LITHUANIA
100

The Lithuania 100% Renewable Energy Study - Interim Results: Electricity System Scenarios for 2030

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Contents

Executive Summary

What is the Lithuania 100 Study?

- Lithuania's Energy Vision aims to achieve **self-sufficiency in electricity generation** by 2035 and **transition to 100% renewable energy** as soon as possible while maintaining **affordability, reliability, and energy security**.

- The **Lithuanian Energy Agency (LEA)** is partnering with the **National Renewable Energy Laboratory (NREL)** to conduct the **Lithuania 100% Renewable Energy Study (Lithuania 100)** to provide evidence-based analysis for development of Lithuania's National Energy Independence Strategy.

- The Lithuania 100 Study leverages NREL's unique tools and capabilities to provide **rigorous technical analysis** of clean energy policies to achieve 100% renewable energy and **assess impacts** on electricity grid operations, hydrogen system development, electricity distribution networks, air quality, and human health outcomes.

- The study is supported by a stakeholder committee chaired by the **Ministry of Energy of Lithuania** and implemented by **four technical working groups**.

Activities and Outcomes (To Date)

- Lithuania 100 kicked off in **August 2023**. Initial activities focused on data gathering, data creation, model development, scenario design, and initial analysis.
- This report highlights **key interim results** from modeling Lithuania's near-term electricity grid through 2030.
  - The study focuses on hourly operations of the future electricity grid. Capacity expansion scenarios for generation, energy storage, and transmission are based on long-term plans and studies previously conducted by the stakeholder team.
- Results show that Lithuania has **sufficient renewable energy potential, flexible generation capacity, and interconnection** with neighboring European Union countries to reliably meet projected 2030 electricity demand with 100% renewable energy.
- A range of scenarios were modeled, each of which achieves **at least 100% renewable energy** in electricity, on average, by 2030.
- Potential **demands for hydrogen** across industrial and transportation sectors were evaluated, as well as an estimation of **electricity demand for hydrogen** produced in Lithuania by 2030.

Study Objectives

1

Develop **detailed models** to increase technical rigor and **provide insights** for Lithuania's energy strategy

2

Identify **key challenges and potential solutions** for the 100% renewable energy transition

3

Increase **the capacity** of Lithuania's institutions and energy sector companies.

Study Scope

100% Pathways for Lithuania’s Power System

TASK 1

Distribution Grid Planning and Analysis

TASK 2

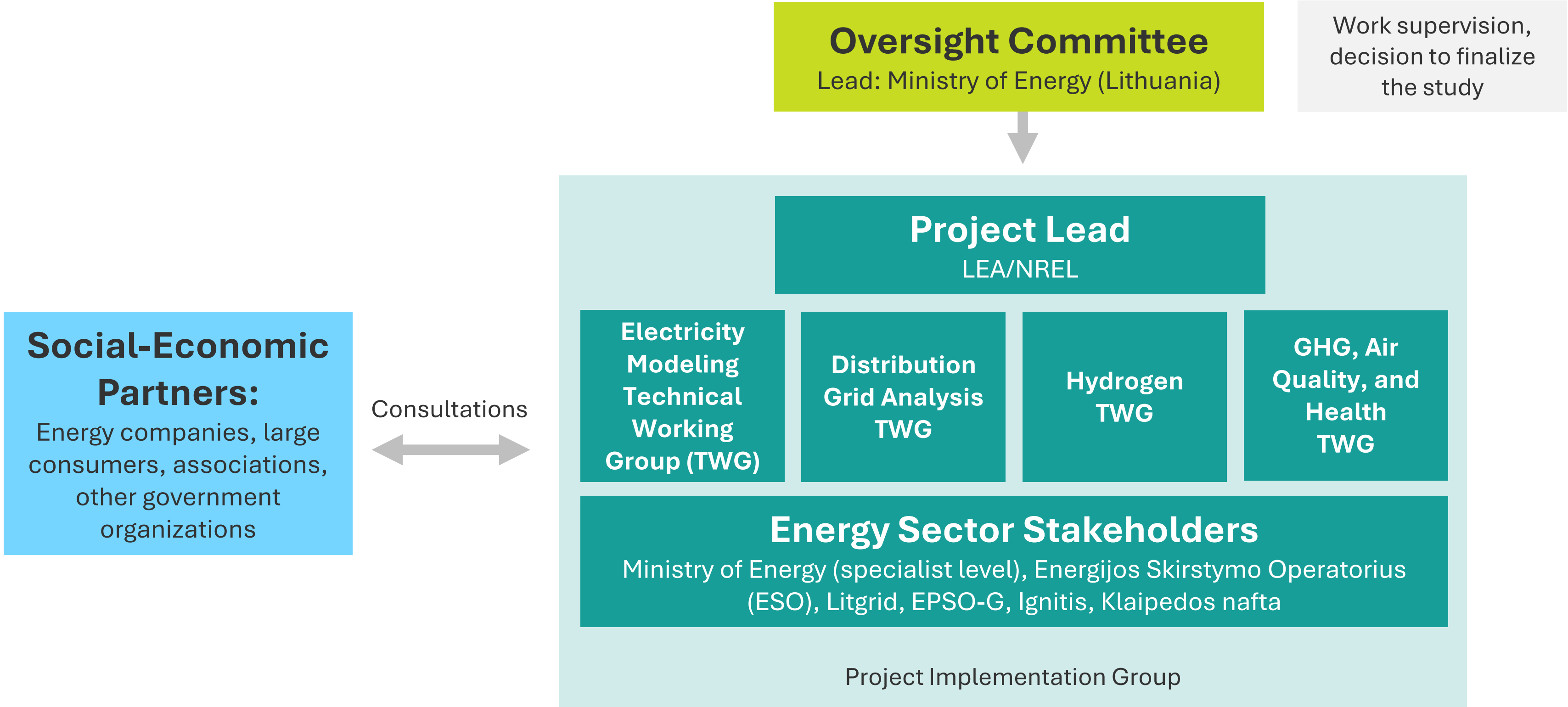
Opportunities for Hydrogen Production and Utilization

TASK 3

Greenhouse Gas (GHG) Emissions, Air Quality, and Health Impacts

TASK 4

Stakeholder Committee and Working Groups



Oversight Committee
Lead: Ministry of Energy (Lithuania)

Work supervision, decision to finalize the study

Project Lead
LEA/NREL

Electricity Modeling Technical Working Group (TWG)

Distribution Grid Analysis TWG

Hydrogen TWG

GHG, Air Quality, and Health TWG

Energy Sector Stakeholders
Ministry of Energy (specialist level), Energijos Skirstymo Operatorius (ESO), Litgrid, EPSO-G, Ignitis, Klaipedos nafta

Project Implementation Group

Social-Economic Partners:
Energy companies, large consumers, associations, other government organizations

Consultations

Lithuania 100 Timeline

2023 September

Kick-off workshop, start of study activities

Geospatial analysis completed

2023 December

2024 April

Initial results and publication of Task 1 interim findings

Initial results for 2040 and 2050 scenarios

2024 August

2024 October

Additional scenarios and sensitivities

Publication of interim results for 2040 and 2050 scenarios

2025 February

2025 August

Final results and study publication

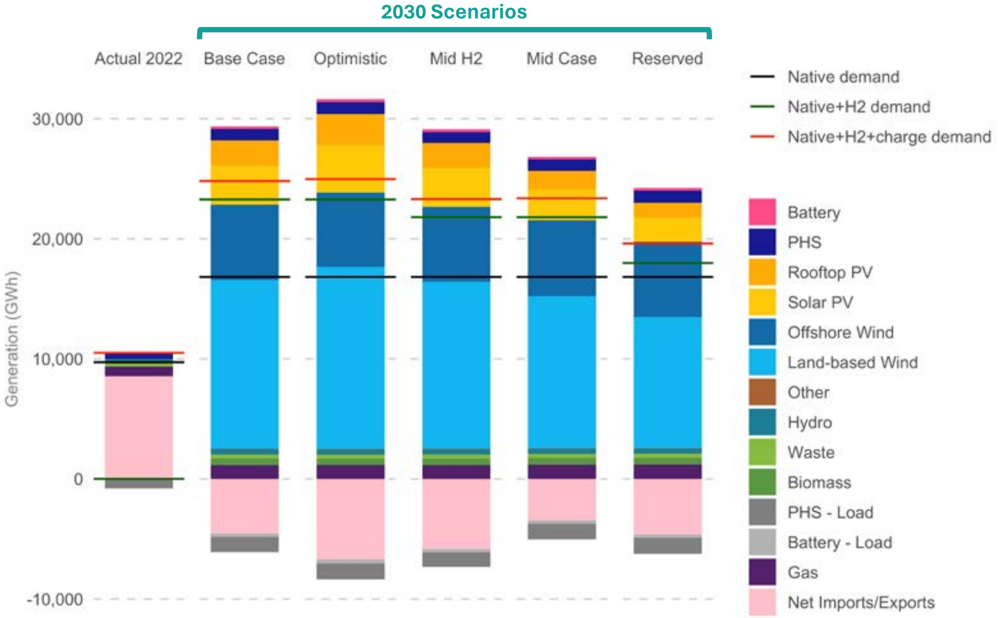
Lithuania 100: 2030 Scenarios

Electricity System Scenarios for 2030

	Annual H2 demand (tons)		
Variable Renewable Energy (VRE) Capacity (GW)	**130k**	**100k**	**50k**
11.5	Optimistic		
10	Base Case	Mid H2	
8.5		Mid Case	
7.4			Reserved

2030	**Optimistic**	**Base Case**	**Mid H2**	**Mid Case**	**Reserved**
Solar	5.1 $\mathrm{GW}_{\mathrm{AC}}$	4.1 $\mathrm{GW}_{\mathrm{AC}}$	4.1 $\mathrm{GW}_{\mathrm{AC}}$	3.1 $\mathrm{GW}_{\mathrm{AC}}$	2.5 $\mathrm{GW}_{\mathrm{AC}}$
Land-based wind	5 GW	4.5 GW	4.5 GW	4 GW	3.5 GW
Offshore wind	1.4 GW	1.4 GW	1.4 GW	1.4 GW	1.4 GW
Total	11.5 GW	10 GW	10 GW	8.5 GW	7.4 GW

Key Results: Generation Mix Across Scenarios



Scenario	VRE Contribution to Total Annual Load (%)	Total Renewable Energy Contribution (%)	Net Exports (TWh)	VRE Curtailment (%)
Base Case	104%	107%	4.6	3.3%
Optimistic	112%	116%	6.7	5.6%
Mid Hydrogen (H2)	109%	113%	5.8	4.0%
Mid Case	99%	103%	3.4	2.0%
Reserved	104%	109%	4.6	3.1%

Note: Interim results are based on a simplified transmission representation with maximum flow limits but no line impedance data. Future work will include a more accurate representation of transmission power flow, which can result in higher VRE curtailment estimates.

Key Takeaways From 2030 Electricity Grid Modeling Scenarios

1. With current targets, **Lithuania can achieve 100% variable renewable energy (VRE) in electricity supply** on an annual timescale.

2. On average, Lithuania can expect to be a **net exporter of electricity in 2030**, with most exports flowing through Poland. Sweden will continue to supply imports during much of the year.

3. **Imports and exports with neighboring countries are valuable** for balancing periods of low/high VRE generation. Limiting electricity trade would require higher VRE curtailment and higher gas utilization.

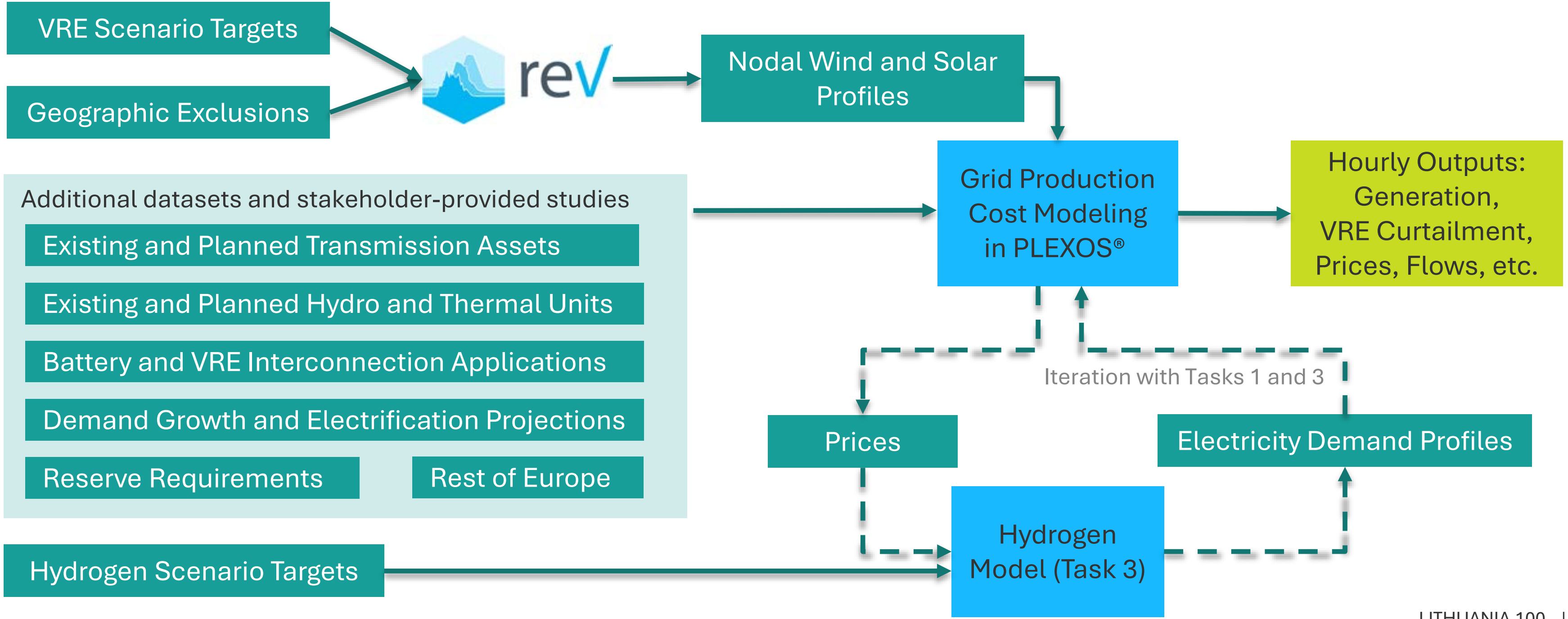
4. **Wind and solar resources are well paired in Lithuania.** The mix of solar and wind resources, in combination with the pattern of demand, does not show a strong seasonal trend. Therefore, we do not see a near-term need for seasonal electricity storage capacity.

5. Given government targets and industry plans for hydrogen sector development, electricity demand for **hydrogen production is likely to be a major component of Lithuania's total demand by 2030**. Flexibility of hydrogen electrolysis can reduce VRE curtailment, mitigate peak electricity prices, and provide significant cost savings for clean hydrogen production.

Methods, Data, and Assumptions

Modeling Overview

Objective: Model Lithuania's future grid to meet its expected energy and reserve requirements with lowest *operational* cost for pre-determined VRE and hydrogen scenarios



VRE Scenario Targets

Geographic Exclusions

rev

Nodal Wind and Solar Profiles

Additional datasets and stakeholder-provided studies

- Existing and Planned Transmission Assets
- Existing and Planned Hydro and Thermal Units
- Battery and VRE Interconnection Applications
- Demand Growth and Electrification Projections
- Reserve Requirements
- Rest of Europe

Grid Production Cost Modeling in PLEXOS®

Hourly Outputs:
Generation,
VRE Curtailment,
Prices, Flows, etc.

Iteration with Tasks 1 and 3

Prices

Electricity Demand Profiles

Hydrogen Model (Task 3)

Hydrogen Scenario Targets

Key Modeling Assumptions and Limitations

- This study uses a **production cost modeling (PCM)** approach to simulate the operation of Lithuania's high-voltage power system on an hourly timescale in 2030. The model ensures demand is met at the lowest possible cost in every hour while maintaining frequency reserves and adhering to physical constraints of electric grid infrastructure.

- We used published long-term plans and studies previously conducted by the stakeholder team to model the planned 2030 transmission lines, thermal and hydropower generators, end-use demand, and reserve requirements. **We did not conduct capacity expansion modeling to optimize the build-out of the 2030 system**. Wind, solar, battery, and hydrogen build-out targets were determined through discussions with the Task 1 and Task 3 stakeholder teams.

- Lithuania’s power system was modeled based on the 2018 weather year while the rest of Europe was modeled based on the 2016 weather year. The **discrepancy in weather modeling can cause an under-estimate of weather impacts**, such as periods of prolonged low wind generation. Modeling a single year also does not capture inter-annual variability of weather conditions, including variability of hydropower resources.

- We investigated whether the proposed system could meet demand and reserve requirements under normal operating conditions. **We did not conduct a full resource adequacy assessment** to verify the proposed system has sufficient capacity to reliably operate under unexpected transmission and generator outages.

- For the transmission lines, **we included maximum flow limits but no line impedance data**, which could impact the practical feasibility of these results. Future simulations with impedance data are planned and follow-on power flow and stability studies can be performed to further assess technical constraints.

The Generation Fleet Is Evolving…

	2022 Capacity (MW)	2030 Base Case (MW)
Pumped Storage	900	1,010
Land-Based Wind	1,186	4,500
Hydropower	126	126
Gas Combined Cycle (CCGT)	474	403
Gas Steam Turbine (ST)	818	729
Other (Waste, Bio)	202	265
Offshore wind	0	1,400
Solar	865	4,100
Battery	1	1,101
Total	**3,706 MW**	**13,630 MW**

…Along With the Rest of Europe

- With the help of Litgrid and the Lithuania Energy Agency, we implemented the proposed generator fleet (previous slide) for Lithuania for 2030 into a PLEXOS® model for the entire ENTSO-E footprint.

- Lithuania is modeled *nodally* (over 300 nodes, 440 lines, and nearly 400 generators), and the rest of Europe is modeled zonally (each country is represented as 1-4 zones, with individual lines connecting each).

- For other countries, we used the 2030 representation of the European Resource Adequacy Assessment 2023 Scenario A.

Electricity Demand in 2030

2022 Annual Demand (excluding pump and battery load)	12.0 TWh
2022 Peak Demand	2,136 MW

2030 Annual Demand (excluding pump and battery load)	23.3 TWh
2030 Peak Demand (excluding pump and battery load)	3,897 MW

- 2030 annual demand includes increased loads from:
  - Electric vehicle consumption (1.1 TWh).
  - Residential heat pump adoption: 10% of heating energy comes from fully electric heat pumps, 3% of heating energy from hybrid electric heat pumps (0.53 TWh).
  - H2 production via electrolysis (6.5 TWh) to meet 130,000 tons of H2 production per year.
  - General load increases, such as in the industrial sector.
- Although detailed analysis of hourly demand will occur later in Task 2 of this study, these factors have the potential to change the daily and seasonal demand shape in Lithuania.

Electricity Demand from Electrolytic Hydrogen Production

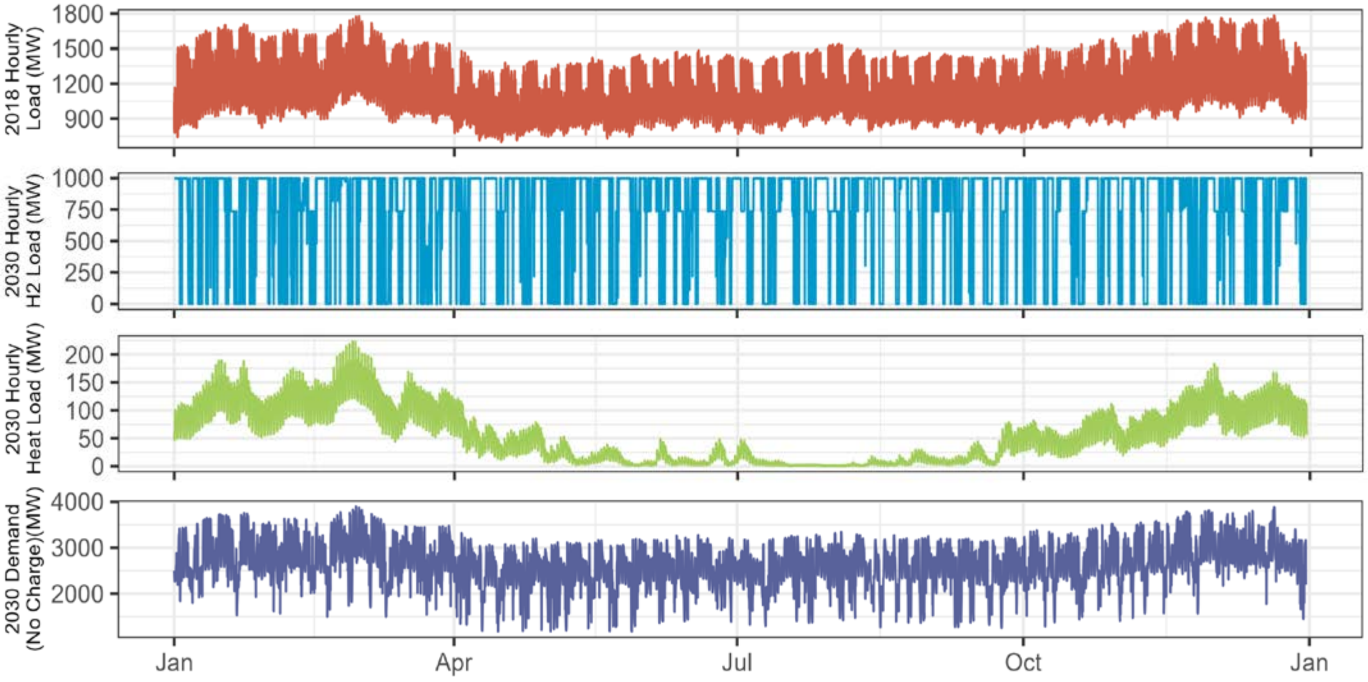
- Hydrogen demand scenarios were developed in cooperation with LEA and the Task 3 working group, based on current plans, national targets, and previous studies.

- Hydrogen demands (but not production) were assumed to be constant for all hours of the year.
  - Constant hydrogen demand is primarily for industrial processes that operate at steady-state.

- Hydrogen production varies hourly with electricity costs, balanced against hydrogen storage needs and costs.

Source of Demand	Optimistic H_2 130 kT	Mid H_2 100 kT	Reserved H_2 50 kT
H_2 Production for Local Industry (Ammonia, Oil Refining, and Methanol)	64 kT (3.2 TWh)		44 kT (2.2 TWh)
Centralized H_2 Production for Other Domestic Industries	27 kT (1.3 TWh)	30 kT (1.5 TWh)	0
H_2 Export	33 kT (1.6 TWh)	0	0
Klaipeda Port Pilot Project	0.1 kT (0.005 TWh)		
H_2 Refueling Stations	Trucks: 5.5 kT (0.3 TWh) Municipal transport: 2.1 kT (0.1 TWh)		

2030 Load Profile Modeling

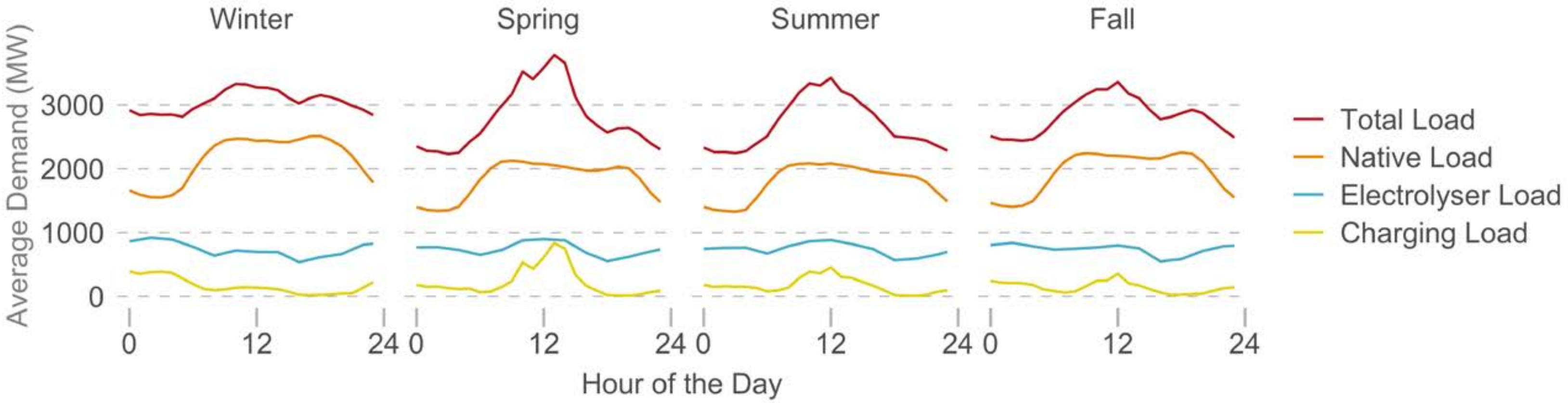


**Note different y-axis scales.*

Development of 2030 hourly demand profile

- Hourly hydrogen electrolysis is input to the grid model as a fixed profile based on hydrogen-sector optimization from the Task 3 modeling team.
- 2030 hourly heat load comes from the "When2Heat" dataset for Lithuania in 2018, assuming 59% multifamily homes and 41% single-family homes (https://data.open-power-system-data.org/when2heat/).
- After accounting for these new load shapes, the remaining increase in load is *scaled* from 2018 to meet 2030 total energy demand.

Average Daily Demand Profile in 2030



- Electrification of heating and vehicles will change load shape, but in 2030 the impact is relatively minor.
- More notable is the larger overall demand (in large part due to H_2 production), as well as a “designed” new daily peak caused by charging storage in the middle of the day to align with solar availability.
- Future work will include additional net load modeling to represent impacts of higher electrification of heating and transportation sectors in 2040 and 2050.

Reserves Requirements

- We implemented requirements for automatic Frequency Restoration Reserve (aFRR) and manual Frequency Restoration Reserve (mFRR), as well as ramping and minimum generation constraints for Lithuania's thermal and hydro generators.
- We are not considering Baltic-wide requirements (or reserve requirements for any other regions), due to computational constraints.
- We assume VRE is permitted to provide downwards but not upwards reserves.

	Hourly MW Requirement*	**Response Time (min)***	**Eligible Generators**
aFRR	103	5	Lietuvos elektrinė G7-G9, Mažeikių elektrinė G1, Kruonio HAE, new batteries
aFRR Downward	103	5	Lietuvos elektrinė G7-G9, Mažeikių elektrinė G1, Kruonio HAE, new batteries, new VRE
mFRR	759	12.5	Lietuvos elektrinė G7-G9, Mažeikių elektrinė G1, Kauno HE, Kruonio HAE, new batteries
mFRR Downward	629	12.5	Lietuvos elektrinė G7-G9, Mažeikių elektrinė G1, Kauno HE, Kruonio HAE, new batteries, new VRE

*Source: Elering. 2022. *Baltic LFC block FRR dimensioning forecast 2024-2031*. https://www.ast.lv/sites/default/files/editor/FRR_dimensioning_forecast_2024-2031.pdf.

Energy Storage Additions

Batteries

	Battery Types	Maximum Power of Fleet	Energy Storage of Fleet	Duration at Maximum Output
Currently Installed	1-hour duration	200 MW	200 MWh	1 hr
Planned 2023-2030	Mix of 1-, 2- and 4-hour duration	1,085 MW	1,565 MWh	1.44 hr average
2030 Target		1,101 MW	**1,500 MWh**	1.36 hr average

Lithium-ion batteries are assumed to operate with an 80% usable state of charge to minimize cycling degradation.

Batteries for 2030 are modeled as 1-, 2- and/or 4-hour duration, based on other batteries planned at each electricity network node.

Pumped Hydro

Additional 110-MW pumped hydro unit planned by 2030.

Total Power	Energy Storage	Duration at Maximum Output
1,010 MW	10.6 GWh	10.5 hr

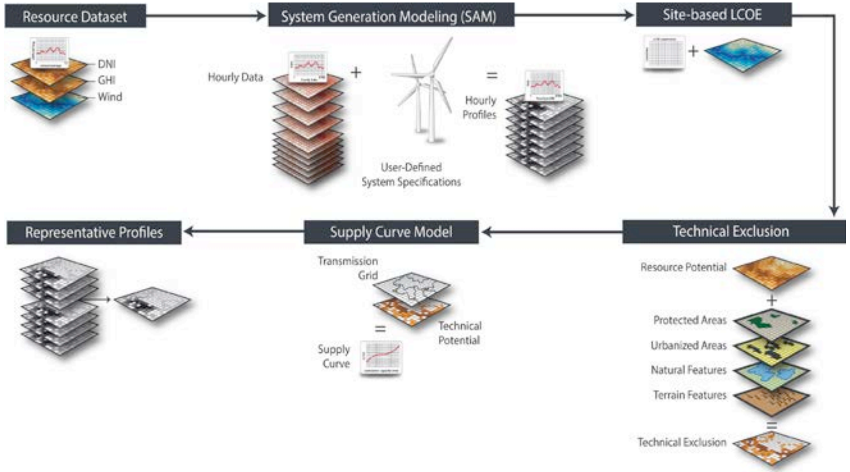
Transmission Updates

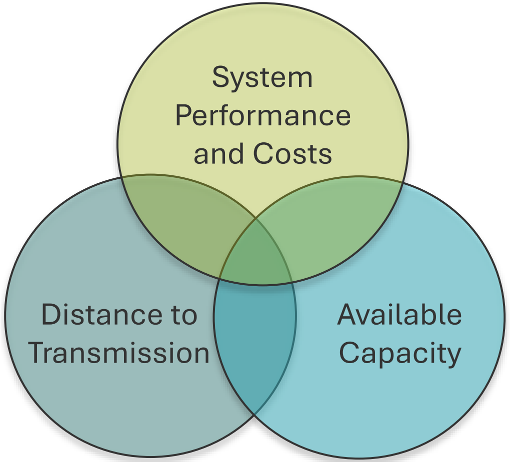
Voltage	Lines	Nodes
110 kV	370	273
330 kV	80	30

- With LitGrid's collaboration, we implemented a detailed nodal representation of Lithuania's high-voltage electricity network.
- We used a zonal representation for the rest of Europe:
  - Each country outside Lithuania is represented with a single node. Some exceptions apply, such as Sweden, which has four nodes.
  - The evolution of power systems in the rest of Europe, including load growth, growth of renewables, and other types of generation, was aggregated to each representative node.
- We included planned new transmission between Lithuania and neighboring European Union countries:
  - New 700-MW Harmony Link routed to Gizai
  - Allowed 150 MW of market transfer over the LitPol Link
  - 1,300-MW market limit on transfer with Latvia
  - 1,200-MW ramp rate limit on interchange with Sweden.

Geospatial Analysis Results

Renewable Energy Potential





- We used NREL's **Renewable Energy Potential (reV) tool** to develop wind and solar resource data inputs for downstream modeling tools.
- reV provides a comprehensive view of Lithuania's technical potential and a **field of possible model plants** from which downstream energy models draw.
- reV optimizes plant layout and **simulates hourly generation** of future wind turbines and solar technologies.

See: *https://github.com/NREL/reV*.
Figure source: The Renewable Energy Potential (reV) Model: A Geospatial Platform for Technical Potential and Supply Curve Modeling
https://www.nrel.gov/docs/fy19osti/73067.pdf.

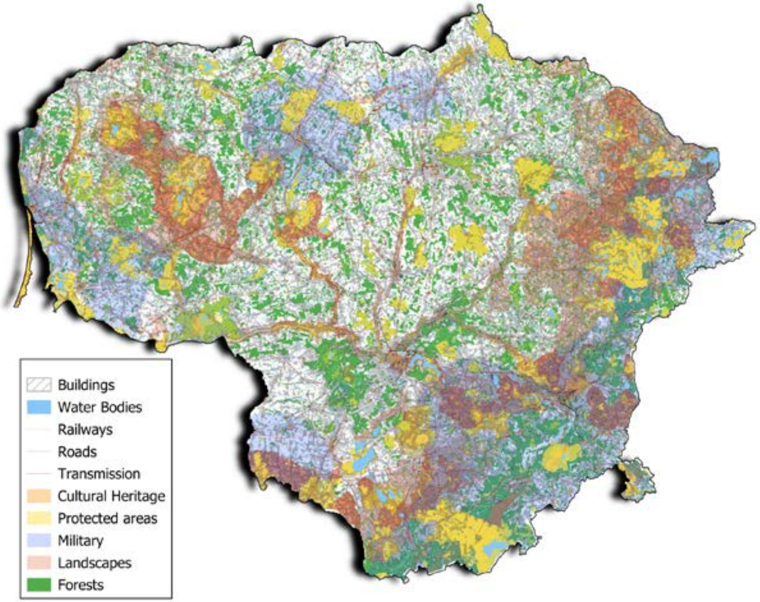
Lithuania Land-Use Assessment and Setback Assumptions

- Land-use data was collected from Lithuania's Centre of Registers.
- Setbacks for land-based wind and solar technologies were based on existing land-use regulations.

Feature	Wind Turbine Setback (height multiplier)	Solar Plant Setback (meters)
Structure	1	75
Road	1	30
Rail	1	30
Transmission	1	30
Water	1	30
Protected Points of Interest	10	0
Airport	1	75
Military Communications	1.5	0

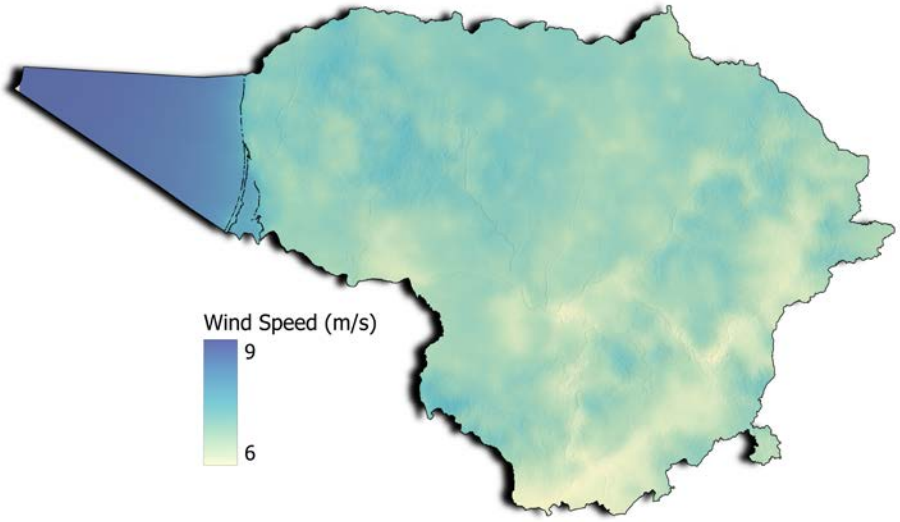
Note: Other exclusions that do not have setbacks, such as land cover classifications and protected areas, are not shown here.

Land exclusions for geospatial analysis of wind and solar potential



Average Wind Speed Across Lithuania

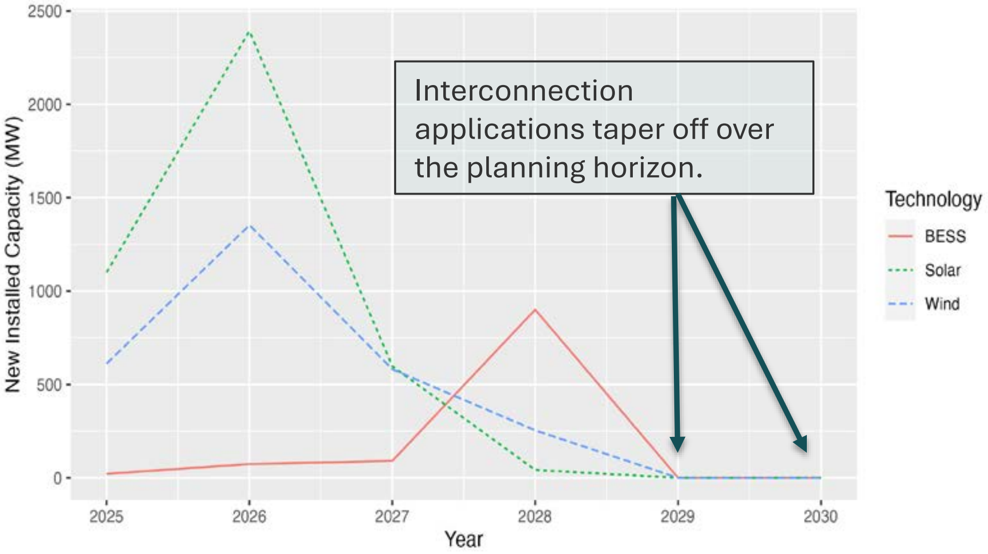
- We used wind speed and wind direction data from the New European Wind Atlas for weather year 2018.
- Average wind speed over land at 100 meters: 6.51 m/s.
- Average offshore wind speed at 100 meters: 8.37 m/s.



Note: Wind generation is modeled with a hub height of 115 meters for land-based wind plants and 150 meters for offshore wind.

Modeling Existing and New Technologies

Target year for new resources applying to Litgrid for interconnection



Interconnection applications taper off over the planning horizon.

- There are currently many interconnection applications for the next few years but forecast tapers off by 2029.

- Capacity factors are modeling *outputs*, based on technology specifications and location inputs.

- Wind:
  - Assumed 70% existing technology and 30% state of the art for 2030.
- Solar:
  - Assumed 100% state-of-the-art solar configurations for utility-scale plants.
  - Assumed 20% reduction in output for distributed solar to capture losses due to tilt, orientation, and shading.

Technical Potential: Land-Based Wind

Total technical potential for land-based wind is 37 GW.

Technology assumptions for state of the art in 2030:

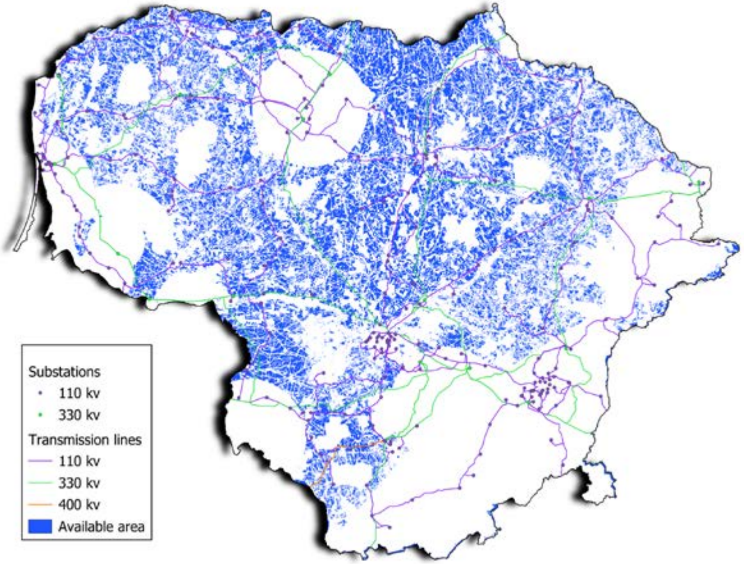
- 6-MW turbine
- 115-m hub height
- 170-m rotor diameter
- 3 MW per km^2.

Representative technology for existing and near-term installations:

- 2.5-MW turbine
- 80-m hub height
- 100-m rotor diameter
- 3 MW per km^2.

Key uncertainties:

- Future turbine design
- Setback regulations
- Availability of forested land.



Available Area: 12,214 sq. km

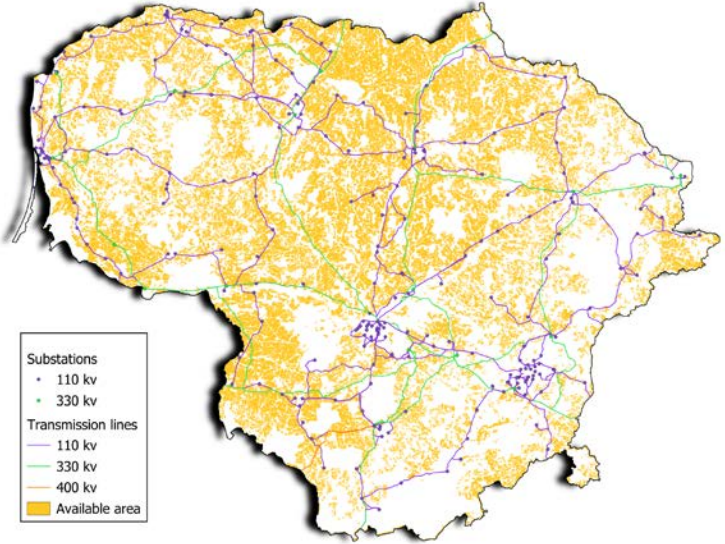
Technical Potential: Ground-Mounted Solar

Technical potential for ground-mounted solar PV is 560 GW_{AC}.

Key assumptions:

- Bifacial modules with single-axis tracking and backtracking
- Nameplate DC capacity density: 31.6 MW_{DC}/km^2
- Ground cover ratio: 0.2
- DC:AC ratio: 1.371

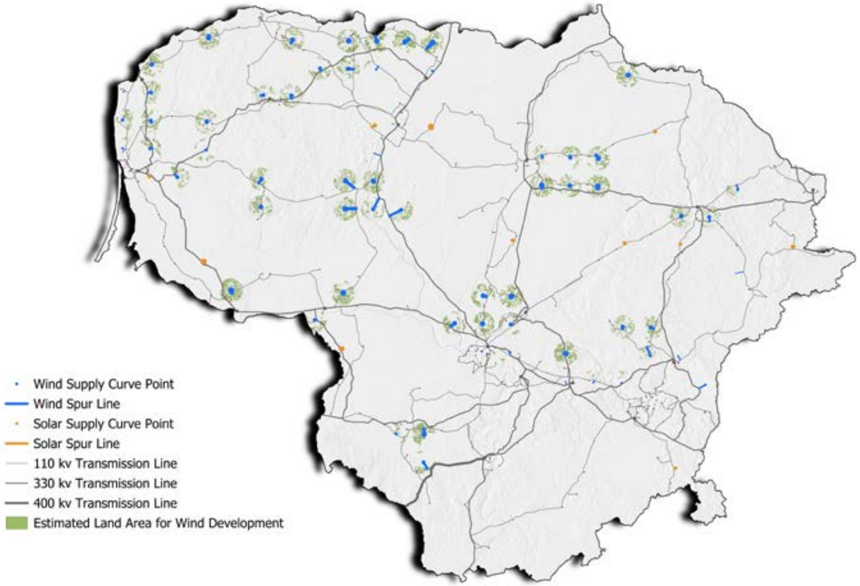
The 2030 target requires **less than 1%** of total available area for solar development.



Available Area: 24,358 sq. km

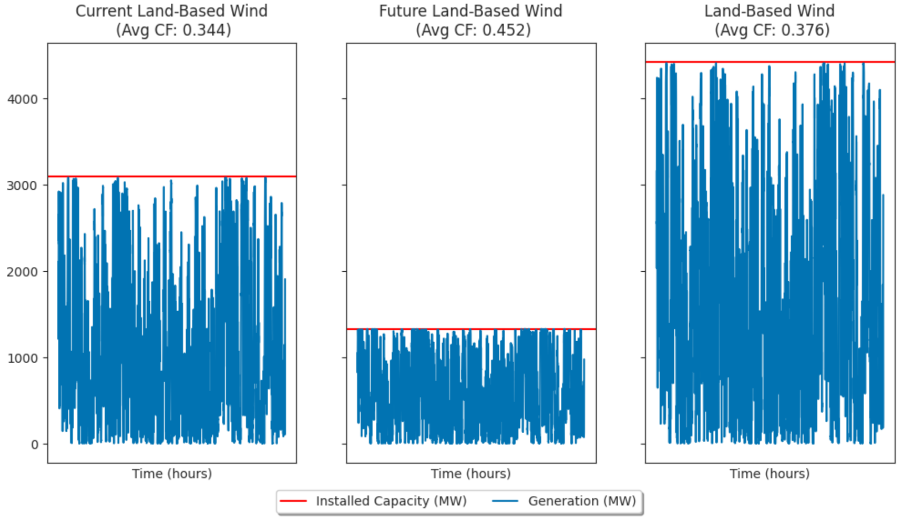
Determining Solar and Wind Buildout Locations and Profiles

- We used interconnection applications of existing and planned wind and solar parks to identify transmission network nodes.
- Sites considered for development are within 50 km of the given network node.
- Sites closer to transmission network incur lower spur line cost.
- Eligible sites were ranked by total levelized cost of energy to determine optimal assignment.



Land-Based Wind Profiles

Land-based wind profiles are based on multiple technology configurations.



We enforced a one-technology-per-site rule to prevent unrealistic land use, giving wind priority over overlapping sites.

- Rule was not applied to DSO Solar, which we assume is largely rooftop.

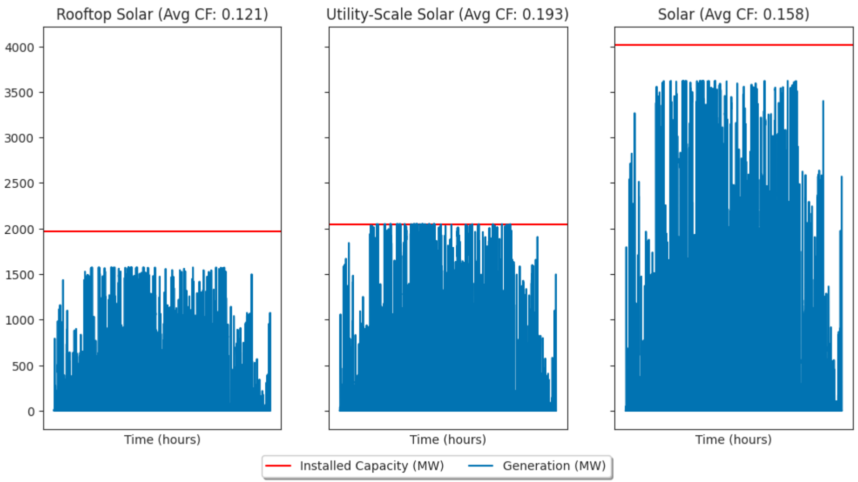
Land-based wind profiles represent a blend of two technology profiles based on current and future technology configurations.

- Assumed 3.1 GW of existing tech and 1.3 GW of new tech.
- Overall average CF: 0.376.

Solar Profiles

Solar profiles are blended to represent a mix of rooftop photovoltaics (PV) and utility-scale solar PV deployment.

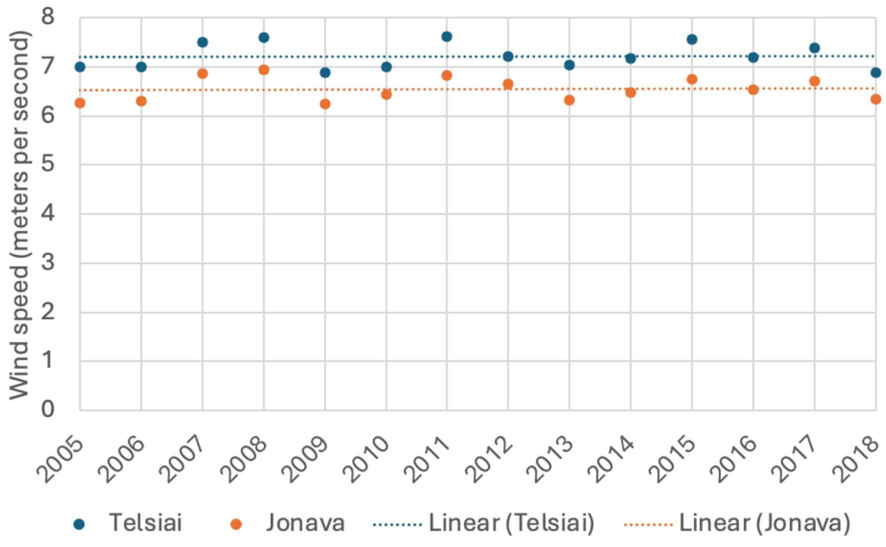
- Rooftop solar profiles are derated to represent suboptimal panel tilt, orientation, and shading losses.
- Average utility-scale capacity factor: 19.3%.
- Average rooftop PV capacity factor: 12.1%.
- Overall average solar capacity factor: 15.8%.



Note: Capacity factors cited in this report are based on the AC capacity of the inverter. Capacity factors based on DC installed capacity are typically lower, particularly in higher-latitude locations where a higher DC-to-AC ratio is more cost-effective.

Comparing the 2018 Weather Year

Historic annual average wind speed at 100 meters for two sites



Source of wind speed data: New European Wind Atlas. https://map.neweuropeanwindatlas.eu/.

How does the 2018 weather year compare to long-term average wind speed?

Wind capacity factors indicated in this report are likely to underestimate the long-term average.

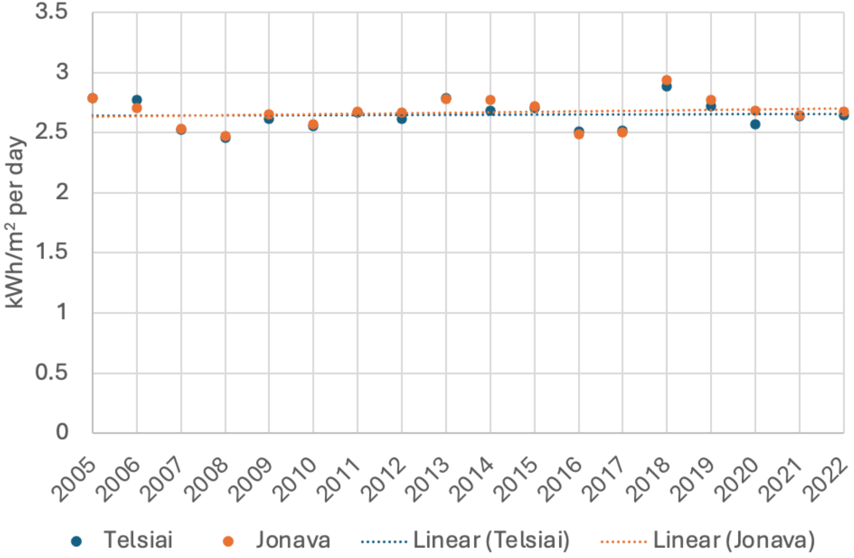
- 2018 was among the lower years for wind speeds between 2005–2018.

Why use 2018 weather data instead of 2022/2023 wind power measurements?

- Measurements at existing wind locations do not provide data to model new builds in new locations.
- Periods of grid stress (peak load, low VRE) are best modeled with load, wind, and solar all based on the same weather patterns.
- All necessary input data for 2022/2023 modeling is not available.

Comparing the 2018 Solar Resource

Historic annual average solar irradiance for two sites



Source of solar irradiance data: NREL's National Solar Radiation Database. https://nsrdb.nrel.gov/

How does 2018 solar resource compare to the long-term average?

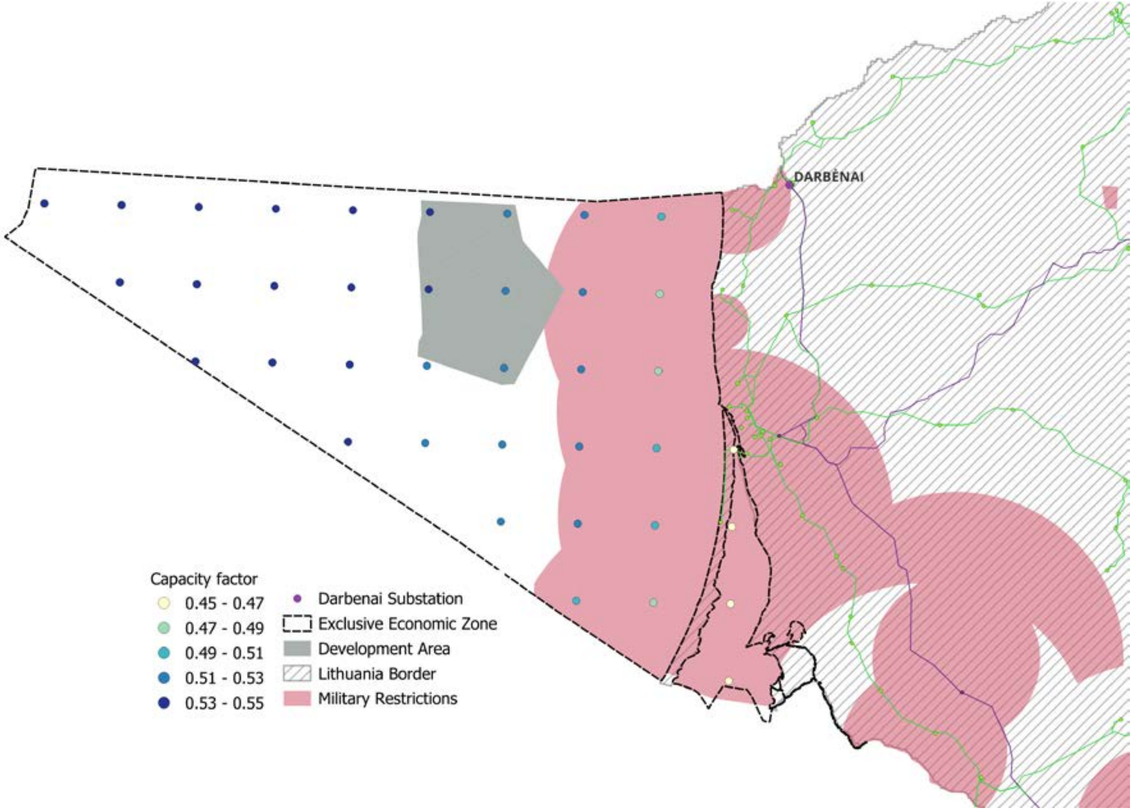
Solar capacity factors indicated in this report are likely to overestimate the long-term average in Lithuania.

- 2018 was the highest year for solar resources between 2005–2022.

Offshore Wind Phase 1 and Phase 2 Wind Generation

- Total capacity: 1,400 MW
- Annual average capacity factor: 0.52
- Technology assumptions for offshore wind:
  - 15-MW turbine
  - 150-m hub height
  - 240-m rotor diameter.

Offshore Wind Supply Curve Points

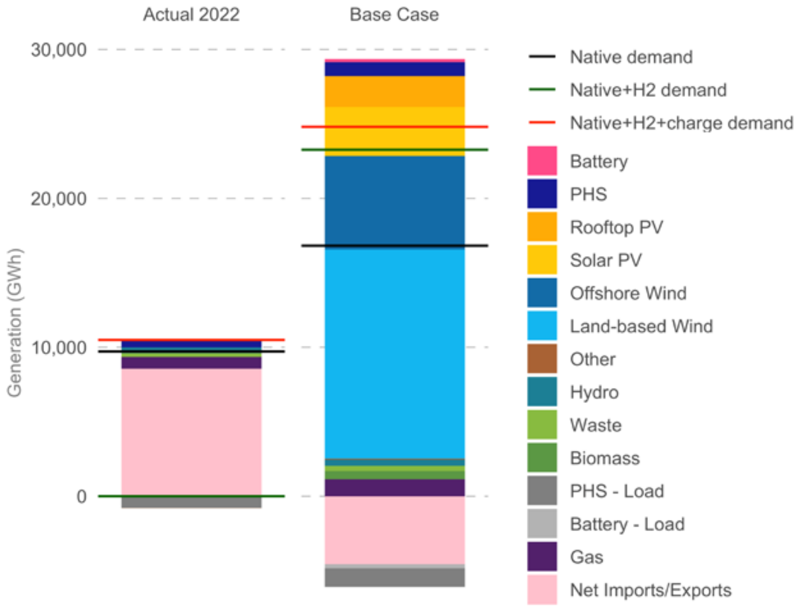


Results for the Base Case in 2030

The Base Case

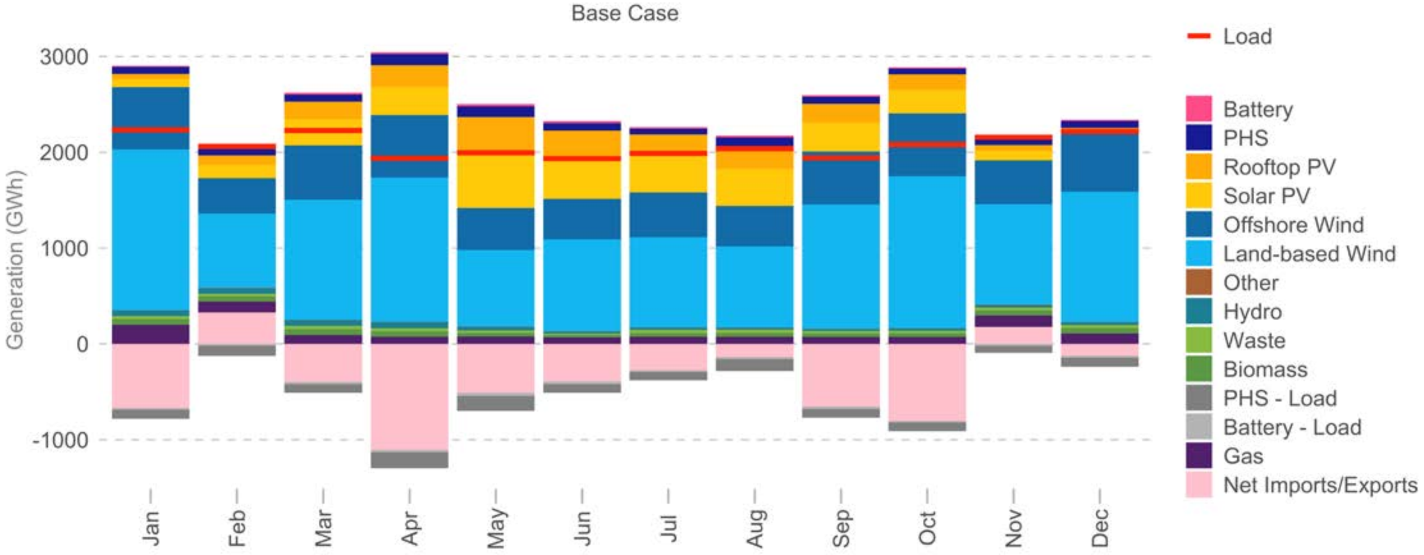
The Base Case has 104% VRE contribution to total demand in 2030.

- 20.3 TWh Wind (82%)
- 5.4 TWh Solar (22%)
- **109% renewable energy contribution, which includes wind, solar, and:**
  - 0.4 TWh hydro
  - 0.5 TWh biomass.
- **4.6 TWh annual exports (compared to 8.5 TWh annual *imports* in 2022).**



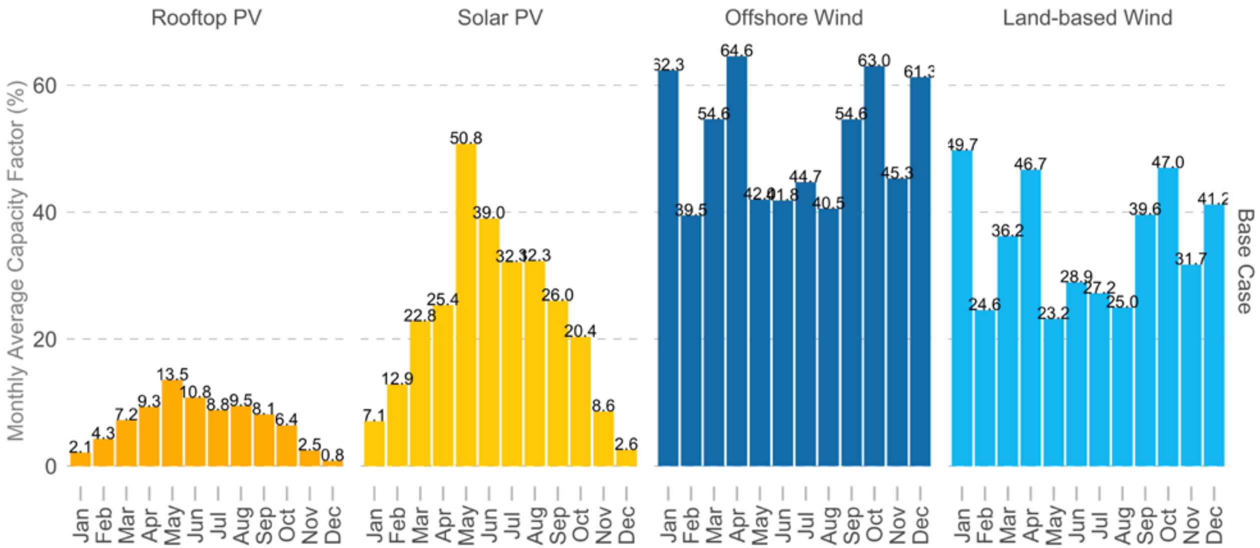
Monthly Generation Mix

The monthly generation mix shows limited seasonal variation in total VRE generation and demand.



Average Monthly VRE Capacity Factors

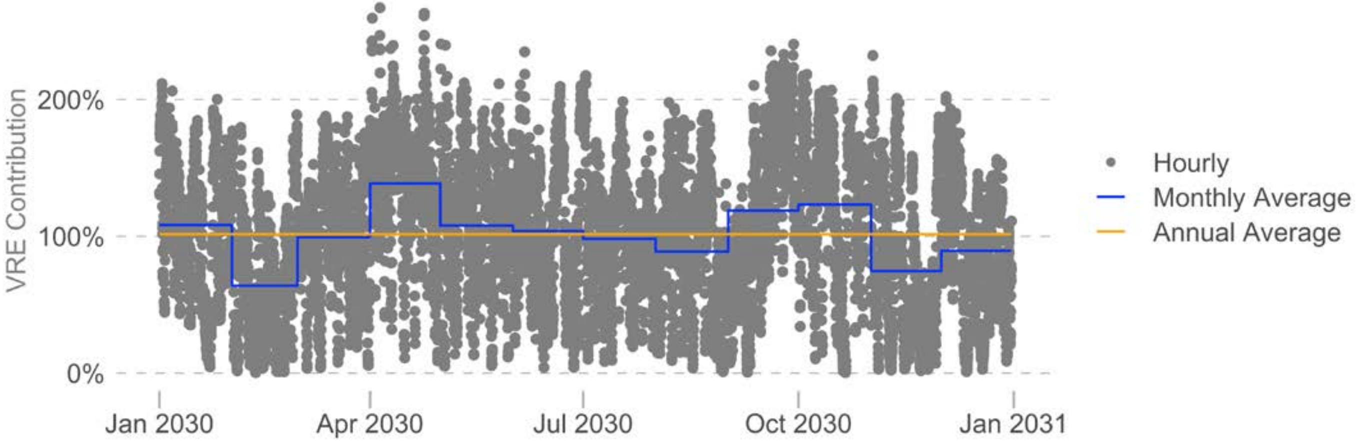
Average monthly VRE capacity factors (after curtailment) show a strong seasonal trend for solar. Wind generation is more variable from month-to-month.



VRE Contributions

VRE contributes over 100% of annual energy relative to Lithuania's total electricity demand.

- Seasonal variation is greatest between late winter and spring.
- Hourly variation is significant, from 0% to over 250%.

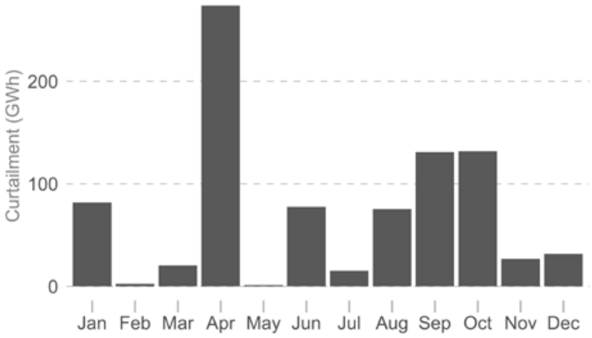


Annual VRE Curtailment

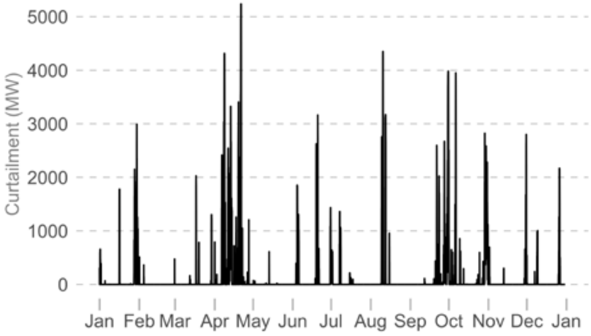
Annual VRE curtailment is relatively low, especially considering that VRE contributes over 100% to total annual demand.

- 0.9 TWh curtailed out of 26.5 total TWh of VRE, or 3.3%
- Note that DSO-connected generation is modeled as “must-take” and cannot be curtailed.

Monthly

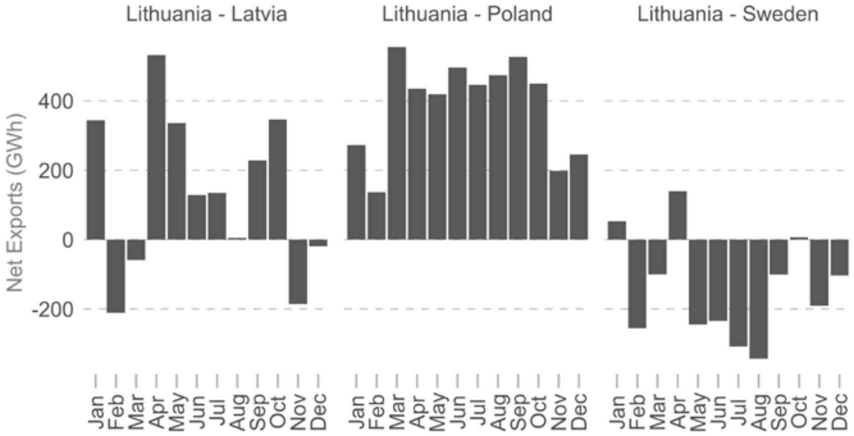


Hourly



Base Case Electricity Exports

Lithuania is a net exporter of electricity in the Base Case.



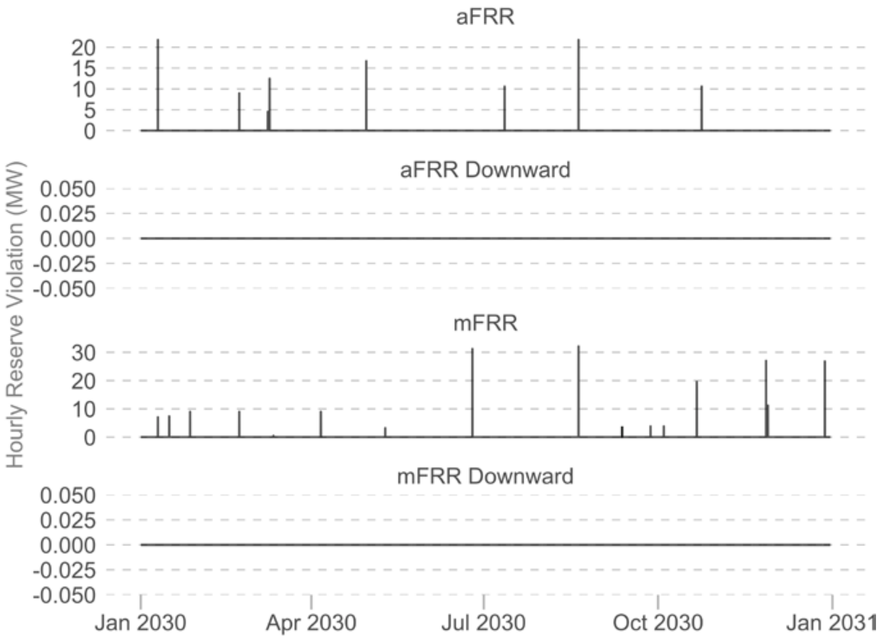
- Positive values are monthly net exports
- Negative values are monthly net imports

	Latvia	Poland	Sweden
Total Line Capacity	2,814 MW (4 lines)	1,200 MW (Harmony Link: 700, LitPol Link: 500)	700 MW (1 line)
Market Constraints	1,300 MW total	150 MW over LitPol Link	--
Net Annual Trade	1,581 GWh net export	4,658 GWh net export	1,681 GWh net import
Hourly Max/Min (MW)	-1,300/ 1,300	-850 / 850	-700 / 700
Hourly Average (MW)	181	533	-192
Max Ramp (MW/hr)	1,553	1,700	1,200

Note: Only high voltage (330 kV) transmission lines with Latvia are included in the model.

Meeting Projected 2030 Electricity Demand

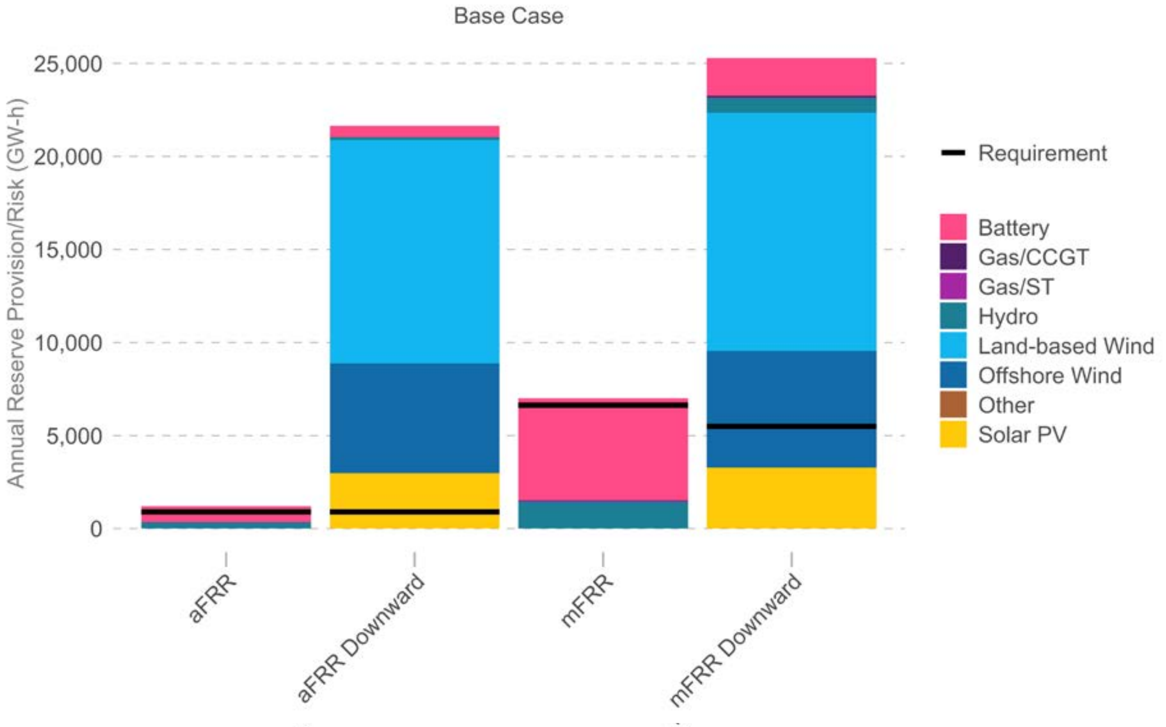
- Hourly simulations for one year indicate Lithuania can meet the projected 2030 electricity demand in every hour.
  - Results show zero hours of unserved energy in Lithuania in the Base Case, as well as all alternative scenarios for 2030.
- Unserved frequency reserves are less than 350 MW-h across about a dozen hours for upward reserves.
  - More analysis is required to understand why a portion of upward reserves requirements are unserved during these periods.
- Note: This modeling does not include a full resource adequacy analysis considering unexpected generator or line outages.



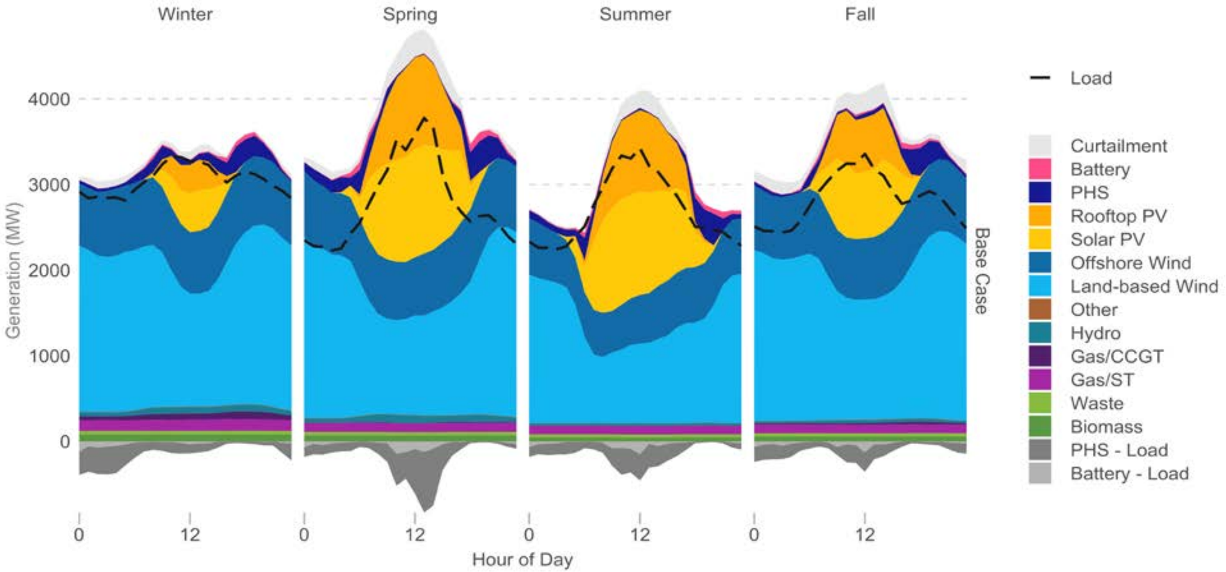
Note: Interim results are based on a simplified transmission representation with maximum flow limits but no line impedance data. Future work will include a more accurate representation of transmission power flow, which can impact reserves results.

Frequency Reserves

- Frequency reserves are provided by wind, solar, batteries, and hydropower.
- Requirement is Lithuania's expected contribution to Baltic targets, as calculated by Litgrid.
- Does not include Baltic-wide requirements or requirements in other regions.
- Upward reserves are provided by batteries and hydro (Kruonis pumped hydro plant).
- Downward reserves are over-procured, due to the availability of more zero-cost generation (wind and solar) available to curtail compared to the reserve requirement.



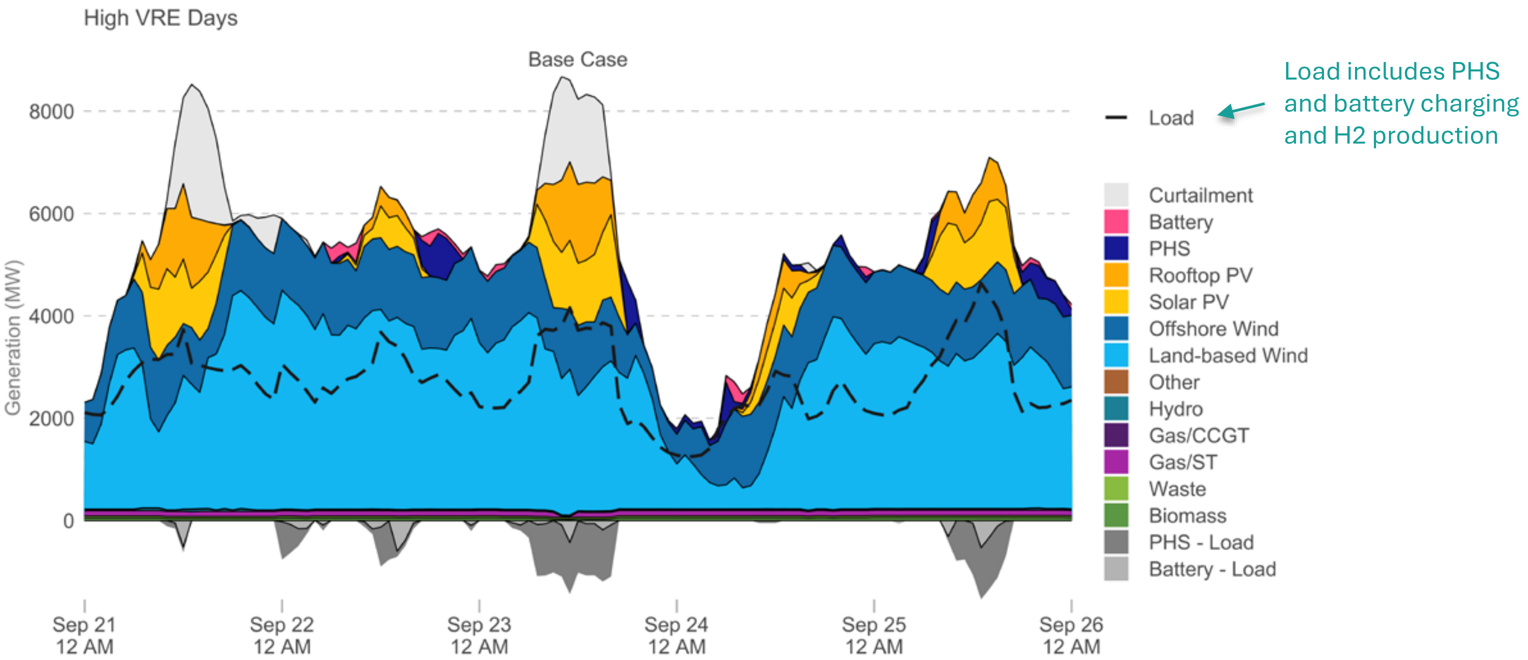
Role of Wind, Solar, and Energy Storage in System Operations



Average daily generation dispatch and load by season in 2030

Note: Load line includes PHS and battery charging and H2 production.

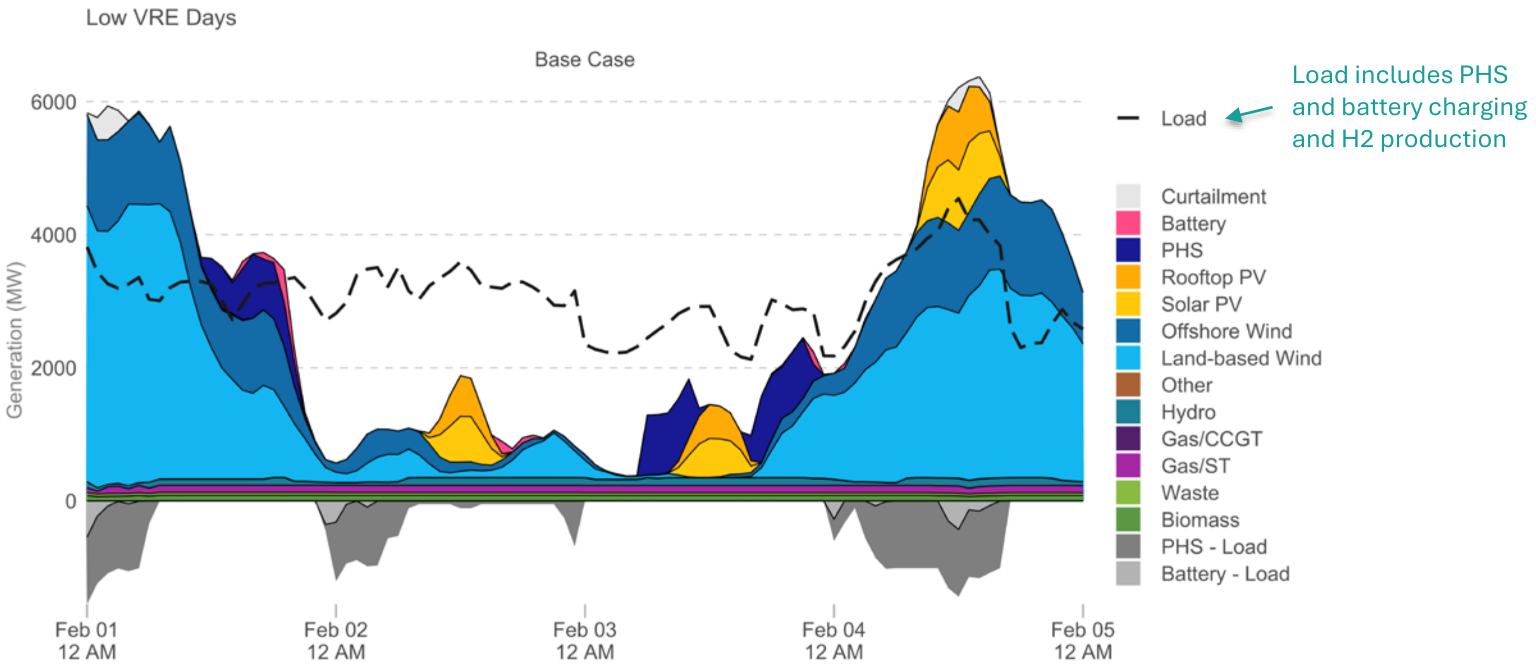
- On average, wind and solar provide the majority of energy supply in every season.
- Average wind generation is relatively consistent across seasons.
- As expected, average solar generation is lowest in winter.
- Patterns of energy storage charging vary by season.
  - Winter charging is concentrated during night and early morning hours.
  - Spring and summer charging is concentrated during high-solar hours.
- On average, Lithuania exports (where total generation is above the load) most during the middle of the day in spring.



September 2030 System Operations

- One week of system operations during a high-VRE period in September 2030

Note: Total generation above load indicates periods when Lithuania exports electricity.



Load includes PHS and battery charging and H2 production

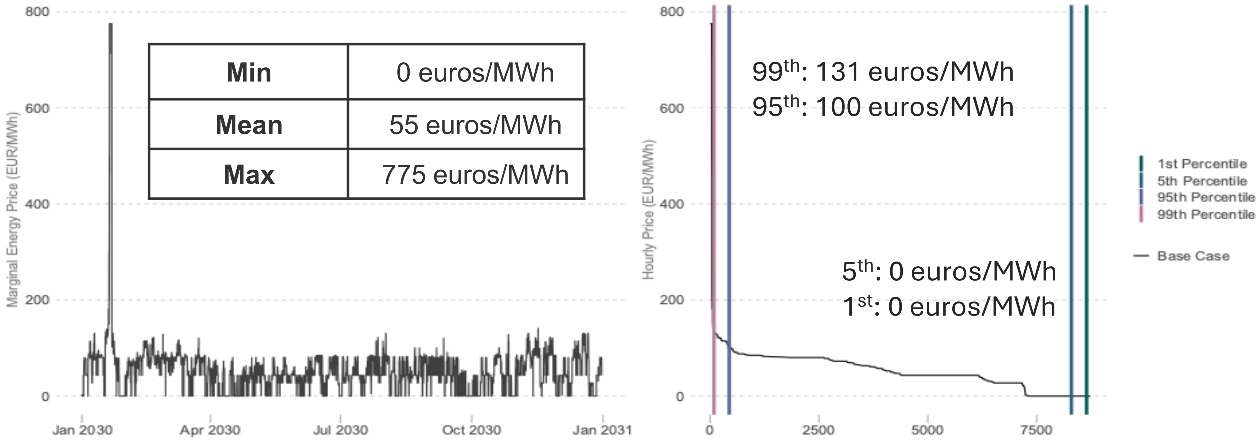
February 2030 System Operations

- One week of system operations during a low-VRE period in February 2030

Note: Total generation below load indicates periods when Lithuania imports electricity.

Peak Electricity Prices

- Peak electricity prices are concentrated during one period of the year in January. Prices at 0 euros/MWh are observed during 11% of hours in the year.
- Future prices for gas fuel are a significant determinant of modeled electricity prices. Assumptions used for this study are based on European Resource Adequacy Assessment 2023 fuel price projections.
- Biomass and waste generators are currently modeled as free to operate, therefore prices may be underestimated.



Min	0 euros/MWh
Mean	55 euros/MWh
Max	775 euros/MWh

99th: 131 euros/MWh
95th: 100 euros/MWh

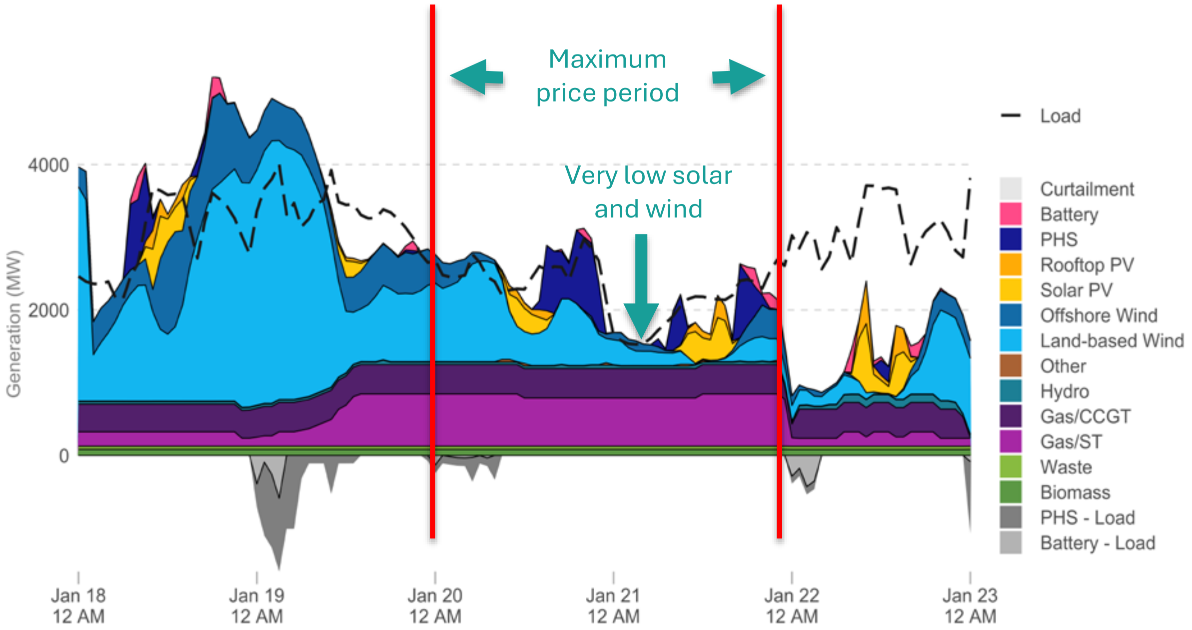
5th: 0 euros/MWh
1st: 0 euros/MWh

Note: Interim results are based on a simplified transmission representation with maximum flow limits but no line impedance data. Future work will include a more accurate representation of transmission power flow, which can result in higher price estimates.

System Operations During the Maximum Price Period

The graph shows system operations during one week in January with the maximum price (775 euros/MWh).

- This is the only period in the year when some gas plants are dispatched.
- Prices also peak in Sweden, Latvia, and Norway.



Note: Load line includes PHS and battery charging and H2 production.

Market Sensitivities

Market Sensitivities

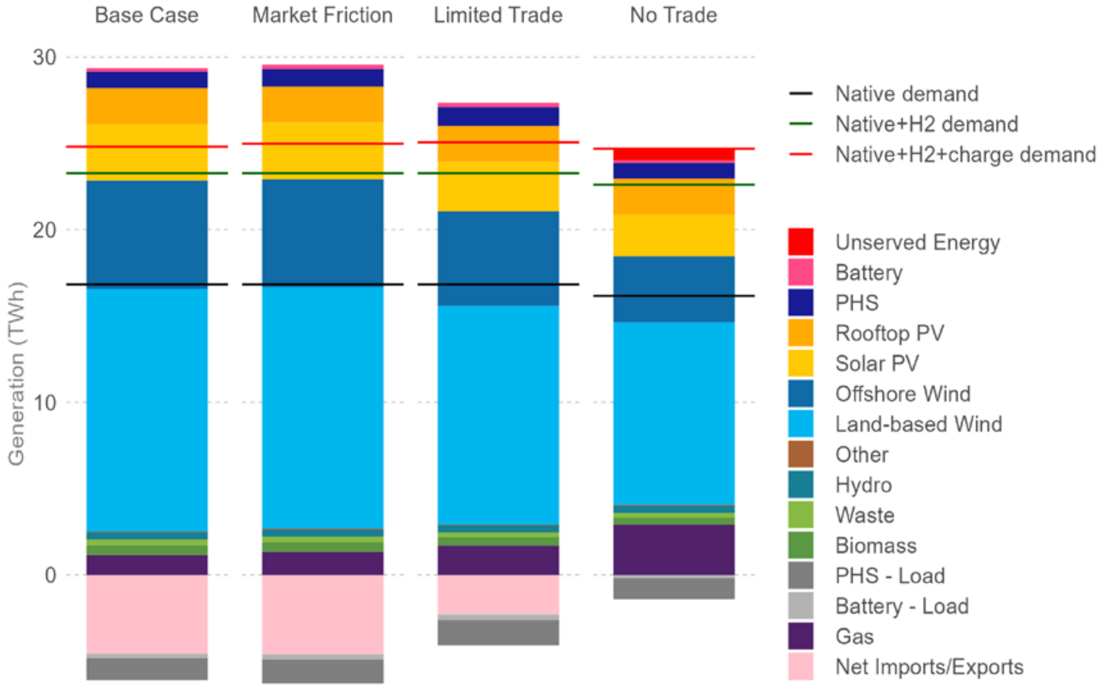
We explored the importance of imports and exports by applying a cost to electricity trade, also known as a wheeling rate, between Lithuania and neighboring European Union countries.

Sensitivity	Wheeling Rate Applied to Regional Transmission Lines (Lithuania-Latvia, Lithuania-Sweden, Lithuania-Poland)
Base Case	0.01 euros/MWh
Market Friction	10 euros/MWh
Limited Trade	50 euros/MWh
No Trade	10,000 euros/MWh

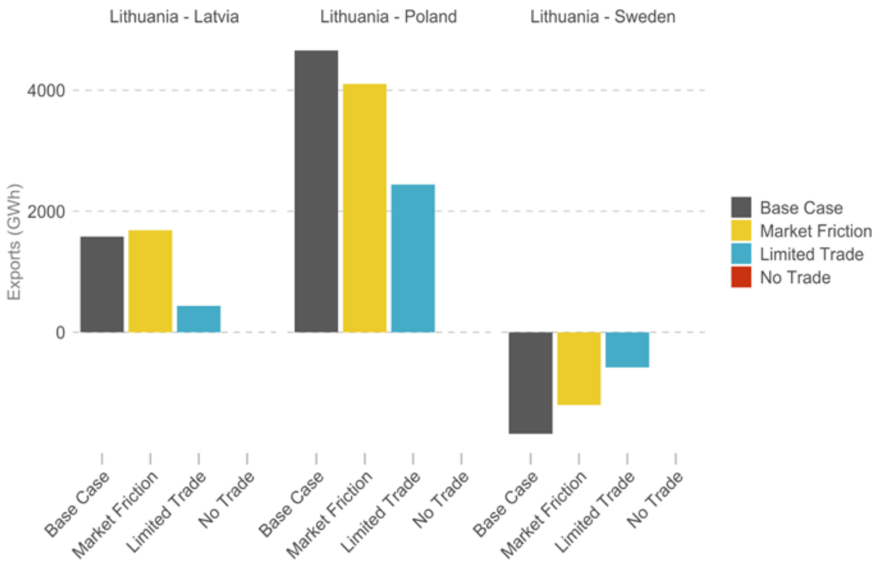
Key takeaways:

- The ability to import during times of low VRE and export during times of high VRE is very important for Lithuania's electricity system reliability.
- However, a small (or even moderate) amount of friction to trade with neighbors does not dramatically change the key outcomes for 2030.
- As trade with neighboring European Union countries goes down, VRE curtailment and in-country gas generation increases.
- In the extreme case with no trade, close to 2.7% of demand cannot be served and 29% of VRE is curtailed.

Generation Mix in Market Sensitivities



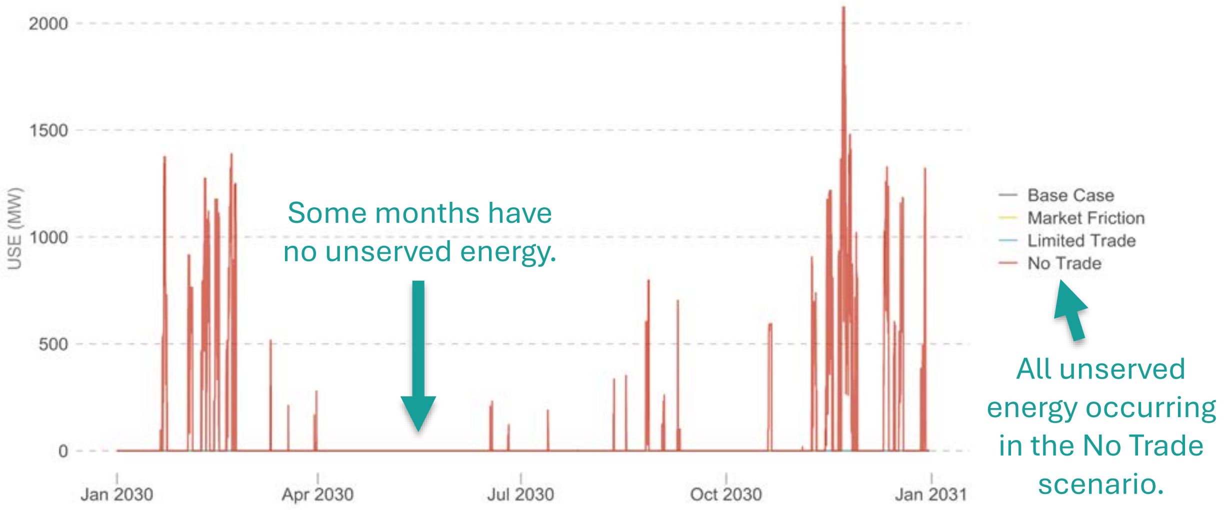
Market Sensitivities Show Electricity Trade's Value



	% Annual Load Served by Renewable Energy (wind, solar, hydro, biomass)	% Annual VRE Curtailment	% Annual Load Not Served
Base Case	107%	3.3%	0%
Market Friction	106%	3.7%	0%
Limited Trade	96%	13%	0%
No Trade	90%	29%	2.7%

Unserved Energy

Unserved energy is observed in Lithuania when electricity trade with neighboring European Union countries is restricted.



Some months have no unserved energy.

All unserved energy occurring in the No Trade scenario.

Hydrogen Electricity Demand Sensitivity

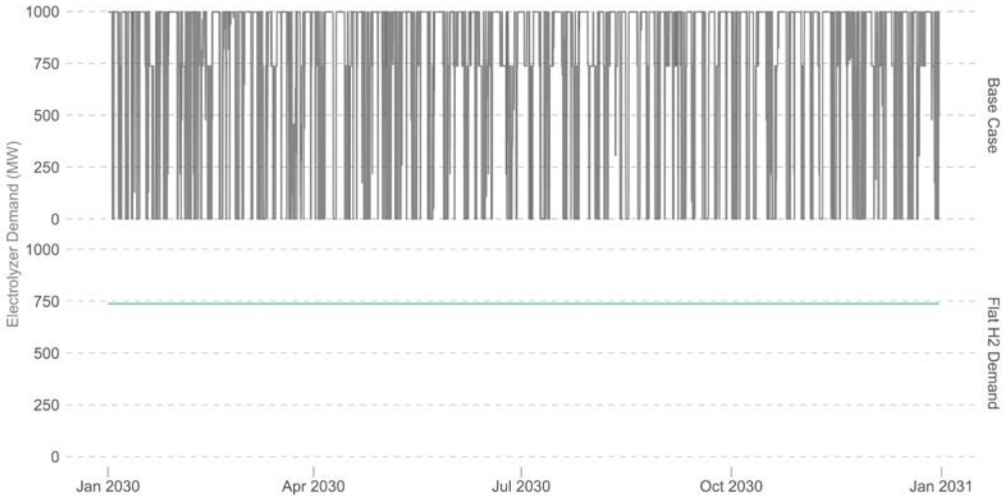
Methodology for Hydrogen Electricity Demand Sensitivity Analysis

Scenario	Description of H2 Electricity Demand Profile
Base Case	This case involves an iteration with the H_2 electrolysis operations modeling conducted under Task 3 of Lithuania 100. We used initial electricity prices from electricity system modeling to perform H_2 system optimization. Results from optimal electrolysis sizing and operations were used to derive the hourly H2 electricity demand at each node. The hourly H_2 electricity profiles were then used as fixed loads in a second iteration of the electricity system modeling.
Flat H2 Demand	This scenario represents a “worst-case scenario” for hydrogen operations. A constant flat load profile was used for each H_2 demand node, with no flexibility in the hourly operations. Total electrolyzer capacity is lower compared to the Base Case. Total annual demand remains the same (6.4 TWh).

Hourly Hydrogen Electricity Demand Profiles

- In the Base Case scenario, H_2 electrolysis operates flexibly in response to electricity prices, which are largely driven by the timing of low-marginal cost renewable energy resources.

- The flat H_2 demand sensitivity achieves the same total annual H_2 production with constant electrolysis operation throughout the year.



Hydrogen Demand Sensitivities Demonstrate the Benefits of Flexible Demand

Flexibility of hydrogen electrolysis can reduce VRE curtailment, mitigate peak electricity prices, and provide significant cost savings for clean hydrogen production.

	Annual VRE Curtailment	Annual Electricity Exports (GWh)	Peak Net Load (MW)	Peak Electricity Price (euros/MWh)	Average Electricity Price (euros/MWh)	Total Cost for Electrolyzer Load (hourly price * hourly load)
Base Case	3.3%	4.6	3,513	775	55.14	292 million euros
Flat H2 Demand	4.3%	4.3	3,518	950	56.06	361 million euros

Conclusion

- This presentation **summarizes interim results** for the Lithuania 100% Renewable Energy Study (Lithuania 100).
- The interim results presented here are from **Task 1 of Lithuania 100**, which focuses on modeling electricity grid development scenarios until 2030.
- Scenario analysis for 2030 assessed different capacities for renewable energy deployment and electricity demand from **clean hydrogen** production.
- **Sensitivities were performed** for electricity market trade with neighboring countries and hydrogen electrolyzer operations. The sensitivities indicate the importance of electricity trade and hydrogen demand flexibility in meeting Lithuania’s **2030 goals**.
- Results show that, if renewable energy capacity is deployed at scale to meet Ministry of Energy targets, **Lithuania can achieve 100% renewable energy in electricity by 2030** while maintaining reliable power system operations.

Next Steps

- Next steps for Lithuania 100 Task 1 are focused on developing electricity system scenarios for 2040 and 2050.

- Other Lithuania 100 Study Tasks are ongoing, including:
  - Task 2: Distribution Networks Planning and Analysis
  - Task 3: Opportunities for Hydrogen Production and Utilization
  - Task 4: Greenhouse Gas Emissions, Air Quality, and Human Health Impacts.

- Stay tuned for future project updates, publications, and data releases! Visit the Lithuania 100 web page for more information: www.nrel.gov/international/lithuania-100-renewable-energy-study.

LITHUANIA
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nrel.gov/international/lithuania-100-renewable-energy-study.html

Thank you.

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May 2024

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