Transitioning to a climate-neutral electricity generation

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

Executive Summary

Introduction

This executive summary outlines the core results of the 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 (used as the baseline for comparisons), 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.

Model scope and key assumptions

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 were calibrated to known historical data and were validated by Elering. Projections begin in 2021 and run through 2050. Geographically, the model distinguishes 21 regions, including: five regions of Estonia; Nord Pool bidding areas for Denmark, Finland, Germany, Latvia, Lithuania, Norway, and Sweden; and Poland.

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. In Estonia, electricity demand for hydrogen production is also modelled as part of an analysis of economically feasible power-to-X.

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. 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.

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.

Several major methodological choices were made to localize the Deliverable 3 optimisation model to the study area and capture critical dynamics of the area's electricity system. 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.

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. The modelling does not consider the implementation of a Carbon Border Adjustment Mechanism (CBAM) as its potential structure, feasibility, and implementation schedule were unclear at the time the model was developed. The model accounts for historical and planned renewable power auctions in Estonia, based on inputs provided by the Estonian Ministry of Economic Affairs and

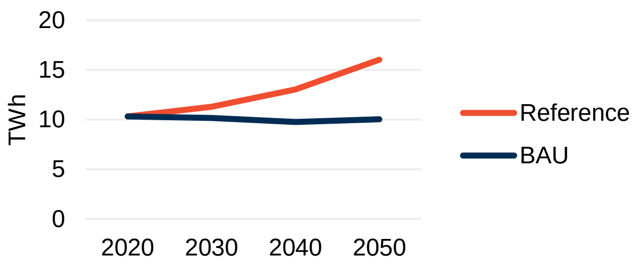
Communications. And the model considers how several power-to-X options including electric vehicles, electrified space heating, and hydrogen production might increase Estonian domestic demand in future years. In all pathways except the BAU, an economically feasible level of power-to-X deployment is assumed, which adds to electricity production requirements.

Extensive further details on the model structure and key assumptions are included in the full Deliverable 3 report.

Core findings – Comparative results across pathways

The business-as-usual pathway projects lower demand in Estonia than the reference pathway, which assumes that economically feasible power-to-X (P2X) options will be deployed in Estonia by 2050 (see this summary's section on the reference pathway for further details). Resulting demand levels for both pathways are depicted in Figure 1. The reference pathway is used as a baseline for comparisons with the climate-neutral pathways.

Figure 1 Projected demand under the BAU vs. reference (baseline) pathways, Estonia, 2020-2050

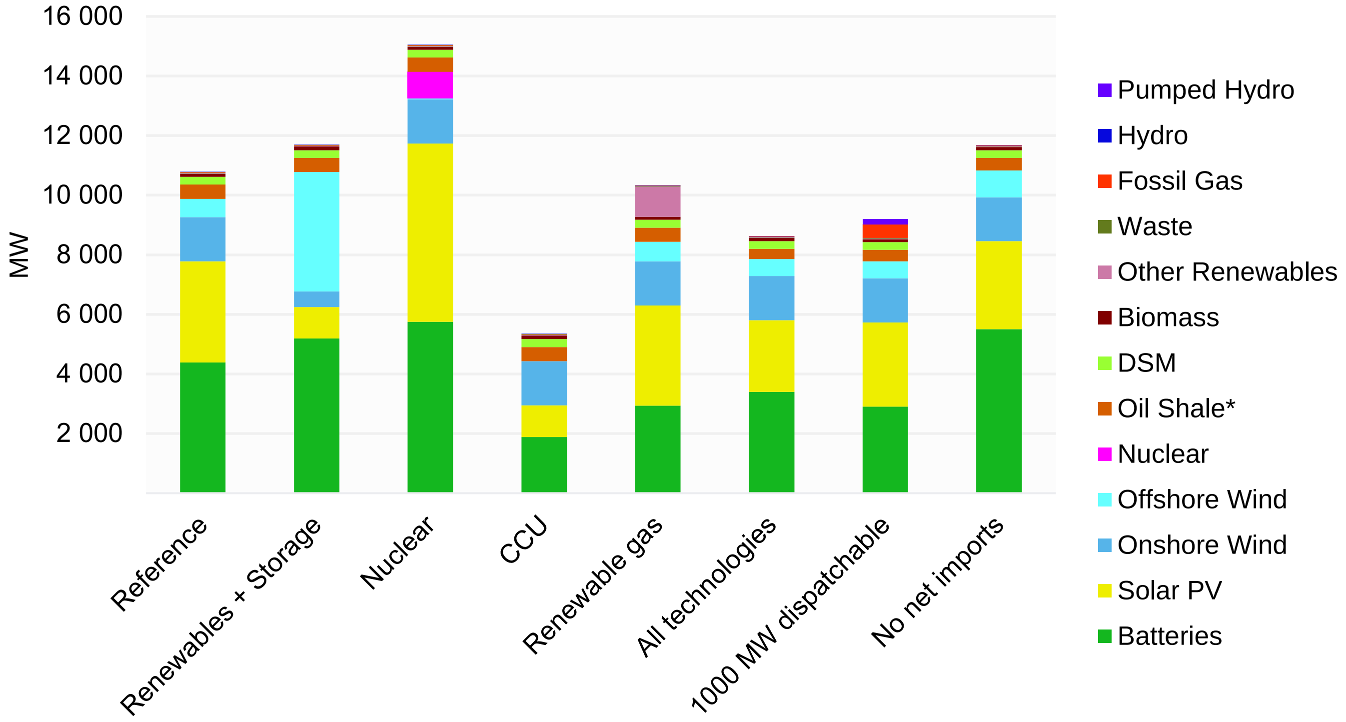


The modelling results indicate that in all climate-neutral (non-baseline) pathways, Estonian electricity production **shifts from oil shale toward wind and solar** (with 70-85% of domestic generation from wind and solar under all pathways by 2050). Fluctuations in wind and solar output are **balanced primarily by built-up dispatchable generation and storage, with some demand-side management (DSM) and electricity imports**.

Among these options, batteries and DSM are particularly cost-competitive across scenarios. A large build-out of batteries (1.9-5.7 GW) is projected in every pathway due to their flexibility and declining costs. 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, but some offshore wind is installed in Estonia in nearly every climate-neutral pathway (in some pathways by 2030 or 2040, in others only by 2050). New transmission investments are needed to exploit Estonia's offshore wind potential (likely 600-1300 MW between Lääne-Eesti and other regions).

Figure 2 shows projected installed capacity in Estonia in 2050 for each pathway. Low technology costs drive significant build-up of batteries, solar PV, and onshore wind across all scenarios. Onshore wind and DSM potential is fully utilized in most scenarios. However, there is limited or no potential to expand waste or biomass capacity, as resource use is limited, or hydropower capacity, which is not cost-competitive compared to alternative technologies.

Figure 2 Projected capacities per pathway, Estonia 2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

Figure 3 shows the distribution of dispatchable vs. intermittent capacity built up in Estonia across all modelled pathways. Storage and dispatchable capacity balance larger shares of intermittent sources, with additional seasonal balancing provided by combined heat and power (CHP) sources.[1] The Auvere and Narva (specifically, the TG11) oil shale plants remain a key source of dispatchable capacity in the Estonian system in all climate-neutral scenarios, where they play an important role in facilitating the integration of variable renewable power. They are made compatible with high carbon prices either by switching to biomass fuel and/or incorporating carbon capture capabilities (including partial carbon capture).

Figure 3 Projected shares of electricity generation capacities per pathway, Estonia 2050

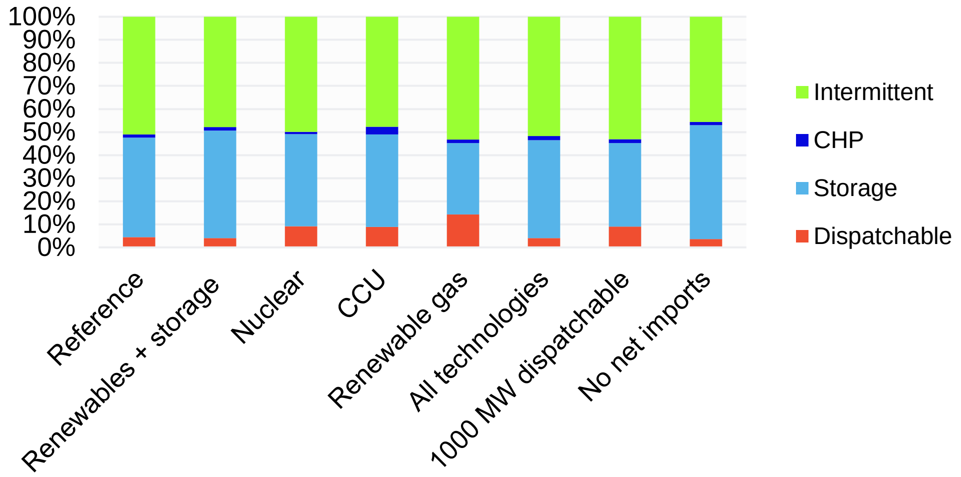
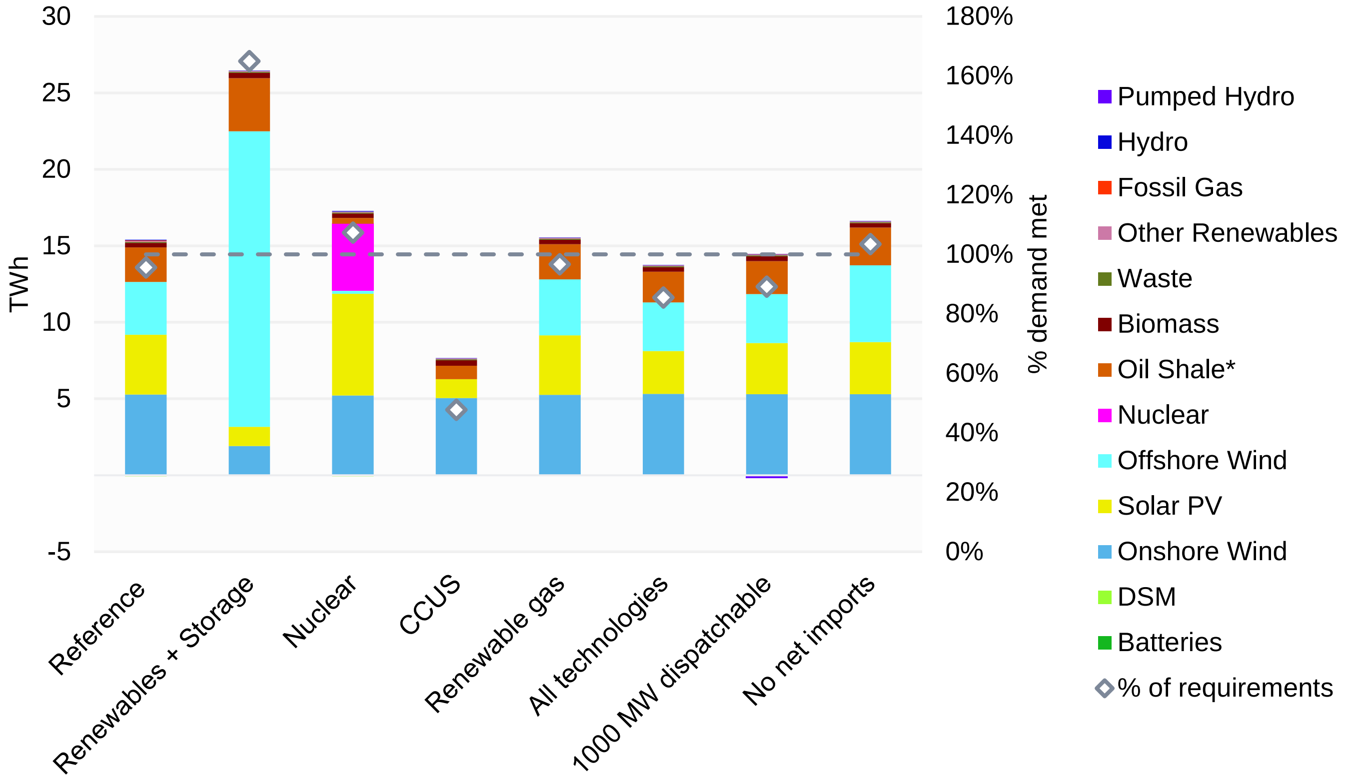


Figure 4 shows electricity generation by technology across all pathways. There is a significant improvement in the share of electricity demand met with domestic generation in most scenarios. Investments in dispatchable capacity facilitate a lower reliance on electricity imports.

[1] CHP is presented separately from dispatchable sources since it was modelled as a resource that is dispatached according to heating requirements (rather than electricity requirements). TalTech recommended this approach.

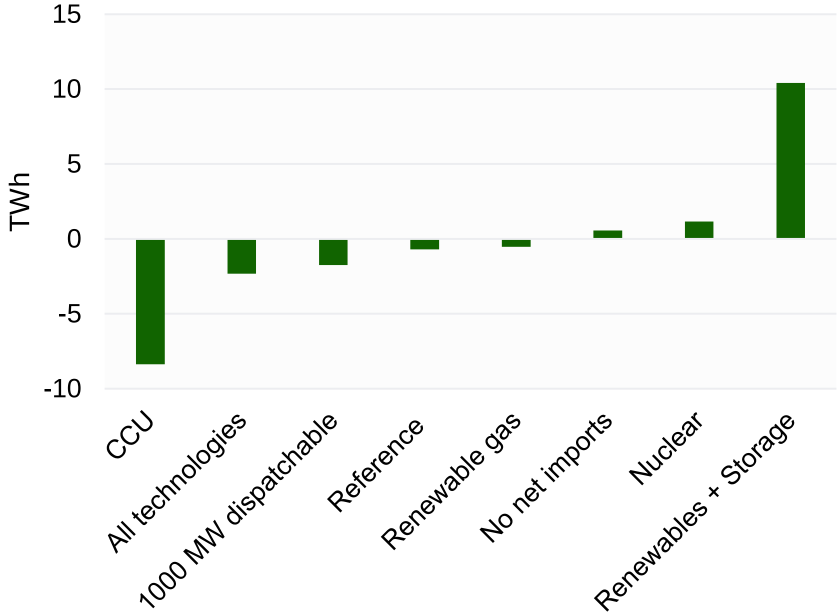
Figure 4 Projected electricity generation in Estonia, 2050[2]



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

In most climate-neutral pathways, Estonia sharply **reduces its net electricity imports over time**, with domestic generation covering ~60% or more of national electricity requirements by 2030, and 85% or more by 2050. Import/export balances per pathway are depicted in Figure 5. Estonia acts as a net exporter of electricity under the No net imports, Nuclear, and Renewables + storage pathways, and is most reliant on imports in the CCU scenario. Imports continue to be used at certain times of the year in all pathways, however. For example, when the national electricity system is at peak load (simulated during a night in winter), some imports are used in all pathways in 2030, and in all pathways except for Renewables + storage in 2050.

Figure 5 Net electricity exports per pathway from Estonia to Latvia or Finland, 2050

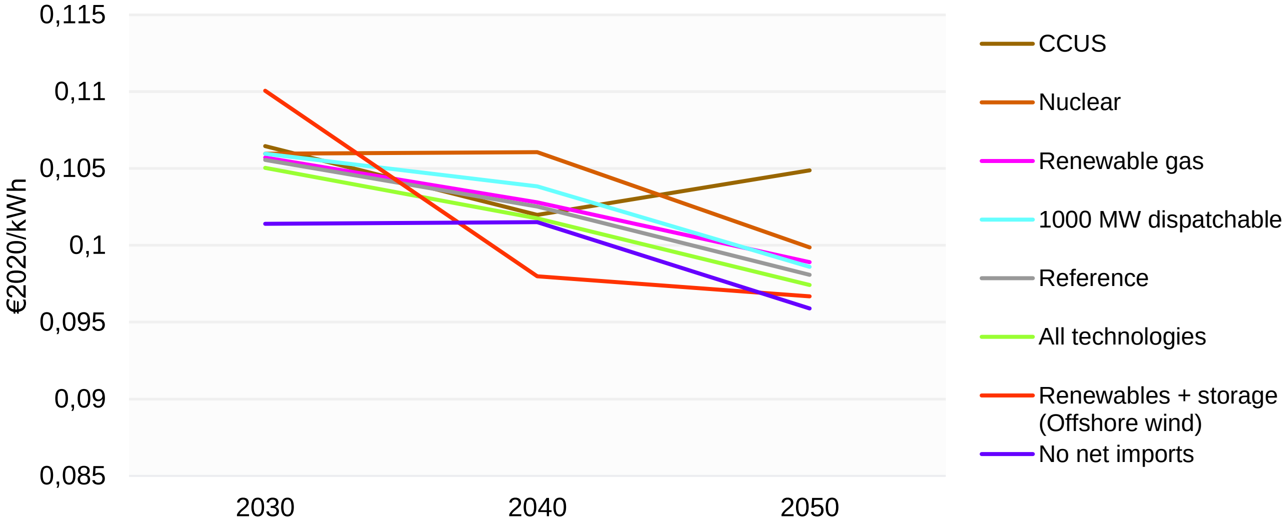


[2] Note that net generation graphs in this summary include batteries because they have a small negative net generation over the course of a year.

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 projects the largest increase in net electricity exports from Estonia (from 1.7 TWh of imports in 2030 to 10.4 TWh of exports by 2050) and the second-lowest long-run electricity prices (from 0.110 €$_{2020}$/kWh in 2030 to 0.097 €$_{2020}$/kWh by 2050). In comparison, the reference pathway projects 3.3 TWh of imports in 2030 and 0.01 TWh of imports in 2050, and an electricity price of 0.105 €$_{2020}$/kWh in 2030 and 0.098 €$_{2020}$/kWh in 2050.

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 0.095 and 0.11 €2020/kWh in the 2030-2050 period, as depicted in Figure *6*. Long-run prices are lowest in the Renewables + storage and No net imports scenarios.

Figure 6 Average electricity price[3] per pathway, Estonia 2030-2050



Further results on projected capacity, generation, dispatchability, and import/export levels, in the short and long terms, are analysed in the subsequent section summarising core findings per pathway. 2030 results are also compared in this document's annex, as well as in the full Deliverable 3 report.

Core findings per pathway

Comparing results across pathways reveals insights into trends that will likely shape the Estonian power sector in 2050. But assessing individual pathways reveals insights into features that will impact the sector if market forces alone prevail, versus if certain technology types drive decarbonisation in the country. Key findings for each pathway are summarised subsequently.

1 – Business as usual pathway

The business as usual (BAU) pathway assesses implications for Estonia if electricity systems in surrounding regions develop as envisioned in EU Reference Scenario 2020, which projects a sharply rising ETS price, as well as significant capacity additions in Estonia's neighbouring Baltic states. The BAU pathway does not impose a climate neutrality requirement on Estonia's electricity grid, but greenhouse gas emissions under the BAU nevertheless fall from 2667 kt of CO_2 equivalent in 2020 to 29 kt by 2050, driven by the sharp rise in the EU ETS price expected by 2050.

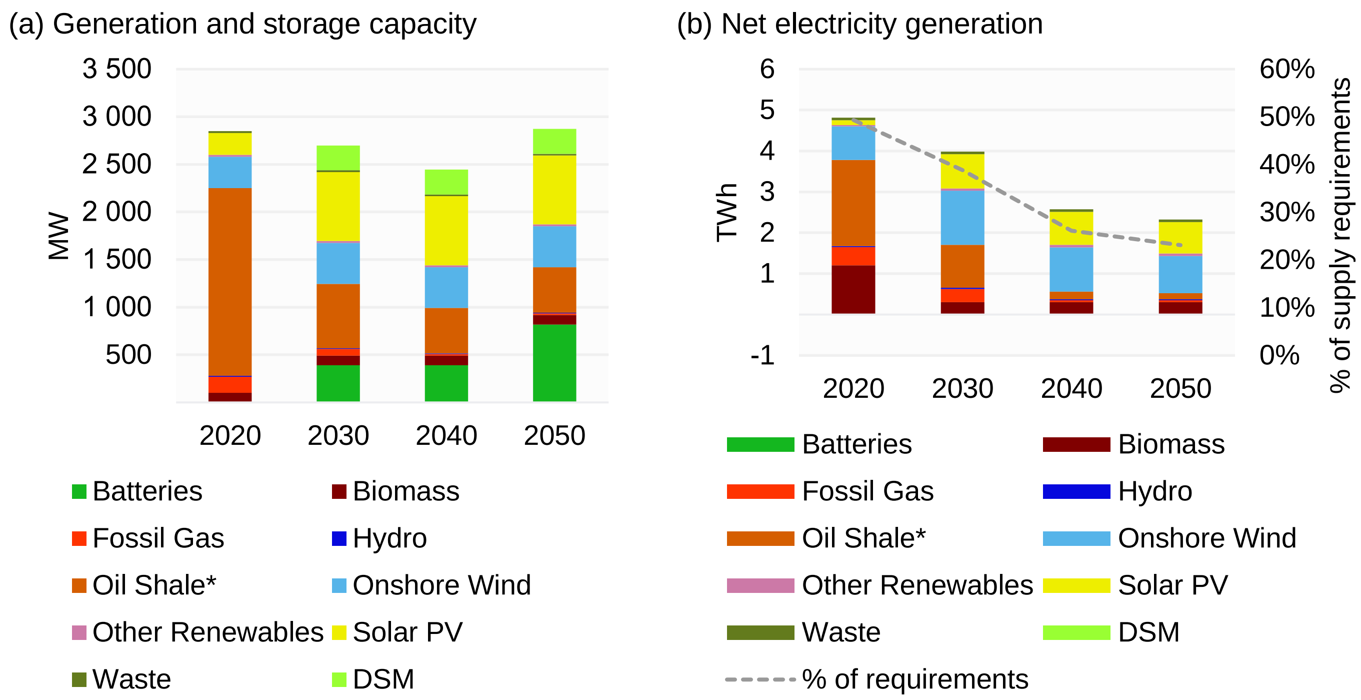
Under the BAU pathway, modest growth in final demand coupled with supply-side efficiencies and desynchronization from the Russian grid leads to **stable electricity production requirements in Estonia over time**. **Higher ETS prices (in line with EU Reference Scenario forecasts) drive substantial**

[3] These figures reflect average yearly wholesale electricity prices, not including VAT or other price components. Note that prices do not reflect electricity market prices, but rather represent projections based on LCOE-driven calculations.

system-wide decarbonization. Electricity **imports continue to increase** in Estonia, reaching 61% by 2030 and 77% by 2050, 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. And estimated annual average wholesale electricity prices in Estonia are projected to rise from current levels, reaching 0.113 €$_{2020}$/kWh in 2030 and slightly decreasing to 0.105 €$_{2020}$/kWh in 2050.

Figure 7(a) shows generation and storage capacity modelled over time under the BAU, and Figure 7(b) shows projected generation by technology type. It also shows the falling proportion of Estonian supply requirements (projected to remain around 10 TWh between 2020-2050 under the BAU) that can be met with domestic generation over time.

Figure 7 Projected capacity build-up and net electricity generation in the BAU scenario, Estonia 2020-2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

2 – Reference pathway

The reference pathway was developed in response to stakeholder feedback that relying on EU Reference Scenario projections tended to limit new generation investments in Estonia (because of significant capacity build-ups calculated for Latvia and Lithuania). The pathway therefore does not assume that the extensive new capacities projected in the Reference Scenario will be built up in Estonia's neighbouring countries. Instead, it uses current capacity figures as input.

So that the reference pathway could serve as a suitable baseline for comparison with climate-neutral scenarios, it also assumes an economically feasible level of power-to-X deployment in Estonia by 2050.[4] he The reference pathway projects 6 TWh more demand than the BAU, driven by: increased demand for economically feasible hydrogen production (assuming 160 kt per year are produced by 2050); expanded electric transport (assuming that 67% of passenger vehicle kilometres in Estonia are driven in electric cars by 2050); and increased electric residential space heating (assuming 69% of residential heating demand is met via electrification by 2050).

Under the reference pathway, the adoption of **economically feasible power-to-X increases Estonia's electricity production requirements 55% by 2050**. Higher demand in Estonia and less exogenously

[4] As specifically requested by the Ministry of Economic Affairs and Communications; please see the full Deliverable 3 report for additional details on reference scenario assumptions and justification.

specified generation capacity elsewhere in the modeled area means that **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. The Auvere and TG11 plants, converted to run entirely on biomass by 2034 and 2028 respectively, play a major role in balancing wind and solar production. Additionally, estimated **wholesale electricity prices** in Estonia are about **10% lower than in the BAU scenario,** due to lower reliance on imports.

Figure 8 shows that in the reference pathway, generation and storage capacity is well-distributed across Latvia, Lithuania, and Estonia in the long run.

Figure 8 Share of generation and storage capacity across Baltic countries in the reference pathway, 2050

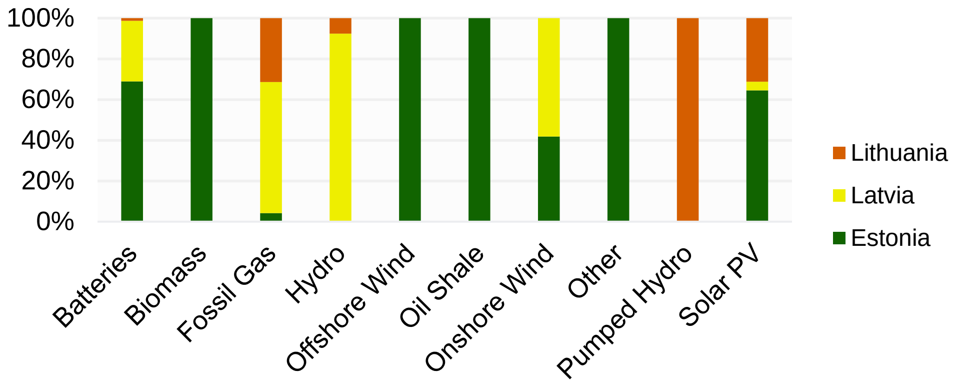
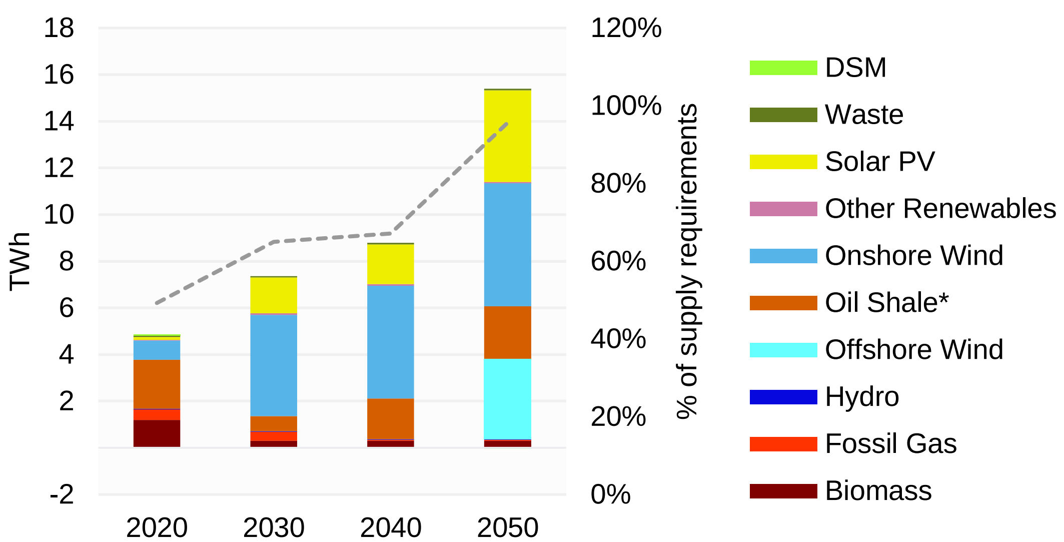


Figure *9* shows projected generation by technology type in Estonia in 2030, 2040 and 2050 under the reference pathway. By 2050, Solar PV, onshore wind, and biomass (burned in former oil shale plants), as well as offshore wind added in the 2040s, all contribute substantially to national production.

Figure 9 *Net electricity generation in the reference pathway, Estonia, 2020-2050*



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

3 – Renewables + storage pathway

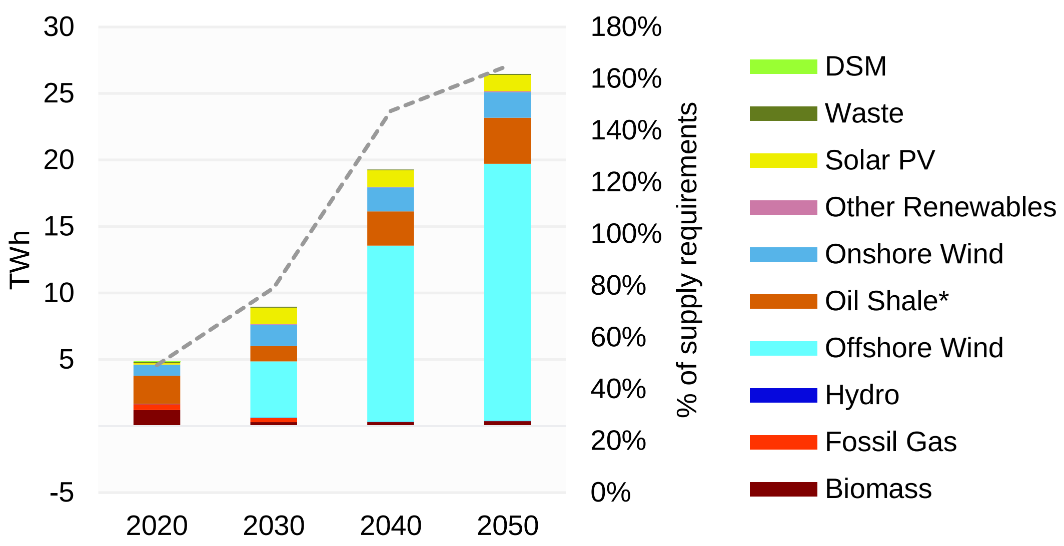
The Renewables + storage scenario evaluates a large deployment of offshore wind in Estonia: 1 GW by 2030, 2 GW by 2035, 3 GW by 2040, and a total of 4 GW by 2050, or about 60% of the country's potential according to the most recent National Energy and Climate Plan (Government of Estonia 2019). The new capacity is constructed in Lääne-Eesti, and 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.

Under the Renewables + storage pathway, 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. And impacts on annual average electricity prices in Estonia are minimal compared to the Reference pathway (0.097 under the renewables pathway vs. 0.098 €$_{2020}$/kWh under the reference pathway by 2050).

Figure 10 depicts electricity generation over time in Estonia under the Renewables + storage pathway. Predictably, electricity generation in Estonia is dominated by offshore wind, but other sources including adapted oil shale plants (re-fitted to use 100% biomass by the early 2030s) and onshore wind also make key contributions.

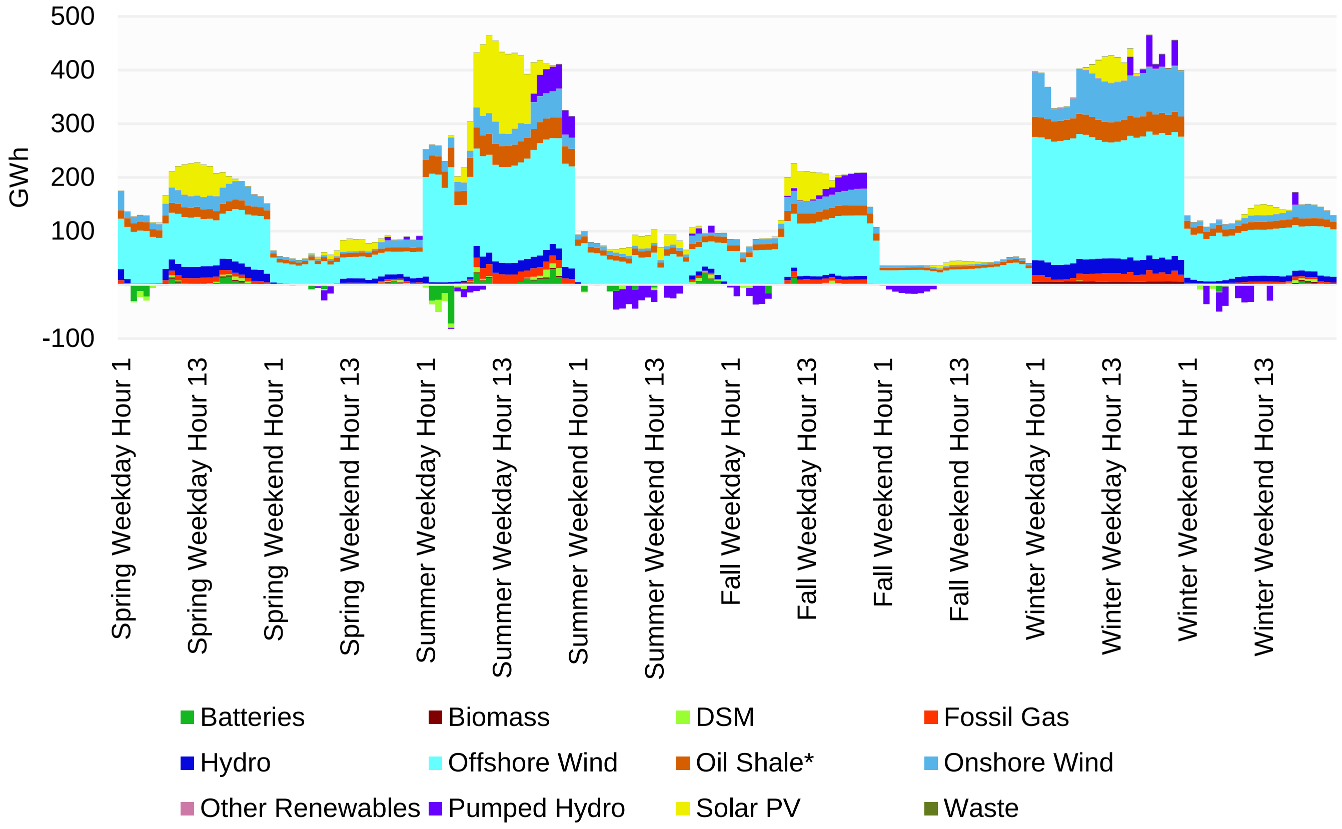
Figure 10 Net electricity generation in the Renewables + storage pathway, Estonia 2020-2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

Systemic changes necessary to absorb new offshore wind production appear clearly at the level of the Baltic region. Figure 11 shows seasonal electricity generation across all modelled Baltic countries in 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 the figure) are also used to fill gaps at certain times.

Figure 11 Time-sliced generation in the Renewables + storage pathway, Baltic Countries, 2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

4 – Nuclear + renewables + storage pathway

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.[5] Critically, the Generation III+ technology is modelled to have high flexibility, allowing it to ensure grid stability when paired with wind and solar. 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.

Deploying almost 1 GW of **nuclear power in Estonia induces a considerable expansion of solar PV** between 2040 and 2050 (from 2 GW of capacity to 6 GW). The **flexibility of nuclear generators is leveraged to integrate solar and wind** production, which rises to 70% of national electricity generation (6.7 TWh) 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. And average electricity prices in Estonia are in line with those in the Reference scenario.

Once constructed, the nuclear facilities are used strategically throughout the year to facilitate solar and wind integration (Figure 13). 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.[6] The availability of nuclear leads to less balancing production from the former oil shale plants using biomass, whose output drops to 0.4 TWh in 2050 (Figure 12). 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.

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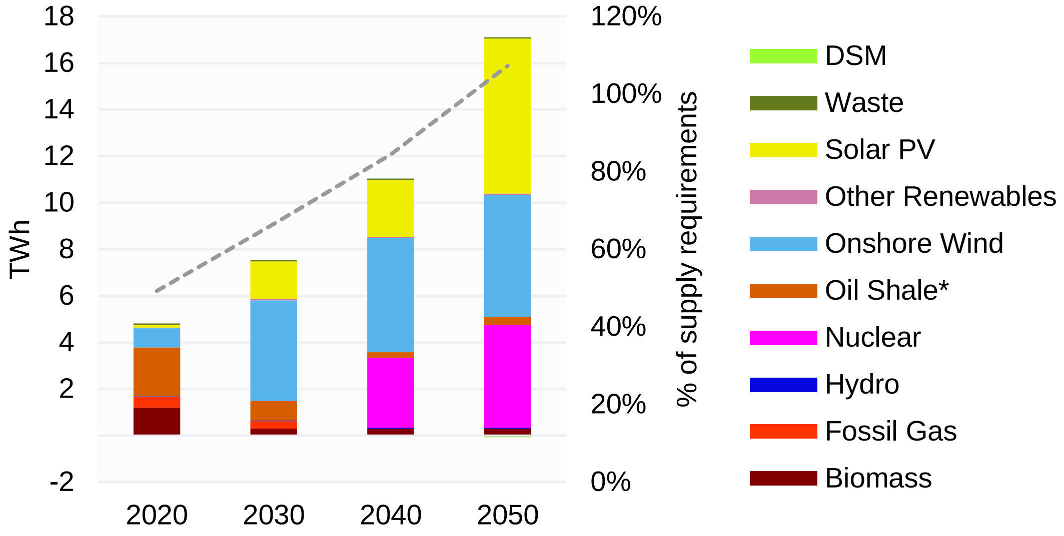
[5] New reactor designs (like the BWRX-300 considered in the model) will be deployed and tested in Canada in upcoming years, which will lead to further clarity on costs and operational profiles associated with the reactor type.

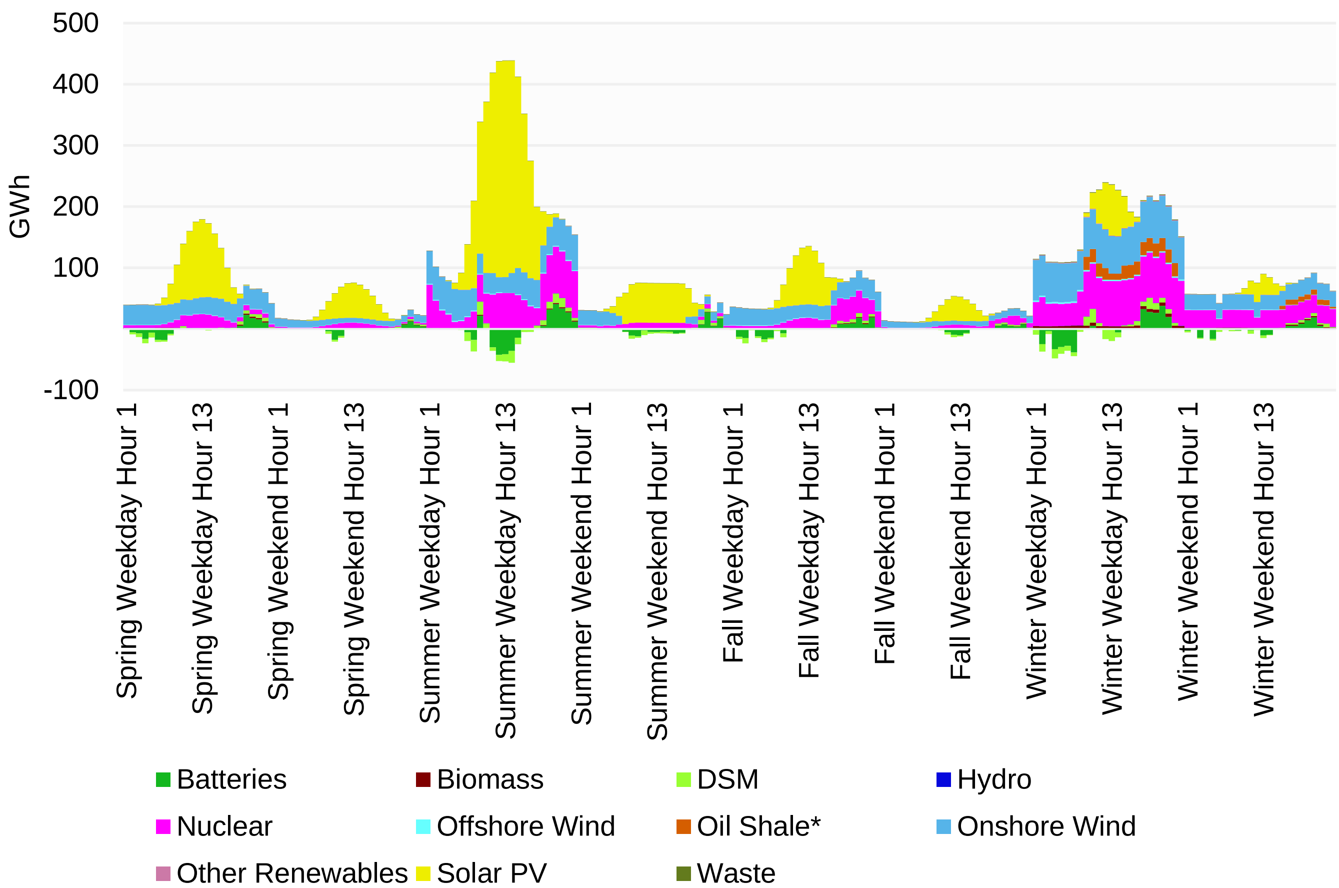
[6] Given feedback from Fermi Energia, it should be noted that the results presented for this scenario reflect how new nuclear plant designs might potentially play a different role in future energy systems (i.e., as a back-up for renewables). 60% dispatch for nuclear plants would be lower than observed 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 12 Net electricity generation in the Nuclear pathway, Estonia 2020-2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

Figure 13 Time-sliced generation in the Nuclear pathway, Estonia, 2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

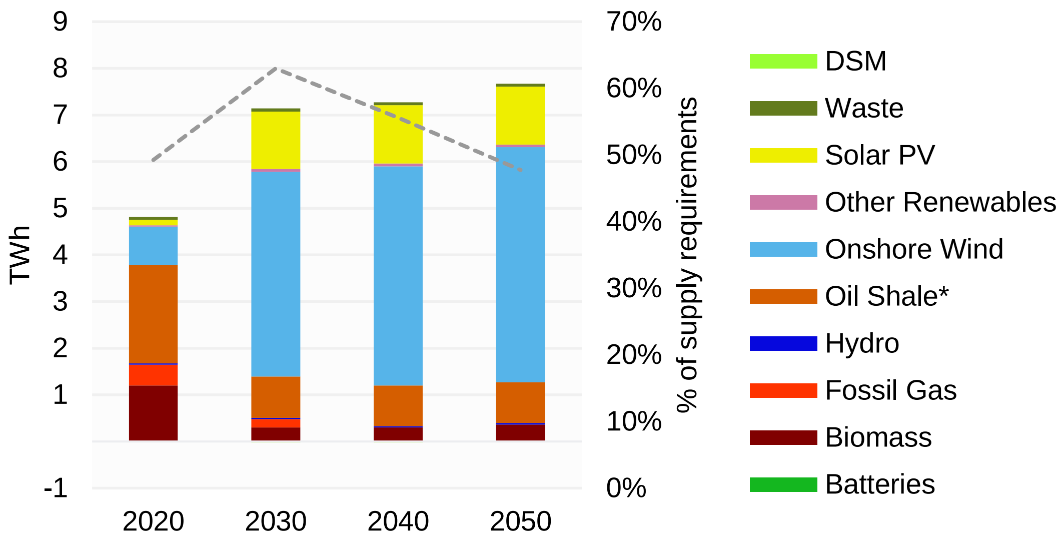
5 – CCU + renewables + storage pathway

The CCU + renewables + storage pathway explores the impacts of adding carbon capture to two large oil shale generators in Estonia, 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. Total captured CO_2 in Estonia is limited to about 700 kt/year.[7]

The estimated **capacity for carbon dioxide utilization** in Estonia is a **binding restriction** on the use of power plants relying on carbon capture rather than biomass use. This restriction leads to decreased output from Auvere and TG11 when these plants are retrofitted with carbon capture technology (compared to the Reference scenario, where they are adapted to use biomass by 2050). 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.

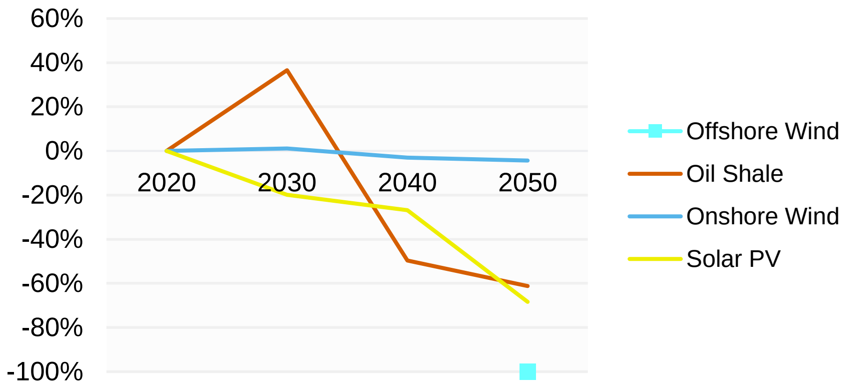
Figure 14 shows projected Estonian electricity generation in 2030, 2040, and 2050 under the CCU pathway. Though production grows by about half from today's levels, this is only enough to keep pace with accelerating requirements from power-to-X adoption. The share of supply requirements met by domestic 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 (as depicted in Figure 15); onshore wind production is not as strongly affected. Production from the CCU generation plants is maximized in 2030, 2040, and 2050 subject to the CO2 utilization limit. The model dispatches Auvere in preference to TG11 due to its higher efficiency.

Figure 14 Net electricity generation in the CCU pathway, Estonia 2020-2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

Figure 15 Proportional change in generation levels in the CCU pathway vs. the reference pathway, Estonia 2020-2050



[7] An estimated potential for carbon utilization in Estonian industry based on several recent studies Please see the Deliverable 2 data collection report for further details on this constraint.

6 – Renewable gas + renewables + storage pathway

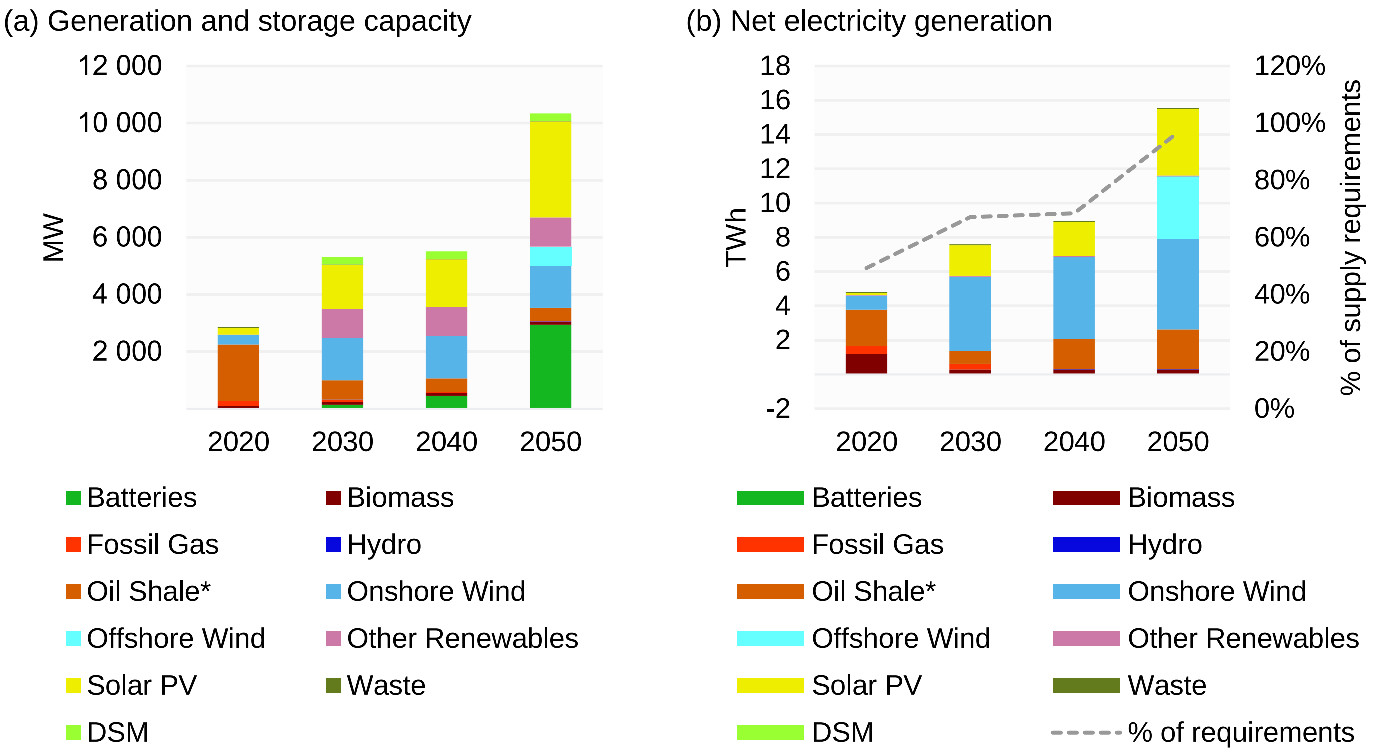
The Renewable gas + renewables + storage scenario models a pathway to climate-neutral electricity production in Estonia assuming implementation of 1 GW of new biogas generation by 2030. This capacity is evenly distributed among Estonia's NUTS 3 regions, and the biogas required to operate it is assumed 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.

The new biogas capacity is essentially incorporated into the electricity system as reserve. Ultimately, 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.

Figure 16(a) shows generation and storage capacity projected over time under the renewable gas pathway, and

Figure 16(b) shows projected generation by technology type as well as the falling proportion of Estonian supply requirements met by domestic generation over time. New biogas capacity, which is reported in the "Other Renewables" category, displaces batteries that are otherwise installed in the Reference scenario. There are no significant differences between the Renewable gas and Reference scenarios in terms of generation, electricity imports and exports, or prices.

Figure 16 Projected capacity build-up and electricity generation in the renewable gas pathway, Estonia, 2020-2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

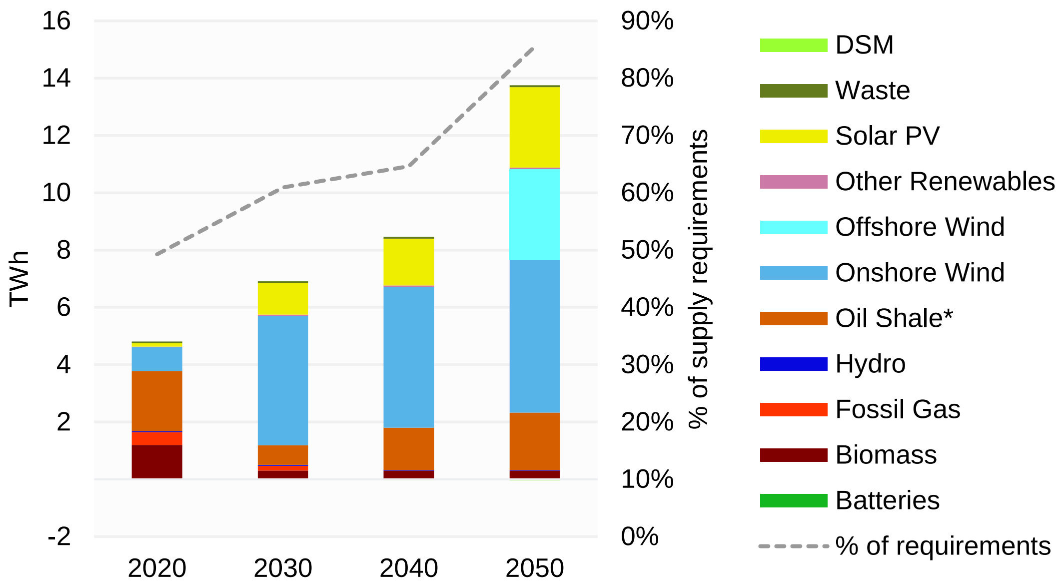
7 – All technologies pathway

The All technologies pathway is the least constrained climate-neutral pathway explored in the Deliverable 3 modelling. Its results affirm a trend observed in the technology-focused pathways as well: proportionally higher use of dispatchable generation facilitates 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.

Under the All technologies pathway, a **partial carbon capture upgrade** at Auvere allows **substantial utilization** of this facility while respecting the climate neutrality requirement and the limit on carbon dioxide 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.

Figure 17 shows calculated net electricity generation per technology type, as well as the proportion of demand supplied domestically under the All technologies pathway. Major oil shale plants are not utilized as completely as in the Reference case, so their output falls along with solar production. 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.

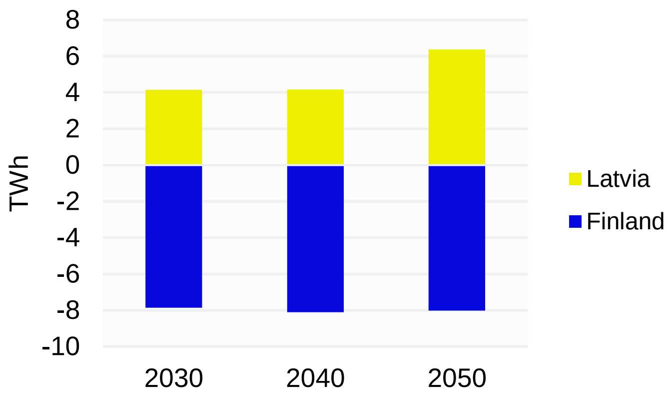
Figure 17 Projected electricity generation in the All technologies pathway, Estonia, 2020-2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

Figure 18 shows the import/export balance in Estonia under the All technologies pathway in 2030, 2040 and 2050. Reduced domestic generation relative to the Reference case requires a greater reliance on imports in 2030 and 2040, but imports decrease over time, levelling out to 1.65 TWh by 2050.

Figure 18 Annual imports to (+) and exports from (-) Estonia in the All technologies pathway, 2030-2050



8 – All technologies + no net imports pathway

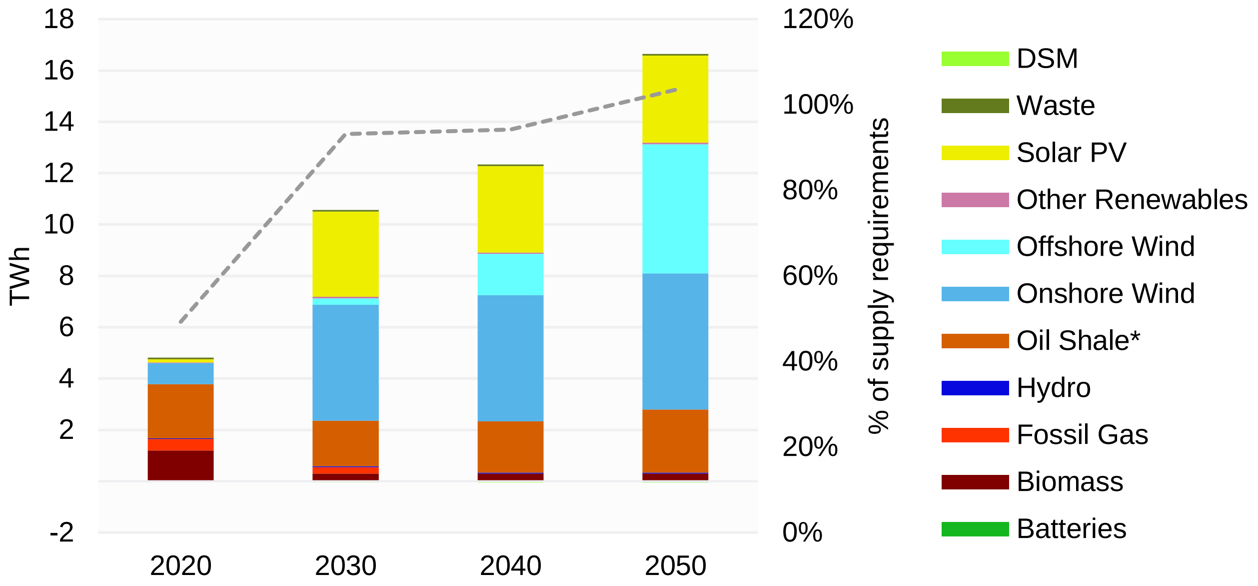
This scenario supplements the All technologies pathway by requiring that Estonia's electricity imports and exports should approximately offset each other. This rule applies in all years of the simulation.

Unsurprisingly, the import restriction 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. Reducing overall reliance on imports leads to a reduction in estimated electricity prices in Estonia, which average between 1-4% lower than in the All technologies scenario and Reference scenarios.

Figure 19 shows projected generation per technology type, as well as the proportion of demand met with domestic supply in Estonia between 2030-2050. Estonian electricity production is greater than in the All technologies case in all future years. Oil shale capacity is used especially in the winter and at times of peak load; this doesn't violate the climate neutrality target because there is captured biogenic carbon dioxide available to offset the greater fossil carbon emissions.

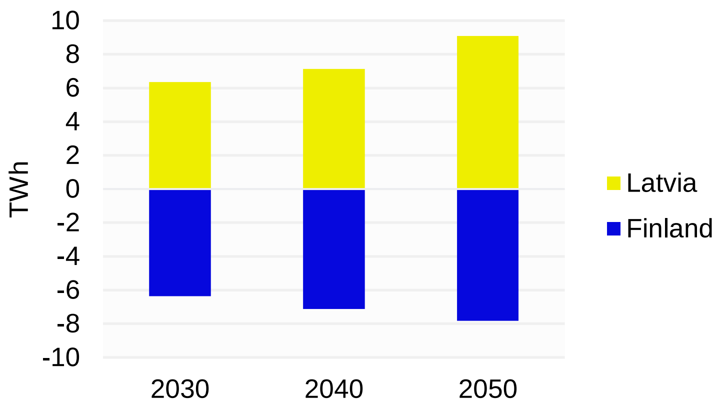
Figure 19 Net electricity generation in the All technologies + No net imports pathway, Estonia, 2020-2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

Figure 20 shows that although net imports of electricity into Estonia are essentially zero in future years, imports and exports do continue. 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 20 Annual imports to (+) and exports from (-) Estonia in the All technologies + No net imports pathway, 2030-2050



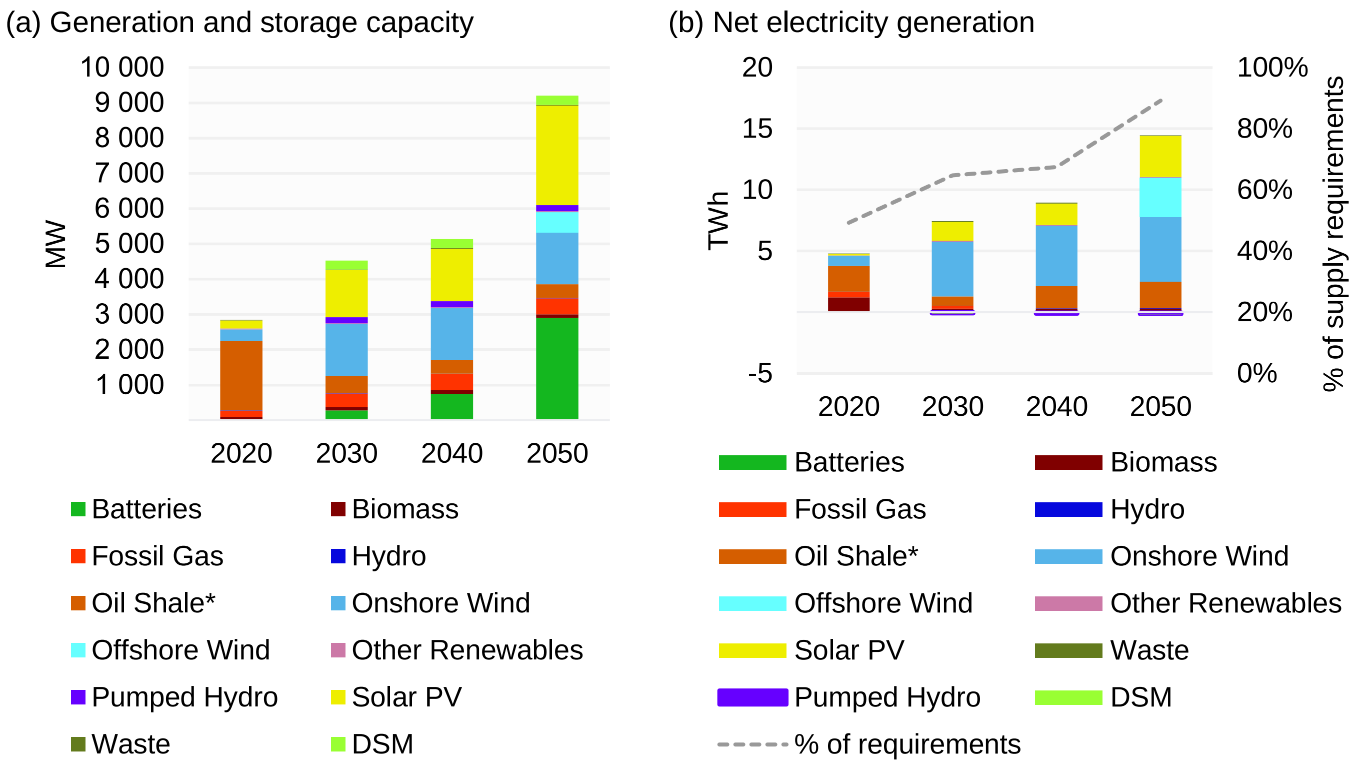
9 – All technologies + 1000 MW dispatchable capacity pathway

This scenario reassesses the All technologies pathway by applying the 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 do not qualify as contributors to dispatchable capacity.

Figure 21(a) shows generation and storage capacity projected over time under the Dispatchable capacity pathway, and Figure 21(b) shows projected generation by technology type as well as the proportion of Estonian supply requirements met by domestic generation over time.

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 the 1000 MW of dispatchable capacity requirement. Capacity factors for these resources in 2050 are 78%, 17%, 66%, and 0.2%, respectively. **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**. However, average electricity prices and GHG emissions from electricity production in Estonia are higher in the Dispatchable capacity pathway than in the Reference pathway (and 1-2% higher than in the All technologies pathway without the dispatchability constraint).

Figure 21 Projected capacity build-up and electricity generation in the All technologies + 1000 MW dispatchable capacity pathway, Estonia, 2020-2050



** By 2050, former oil shale plants are converted to use 100% biomass, unless they're retrofitted with CCU (only permissible in the CCU and All technologies pathways).*

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 given:

- 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; and
- 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. Finally, 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.

Annex to the summary document

Spreadsheets of model results and report charts

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.

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

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. It references sources for all data inputted into the model.

Tables with summary figures on projected capacity and generation for all modelled pathways in 2030 and 2050

Table 1 Pathway comparison – key assumptions and inputs

Pathway		Core assumptions[8]
Baseline	**Business as usual**	- EU Reference Scenario 2020 projections of electricity demand, generation and storage capacity, and ETS price - No climate neutrality requirement
	Reference	- BAU unconstrained by EU Reference Scenario 2020 capacity projections - Includes demand for economically feasible levels of power-to-X
Technology-focused	**Renewables + storage (offshore wind)**	- 1 GW offshore wind installed in Estonia by 2030, 2 by 2035, 3 by 2040, 4 by 2050
	Nuclear	- 900 MW Gen III+ small modular reactor capacity built in Estonia by 2040
	CCU	- Carbon capture added to TG11 in 2025 and Auvere in 2030 and the plants continue to use oil shale rather than biomass
	Renewable gas	- 1 GW of renewable gas capacity built in Estonia by 2030
Technology competition	**All technologies**	- Investments in all low-carbon technologies allowed - No additional constraints on imports or capacity
	1000 MW dispatchable capacity	- Investments in all low-carbon technologies allowed - At least 1000 MW of dispatchable capacity installed in Estonia at all times
	No net imports	- Investments in all low-carbon technologies allowed - Balanced electricity imports/exports into/out of Estonia each year

[8] 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 **Tõrge! Ei leia viiteallikat.**.

*Table 2 Pathway comparison – capacity results for **2030***

Pathway		Capacity in Estonia (MW by 2030)														
		Batteries	***Biogas & other renewables***	***Biomass***	***DSM***	***Fossil gas***	***Hydro***	***Nuclear***	***Offshore wind***	***Onshore wind***	***Oil shale (inc. CCU)***[9]	***Pumped hydro***	***Solar PV***	***Waste***	***Total***	***% Dispatchable***[10]
Baseline	**Business as usual**	391	20	101	261	70	8	0	0	429	676 (biomass, retort gas)	0	725	19	2699	48%
	Reference	640	20	101	261	70	8	0	0	1479	676 (biomass, retort gas)	0	1327	19	4601	35%
Technology-focused	**Renewables + storage (offshore wind)**	984	20	101	261	70	8	0	1000	529	676 (biomass, retort gas)	0	1057	19	4725	41%
	Nuclear	616	20	101	261	70	8	0	0	1479	676 (biomass, retort gas)	0	1393	19	4644	34%
	CCU	623	20	101	261	70	8	0	0	1479	676 (biomass, oil shale, retort gas)	0	1067	19	4323	37%
	Renewable gas	137	1020	101	261	70	8	0	0	1479	676 (biomass, retort gas)	0	1539	19	5310	40%
Technology competition	**All technologies**	615	20	101	261	70	8	0	0	1479	279 (biomass, oil shale, retort gas)	0	951	19	3803	31%
	1000 MW dispatchable capacity	277	20	101	261	379	8	0	0	1479	483 (biomass, oil shale, retort gas)	174	1330	19	4532	34%
	No net imports	1921	20	101	261	70	8	0	59	1479	483 (biomass, oil shale, retort gas)	0	2945	19	7366	37%

9 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.

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

*Table 3 Pathway comparison – capacity results for **2050***

Pathway		Capacity in Estonia (MW by 2050)														
		Batteries	***Biogas & other renewables***	***Biomass***	***DSM***	***Fossil gas***	***Hydro***	***Nuclear***	***Offshore wind***	***Onshore wind***	***Oil shale plants[11]***	***Pumped hydro***	***Solar PV***	***Waste***	***Total***	***% Dispatchable[12]***
Baseline	**Business as usual**	818	20	101	261	16	8	0	0	429	476 (biomass)	0	725	19	2873	54%
	Reference	4386	20	101	261	16	8	0	619	1479	476 (biomass)	0	3397	19	10782	48%
Technology-focused	**Renewables + storage (offshore wind)**	5190	20	123	261	16	8	0	4000	529	476 (biomass)	0	1057	19	11699	51%
	Nuclear	5749	20	101	261	16	8	900	31	1479	476 (biomass)	0	5986	19	15047	49%
	CCU	1885	20	123	261	16	8	0	0	1479	476 (biomass, oil shale, retort gas)	0	1067	19	5354	49%
	Renewable gas	2939	1020	101	261	16	8	0	656	1479	476 (biomass)	0	3362	19	10337	45%
Technology competition	**All technologies**	3403	20	101	261	16	8	0	573	1479	344 (biomass, oil shale, retort gas)	0	2402	19	8626	46%
	1000 MW dispatchable capacity	2903	20	101	261	456	8	0	572	1479	385 (biomass, oil shale, retort gas)	174	2827	19	9204	45%
	No net imports	5509	20	101	261	16	8	0	902	1479	418 (biomass, oil shale, retort gas)	0	2945	19	11678	53%

11 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.

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

*Table 4 Pathway comparison – net generation[13] results for **2030***

	Pathway	Net generation in Estonia (GWh in 2030)																		
		Batteries	*Biogas & other renewables*	*Biomass*	*DSM*	*Fossil gas*	*Hydro*	*Nuclear*	*Offshore wind*	*Onshore wind*	*Oil shale plants[14]*			*Pumped hydro*	*Solar PV*	*Waste*	*Total*	Share of domestic electricity production requirements[15] met	Net exports (TWh)	Domestic demand (TWh)
											Biomass	*Oil Shale*	*Retort Gas*							
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	10.03
	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	16.03
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	16.03
	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	16.03
	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	16.03
	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	16.03
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	16.03
	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	16.03
	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	16.03

13 Net generation in this table refers to generation net of storage charging.
14 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.
15 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).

*Table 5 Pathway comparison – net generation[16] results for **2050***

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)[17]*			*Pumped hydro*	*Solar PV*	*Waste*	*Total*	Share of domestic electricity production requirements[18] 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	10.03
	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	16.03
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	16.03
	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	16.03
	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	16.03
	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	16.03
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	16.03
	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	16.03
	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	16.03

16 Net generation in this table refers to generation net of storage charging.
17 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.
18 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).

Table 6 Pathway comparison – average electricity prices in 2030, 2040, and 2050

Pathway		2030	2040	2050
Baseline	**Reference**	€ 0.1056	€ 0.1025	€ 0.0981
Technology-focused	**Renewables + storage (offshore wind)**	€ 0.1101	€ 0.0980	€ 0.0967
	Nuclear	€ 0.1060	€ 0.1061	€ 0.0999
	CCU	€ 0.1065	€ 0.1020	€ 0.1049
	Renewable gas	€ 0.1057	€ 0.1028	€ 0.0989
Technology competition	**All technologies**	€ 0.1050	€ 0.1018	€ 0.0974
	1000 MW dispatchable capacity	€ 0.1014	€ 0.1015	€ 0.0959
	No net imports	€ 0.1060	€ 0.1038	€ 0.0986