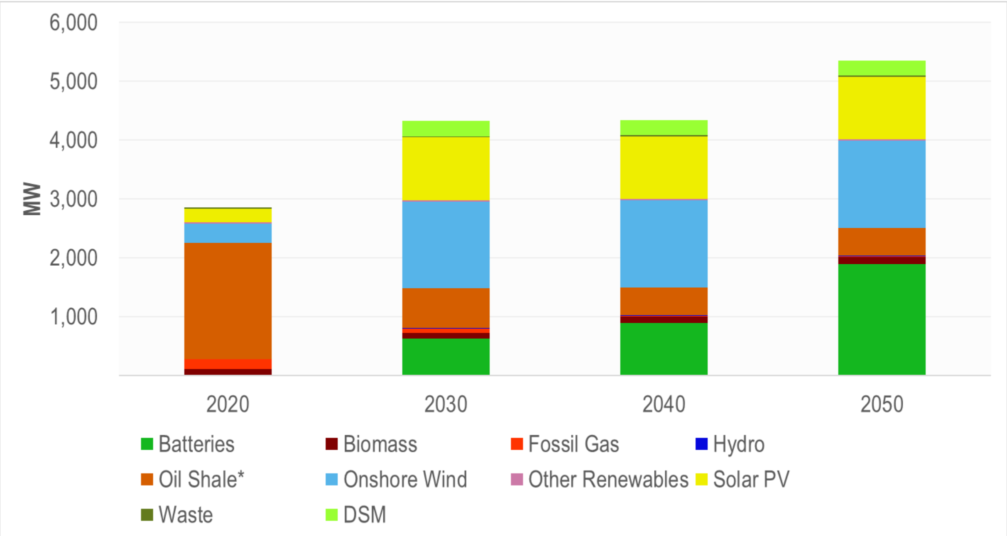
The CCU + renewables + storage pathway explores impacts of adding carbon capture to two large oil shale generators, TG11 and Auvere. The TG11 facility is outfitted with carbon capture at its scheduled refurbishment in 2025, and Auvere is upgraded in 2030. As in the other technology-focused pathways, there is a requirement of climate-neutral electricity production in Estonia by 2050, and the model is permitted to build supplemental storage and renewable generation in Estonia as shown in Table 2-2.

A key parameter in this scenario is the limit on CO_2 capture in Estonia: about 700 kt/year, based on industrial utilization potential (section 2.4.2). This circumscribes potential generation from the upgraded oil shale plants, holding it to about 0.9 TWh per year. The ceiling on generation in turn has effects on other parts of the electricity system.

As discussed in section 3.2, in the Reference scenario Auvere and TG11 are an important enabler of increased variable renewable generation in Estonia. Together with batteries, DSM, and imports, they are used to buffer seasonal, daily, and hourly fluctuations in wind and solar production. Their dispatchable generation helps make it cost-effective for Estonia to exploit substantial new wind and solar resources, including a non-negligible amount of offshore wind. By 2050, when growth in wind and solar have made Estonia almost self-sufficient in electricity, Auvere and TG11 are regularly utilized throughout the year. They have a combined capacity factor of 55% and generate 2.3 TWh of output.

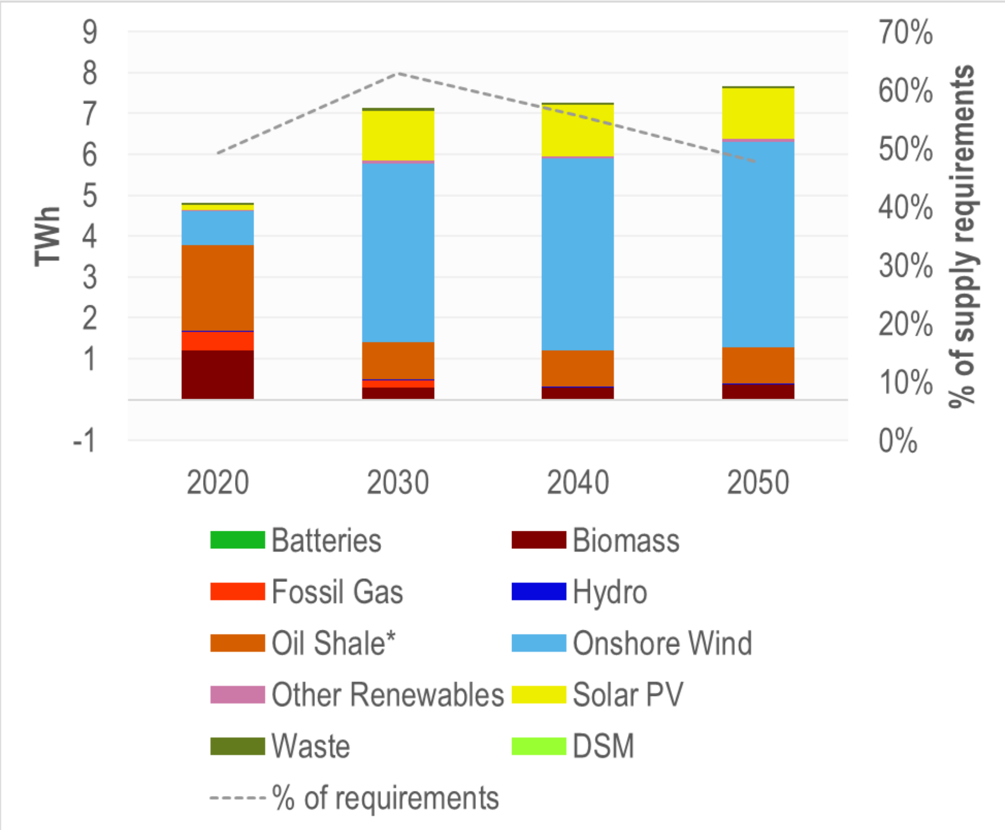
When these plants' utilization is limited in the CCU scenario, however, a lower build-out of wind and solar is achieved (Figure 4-10). Total Estonian generation and storage capacity in the CCU + renewables + storage scenario is 5.4 GW less than in the Reference scenario by 2050, a decline of about 50%. Solar PV and battery capacity is reduced, and no offshore wind is constructed (although the model does continue endogenously to add 1150 MW of onshore wind and 342 MW of solar by 2050). Over the projection, domestic investment in generation and storage is around €$_{2020}$ 1 billion less than in the Reference scenario.

Figure 4-10: CCU + renewables + storage – electricity generation and storage capacity in Estonia



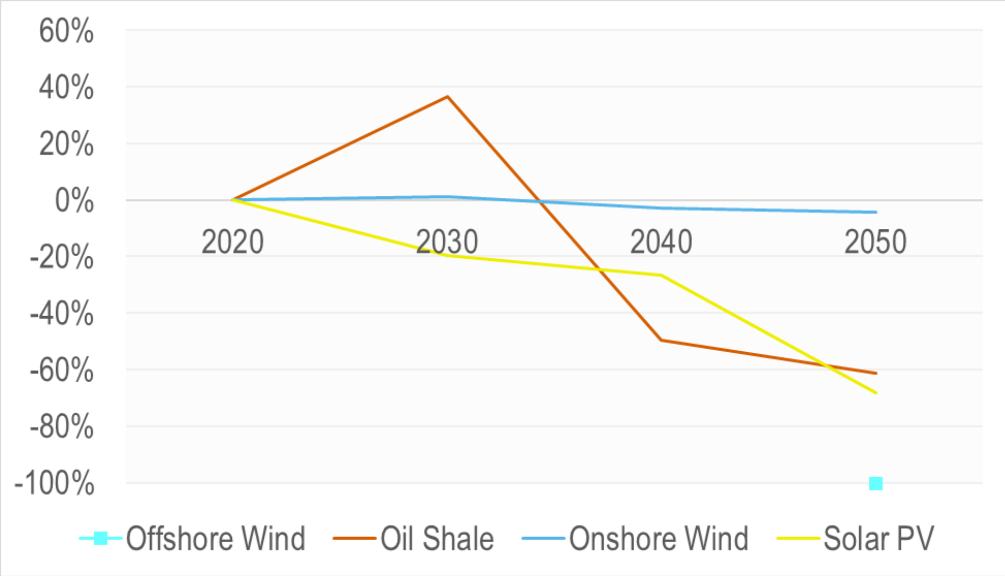
Concurrently, electricity production in Estonia decreases compared to the Reference case (Figure 4-11). Though production grows by about half from today's levels, this is only enough to keep pace with accelerating requirements from power-to-X adoption. The share of supply requirements met by domestic production remains around 50% through the projection. Generation from offshore wind, solar, and the former oil shale plants is cut most sharply relative to the Reference scenario (Figure 4-12); onshore wind production is not as strongly affected. As Figure 4-11 indicates, production from the CCU generation plants is maximized in 2030, 2040, and 2050 subject to the CO_2 utilization limit. The model dispatches Auvere in preference to TG11 due to its higher efficiency.

Figure 4-11: CCU + renewables + storage – net electricity generation in Estonia



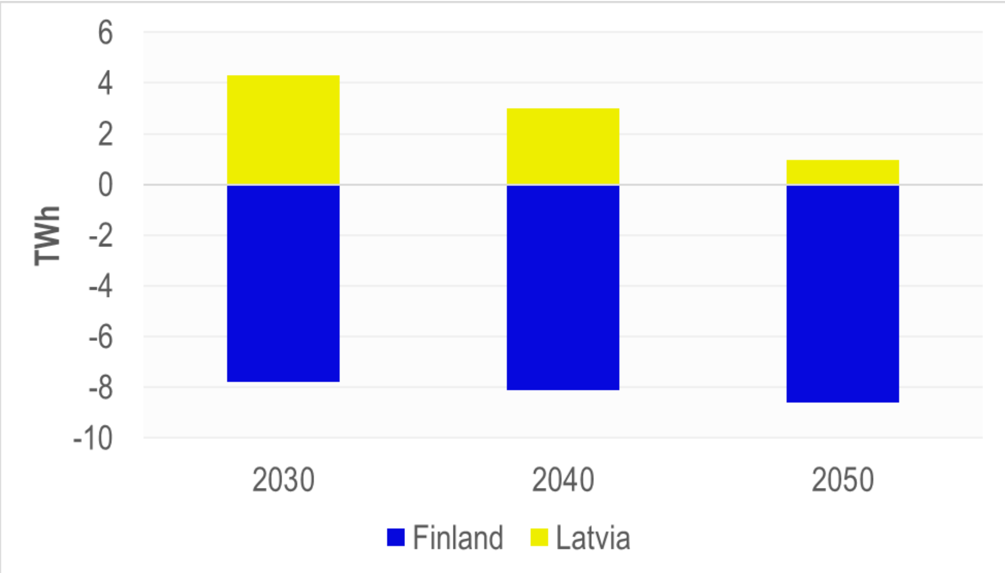
** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Figure 4-12: CCU + renewables + storage – % change in generation in Estonia compared to Reference scenario



Over the long run, Estonia has low net electricity exports to Latvia and significant net imports from Finland (Figure 4-13). The exports to Latvia occur mostly in the summer; some power from the Baltics is imported in other seasons. Imports from Finland are taken throughout the year.

Figure 4-13: CCU + renewables + storage – electricity imports to (-) and exports from (+) Estonia



Estimated average electricity prices in Estonia exceed those in the Reference scenario by about 7% by 2050 (Table 4-3). The need to import power during peak winter hours is a key factor behind this increase.

Table 4-3: CCU + renewables + storage – annual average electricity prices in Estonia

Year	Price (€$_{2020}$/kWh)
2030	0.1065
2040	0.1020
2050	0.1049

The climate neutrality target for Estonian electricity production in 2050 is achieved without using direct air capture. Because the Auvere and TG11 plants burn some biomass with carbon capture, they can be considered to generate negative emissions of CO_2 (300-400 kt/year), which could in principle offset emissions in other sectors.

4.4 Renewable gas + renewables + storage scenario

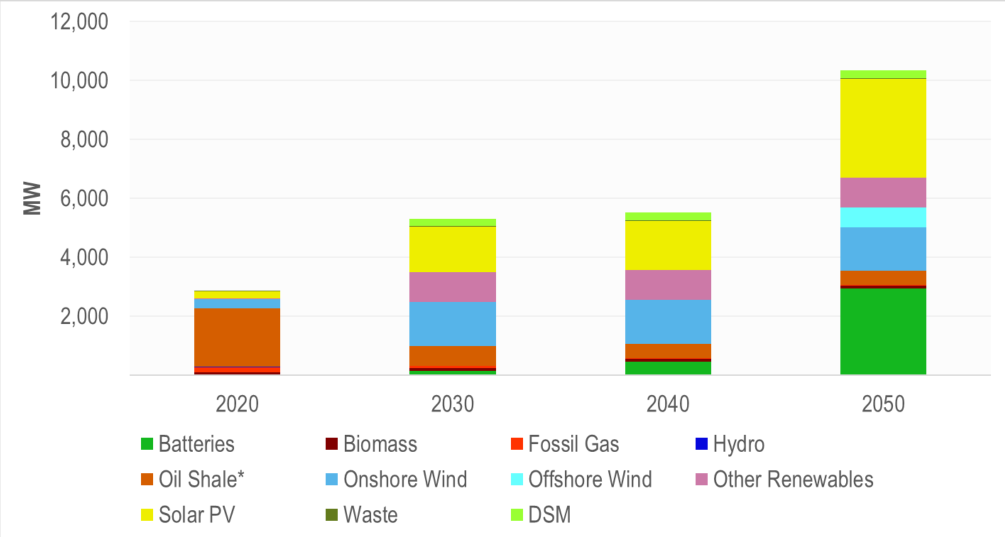
Key findings
• The high expected cost of biogas prevents meaningful utilization of biogas generators. • Adding 1 GW of biogas generation capacity in Estonia alters the mix of capacity used as system reserves, but it does not have an appreciable impact on electricity generation, imports and exports, or prices.

The Renewable gas + renewables + storage scenario models a pathway to climate-neutral electricity production in Estonia assuming implementation of 1 GW of new biogas generation by 2030. This capacity is evenly distributed among Estonia's NUTS 3 regions, and the biogas required to operate it is assumed to be freely available at the cost reported in Eesti Arengufond (2015). Like in the other technology-focused pathways, the model may endogenously add other renewable generation capacity and storage in Estonia (Table 2-2).

The new biogas capacity is essentially incorporated into the electricity system as reserve. Due to the high cost of biogas – about 80 €$_{2020}$/MWh, which is 2.5 times the projected cost of natural gas and more than four times the projected cost of biomass – it is not cost-effective to dispatch the biogas generators. As a result, the Renewable gas scenario ends up resembling the Reference scenario, which as noted above sees substantial decarbonisation of Estonian electricity production.

Figure 4-14 depicts generation and storage capacity in Estonia in the Renewable gas scenario. The new biogas, which is reported in the "Other Renewables" category, displaces batteries that are otherwise installed in the Reference scenario; this substitution rises to 1.4 GW by 2050. Some solar PV is built more quickly than in the Reference scenario, but the total deployment of solar over the long run is about the same. The investment in onshore and offshore wind is likewise comparable in the two scenarios.

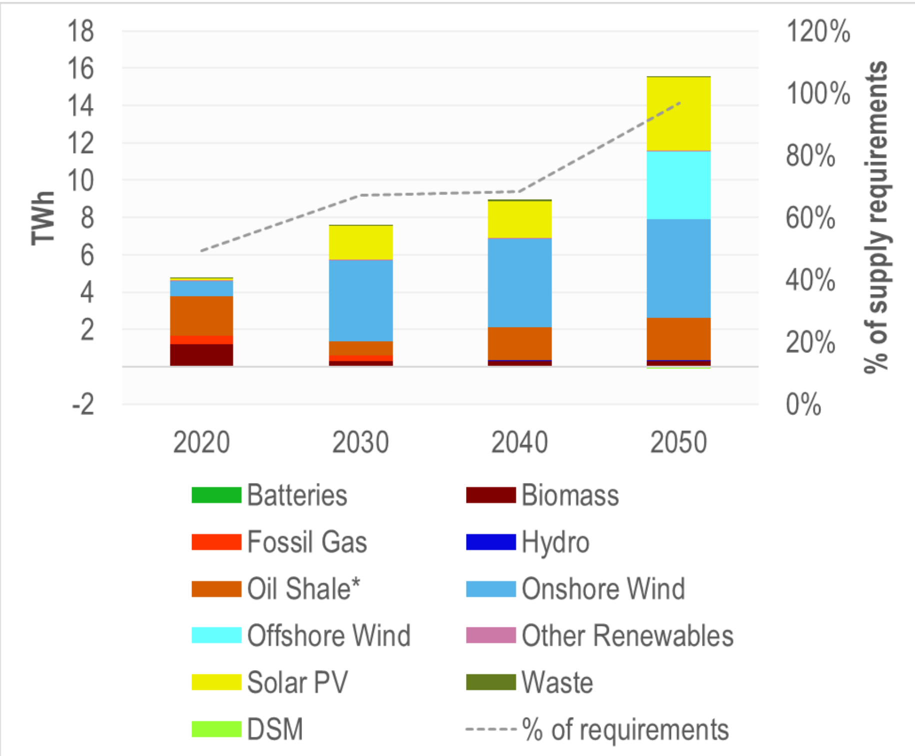
Figure 4-14: Renewable gas + renewables + storage – electricity generation and storage capacity in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

There are no significant differences between the Renewable gas and Reference scenarios in terms of generation, electricity imports and exports, or prices (Figure 4-15, Figure 4-16, Table 4-4).

Figure 4-15: Renewable gas + renewables + storage – net electricity generation in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Figure 4-16: Renewable gas + renewables + storage – electricity imports to (-) and exports from (+) Estonia

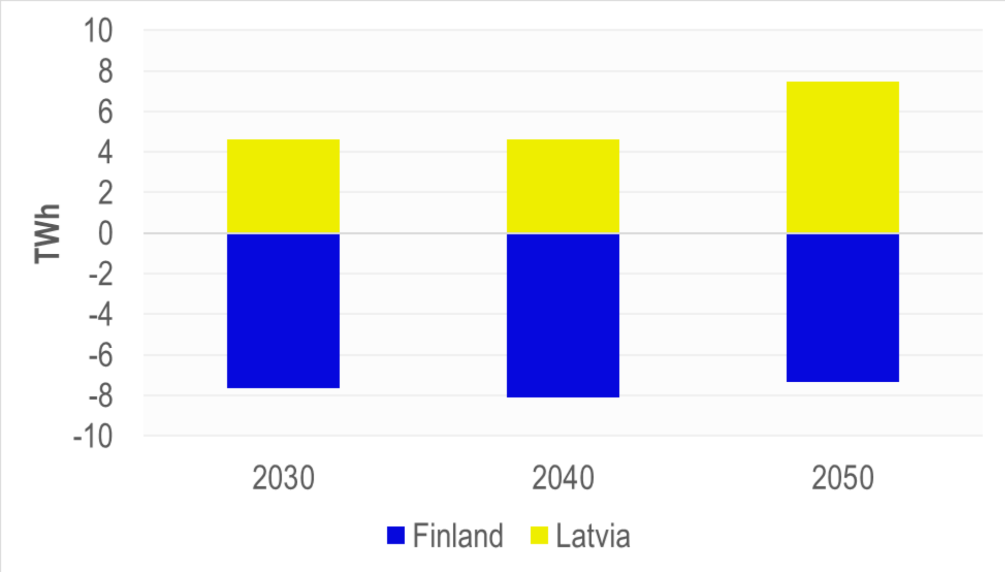


Table 4-4: Renewable gas + renewables + storage – annual average electricity prices in Estonia

Year	Price (€$_{2020}$/kWh)
2030	0.1057
2040	0.1028
2050	0.0989

The decarbonisation target is attained without relying on direct air capture, and by the end year power sector GHG emissions in Estonia consist of a small amount of CH_4 and N_2O from biomass combustion (about 43 kt of CO_2-equivalent).

5 Analysis of technology competition pathways

This section examines scenarios of climate-neutral electricity production in Estonia that take no power sector investments as a given except those in the Reference case. Starting with this baseline, the model is allowed to find the mix of additional investments that meets the climate neutrality target at least cost. Candidates for investment are as outlined in Table 2-2 and include renewable generation, CCU retrofits of oil shale plants, nuclear, energy storage, DSM, and transmission enhancements. The key objective is that by 2050, net CO_2 emissions from Estonian electricity production should be zero.

Three variants of this paradigm are considered: the All technologies scenario, which allows all investment options to compete on cost without further constraints; the All technologies + no net electricity imports scenario, which adds a requirement that net electricity imports into Estonia should be approximately zero; and the All technologies + 1000 MW scenario, which introduces a constraint that Estonia should have at least 1000 MW of readily dispatchable capacity at all times. Major findings from these cases are discussed below, emphasizing differences vis-à-vis each other and the Reference scenario.

5.1 All technologies scenario

Key findings

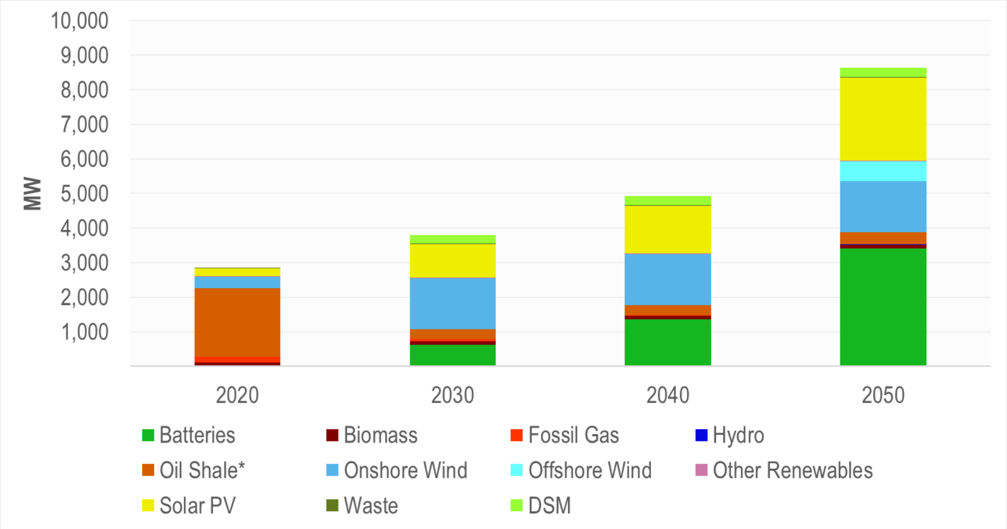
- A partial carbon capture upgrade at Auvere allows substantial utilization of this facility while respecting the climate neutrality requirement and the limit on CO_2 utilization in Estonia.
- The upgraded capacity at Auvere (along with battery storage, DSM, new transmission, and strategically used imports) facilitates the integration of significant solar and wind power in the Estonian grid.
- Estonian electricity production is climate neutral by 2050, and the import-export balance improves considerably over time.
- Projected average electricity prices in Estonia are similar to prices in the Reference case.

The All technologies scenario is the least constrained climate-neutral pathway explored in the Deliverable 3 modelling. Its results highlight a dynamic raised in the technology-focused pathways as well: the role of dispatchable generation in facilitating the grid integration of solar and wind power. In each of the technology-focused pathways, Estonia's major oil shale plants – Auvere and TG11, which are among the largest dispatchable generators in the country – are pivotal to enabling the exploitation of solar and wind resources. This relationship is most notably brought into focus in the CCU + renewables + storage scenario, in which Auvere and TG11 are retrofitted with carbon capture technology. As explained in section 4.3, limits on CO_2 utilization in Estonia restrict the dispatch of Auvere and TG11 once the CCU retrofit is complete. Lowering the potential use of these plants in turn inhibits the uptake of low-cost solar and wind and increases Estonia's electricity imports.

In the All technologies scenario, the model balances access to dispatchable oil shale capacity with the 2050 climate neutrality requirement. It implements a partial carbon capture upgrade at Auvere, corresponding to about 25% of the capture in the CCU + renewables + storage scenario. It also effectively retires at TG11. Partial carbon capture can have important technical and cost benefits (Hildebrand and Herzog 2009), and it may be a more realistic possibility for Auvere than full carbon capture since Eesti Energia does not at present envision adding carbon capture to its generation facilities (Tropp 2021). As compared to the CCU scenario, the partial capture upgrade allows for greater production from Auvere before hitting the national CO_2 utilization limit. The increased production is allowable under the climate neutrality target because the plant's non-biogenic CO_2 emissions are offset by captured biogenic CO_2 (following guidance from Eesti Energia, the input fuel mix contains 50% biomass). With the enhanced effective availability of Auvere, the implementation of variable renewables in Estonia is greater.

Figure 5-1 depicts the results in terms of electricity generation and storage capacity in Estonia. By 2050, solar PV capacity and battery capacity are each about 1 GW lower than in the Reference scenario, but they exceed the deployment in the CCU scenario by almost 3 GW. The model builds the same amount of onshore wind as in the Reference scenario, and a bit less offshore wind. To support the offshore wind, it adds 372 MW of new transmission between Lääne-Eesti and Lõuna-Eesti (about the same as in the Reference scenario) and 217 MW between Lääne-Eesti and Latvia (about 1/3 less than in the Reference scenario). Over the modelled period, there is $€_{2020}$ 178 million less investment in generation, storage, and transmission in Estonia compared to the Reference scenario, and $€_{2020}$ 144 million more compared to the CCU scenario.

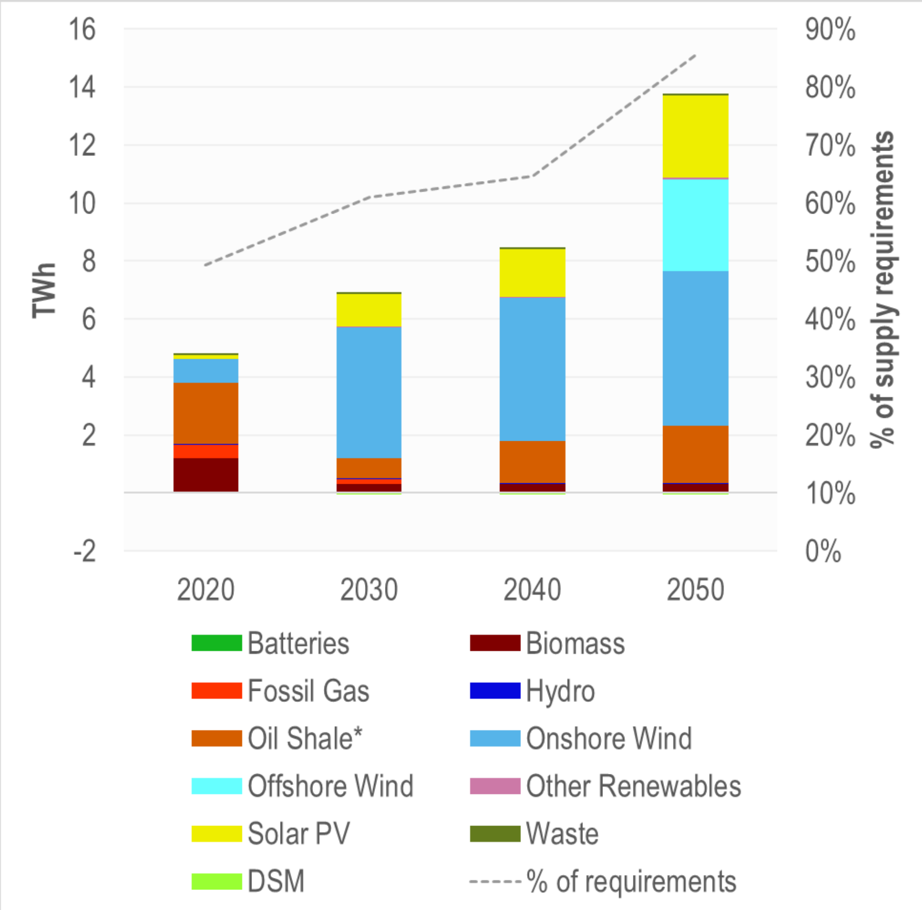
Figure 5-1: All technologies – electricity generation and storage capacity in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Turning to generation, the major oil shale plants are not utilized as completely as in the Reference case, so their output falls along with solar production (Figure 5-2). Somewhat lower offshore wind production is realized as well. Total net generation by 2050 is 1.6 TWh lower than in the Reference scenario but 6.1 TWh higher than in the CCU + renewables + storage scenario.

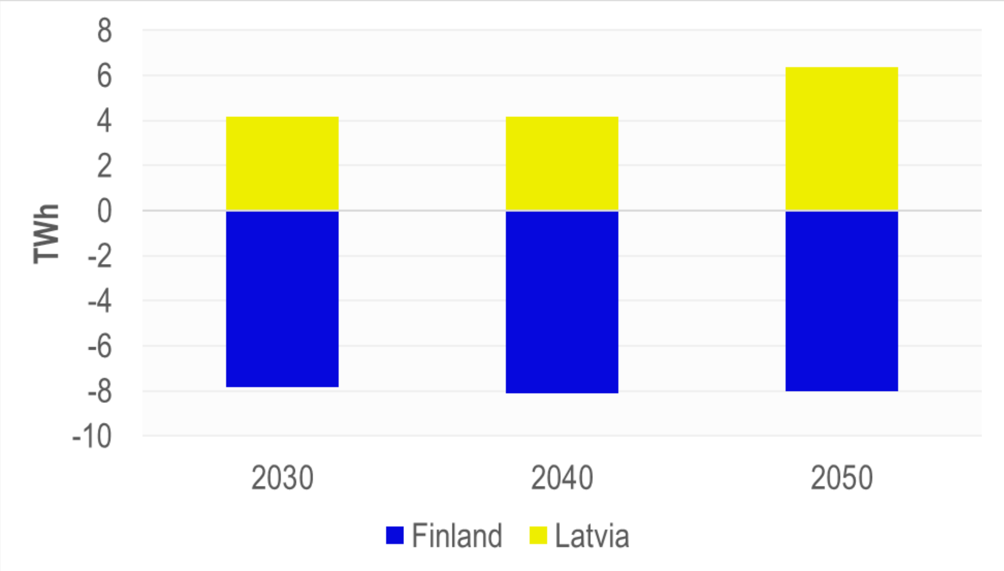
Figure 5-2: All technologies – net electricity generation in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

The reduced domestic generation relative to the Reference case means a greater reliance on imports. Net electricity imports into Estonia range between 2 and 4 TWh per year in the projection (Figure 5-3). Imports from Finland are higher, and exports to Latvia are lower, which induces a modest amount of additional onshore wind in Latvia. In comparison to the CCU + renewables + storage scenario, net imports are substantially lower in 2040 and 2050.

Figure 5-3: All technologies – electricity imports to (-) and exports from (+) Estonia



Estimated annual average electricity prices in Estonia are consistent with the prices in the Reference case (Table 5-1).

Table 5-1: All technologies – annual average electricity prices in Estonia

Year	Price (€$_{2020}$/kWh)
2030	0.1050
2040	0.1018
2050	0.0974

Estonia reaches the climate neutrality target in 2050 without direct air capture. The oil shale generation with partial carbon capture yields a small amount of negative CO_2 emissions from 2030 onwards (84-357 kt/year accounting for all emissions from Estonian power production).

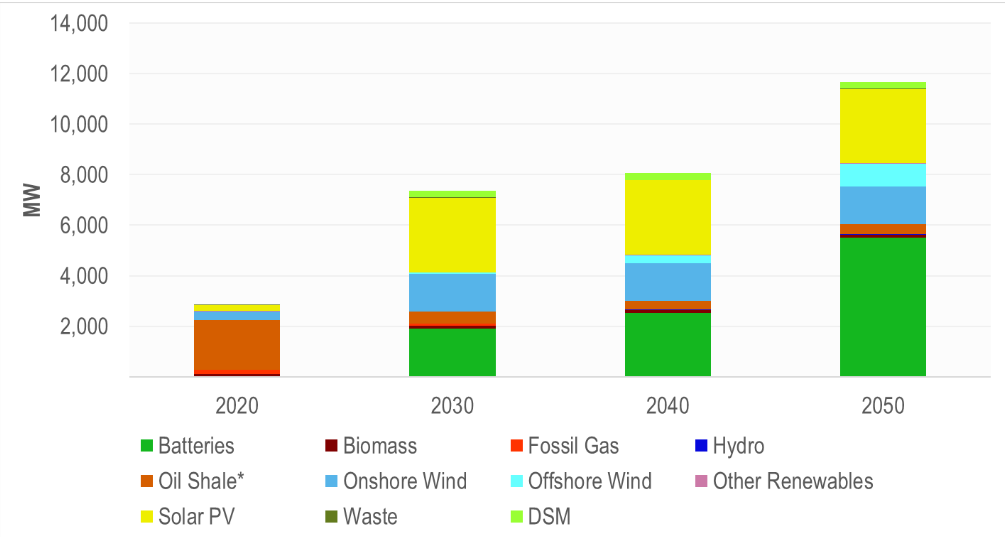
5.2 All technologies + no net electricity imports scenario

Key findings
• Modifying the All technologies pathway with a requirement that Estonia have no net electricity imports leads to increased investment in the national power system and domestic electricity production, notably from offshore wind and solar PV. • Almost 3 GW of solar PV and 1 GW of offshore wind are installed in Estonia by 2050, backed by increased investments in batteries, transmission, and oil shale retrofits (including a more extensive implementation of carbon capture at the Auvere plant). • Despite the restriction on net imports, Estonia continues importing power from Finland and exporting power to Latvia at certain times of the year. • Estimated average electricity prices in Estonia are a few percent lower than in the All technologies scenario.

This scenario adds to the All technologies pathway a requirement that Estonia's electricity imports and exports should approximately offset each other. This rule applies in all years of the simulation.

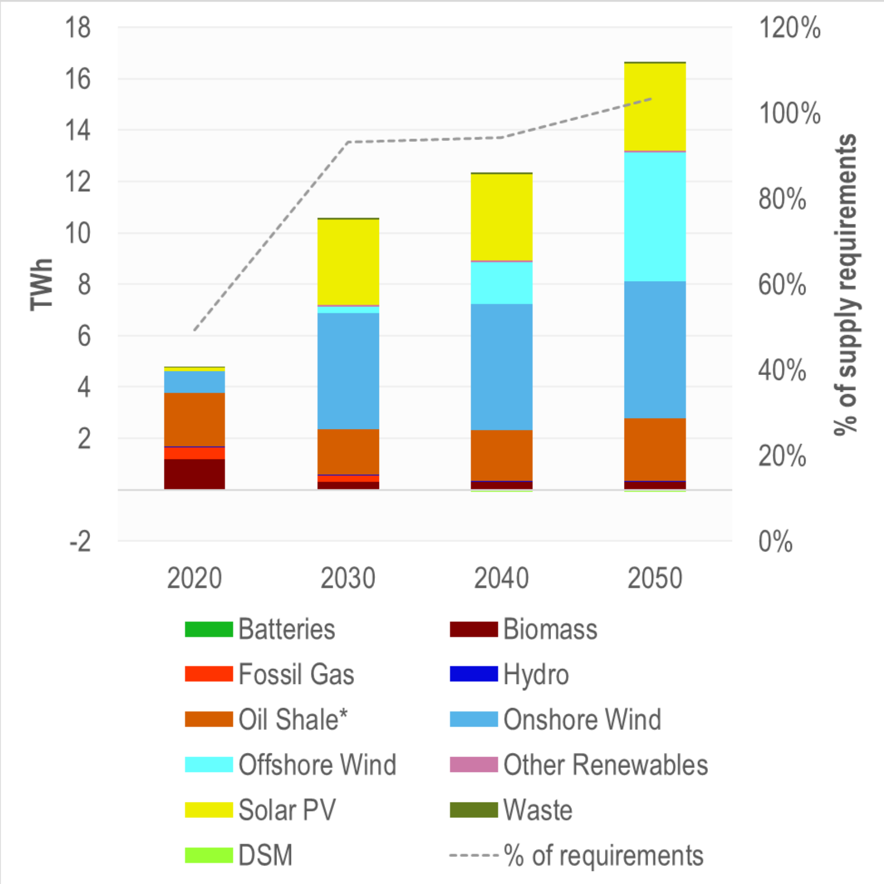
Unsurprisingly, the import restriction causes an increase in Estonian generation capacity and output in comparison to the All technologies scenario (Figure 5-4, Figure 5-5). The expansion is mostly predicated on offshore wind and solar PV. By the end of the projection, offshore wind capacity is 0.3 GW higher than in the All technologies scenario, solar PV capacity is 0.5 GW higher, and an additional 2.1 GW of batteries are installed. To support the offshore wind, the model constructs 200 MW of new transmission from Lääne-Eesti to Kesk-Eesti, 230 MW of new transmission from Lääne-Eesti to Lõuna-Eesti, and 480 MW of new transmission from Lääne-Eesti to Latvia. At the same time, a more extensive partial carbon capture upgrade is implemented at Auvere (35% of the capture in the CCU scenario); and TG11 is refurbished for continued use (without carbon capture). Through 2050, total investment in generation, storage, and transmission in Estonia is €$_{2020}$ 1.33 billion higher than in All technologies.

Figure 5-4: All technologies + no net electricity imports – electricity generation and storage capacity in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

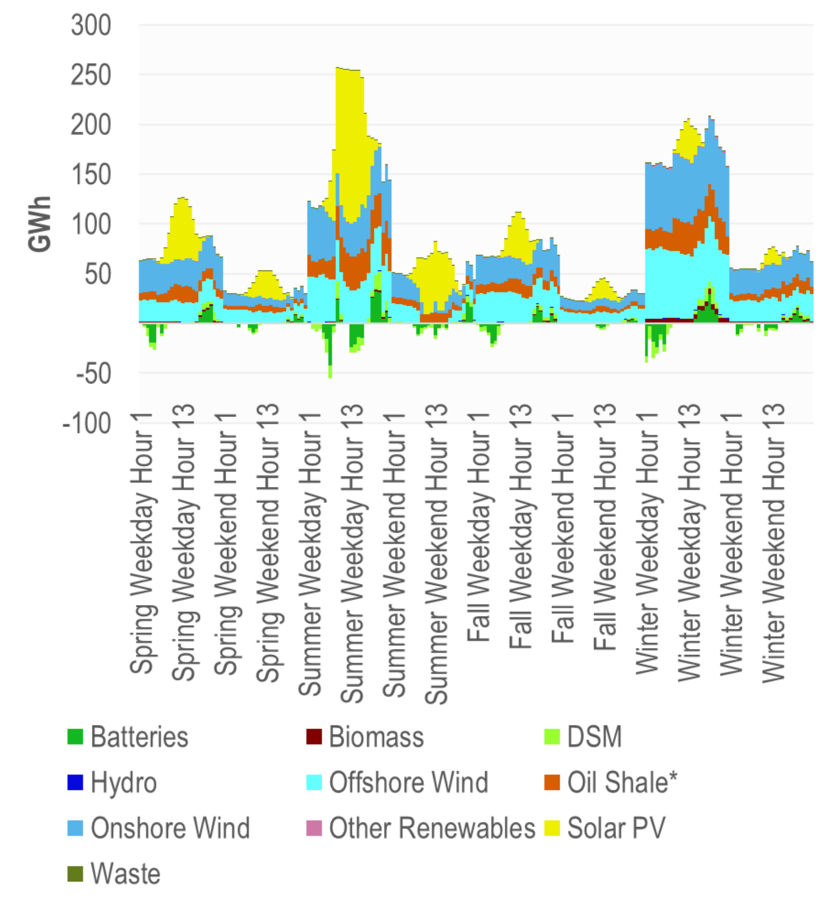
Figure 5-5: All technologies + no net electricity imports – net electricity generation in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Estonian electricity production is greater than in the All technologies case in all future years. The differences are largest in 2030 and 2040, reaching almost 4 TWh/year. In 2050, production exceeds the All technologies level by 2.9 TWh owing to 1.9 TWh of additional offshore wind generation, 0.6 TWh of additional solar, and approximately 0.5 TWh of additional output from the major oil shale plants. The oil shale capacity is used especially in the winter and at times of peak load (Figure 5-6). The model is able to increase the utilization of the oil shale plants without violating the climate neutrality target because there is captured biogenic CO_2 available to offset the greater fossil carbon emissions. Captured biogenic CO_2 is not fully allocated to offsets in the All technologies scenario as it is not cost-minimizing to do so.

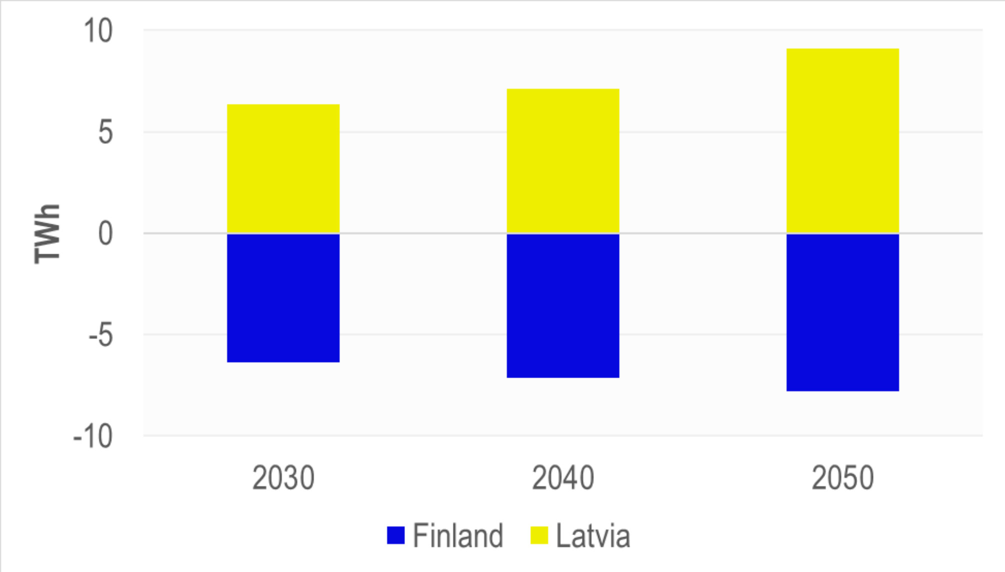
Figure 5-6: All technologies + no net electricity imports – time-sliced electricity generation in Estonia in 2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Although net imports of electricity into Estonia are essentially zero in future years, imports and exports do continue (Figure 5-7). Exports to Latvia are consistent across years and include surplus solar production in the summer and wind production in the winter. Imports from Finland are greatest during overnight and winter periods when solar output is reduced.

Figure 5-7: All technologies + no net electricity imports – electricity imports to (-) and exports from (+) Estonia



Projected electricity prices in Estonia are 1-4% lower than in the All technologies and Reference scenarios (Table 5-2). As in the All technologies scenario, the 2050 climate neutrality goal is met without direct air capture and with small negative power-sector CO_2 emissions.

Table 5-2: All technologies + no net electricity imports – annual average electricity prices in Estonia

Year	Price (€$_{2020}$/kWh)
2030	0.1014
2040	0.1015
2050	0.0959

5.3 All technologies + 1000 MW scenario

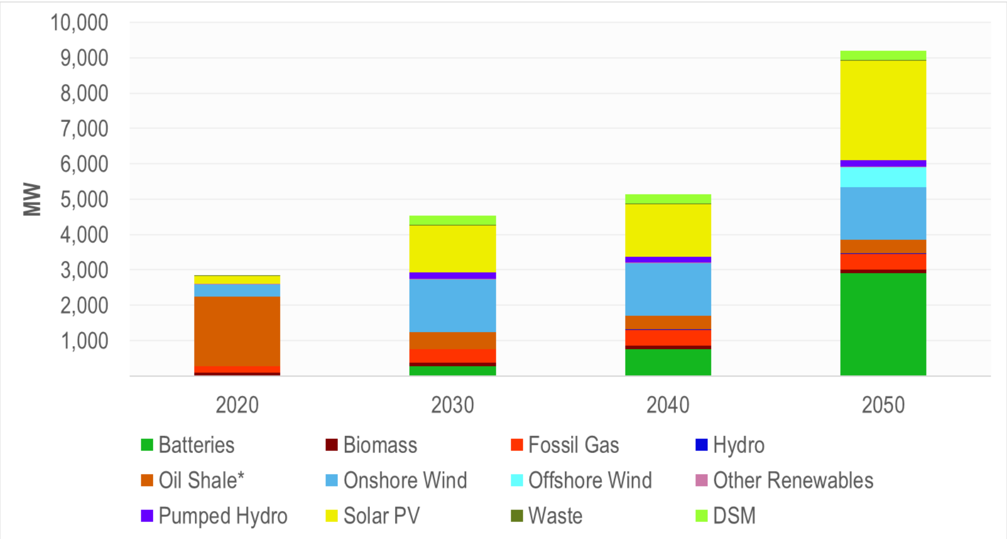
Key findings

- The Auvere and TG11 plants, one phase of the Paldiski pumped hydro facility, and 440 MW of new open cycle gas are used to satisfy a requirement of 1000 MW of dispatchable capacity in Estonia.
- Higher dispatchable capacity in Estonia (compared to the All technologies scenario) enables the construction and utilization of 425 MW of additional solar PV.
- The new solar and dispatchable resources augment Estonia's electricity generation and cause a small reduction in net electricity imports.
- Average electricity prices and GHG emissions from electricity production in Estonia are slightly higher than in the All technologies case.

This scenario reassesses the All technologies pathway with a constraint that Estonia have at least 1000 MW of readily dispatchable electricity production capacity at all times. Technologies qualifying toward the 1000 MW requirement include non-CHP fossil fuel, biomass, and biogas; nuclear; landfill gas; and the Paldiski pumped hydro facility. Batteries are excluded.

As shown in Figure 5-8, the model satisfies the new constraint by adding open cycle gas turbines (440 MW) and one phase of the Paldiski plant (174 MW). Essentially the same carbon capture retrofit of Auvere is performed as in the All technologies scenario, and TG11 is refurbished and retained without carbon capture. These changes in dispatchable capacity allow the model to forgo 500 MW of batteries by 2050, and to build an additional 425 MW of solar PV by that year.

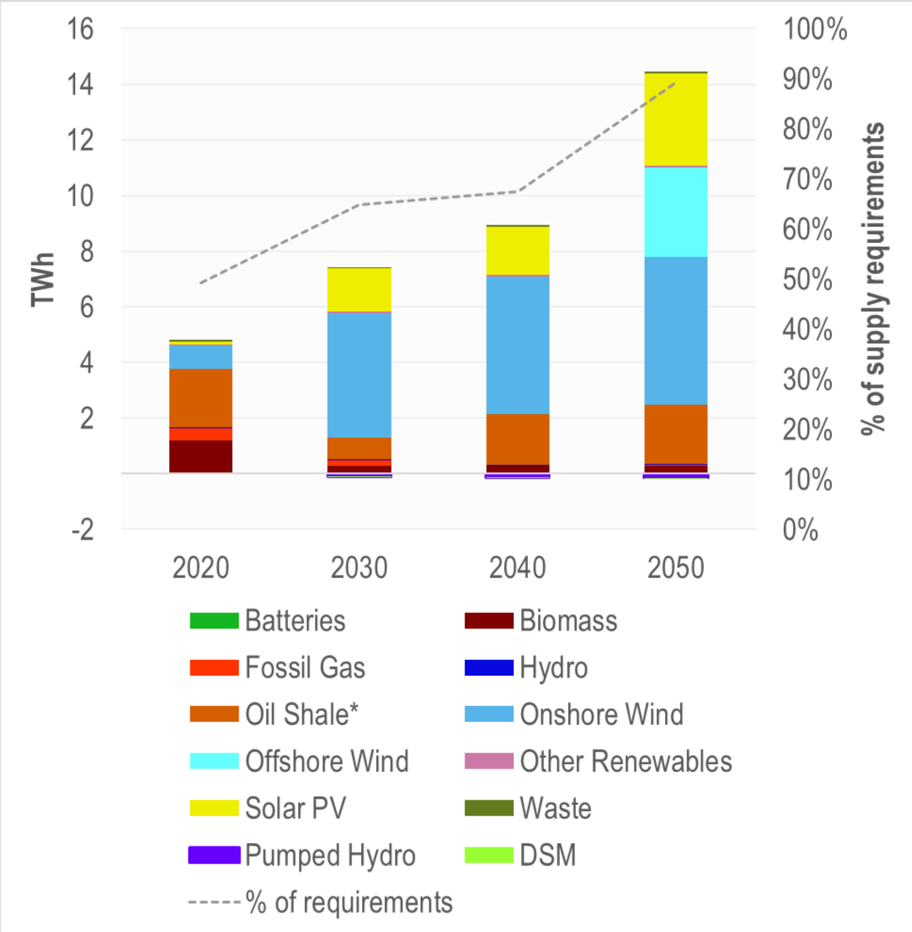
Figure 5-8: All technologies +1000 MW – electricity generation and storage capacity in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Electricity generation in Estonia is broadly the same as in the All technologies scenario, excepting output from the additional solar PV (about 0.5 TWh by 2050; Figure 5-9). The extra solar creates a small improvement in the import-export balance – on the order of a few percent of supply requirements covered by domestic production each year. The open cycle gas is dispatched sparingly, at times of peak load, and the pumped hydro is used both to capture surplus wind production in overnight hours and to move solar production from mid-day to the early evening.

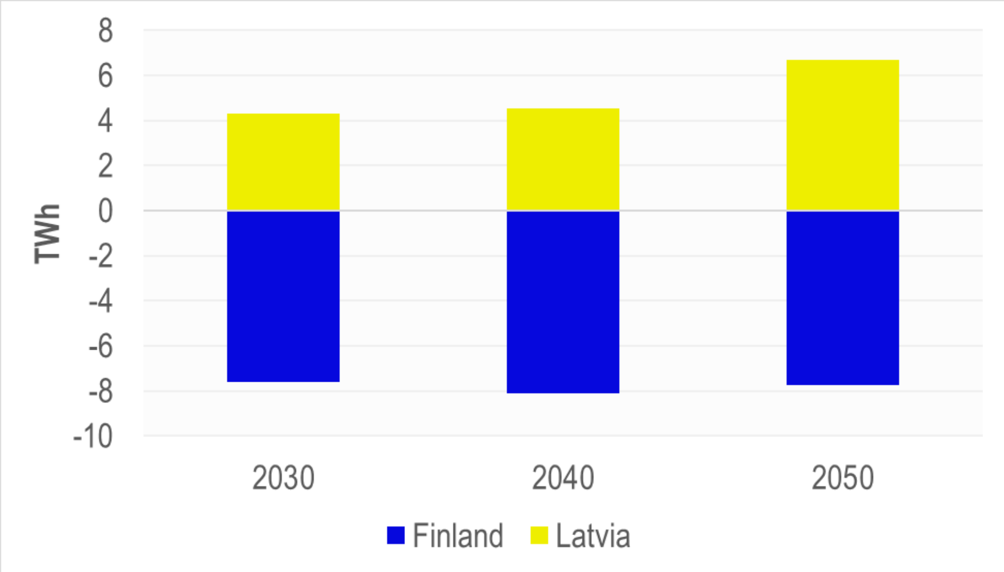
Figure 5-9: All technologies +1000 MW – net electricity generation in Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Consistent with these outcomes, the flow of electricity imports and exports in Estonia does not change much from the All technologies scenario (Figure 5-10). Estonia continues to export power to Latvia, including solar generation in the summer and wind generation in the winter, and to import from Finland when needed throughout the year.

Figure 5-10: All technologies + 1000 MW – electricity imports to (-) and exports from (+) Estonia



Average electricity prices in Estonia are marginally higher (1-2%) than in the All technologies scenario (Table 5-3). GHG emissions from Estonian electricity production are also slightly higher than in the All technologies projection, with a maximum difference of 104 kt of CO_2-equivalent realized in 2050. The climate neutrality target is still achieved, however, due to negative CO_2 emissions from generation at Auvere with carbon capture.

Table 5-3: All technologies + 1000 MW – annual average electricity prices in Estonia

Year	Price ($€_{2020}$/kWh)
2030	0.1060
2040	0.1038
2050	0.0986

6 Comparison of results across pathways

Key findings

- Driven by cost differences, Estonian electricity production shifts from oil shale toward wind and solar in all climate-neutral scenarios (70-85% of domestic generation from wind and solar by 2050). Fluctuations in wind and solar output are balanced by dispatchable generation, storage, DSM, and electricity imports. Among these options, batteries and DSM are particularly cost-competitive across scenarios. A **large build-out of batteries is projected due to their flexibility and declining costs (1.9-5.7 GW** in Estonia by 2050).
- There are reliability advantages to developing wind and solar power together in Estonia owing to complementarity in the availability of wind and solar resources.
- Onshore wind is generally more cost-competitive than offshore wind across scenarios. In most climate-neutral pathways, the **full modelled potential for onshore wind in Estonia is exploited (1.5 GW**). Notwithstanding, some **offshore wind is projected to be installed in Estonia in nearly every pathway (0.6-0.9 GW**). New transmission investments are needed to support these offshore installations (0.6-1.3 GW between Lääne-Eesti and other regions).
- The Auvere and TG11 oil shale plants are a key source of dispatchable capacity in the Estonian system (274 and 192 MW respectively) and could play an important role in integrating variable renewable power. They could be made compatible with high carbon prices by switching to biomass fuel and/or adding carbon capture capabilities (including partial carbon capture).
- In most climate-neutral pathways, Estonia sharply reduces its net electricity imports by 2050, with domestic generation covering 85% or more of **national electricity supply requirements (i.e., 13.6 TWh or more) by that year.**
- Projected wholesale electricity prices in Estonia are higher in all climate-neutral pathways than they are today, but prices generally decrease between 2030 and 2050. **Across scenarios, projected prices range between 0.096 and 0.11 €$_{2020}$/kWh in the 2030-2050 period (0.101-0.11 €$_{2020}$/kWh in 2030, 0.096-0.105 €$_{2020}$/kWh in 2050).**
- Investments in generation capacity in Estonia tend to improve the electricity import-export balance and reduce electricity prices. These results occur even if the investments are not cost-minimizing from the perspective of the entire modelled area (i.e., considering the electricity system in all modelled countries). The Renewables + storage pathway, which includes a 4 GW investment in offshore wind in Estonia by 2050, shows these dynamics most clearly. Of all the climate-neutral scenarios, it envisions the largest increase in net electricity exports from Estonia (10.4 TWh by 2050) and the second-lowest long-run electricity prices (0.097 €$_{2020}$/kWh by 2050).
- Cross-scenario insights about Estonian generation, capacity, net imports, and electricity prices likely hold over a range of potential future ETS prices.

This section provides a side-by-side comparison of the modelled scenarios' key inputs and results. Scenario-specific assumptions and calculations are discussed in more detail in previous sections, but analysing all scenarios in conjunction highlights synoptic insights from the Deliverable 3 modelling.

Table 6-1 summarises the core assumptions behind each modelled scenario and results on capacity build-up for 2030 and 2050. Table 6-2 delineates the main results for electricity generation in the same years. Capacity and generation projections are further explored in Figure 6-1, Figure 6-2, and Figure 6-3.

Table 6-1: Pathway comparison – assumptions and capacity results for 2030 and 2050

	Pathway	Core assumptions[29]	Capacity in Estonia (MW by 2030)														
			Batteries	*Biogas & other renewables*	*Biomass*	*DSM*	*Fossil gas*	*Hydro*	*Nuclear*	*Offshore wind*	*Onshore wind*	*Oil shale (inc. CCU)*[30]	*Pumped hydro*	*Solar PV*	*Waste*	*Total*	*% Dispatchable*[31]
Baseline	**Business as usual**	- EU Reference Scenario 2020 projections of electricity demand, generation and storage capacity, and ETS price - No climate neutrality requirement	391	20	101	261	70	8	0	0	429	676 (biomass, retort gas)	0	725	19	2699	48%
Baseline	**Reference**	- BAU unconstrained by EU Reference Scenario 2020 capacity projections - Includes demand for economically feasible levels of power-to-X	640	20	101	261	70	8	0	0	1479	676 (biomass, retort gas)	0	1327	19	4601	35%
Technology-focused	**Renewables + storage (offshore wind)**	- 1 GW offshore wind installed in Estonia by 2030, 2 by 2035, 3 by 2040, 4 by 2050	984	20	101	261	70	8	0	1000	529	676 (biomass, retort gas)	0	1057	19	4725	41%
Technology-focused	**Nuclear**	- 900 MW Gen III+ small modular reactor capacity built in Estonia by 2040	616	20	101	261	70	8	0	0	1479	676 (biomass, retort gas)	0	1393	19	4644	34%
Technology-focused	**CCU**	- Carbon capture added to TG11 in 2025 and Auvere in 2030	623	20	101	261	70	8	0	0	1479	676 (biomass, oil shale, retort gas)	0	1067	19	4323	37%
Technology-focused	**Renewable gas**	- 1 GW of renewable gas capacity built in Estonia by 2030	137	1020	101	261	70	8	0	0	1479	676 (biomass, retort gas)	0	1539	19	5310	40%
Technology competition	**All technologies**	- Investments in all low-carbon technologies allowed - No additional constraints on imports or capacity	615	20	101	261	70	8	0	0	1479	279 (biomass, oil shale, retort gas)	0	951	19	3803	31%
Technology competition	**1000 MW dispatchable capacity**	- Investments in all low-carbon technologies allowed - At least 1000 MW of dispatchable capacity installed in Estonia at all times	277	20	101	261	379	8	0	0	1479	483 (biomass, oil shale, retort gas)	174	1330	19	4532	34%
Technology competition	**No net imports**	- Investments in all low-carbon technologies allowed - Balanced electricity imports/exports into/out of Estonia each year	1921	20	101	261	70	8	0	59	1479	483 (biomass, oil shale, retort gas)	0	2945	19	7366	37%

29 In the technology-focused and technology competition pathways, no net non-biogenic CO_2 emissions are allowed from electricity production in Estonia in 2050, and direct air capture of CO_2 is available. Each technology-focused pathway requires an investment in a core low-carbon technology, with additional investments in all storage and renewable generation technologies (e.g., onshore wind, solar PV, Paldiski hydro plant, batteries) permitted. Full definitions of all scenarios are provided in section 2.5.

30 The oil shale category in this table refers to Estonian plants that were originally constructed to burn oil shale. In all of the modelled scenarios, large oil shale plants are converted to use 100% biomass by the early 2030s unless they are retrofitted with carbon capture (see section 2.4.2). Carbon capture retrofits are only allowed in certain cases, however: in the CCU + renewables + storage pathway and the All technologies pathways (see section 2.5). In other scenarios, capacity in the oil shale category essentially represents biomass after 2035. Fuels used by the capacity are shown in parentheses.

31 Dispatchable capacity in this table includes non-CHP fossil fuel, biomass, and biogas; nuclear; landfill gas; pumped hydro; batteries; and DSM.

	Pathway	Core assumptions[32]	Capacity in Estonia (MW by 2050)														
			Batteries	*Biogas & other renewables*	*Biomass*	*DSM*	*Fossil gas*	*Hydro*	*Nuclear*	*Offshore wind*	*Onshore wind*	*Oil shale (inc. CCU)*[33]	*Pumped hydro*	*Solar PV*	*Waste*	*Total*	*% Dispatchable*[34]
Baseline	**Business as usual**	- EU Reference Scenario 2020 projections of electricity demand, generation and storage capacity, and ETS price - No climate neutrality requirement	818	20	101	261	16	8	0	0	429	476 (biomass)	0	725	19	2873	54%
Baseline	**Reference**	- BAU unconstrained by EU Reference Scenario 2020 capacity projections - Includes demand for economically feasible levels of power-to-X	4386	20	101	261	16	8	0	619	1479	476 (biomass)	0	3397	19	10782	48%
Technology-focused	**Renewables + storage (offshore wind)**	- 1 GW offshore wind installed in Estonia by 2030, 2 by 2035, 3 by 2040, 4 by 2050	5190	20	123	261	16	8	0	4000	529	476 (biomass)	0	1057	19	11699	51%
Technology-focused	**Nuclear**	- 900 MW Gen III+ small modular reactor capacity built in Estonia by 2040	5749	20	101	261	16	8	900	31	1479	476 (biomass)	0	5986	19	15047	49%
Technology-focused	**CCU**	- Carbon capture added to TG11 in 2025 and Auvere in 2030	1885	20	123	261	16	8	0	0	1479	476 (biomass, oil shale, retort gas)	0	1067	19	5354	49%
Technology-focused	**Renewable gas**	- 1 GW of renewable gas capacity built in Estonia by 2030	2939	1020	101	261	16	8	0	656	1479	476 (biomass)	0	3362	19	10337	45%
Technology competition	**All technologies**	- Investments in all low-carbon technologies allowed - No additional constraints on imports or capacity	3403	20	101	261	16	8	0	573	1479	344 (biomass, oil shale, retort gas)	0	2402	19	8626	46%
Technology competition	**1000 MW dispatchable capacity**	- Investments in all low-carbon technologies allowed - At least 1000 MW of dispatchable capacity installed in Estonia at all times	2903	20	101	261	456	8	0	572	1479	385 (biomass, oil shale, retort gas)	174	2827	19	9204	45%
Technology competition	**No net imports**	- Investments in all low-carbon technologies allowed - Balanced electricity imports/exports into/out of Estonia each year	5509	20	101	261	16	8	0	902	1479	418 (biomass, oil shale, retort gas)	0	2945	19	11678	53%

32 In the technology-focused and technology competition pathways, no net non-biogenic CO_2 emissions are allowed from electricity production in Estonia in 2050, and direct air capture of CO_2 is available. Each technology-focused pathway requires an investment in a core low-carbon technology, with additional investments in all storage and renewable generation technologies (e.g., onshore wind, solar PV, Paldiski hydro plant, batteries) permitted. Full definitions of all scenarios are provided in section 2.5.

33 The oil shale category in this table refers to Estonian plants that were originally constructed to burn oil shale. In all of the modelled scenarios, large oil shale plants are converted to use 100% biomass by the early 2030s unless they are retrofitted with carbon capture (see section 2.4.2). Carbon capture retrofits are only allowed in certain cases, however: in the CCU + renewables + storage pathway and the All technologies pathways (see section 2.5). In other scenarios, capacity in the oil shale category essentially represents biomass after 2035. Fuels used by the capacity are shown in parentheses.

34 Dispatchable capacity in this table includes non-CHP fossil fuel, biomass, and biogas; nuclear; landfill gas; pumped hydro; batteries; and DSM.

Table 6-2: Pathway comparison – net generation[35] results for 2030 and 2050

Pathway		Net generation in Estonia (GWh in 2030)																		
											Oil shale (inc. CCU)[36]									
		Batteries	*Biogas & other renewables*	*Biomass*	*DSM*	*Fossil gas*	*Hydro*	*Nuclear*	*Offshore wind*	*Onshore wind*	*Biomass*	*Oil Shale*	*Retort Gas*	*Pumped hydro*	*Solar PV*	*Waste*	*Total*	**Share of domestic electricity production requirements[37] met**	**Net exports (TWh)**	**Top sources**
Baseline	**Business as usual**	-4.17	60.01	300.06	-16.82	322.94	28.78	0.00	0.00	1317.32	718.78	96.65	240.02	0.00	835.43	62.99	3962.01	39%	-6.2	1. Onshore wind 2. Oil shale 3. Solar PV
	Reference	-7.55	60.01	300.06	-16.42	385.62	28.78	0.00	0.00	4339.11	359.48	96.93	193.57	0.00	1538.54	62.99	7341.13	65%	-4.0	1. Onshore wind 2. Solar PV 3. Oil shale
Technology-focused	**Renewables + storage (offshore wind)**	-11.73	60.01	300.06	-15.60	312.32	28.78	0.00	4219.85	1614.01	715.22	95.15	339.57	0.00	1220.49	62.99	8941.11	79%	-2.4	1. Offshore wind 2. Onshore wind 3. Solar PV
	Nuclear	-7.09	60.01	300.06	-15.77	305.64	28.78	0.00	0.00	4331.37	483.54	94.49	260.37	0.00	1610.23	62.99	7514.63	67%	-3.8	1. Onshore wind 2. Solar PV 3. Oil shale
	CCU	-7.37	60.01	300.06	-16.44	177.33	28.78	0.00	0.00	4387.53	396.51	213.55	277.56	0.00	1233.78	62.99	7114.30	63%	-4.2	1. Onshore wind 2. Solar PV 3. Oil shale
	Renewable gas	-1.78	60.01	300.06	-17.54	299.77	28.78	0.00	0.00	4322.40	427.71	94.15	230.30	0.00	1771.33	62.99	7578.19	67%	-3.7	1. Onshore wind 2. Solar PV 3. Oil shale
Technology competition	**All technologies**	-7.28	60.01	300.06	-16.14	170.41	28.78	0.00	0.00	4503.15	304.50	175.35	207.50	0.00	1096.32	62.81	6885.49	61%	-4.4	1. Onshore wind 2. Solar PV 3. Oil shale
	1000 MW dispatchable capacity	-3.47	60.01	300.06	-16.18	195.69	28.73	0.00	0.00	4481.28	355.11	177.75	238.13	-97.60	1537.75	62.99	7320.27	65%	-4.0	1. Onshore wind 2. Solar PV 3. Oil shale
	No net imports	-22.79	60.01	300.06	-17.09	250.53	28.78	0.00	246.39	4518.95	982.29	205.64	592.52	0.00	3318.36	62.99	10526.65	93%	-0.8	1. Onshore wind 2. Solar PV 3. Oil shale

[35] Net generation in this table refers to generation net of storage charging.

36 The oil shale category in this table refers to generation from Estonian plants that were originally constructed to burn oil shale. In all of the modelled scenarios, large oil shale plants are converted to use 100% biomass by the early 2030s unless they are retrofitted with carbon capture (see section 2.4.2). Carbon capture retrofits are only allowed in certain cases, however: in the CCU + renewables + storage pathway and the All technologies pathways (see section 2.5). In other scenarios, generation in the oil shale category is essentially all from biomass after 2035.

37 As used in this report, electricity supply or production requirements include all requirements for electricity within a modelled region (or regions): final electricity demand, electricity demand for other energy production (e.g., hydrogen), producer own-use, transmission and distribution losses within the region, and third-country exports from the region (which are modelled as additional final demand; see section 2.4.2).

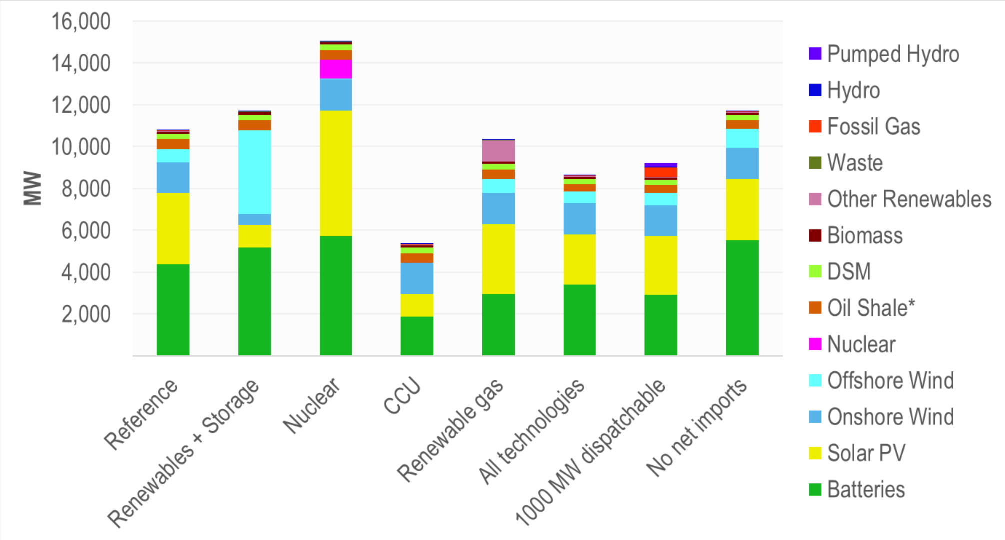
	Pathway	Net generation in Estonia (GWh in 2050)																		
		Batteries	Biogas & other renewables	Biomass	DSM	Fossil gas	Hydro	Nuclear	Offshore wind	Onshore wind	Oil shale (inc. CCU)[38]			Pumped hydro	Solar PV	Waste	Total	Share of domestic electricity production requirements[39] met	Net exports (TWh)	Top sources
											Biomass	Oil Shale	Retort Gas							
Baseline	**Business as usual**	-1.39	60.01	300.06	-6.77	46.94	28.78	0.00	0.00	911.30	146.25	0.00	0.00	0.00	763.78	62.99	2311.96	23%	-7.7	1. Onshore wind 2. Solar PV 3. Biomass
Baseline	**Reference**	-42.92	60.01	300.06	-16.41	46.94	28.78	0.00	3449.64	5269.81	2247.78	3.97	0.00	0.00	3921.43	62.99	15332.08	96%	-0.7	1. Onshore wind 2. Solar PV 3. Offshore wind
Technology-focused	**Renewables + storage (offshore wind)**	-21.11	60.01	365.43	-8.35	0.00	28.78	0.00	19331.29	1915.29	3421.87	42.95	0.00	0.00	1242.55	62.99	26441.70	165%	10.4	1. Offshore wind 2. Oil shale 3. Onshore wind
Technology-focused	**Nuclear**	-56.10	60.01	300.06	-18.63	0.00	28.78	4410.40	167.75	5220.70	367.67	0.00	0.00	0.00	6656.80	62.99	17200.44	107%	1.2	1. Solar PV 2. Onshore wind 3. Nuclear
Technology-focused	**CCU**	-8.26	60.01	365.43	-9.81	0.00	28.78	0.00	0.00	5040.22	396.51	199.55	277.56	0.00	1240.21	62.99	7653.18	48%	-8.4	1. Onshore wind 2. Solar PV 3. Oil shale
Technology-focused	**Renewable gas**	-33.86	60.01	300.06	-16.52	0.00	28.78	0.00	3660.15	5267.03	2287.53	4.14	0.00	0.00	3884.86	62.99	15505.18	97%	-0.5	1. Onshore wind 2. Solar PV 3. Offshore wind
Technology competition	**All technologies**	-30.95	60.01	300.06	-15.89	0.00	28.78	0.00	3176.32	5316.02	1616.47	187.31	196.67	0.00	2808.81	62.99	13706.61	86%	-2.3	1. Onshore wind 2. Offshore wind 3. Solar PV
Technology competition	**1000 MW dispatchable capacity**	-29.45	60.01	300.06	-16.27	9.33	28.49	0.00	3213.50	5295.42	1856.85	93.50	203.32	-125.89	3343.99	62.99	14295.86	89%	-1.7	1. Onshore wind 2. Solar PV 3. Offshore wind
Technology competition	**No net imports**	-38.83	60.01	300.06	-15.67	0.00	28.78	0.00	5033.22	5307.78	2057.35	126.08	277.56	0.00	3391.89	62.99	16591.23	103%	0.6	1. Onshore wind 2. Offshore wind 3. Solar PV

38 The oil shale category in this table refers to generation from Estonian plants that were originally constructed to burn oil shale. In all of the modelled scenarios, large oil shale plants are converted to use 100% biomass by the early 2030s unless they are retrofitted with carbon capture (see section 2.4.2). Carbon capture retrofits are only allowed in certain cases, however: in the CCU + renewables + storage pathway and the All technologies pathways (see section 2.5). In other scenarios, generation in the oil shale category is essentially all from biomass after 2035.

39 As used in this report, electricity supply or production requirements include all requirements for electricity within a modelled region (or regions): final electricity demand, electricity demand for other energy production (e.g., hydrogen), producer own-use, transmission and distribution losses within the region, and third-country exports from the region (which are modelled as additional final demand; see section 2.4.2).

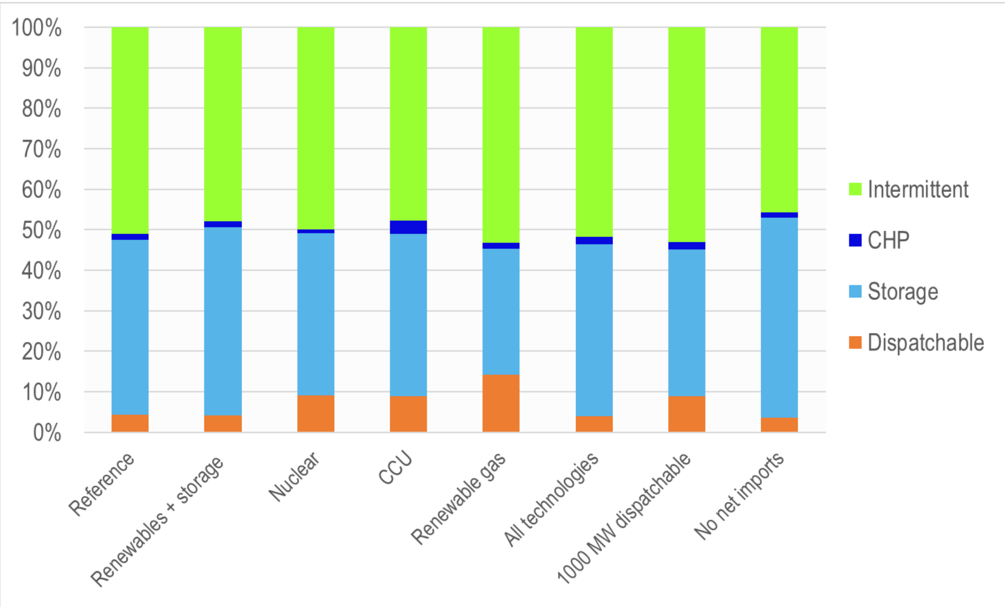
Figure 6-1 graphs installed generation and storage capacity by technology in Estonia in 2050. Figure 6-2 shows shares of dispatchable generation, intermittent generation, CHP, and storage capacity in Estonia in that year.

Figure 6-1: Electricity generation and storage capacity by scenario – Estonia, 2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Figure 6-2: Shares of electricity generation and storage capacity by scenario – Estonia, 2050[40]



40 Dispatchable capacity in this chart includes non-CHP fossil fuel, biomass, and biogas; nuclear; and landfill gas. Storage capacity includes pumped hydro, batteries, and DSM. CHP is presented as a separate category since it was modelled as a resource that is dispatched according to heating requirements (rather than electricity requirements).

A result highlighted by these charts is the substantial deployment of battery storage across scenarios. Battery capacity grows significantly in all cases and especially in the Renewables + storage, Nuclear, and No net imports pathways. Fundamentally, the model chooses batteries because they are projected to be a cost-effective way of handling fluctuations in low-cost variable renewable generation. The input cost assumptions for batteries, developed under Deliverable 2, imply they are more cost-competitive than pumped hydro (which is only selected in the 1000 MW scenario) and than constructing new flexible, low-carbon generation such as biogas.

While large, the build-out of batteries in the Deliverable 3 projections is consistent with other studies of decarbonised energy systems. For example, the International Renewable Energy Agency's 2021 *World Energy Transitions Outlook* finds that to hold average global warming to 1.5° C or less, 16,000 GWh of stationary grid-connected battery storage will be needed worldwide by 2050 (International Renewable Energy Agency 2021). In determining this number, the *Outlook* takes into account constraints on battery production, including raw material requirements. If the global total is distributed among countries according to shares of projected world population in the United Nations' *World Population Prospects*, it implies the countries modelled for Deliverable 3 will have about 240 GWh of stationary grid-connected battery storage in 2050. All of the Deliverable 3 scenarios show battery capacity increasing over time, but including all countries, the highest level reached in any scenario is 66 GWh.

In addition to battery storage, DSM is consistently selected for its ability to help balance variable renewable generation. DSM in Estonia is capped at about 261 MW of effective capacity, but this amount is quite useful at times of peak load and peak renewables production. The full available DSM potential is exploited in all pathways by 2030. Although Estonia does not have a history of significant DSM programs, these findings suggest DSM deserves more policy attention in a future focused on decarbonisation.

Alongside batteries and DSM, solar PV and onshore wind capacities are greatly expanded in all scenarios, driven by their relatively low costs. As noted in other sections, a rough seasonal complementarity between solar and wind makes it beneficial to deploy these technologies together. Onshore wind is generally found to be more cost-competitive than offshore wind in Estonia, but some offshore wind is installed in every scenario except for the CCU pathway and BAU. The highest level of offshore wind is in the Renewables + storage scenario, which requires 4 GW of the technology by 2050. In most other scenarios, 0.6-0.9 GW of offshore wind is constructed. The modelled potential for onshore wind (1.5 GW) is fully utilized in many of the scenarios, further evidence of its cost advantages over offshore wind.

Adding transmission capacity to Lääne-Eesti is a prerequisite for accessing a significant amount of Estonia's offshore wind resources. The model considers potential new transmission connections between Lääne-Eesti and Põhja-Eesti, Kesk-Eesti, Lõuna-Eesti, and Latvia. As outlined in Table 6-3, the options to Lõuna-Eesti and Latvia are most frequently selected, with several hundred MW on average deployed in each case. Further exploitation of offshore wind could be realized if other candidate transmission projects were taken into account. The Deliverable 3 team worked with stakeholders to identify such possibilities, but no consensus on potential projects was reached.

Table 6-3: New endogenously built transmission to Lääne-Eesti by scenario

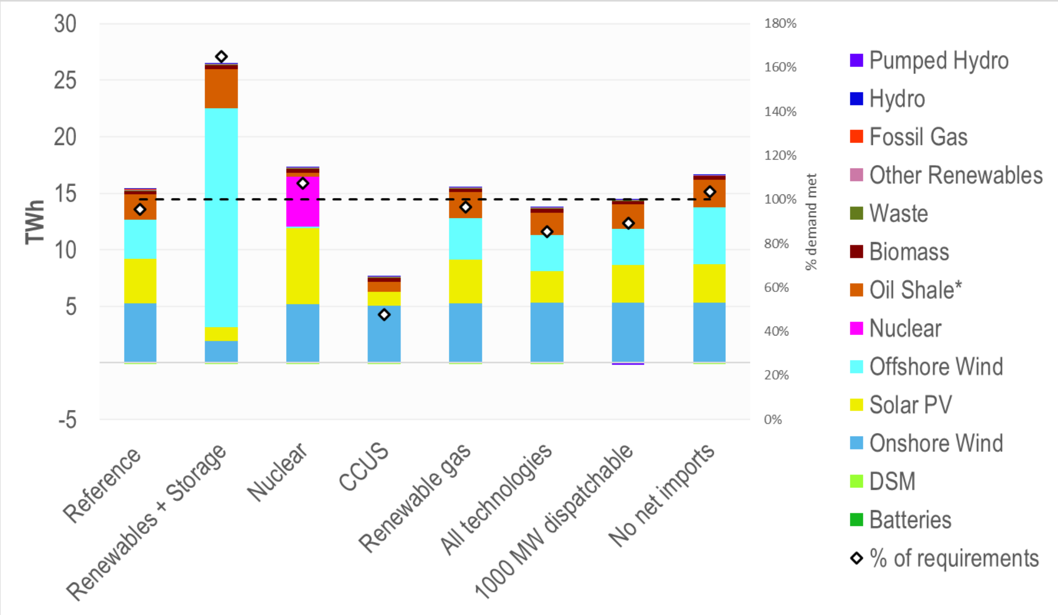
Scenario	Capacity (MW)		
	Kesk-Eesti	Latvia	Lõuna-Eesti
Reference	0	326	347
Renewables + storage	0	1180	150
Nuclear	100	523	262
CCU	0	0	704
Renewable gas	0	339	349
All technologies	0	217	372
1000 MW	0	274	303
No net imports	204	484	234

Nuclear capacity is only added under the Nuclear pathway, where 900 MW of Generation III+ small modular capacity is required. A relatively high LCOE prevents the uptake of nuclear power in the other scenarios.

Fossil gas capacity in Estonia remains low – 16 MW in the long run – in every scenario except for the 1000 MW pathway, where dispatchability requirements prompt a build-up to 456 MW. Biomass capacity (including biomass CHP) is between 101-123 MW for all pathways, with higher levels reached in the Renewables + storage and CCU scenarios. The biomass figures exclude the major oil shale plants if they are converted to run on biomass (these are shown in the oil shale category instead). As discussed in earlier sections, the dispatchable capacity at the major oil shale plants is important in most scenarios, particularly if it is retrofitted with partial carbon capture.

These capacity projections directly inform the electricity generation projections, depicted by technology type and scenario in Figure 6-3. This figure also shows the proportion of Estonian electricity production requirements that is satisfied by domestic generation.

Figure 6-3: Net electricity generation by scenario – Estonia, 2050

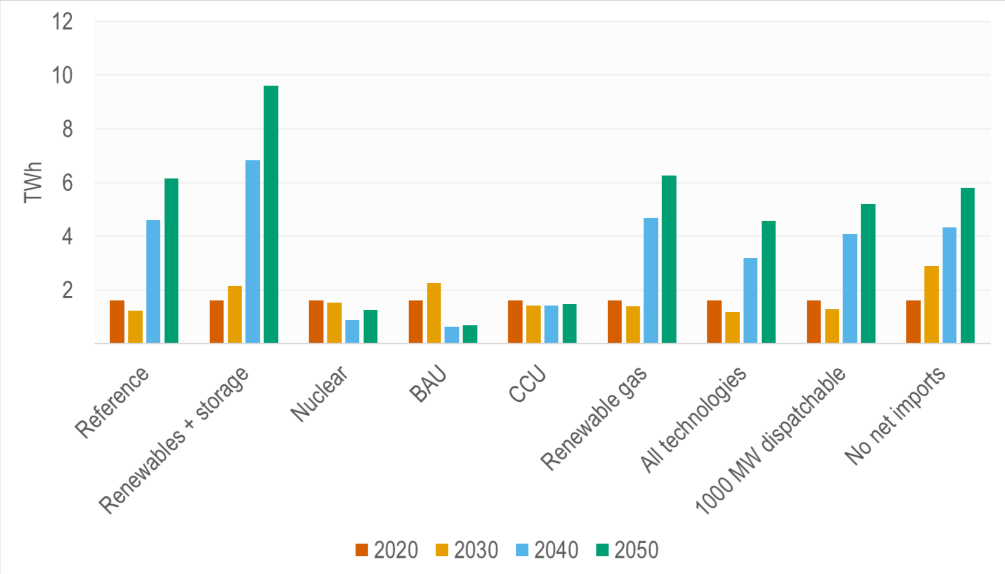


** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

Onshore wind is projected to be the primary generation source under nearly all scenarios (see also the “Top sources” column in Table 6-2). In the Renewables + storage pathway, offshore wind leads instead; and in the Nuclear pathway, solar is the largest contributor. Taken together, onshore wind, offshore wind, and solar come to dominate generation in the long run. This is an essential pattern in the Deliverable 3 modelling: cost advantages drive a shift in the Estonian system from oil shale to wind and solar. The variability of these resources is managed through a combination of dispatchable generation, storage, DSM, and imports.

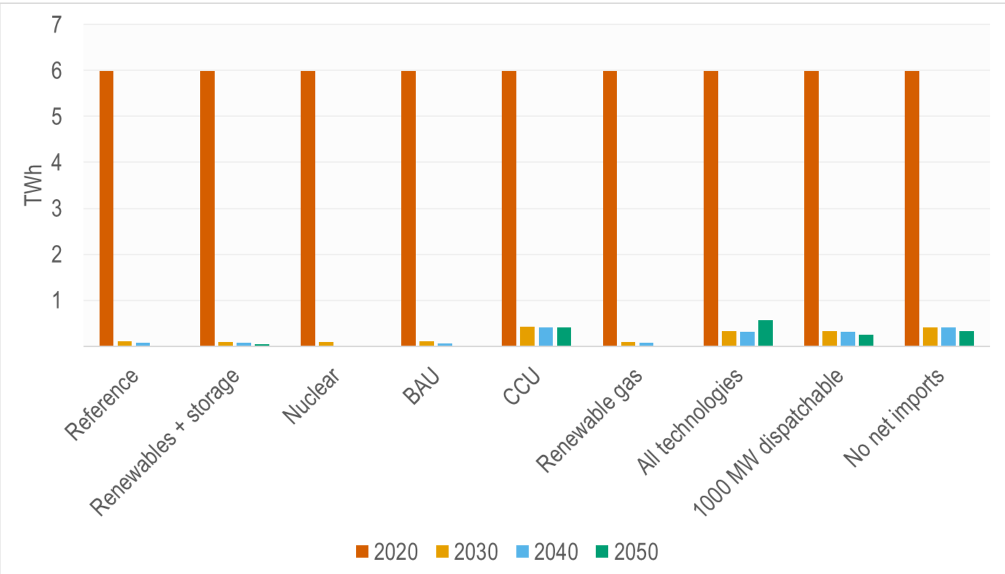
Notwithstanding the pre-eminence of wind and solar, biomass generation also makes important contributions in many scenarios. Biomass CHP plants (shown in the Biomass category in Figure 6-3) and former oil shale plants running on biomass (in the Oil Shale category in Figure 6-3) together provide 4-17% of Estonian generation in 2050, with the share 10% or higher in all cases except the Nuclear pathway. Maintaining a significant role for biomass as electricity production increases over time implies growing biomass consumption for electricity generation, as shown in Figure 6-4. Compared to the present, projected biomass inputs to generation rise in most of the climate-neutral pathways. The consumption is highest in the Renewables + storage pathway in the long run, reaching 9.6 TWh by 2050. This amount equates to around 3.1 million cubic meters of wood, or approximately one third of the Estonian wood harvest in recent years (Estonian Forest and Wood Industries Association 2021).

Figure 6-4: Biomass consumption for electricity generation by scenario – Estonia



At the same time, consumption of oil shale for electricity generation in Estonia decreases in all scenarios, as shown in Figure 6-5.

Figure 6-5: Oil shale* consumption for electricity generation by scenario – Estonia



** By 2050, former oil shale plants are converted to use 100% biomass, unless they are retrofitted with carbon capture (only permissible in the CCU and All technologies pathways) – see footnote 23.*

In most of the modelled scenarios, the expansion of renewable generation allows Estonia to return to electricity self-sufficiency (with production greater than or equal to domestic requirements) by 2050. Investments in dispatchable resources, such as in the Nuclear and Renewable gas pathways, facilitate this development. The Auvere and TG11 oil shale plants are also critical in this context. They are a key source of dispatchable generation that the model uses to fill gaps in wind and solar production. As the CCU scenario shows, national electricity generation drops significantly and net electricity imports rise when the output of Auvere and TG11 is restricted. Finding a way to operate these plants in the carbon-constrained future, whether through carbon capture, fuel switching, or emission offsets, should yield important benefits for Estonia.

In three of the climate-neutral scenarios – Renewables + storage, Nuclear, and No net imports – Estonia is a net electricity exporter by 2050 (Figure 6-6). The level of net exports is greatest in the Renewables + storage pathway, exceeding 10 TWh/year. Generally speaking, Estonian exports in the modelled scenarios go to Latvia for use in other Baltic countries, while connections with Finland are mainly used for imports. Even in scenarios where net exports are positive, imports play a role in meeting Estonian requirements.

Figure 6-6: Net electricity exports by scenario – Estonia, 2050

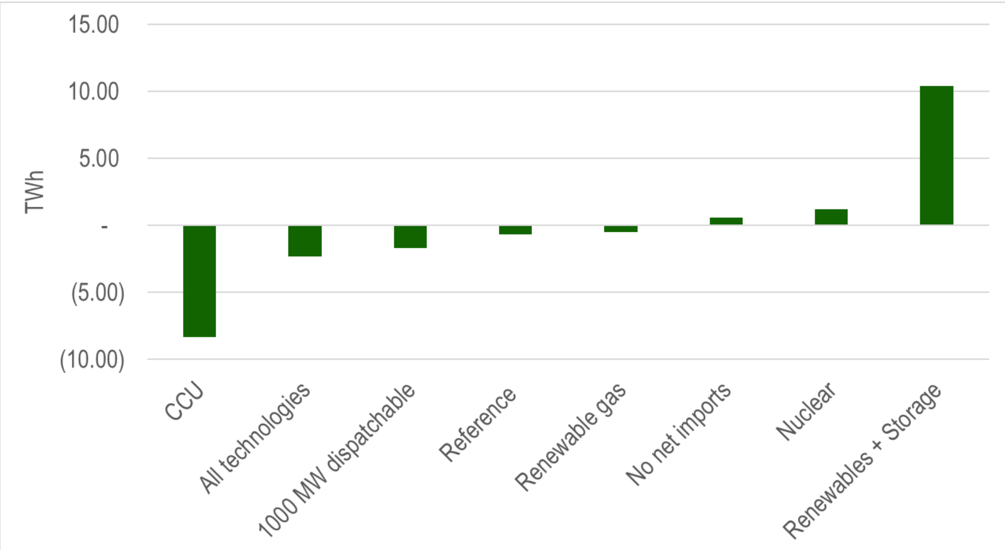
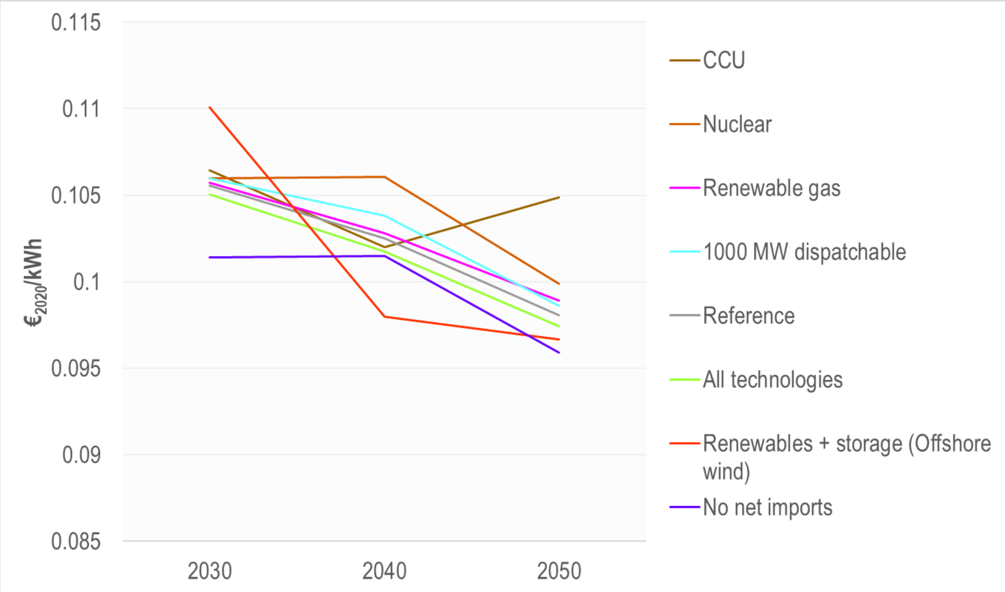


Figure 6-7 depicts average electricity prices in Estonia by scenario.

Figure 6-7: Average electricity prices by scenario – Estonia[41]



In all scenarios, projected prices are higher than current prices, but they fall between 2030 and 2050 as Estonia transitions to climate-neutral generation. The average price declines least under the CCU pathway, dropping from 0.106 in 2030 to 0.102 €$_{2020}$/kWh in 2040 before rising to 0.105 €$_{2020}$/kWh in 2050. This gives the CCU pathway the highest estimated price in 2050, followed by the Nuclear and Renewable gas scenarios. Long-run prices are lowest in the Renewables + storage and No net imports scenarios, reaching 0.097 and 0.096 €$_{2020}$/kWh respectively in 2050. As Figure 6-7 illustrates, scenarios involving less electricity production in Estonia and greater imports do not necessarily imply better prices for Estonians. Selected investments in domestic production can reduce prices in the Estonian market by making low-cost electricity available in critical periods.

The cross-scenario trends in Estonian capacity, generation, net imports/exports, and electricity prices likely hold for a range of future ETS prices. The Deliverable 3 team probed this question by testing ETS price sensitivity in the All technologies pathway. Two additional cases were explored:

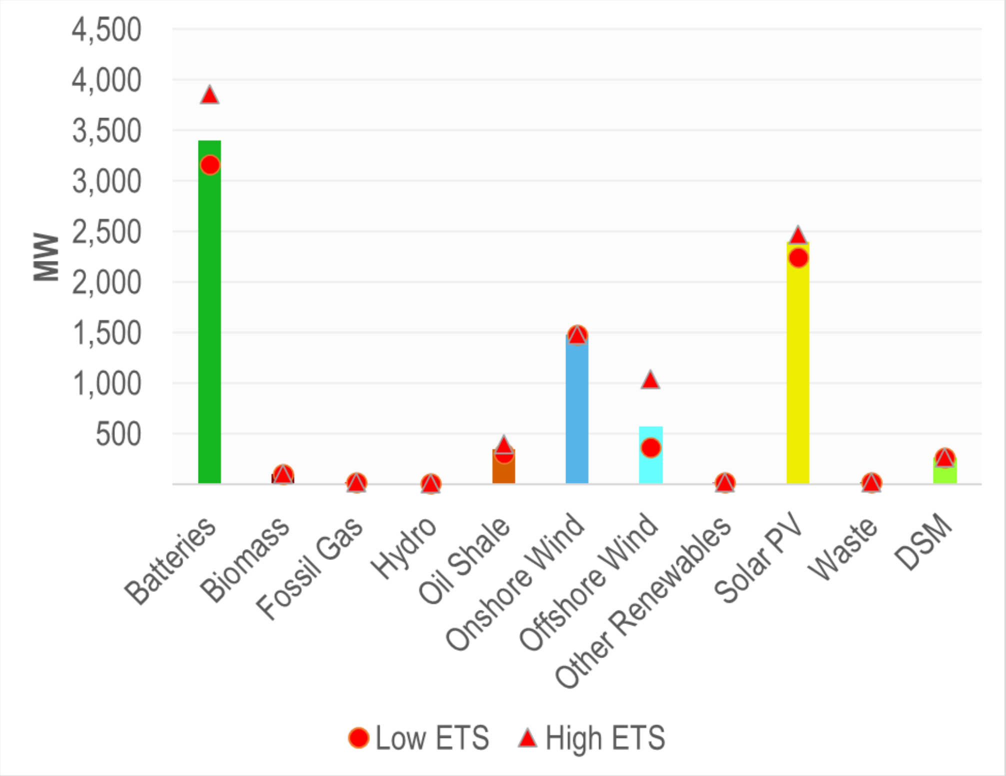
- A low case that holds the ETS price at its 2021 level (43 €$_{2020}$/tCO_2) through 2050

[41] As explained in section 2.4.2, these prices are LCOE-based. They do not include taxes or subsidies.

- A high case in which the ETS price rises linearly from its 2021 level to 250 €$_{2020}$/tCO_2 in 2050 (compare to 159 €$_{2020}$/tCO_2 in 2050 in All technologies)

Overall, lower ETS prices in the All technologies pathway induce more moderately carbon-intensive generation (notably gas) outside Estonia, which in turn lowers renewable power investments and output in Estonia. Higher ETS prices have an opposite effect. The total impact is modest, however, as illustrated in Figure 6-8. This chart depicts installed capacity in Estonia in 2050, when the range of ETS prices is most pronounced. Total capacity in the alternate ETS price cases varies by 8-12% from the All technologies pathway, with changes most noticeable for batteries, offshore wind, and solar PV. In the low ETS case, the model forgoes a partial carbon capture retrofit at Auvere, and in the high ETS case it implements carbon capture for about 100 MW at Auvere rather than the 70 MW in All technologies.

Figure 6-8: All technologies ETS price sensitivity – electricity generation and storage capacity in Estonia in 2050



The differences in capacity lead to differences in domestic generation, which is 12% lower in the low ETS case by 2050 (compared to All technologies) and 24% higher in the high ETS case. Changes in generation entrain corresponding minor changes in net electricity imports.

The relative insensitivity of the capacity and generation results to ETS price variation underscores an essential finding: cost projections for renewables and storage imply they are a compelling alternative to conventional generation even at moderate carbon prices. In the low ETS case, the regional electricity system shifts substantially toward variable renewables (70% of generation capacity in the Baltics and Finland by 2050), leaving little room for major changes if carbon prices are higher. This dynamic is visible also in the projected electricity prices for Estonia. Because the country's power comes from a similar mix of technologies in the All technologies pathway and the two ETS price cases, estimated electricity prices are comparable in the three simulations (differing most in high ETS case, when they are 0.001-0.002 €$_{2020}$/kWh greater than in All technologies).

7 Pathway modelling results as inputs into upcoming analyses

The analyses developed for Deliverable 3 and presented in this report represent the first phase of results for the broader study on “Transitioning to a climate-neutral electricity generation.” The results from the pathway modelling will feed directly into analysis for upcoming project deliverables. In Deliverable 4, the socioeconomic impacts of the different pathways will be calculated and explored. In Deliverable 5, risks associated with implementing each pathway will be mapped out, and measures for mitigating identified risks will be proposed. Sensitivity analyses to test and complement the results of the pathway modelling and the socioeconomic impact assessment will be run in Deliverable 6.

Specifically, modelling in Deliverable 6 will consider several “sensitivity scenarios” related to the pathways, which were developed in response to stakeholder comments and questions received on the Deliverable 3 outputs. The sensitivity analysis will consider how the pathway modelling outputs would change if:

- Wind variability is assumed to be much higher in the Renewables + storage pathway or the All technologies pathway
- 90% minimum utilization is assumed for the nuclear capacity in the Nuclear + renewables + storage pathway
- The amount of biomass that can be consumed for electricity generation is more strictly limited in the Renewables + storage pathway or All technologies pathway.

The implications of these sensitivities will be presented in the Deliverable 6 report. Results from the sensitivity analyses will be synthesised in the development of policy recommendations and in the project’s final report.

Policy action plans will be developed for each pathway in Deliverable 7, which will include recommendations on the regulatory, financial, and social instruments that can be deployed to ensure successful their implementation. Deliverables 5 and 7 in particular will investigate the policy implications of the pathway modelling results, including the results of the sensitivity analysis. Along with findings from Deliverable 3, results from all subsequent project phases will be provided to the Ministry of Economic Affairs and Communications, to inform their decision-making on what course(s) of action should be pursued.

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Annex A – Deliverable 3 model

The Deliverable 3 model presented in this report can be downloaded via this link (password = estonia2050). The model is compatible with LEAP version 2020.1.0.37 (64-bit) and NEMO version 1.6.

Annex B – Spreadsheets of model results

Scenario-specific spreadsheets with major results from the model are available at this link (password = estonia2050). These files have been edited to emphasise trends that are discussed in the "Responses to stakeholder feedback" file compiled to answer questions received from Estonian stakeholders.

Annex C – Spreadsheet of report charts

A spreadsheet used to prepare the charts for this report can be accessed at this link (password = estonia2050).

Annex D – Power plants and technologies included in Deliverable 3 modelling of Estonia

Name	Historical / existing / new[42]	Input fuel(s)	Capacity in 2020 (MW)	Overnight capital cost (million €2020/MW)		Fixed operation & maintenance cost (thousand €2020/MW)		Variable operation & maintenance cost (€2020/MWh)	
				2020	2050	2020	2050	2020	2050
Auvere Elektrijaam	Existing	Biomass, oil shale, retort gas	274.0	2.2	2.2	31.7	31.7	2.1	2.1
Auvere Elektrijaam with carbon capture	New	Biomass, oil shale, retort gas	0.0	3.6	3.6	82.4	82.4	2.7	2.7
Balti Elektrijaam TG9	Historical	Oil shale	0.0	2.2	2.2	34.9	34.9	4.2	4.2
Balti Elektrijaam TG11	Existing	Biomass, oil shale	192.0	2.2	2.2	34.9	34.9	4.2	4.2
Balti Elektrijaam TG11 refurbishment	New	Biomass, oil shale	0.0	0.4	0.4	34.9	34.9	4.2	4.2
Balti Elektrijaam TG11 with carbon capture	New	Biomass, oil shale	0.0	3.6	3.6	90.7	90.7	5.5	5.5

42 Indicates a facility's/technology's status:

- Historical – had installed capacity between 2015 and 2019 but not in 2020. Cannot be reconstructed after 2020.
- Existing – had installed capacity in 2020. Many facilities in this category are scheduled to retire in the early 2020s (e.g., Eesti Elektrijaam TG1-TG7, Iru Elektrijaam TG2). As noted in Table 2-2, the model can endogenously add capacity after 2020 for some technologies in this category (e.g., onshore wind, solar PV).
- New – is an option the model can build after 2020 (sometimes with scenario restrictions; see Table 2-2).

Name	Historical / existing / new[42]	Input fuel(s)	Capacity in 2020 (MW)	Overnight capital cost (million €2020/MW)		Fixed operation & maintenance cost (thousand €2020/MW)		Variable operation & maintenance cost (€2020/MWh)	
				2020	2050	2020	2050	2020	2050
Balti Elektrijaam TG12	Existing	Oil shale	130.0	2.2	2.2	31.7	31.7	4.2	4.2
Batteries	New	N/A (storage)	0.0	0.3	0.1	0.6	0.6	2.1	1.7
Biogas engine	Existing	Biogas	5.8	2.6	2.6	10.6	10.6	8.5	8.5
Biogas plant	New	Biogas	0.0	2.6	2.6	139.8	139.8	2.6	2.6
Biomass CHP	Existing	Biomass	12.4	2.1	2.1	50.7	50.7	0.3	0.3
DSM 1 hour shiftability	New	N/A (storage)	0.0	0.1	0.1	0.0	0.0	80.0	80.0
DSM 1 to 2 hours shiftability	New	N/A (storage)	0.0	0.0	0.0	0.0	0.0	80.0	80.0
DSM 1 to 8 hours shiftability	New	N/A (storage)	0.0	0.1	0.1	0.0	0.0	80.0	80.0
Eesti Elektrijaam TG1	Existing	Oil shale	163.0	2.2	2.2	34.9	34.9	4.2	4.2
Eesti Elektrijaam TG2	Existing	Oil shale	163.0	2.2	2.2	34.9	34.9	4.2	4.2
Eesti Elektrijaam TG3	Existing	Oil shale	163.0	2.2	2.2	34.9	34.9	4.2	4.2
Eesti Elektrijaam TG4	Existing	Oil shale	163.0	2.2	2.2	34.9	34.9	4.2	4.2
Eesti Elektrijaam TG5	Existing	Oil shale	173.0	2.2	2.2	34.9	34.9	4.2	4.2
Eesti Elektrijaam TG6	Existing	Oil shale	173.0	2.2	2.2	34.9	34.9	4.2	4.2

Name	Historical / existing / new[42]	Input fuel(s)	Capacity in 2020 (MW)	Overnight capital cost (million €2020/MW)		Fixed operation & maintenance cost (thousand €2020/MW)		Variable operation & maintenance cost (€2020/MWh)	
				2020	2050	2020	2050	2020	2050
Eesti Elektrijaam TG7	Existing	Oil shale	163.0	2.2	2.2	34.9	34.9	4.2	4.2
Eesti Elektrijaam TG8	Existing	Biomass, oil shale, retort gas	194.0	2.2	2.2	31.7	31.7	4.2	4.2
Enefit 280	Existing	Oil shale	10.0	2.2	2.2	0.0	0.0	0.0	0.0
Fuel cells	New	Hydrogen	0.0	1.6	1.0	0.1	0.0	0.0	0.0
Horizon tselluloosi ja paberi AS	Existing	Black liquor	14.4	2.1	2.1	50.7	50.7	0.3	0.3
Hydro run of river	Existing	Hydro	8.4	2.9	2.9	41.1	41.1	0.0	0.0
Iru Elektrijaam TG1	Historical	Natural gas	0.0	1.3	1.1	0.0	0.0	0.0	0.0
Iru Elektrijaam TG2	Existing	Natural gas	94.0	1.3	1.1	12.7	12.7	0.4	0.4
Iru Elektrijaam TG3	Existing	Waste	17.0	9.0	7.5	22.2	22.2	0.4	0.4
Landfill gas	Existing	Landfill gas	1.5	2.6	2.6	10.6	10.6	5.7	5.7
Natural gas	New	Natural gas	0.0	0.9	0.8	15.9	15.9	2.0	2.0
New open cycle gas	New	Natural gas	0.0	0.5	0.4	8.6	7.8	4.8	4.8
Nuclear Generation III BWRX300	New	Nuclear	0.0	2.6	2.6	51.0	51.0	7.0	7.0

Name	Historical / existing / new[42]	Input fuel(s)	Capacity in 2020 (MW)	Overnight capital cost (million €$_{2020}$/MW)		Fixed operation & maintenance cost (thousand €$_{2020}$/MW)		Variable operation & maintenance cost (€$_{2020}$/MWh)	
				2020	2050	2020	2050	2020	2050
Nuclear Generation IV	New	Nuclear	0.0	4.8	4.8	107.1	107.1	6.5	6.5
Offshore wind	New	Wind	0.0	2.3	1.9	42.3	34.2	3.2	2.5
Onshore wind	Existing	Wind	329.0	1.2	1.0	14.8	12.0	1.6	1.3
Other gas CHP	Existing	Natural gas	15.8	1.3	1.1	21.1	21.1	4.8	4.8
Paldiski pumped hydro	New	N/A (storage)	0.0	1.1	1.1	41.1	41.1	0.0	0.0
Pärnu Elektrijaam Turbiin 1	Existing	Biomass	20.5	2.1	2.1	50.7	50.7	0.3	0.3
Retort gas CHP VKG	Existing	Retort gas	17.0	1.3	1.1	21.1	21.1	4.8	4.8
Retort gas condensing VKG	Existing	Retort gas	37.0	2.2	2.2	21.1	21.1	4.8	4.8
Sillamäe CHP New	Existing	Biomass	7.0	2.1	2.1	50.7	50.7	0.3	0.3
Sillamäe SEJ CHP	Existing	Natural gas	6.0	1.0	0.9	10.6	10.6	5.7	5.7
Sillamäe SEJ Turbiin 1	Existing	Oil shale	5.5	2.1	2.1	50.7	50.7	0.3	0.3
Sillamäe SEJ Turbiin 2	Existing	Oil shale	5.5	2.1	2.1	50.7	50.7	0.3	0.3

Name	Historical / existing / new[42]	Input fuel(s)	Capacity in 2020 (MW)	Overnight capital cost (million $€_{2020}$/MW)		Fixed operation & maintenance cost (thousand $€_{2020}$/MW)		Variable operation & maintenance cost ($€_{2020}$/MWh)	
				2020	2050	2020	2050	2020	2050
Solar PV	Existing	Solar	230.0	0.4	0.3	7.4	5.3	0.0	0.0
Tallinna Elektrijaam Turbiin 1	Existing	Biomass	21.0	2.1	2.1	50.7	50.7	0.4	0.4
Tartu Elektrijaam Turbiin 1	Existing	Biomass	22.1	2.1	2.1	50.7	50.7	0.3	0.3
Väo elektrijaam II	Existing	Biomass	18.0	2.1	2.1	50.7	50.7	0.3	0.3

Annex E – Follow-up items prepared for Elering during 25 October 2021 round of comments on this report

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