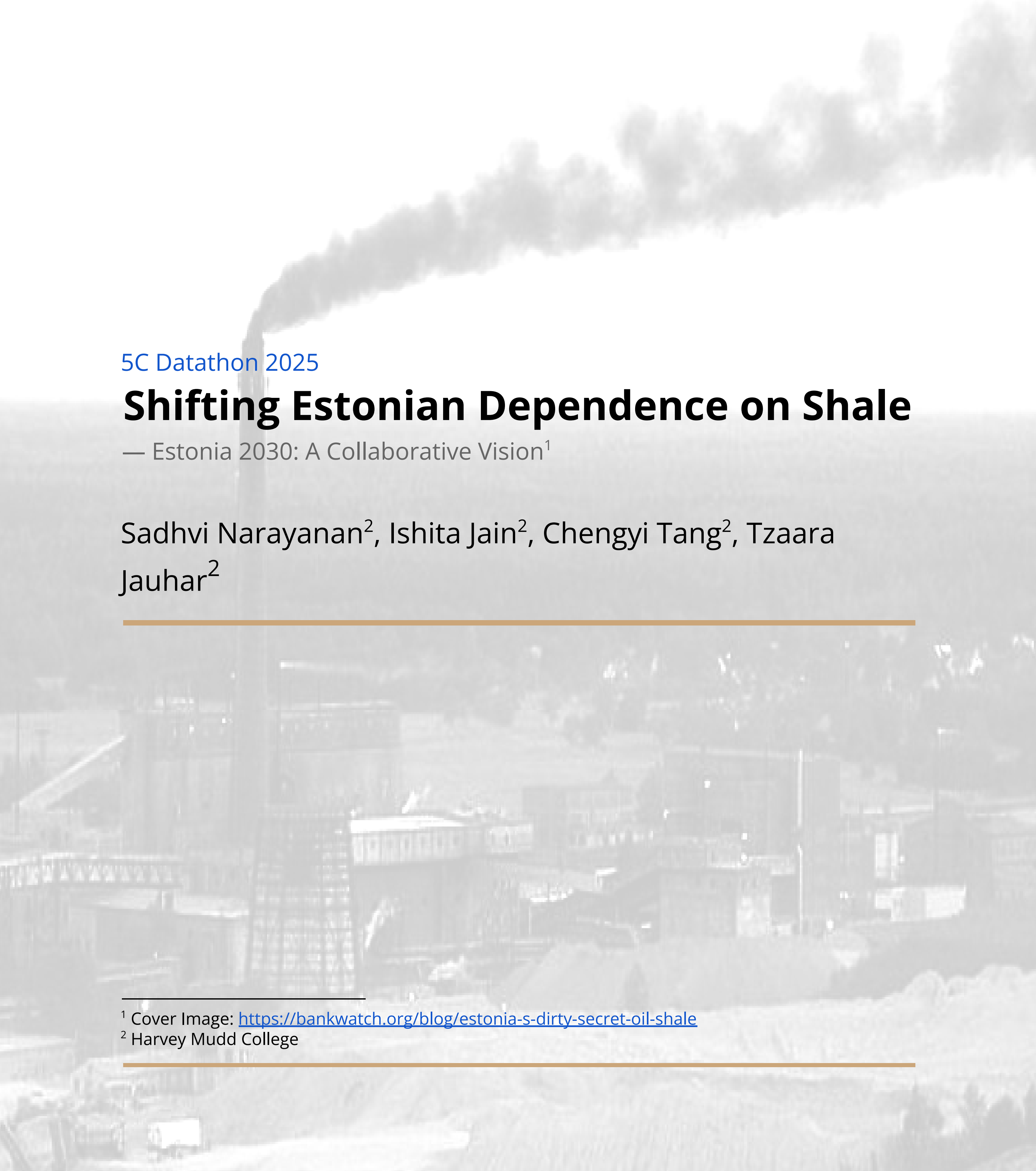

5C Datathon 2025

Shifting Estonian Dependence on Shale

— Estonia 2030: A Collaborative Vision[1]

Sadhvi Narayanan[2], Ishita Jain[2], Chengyi Tang[2], Tzaara Jauhar[2]

[1] Cover Image: https://bankwatch.org/blog/estonia-s-dirty-secret-oil-shale
[2] Harvey Mudd College

Executive Summary

Estonia faces a critical challenge in its energy transition: despite ambitious climate goals of achieving 100% renewable electricity by 2030, the country remains heavily dependent on carbon-intensive oil shale. This fossil fuel dominates Estonia's energy mix, underpinning national energy security, regional employment, and generating significant tax revenue—approximately €391 million (2% of government revenue) in 2023 alone.

Our analysis reveals that oil shale is the primary driver of Estonia's high carbon intensity, with regression analysis showing it explains 81.9% of the variation in national carbon emissions. While Estonia has made progress—increasing carbon-free electricity from 40% in 2021 to 70% in 2024—the transition away from oil shale presents formidable challenges. To address these challenges, we examined three key research questions:

How does Estonia’s reliance on oil shale impact its ability to achieve 100% renewable electricity by 2030?

Estonia must replace 1,700 GWh of oil shale power by 2030 to meet its renewable targets. Time series forecasting indicates oil shale will still constitute 26.2% of Estonia's energy mix by 2030 without additional intervention, leaving a gap of approximately 403,856 MWh/year.

Is solar energy a feasible and affordable replacement for oil shale in Estonia’s electricity mix by 2030?

Despite favorable cloud cover conditions compared to neighboring Lithuania, solar energy alone cannot economically bridge the oil shale gap. Economic modeling shows Estonia would need roughly €4 billion in funding through 2030—far exceeding available EU support of €86.1 million—while generating just €6.1 million in carbon offset savings annually.

Can regional energy trade among the Baltic countries effectively bridge the gap between Estonia’s renewable goals and its current capabilities?

Our linear programming optimization model demonstrates that Baltic regional cooperation offers the most viable path to achieving Estonia's renewable goals. Coordinated energy policies among Estonia, Latvia, and Lithuania could reduce regional emissions by 13% while optimizing each country's renewable energy strengths.

Based on these findings, we recommend a three-pronged approach: (1) establish joint Baltic climate goals rather than individual national targets; (2) invest in increased transmission capacity between the three countries; and (3) target a maximum 80% regional renewable energy mix by 2030 to avoid exponential cost increases while maintaining structural stability in the energy system.

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1 - Introduction

Estonia, a small Baltic nation known for its digital innovation and sustainability efforts, faces a critical paradox in its energy policy. Despite setting ambitious climate goals aligned with European Union mandates, Estonia remains one of the world's most oil shale–dependent countries. This carbon-intensive fossil fuel continues to dominate the nation's energy mix, supporting electricity production, regional employment, and political autonomy. However, oil shale's heavy environmental toll—particularly its significant contribution to greenhouse gas emissions—undermines Estonia's broader environmental ambitions.

To address this, Estonia has committed to achieving climate neutrality by 2050 and transitioning to 100% renewable electricity by 2030. Key strategies include reducing emissions, improving energy efficiency, and expanding renewable capacity, especially solar. These efforts are not only environmentally motivated but also aim to enhance energy security and drive green innovation. This report investigates the barriers to phasing out oil shale and evaluates the feasibility of solar as a primary alternative. We forecast Estonia's solar capacity through 2030, analyze the economic viability of the shift, and explore how greater energy cooperation with neighboring Baltic states could support a more resilient and sustainable regional energy future.

2 - Data Exploration

2-1 Data Gathering

We used the following provided data:

Historic Estonian Weather Data: weather data for Estonia from 2021-2023. We will explain cleaning feature engineering work in section 3.

In addition to the provided data, we gathered the following data from various sources:

- **Electricity Production Data** from Entose Transparency Platform**:** hourly electricity production data by sources of energy. Sources of energy include fossil fuels (coal, natural gas, oil shale, peat) as well as renewable energy sources (solar, wind, hydro, waste, biomass). We gathered production information for Estonia, Lithuania, and Latvia for the years 2021-2024. We converted the hourly data to daily data by summing over all production values of a given source at a given country within a day. Production is measured in units of MWh. The final table includes entries for *date*, *country*, *production method*, and *production amount*.
- **Electricity Load Data** from Entose Transparency Platform: hourly electricity load (i.e. consumption) data. We gathered load information for Estonia, Lithuania, and Latvia for the years 2021-2024. We converted the hourly data to daily data. The load could be seen as a measure of *demand* for electricity in a given country in a given day. The final table includes entries for *date*, *country*, and *load*.
- **Electricity Transmission Data** from Entose Transparency Platform: hourly electricity transmission data between countries. We gathered transmission data to and from Estonia, Lithuania, and Latvia. We converted the hourly data to daily data. The final table includes entries for *date, source country, destination country,* and *transmission amount*.
- **Carbon Intensity Data** from Electricity Maps: daily data on carbon intensity as well as renewable and carbon-free energy sources. We gathered data for Estonia, Lithuania, and Latvia. We did not perform any cleaning or feature engineering work. Carbon intensity is measured in g CO_2 equivalent per kWh energy produced and renewable and carbon-free energy are measured as percentage of total energy produced. The final table includes entries for *date*, *country*, *direct carbon intensity, lifetime carbon intensity*, *% renewable energy*, and *% carbon-free energy*.

2-2 Exploratory Data Analysis

To assess Estonia's sustainability trajectory, we first analyzed its energy, comparing renewable and non-renewable. While initial figures showed notable renewable energy, we realized we needed to contextualize Estonia's progress by comparing it with its Baltic neighbors, Latvia and Lithuania.

These countries share geographic, demographic, and historical characteristics. All three are small, low-lying nations with declining populations, having transitioned from centrally planned to market economies since the 1990s. As EU members, they are bound by common regulatory frameworks—including targets like carbon neutrality by 2050—making them ideal for comparative analysis.

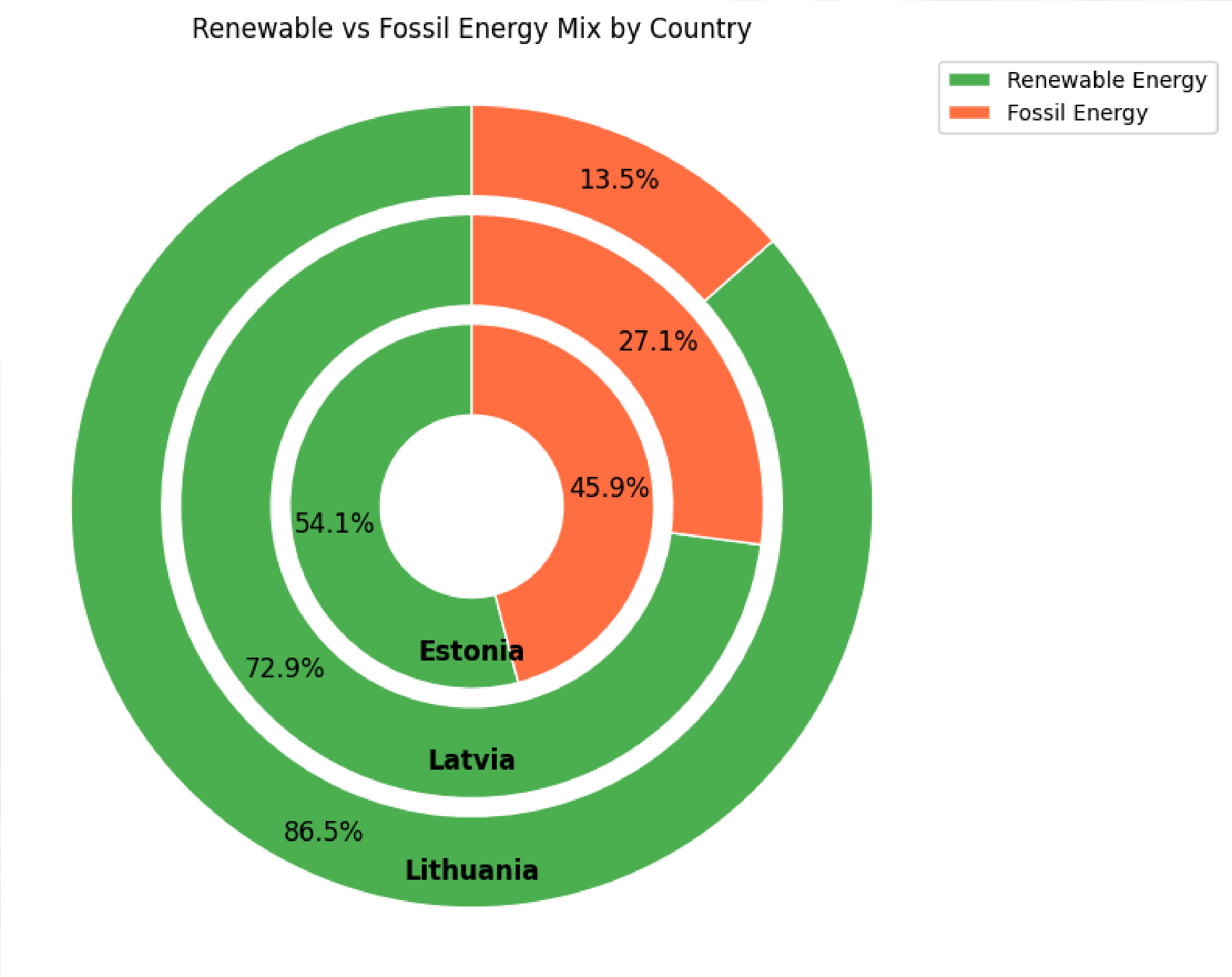


Fig 1: Total Renewable vs Fossil Energy Generation in Baltic Countries in 2024

Despite these parallels, our analysis revealed that Estonia stands out in one critical respect: its continued reliance on oil shale.

2-3 Oil Shale’s Contribution To Carbon Intensity

Oil shale is Estonia's largest carbon dioxide source. Our analysis shows a strong correlation (r=0.905) between oil shale power generation and carbon intensity, explaining 81.9% of Estonia's emissions variation.

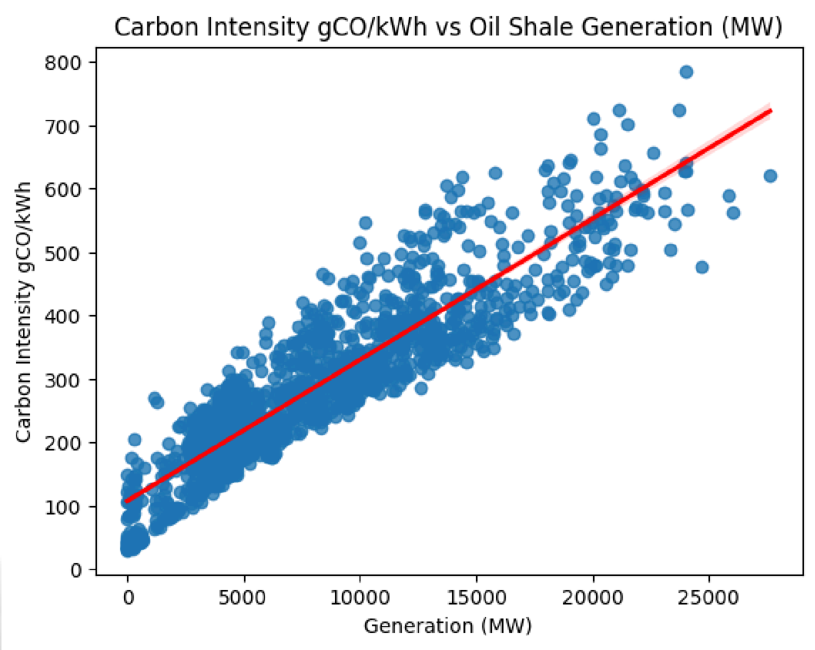


Fig 2 - Oil Shale Power Generation vs. Carbon Intensity

The extraction process—heating kerogen-rich rock at high temperatures—emits 2.15 moles of CO_2 per megajoule produced. Despite plans to phase out oil shale by 2035, significant challenges remain. The industry employs 7,000 people (1% of workforce), includes 200+ businesses, and contributed €391M in taxes (2% of government revenue) in 2023. To achieve 100% renewable electricity by 2030, Estonia must replace approximately 1,700 GWh of oil shale power and 475 GWh of coal-gas power—enough to serve nearly one million people. Thus, it is difficult for Estonia to easily let go of oil shale.

3 - Developments in Renewable Energy

Estonia has a growing portfolio of renewable and carbon-free energy sources—such as biomass, hydropower, solar, and wind[3]—that is essential for meeting its 2030 target of 100% renewable electricity. Despite recent progress in reducing oil shale reliance, fossil fuels remain the country's dominant source of electricity. This section explores the potential and limitations of various renewable sources within Estonia, with comparisons to neighboring Baltic countries to contextualize feasibility.

3-1 Trends in Carbon-Free Energy Generation

Estonia has made notable strides in increasing its share of carbon-free energy over the past few years.

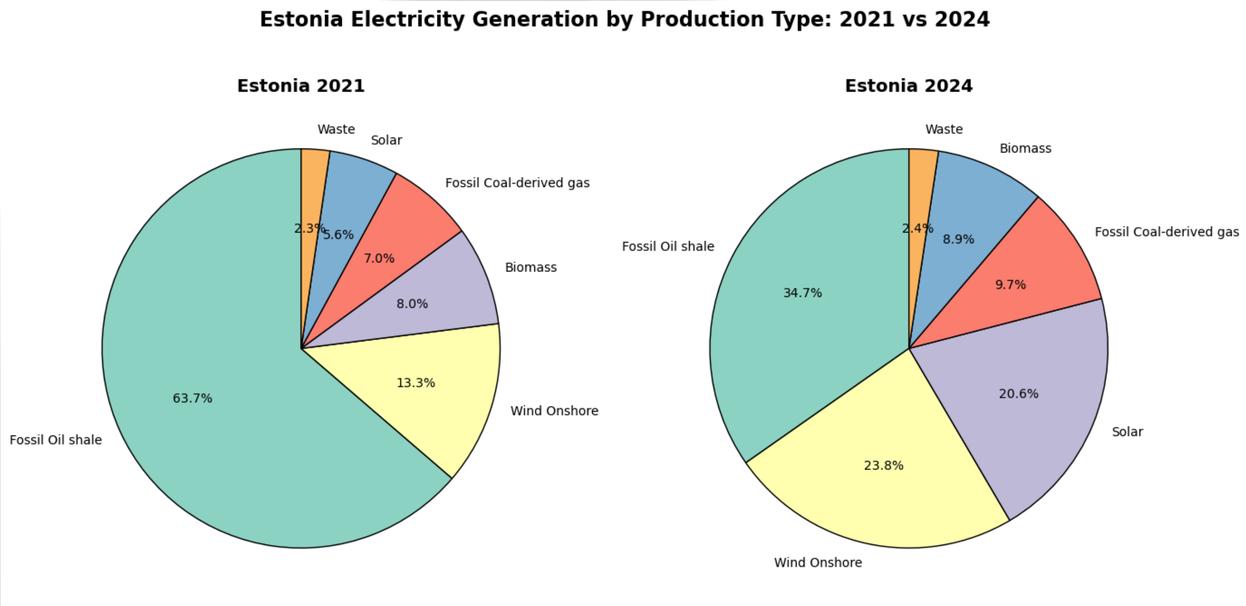


Fig 3 - Estonian Energy Source Type in 2021 and 2024 (only energy types contributing to more than 1% of total electricity generation are shown)

Figure 3 shows the changes in energy source distribution between 2021 and 2024, highlighting a decrease in oil shale dependence.

3-2 Limitations of Hydropower

[3] Data source: https://www.ast.lv/en/content/power-system-state-0

Drawing inspiration from Estonia's neighbors, we wanted to examine the particular renewable energies that Estonia could explore that were feasible in their goal of achieving all renewable electricity.

Latvia, located to the south of Estonia, possesses significant hydroelectric infrastructure along the Daugava River, which contributes up to 90% of the country's electricity generation. In contrast, Estonia is characterized by low average elevation (approximately 50 meters above sea level) and minimal elevation gradients, which limits the potential for large-scale hydroelectric development. Additionally, the absence of long, high-flow rivers further constrains the feasibility of hydroelectric power generation within Estonia.

3-3 Limitations of Wind Energy

We also wanted to explore whether wind energy could be a viable alternative to Estonia's oil shale. To determine this, we decided to compare climate conditions across the Baltic countries by extracting weather data from 2021-2023[4]. We computed the overall daily wind speed of Estonia from the Pythagoras theorem by using the north-south (u_{10}) and east-west (v_{10}) wind components:

$$\text{wind speed (m/s)} = \sqrt{(u_{10})^2 + (v_{10})^2}$$

Equation 1- Wind Speed from NS/EW components

To produce wind energy, the biggest factor is wind speed. The output is proportional to wind speed cubed.

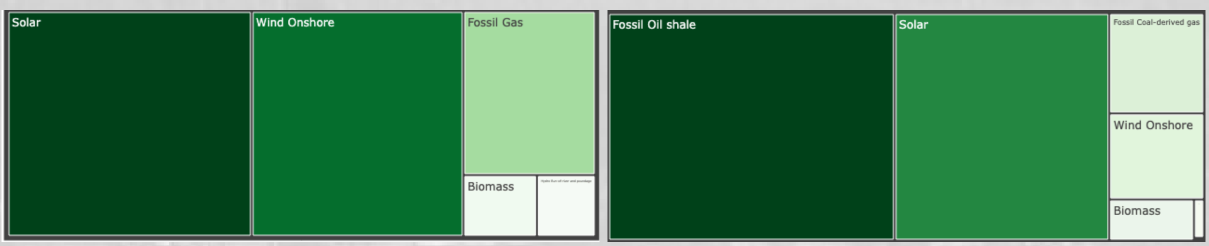


Fig 5- Lithuania (left) and Estonia (right) Energy Distribution

As we can see in Figure 5, Lithuania has 43% electricity supplied by onshore wind farms in 2024, while Estonia has only 24%. This difference could be explained by Estonia having much weaker wind speeds than Lithuania[5] (Figure 6).

[4] Data source: https://www.wunderground.com. Wind speed taken at their respective capitals. We make the assumption that since the countries are small in area, regional variations in wind speeds are negligible.
[5] And Latvia; results not shown.

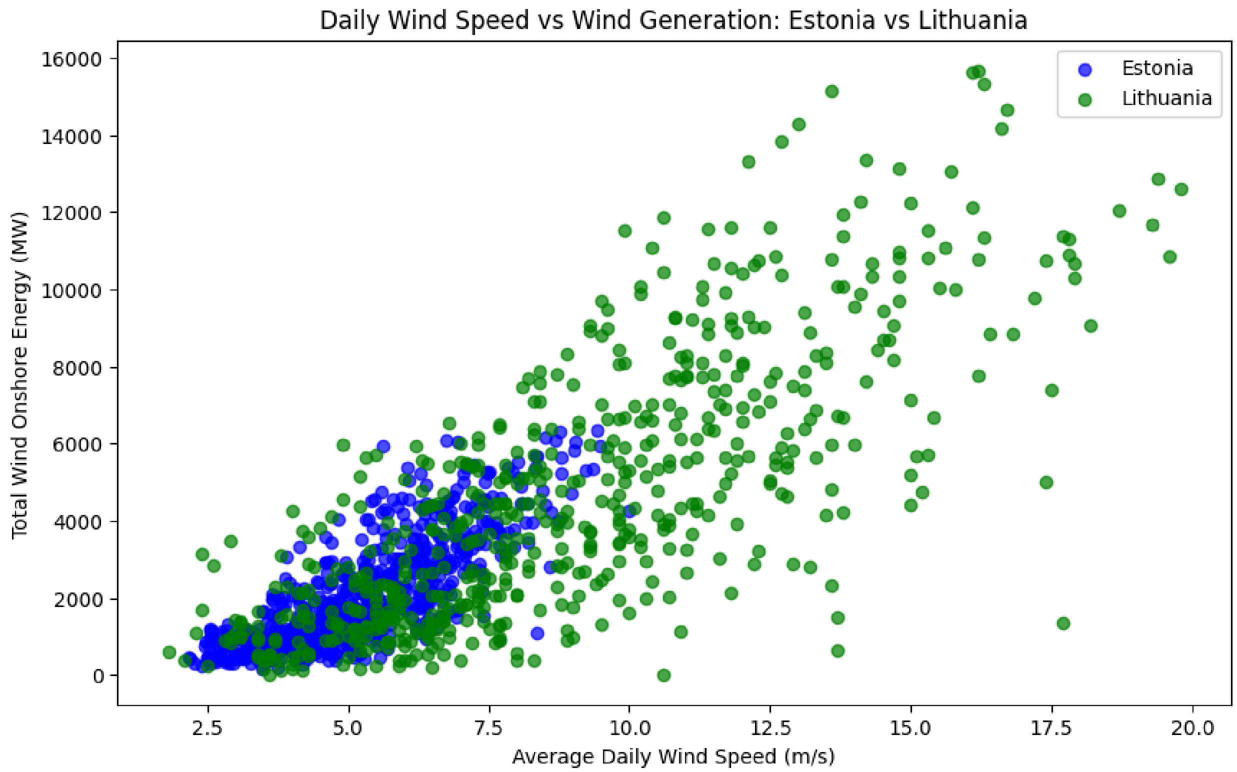


Figure 6- Wind Speed vs Energy Generation in Lithuania and Estonia

Country	Estonia	Lithuania
Mean Wind Speed	5.275 m/s	8.899 m/s
Std. Dev Wind Speed	1.549 m/s	3.633 m/s

Table 1: Mean and Standard Deviations of Wind Speeds of Estonia and Lithuania

As we can see, the wind speed in Lithuania is much higher than wind speed in Estonia. This likely explains why Lithuania produces more wind energy than Estonia. It also means that wind energy is not a great remedy for its dependence on oil shale since Estonia doesn't have the highest wind speed.

3-4 Evaluating Solar Energy Potential

Given wind's limited potential, we turned to solar energy. We can see from Figure 5 that this is Lithuania's primary energy source, unlike Estonia. To assess solar feasibility, we analyzed cloud cover and solar radiation data:

- For **cloud cover**, we combined dew point depression (DPD) and relative humidity to model daily cloudiness for Lithuania and used provided data for Estonia.
- For **solar radiation**, we used:
    - **Lithuania**: Global Horizontal Irradiance (GHI) from the PV Watts calculator (kWh/m^2/day)
    - **Estonia**: Converted surface solar radiation downwards (W/m^2) to GHI

The monthly weather data for Lithuania included daily temperature, dew point, humidity, wind speed, and pressure, from which we estimated the cloud coverage.

The dew point indicates when air becomes saturated with water vapor. We calculated the dew point depression (DPD) as the difference between the average temperature and dew point. A smaller DPD suggests more moisture in the air, leading to cloud formation. We normalized and clipped the DPD to a 0-1 scale.

Relative humidity, indicating the air's moisture capacity, also plays a role. High humidity means the air is near saturation, and even a small temperature drop can trigger cloud formation. Using a weighted combination of DPD (60%) and humidity (40%)[6], we computed daily cloud coverage for Lithuania.

Equation for calculating cloud coverage:

$$Estimated\_Cloud\_Cover = 0.4 \cdot \left(\frac{Humidity\_Avg}{100}\right) + 0.6 \cdot \text{clip}\left(1 - \frac{Temp\_Avg - DewPoint\_Avg}{25},\ 0,\ 1\right)$$

Equation 3- Estimated Cloud Coverage

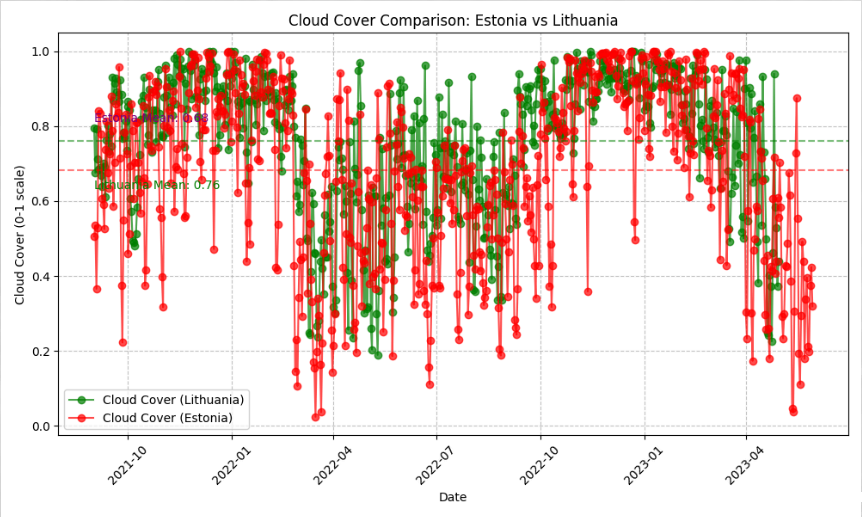


Figure 7- Comparative Cloud Cover(Estonia vs Lithuania)

[6] Data source: https://doi.org/10.1038/s41598-021-00555-5

For Lithuania, we used monthly global horizontal irradiance (GHI) data from the NREL's PV Watts calculator[7]. Assuming consistent solar patterns over this short timeframe, we compared monthly solar radiation between both countries as shown in Figure 8.

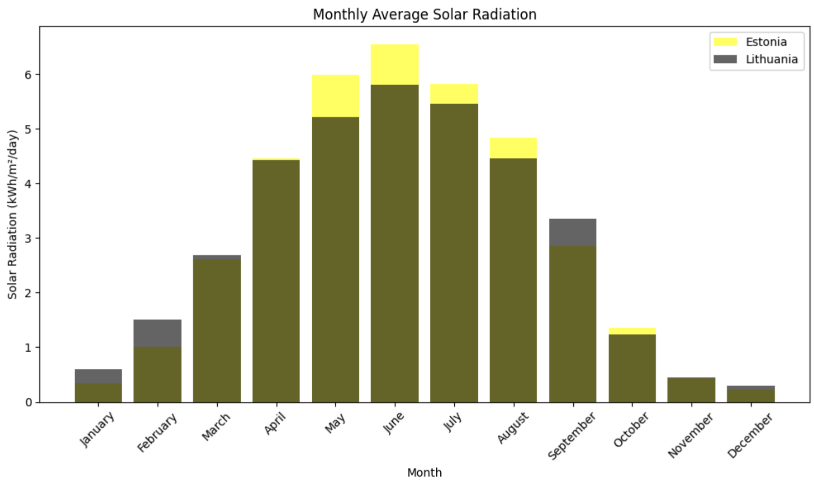


Fig 8- Monthly GHI for Lithuania and Estonia

Country	Estonia	Lithuania
Mean Daily Cloud Cover(%)	68.2 %	76.1%
Std. Dev Daily Cloud Cover(%)	23.7%	18.7%
Mean Monthly GHI (kWh/m2/day)	2.658	2.501
Std. Dev Monthly GHI (kWh/m2/day)	2.278	1.881

Table 2: Mean and Standard Deviation of Solar Energy Potential in Estonia and Lithuania

Since the mean and standard deviation of the daily cloud cover and the irradiance data are similar for Lithuania and Estonia, it is natural to question whether Estonia can improve its dependence on oil shale by producing more electricity created by solar energy.

[7] Data source: PVWatts Calculator

4 - Feasibility of Solar Energy

To assess the plausibility of Estonia replacing a significant portion of its oil shale energy production with solar energy by 2030, we performed a feasibility analysis. This combined weather-based forecasting, predictive modeling of energy production and consumption, and economic cost assessments, underpinned by transparent assumptions and rigorous statistical validation. The core objective was to evaluate whether Estonia, under current climate conditions and economic structures, could feasibly bridge the forecasted oil shale energy gap using solar infrastructure alone.

4-1 Key Research Questions

Our feasibility study was structured to answer five guiding questions:

1. What is a reasonable trajectory for oil shale energy production from 2024 to 2030, assuming existing policies continue?
2. How much solar energy can be generated under forecasted Estonian weather conditions?
3. What is the expected baseline solar power generation in 2030, assuming no new installations?
4. What is the projected energy gap by 2030 between reduced oil shale and existing solar capacity?
5. Can this gap be economically and spatially bridged through additional solar infrastructure?

The goal is to determine whether replacing oil shale with solar energy is a viable option for Estonia.

4-2: Modeling Weather-Dependent Solar Production

We first explored solar energy production as a function of weather, leveraging daily-level historical data on solar output and meteorological indicators, including:

- Direct solar radiation
- Temperature
- Total cloud cover

The data was obtained from Historic Estonian Weather Data. Production was obtained from Electricity Production Data. To ensure interpretability and avoid overfitting, we performed feature engineering and multicollinearity testing using the Variance Inflation Factor (VIF). The final model included direct solar radiation, total cloud cover, temperature, and precipitation, as all had VIF < 5.

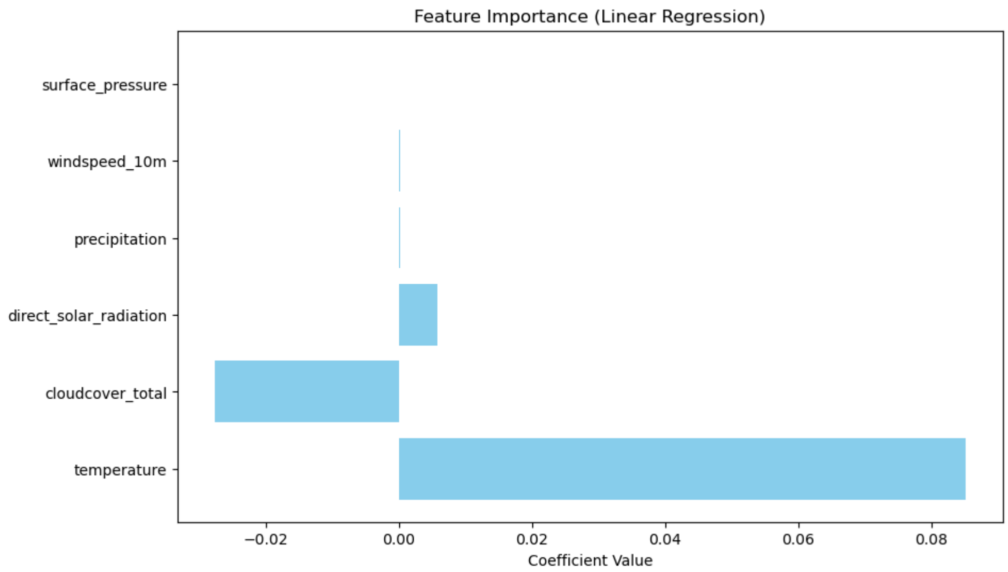


Fig 9: Feature importance for predicting energy production

We then constructed a multiple linear regression model to predict solar output. We validated standard regression assumptions—linearity, homoscedasticity, normality of residuals, and lack of autocorrelation—and achieved an adjusted R^2 of 0.70, suggesting a strong relationship between weather conditions and solar energy production.

$$\textbf{Production (MW)} = 11.6539 * \textbf{temperature (Celcius)} - 6.8483 * \textbf{cloud cover (pct)} + 15.26 * \textbf{radiation}(W/m^2)$$

Equation 4- Solar energy production based on weather conditions

These are all reliable, as temperature tends to increase the production of solar energy, cloud cover tends to decrease it, and radiation, as well, tends to increase solar energy production[8].

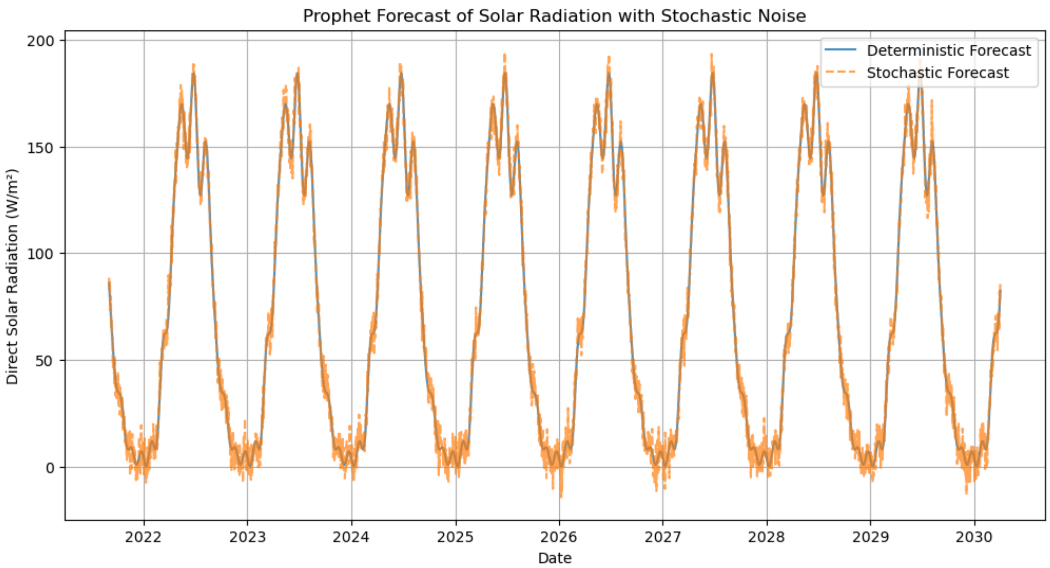
Forecasting Weather Inputs (2024–2030)

To build a robust baseline model for solar energy production, we used Facebook's **Prophet** algorithm for time-series forecasting, enhanced with **stochastic components** to reflect real-world weather volatility. This was crucial to avoid underestimating the impact of extreme weather events on solar efficiency.

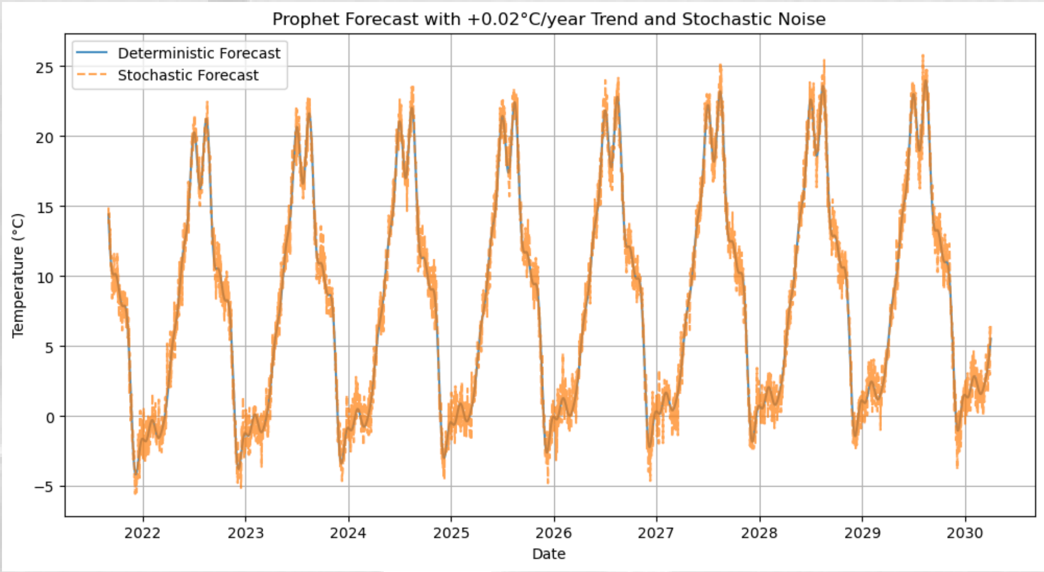
- **Direct Solar Radiation**: We used multiplicative seasonality to model the observed variation in radiation, which showed increasing amplitude over time (i.e., heteroscedasticity). A stochastic noise component with $\sigma = 5$ W/m² was added to

[8] This agrees with the equation for solar panel output and solar radiation. The coefficient is the efficiency of solar panels (0.2) multiplied by the capacity of a panel.

capture random fluctuations in atmospheric opacity. The model showed good performance, with a validation RMSE of 8.2 W/m².



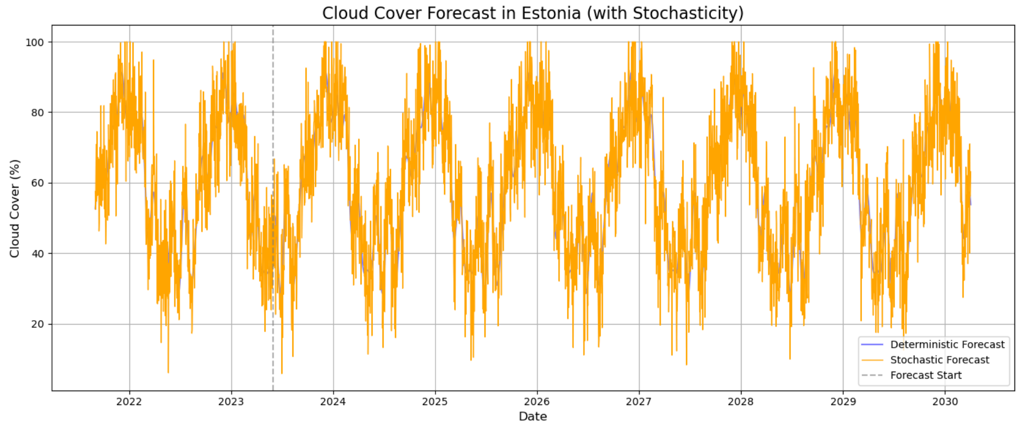
- **Temperature**: We applied the default additive seasonality and incorporated a linear warming trend of +0.5°C per year[9]. The stochastic volatility was set at $\sigma = 1$°C, statistically validated by posterior sampling ($p < 0.01$).



- **Cloud Cover**: To reduce overfitting, we used a conservative changepoint prior scale (changepoint_prior_scale = 0.05). Cloud cover required a significantly higher

[9] based on the IPCC AR6 projections for Northern Europe under the RCP4.5 scenario

stochastic component (σ = 15%) due to its non-Gaussian residuals (Shapiro-Wilk test: $p < 0.001$) and the inherently chaotic dynamics of cloud formation.



Figures 10–12: Forecasts for Radiation, Temperature, and Cloud Cover

We then fed these weather forecasts into our regression model to estimate baseline solar production assuming no increase in panel installation, using our linear model from above.

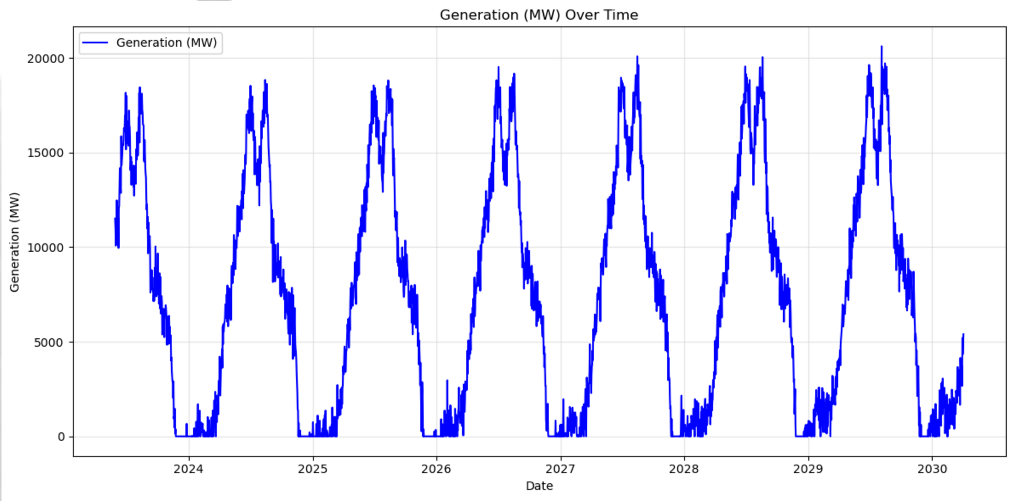


Figure 13: Forecasted Solar Generation (Baseline)

This is our baseline estimate that if the solar panel use doesn't increase in 2030, we can, by current calculations and only depending on weather and seasonality, hope to produce this much.

4-3 Forecasting Oil Shale Reduction

To assess solar's potential role, we forecasted Estonia's oil shale energy production using a Seasonal ARIMA (SARIMA) model, which captures both trends and seasonal patterns, such as winter spikes in output.

We chose SARIMA, as it expanded above the ARIMA time forecasting model while incorporating trends in seasonality, as Fossil Oil Shale production increased during winter seasons each year. For this baseline model, we assumed Estonia would maintain its current phase-out trajectory and regulatory stance in the upcoming years, gradually phasing out oil shale.

Modeling under these assumptions predicted:

- 2024 Oil Shale Output: 1,696,349.2 MWh annually
- 2030 Forecasted Output: Monthly average of 107,707.7 MWh
- Total 2030 Output: 1,292,492.4 MWh annually (approx.)

Assuming total energy production remains stable at 4,930,209.5 MWh annually, oil shale's share would drop from 34.41% in 2024 to 26.22% in 2030. This results in a 403,856.4 MWh annual shortfall that must be replaced, highlighting the need to evaluate solar energy's feasibility within Estonia's evolving energy mix.

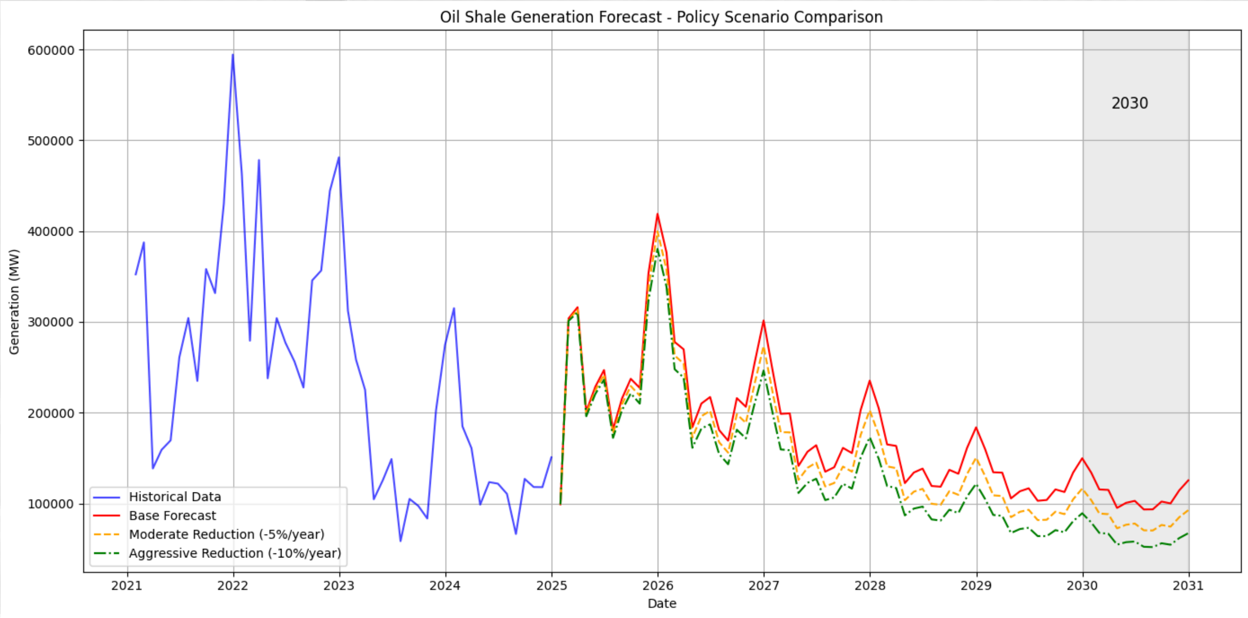


Fig 14: Forecasted Oil Shale Generation Over Time

4-4: Economic Feasibility of Scaling Solar

We then evaluated whether Estonia could economically replace 10% of its current oil shale energy production with solar energy by 2030.

Cost Model Assumptions:

Cost per kW solar capacity:	€1,000 (EU average estimate)[10]
EU renewable energy funding (Estonia):	€88 million[11]
Average solar productivity in Estonia:	1,800 hours/year[12]
CO_2 offset per MWh of fossil energy avoided:	0.4 tons[13]
Carbon price per ton (EU ETS):	€37.74[14]
Solar Panel Capacity	0.15[15]

Table 3- Solar Panel Cost Model Assumptions

Step-by-Step Calculation:

[10] Data Sources: https://energy.ec.europa.eu/system/files/2020-10/final_report_levelised_costs_0.pdf?utm_source
[11] Data Sources: https://commission.europa.eu/system/files/2023-08/Estonia_Draft_Updated_NECP_2021-2030_en_1.pdf
[12] Data Sources: https://www.pvknowhow.com/solar-report/estonia/?utm_source
[13] Data Sources: https://www.eia.gov/todayinenergy/detail.php?id=48296&utm_source
[14] Data Sources: https://www.pvknowhow.com/solar-report/estonia/?utm_source
[15] Data Sources: https://pmc.ncbi.nlm.nih.gov/articles/PMC8717974/?utm_source

Affordable Solar Capacity with EU Funding	€88M / €1,000 per kW = 88000 kW
Annual Energy from This Capacity	88000 kW × 1,800 hours * 0.15 = 23760 MWh
Total Production Until 2030 (6 years)	23760 MWh × 6 =142560 MWh
Required Annual Replacement (10% of oil shale loss):	Gap from 2024 to 2030 = 405518 MWh Annual replacement need = 405518 / 6 = 67586 MWh
Required Capacity:	67586 MWh * 1000 / (1,800 hours * 0.15) = 250,320 kW
Annual Cost to Build This Capacity:	250,320 kW × €1,000 = € 250 million/year
Funding Difference Needed:	250 Million - 88 Million = **162 Million**
Carbon Offset Value:	403,856 MWh × 0.4 tons/MWh = 161,542 tons of CO_2 avoided Offset value = 161,542 × €37.74 = €6.1 million

Table 4- Solar Panel Cost Model Assumptions

Even under optimistic assumptions, Estonia would need an additional €972 million in funding over 6 years to fully replace its oil shale shortfall with solar, an amount far exceeding current EU support. Moreover, the carbon offset savings of just €6.1 million/year fall well short of making this investment financially attractive under a purely market-driven lens.

5 - Optimal Trade and Energy Production Allocation

5-1 Trade as a Step Towards Carbon Neutrality

While Estonia alone cannot meet its renewable and carbon neutrality goals through solar, regional collaboration offers a viable path forward. Latvia and Lithuania have invested in wind, hydro, and biomass, creating complementary energy profiles across the Baltic states. Strategic partnerships can help minimize costs and emissions while meeting shared energy needs.

This section introduces a multi-country linear programming (LP) model to optimize energy production and trade across Estonia, Latvia, and Lithuania. The model balances two key objectives:

- Minimizing total energy cost, including production and transmission
- Minimizing total carbon emissions, allowing for carbon pricing scenarios

Decision variables include energy produced per source per country and cross-border energy flows. LP is well-suited for this task due to its efficiency, transparency, and ease of sensitivity analysis.

$$
\begin{aligned}
\min \quad & \alpha\left(\sum_{c,s} C_{s,c}P_{s,c} + \sum_{c_1,c_2} T_{c_1\to c_2}Q_{c_1\to c_2}\right) + \beta\sum_{s,c} E_s P_{s,\mathrm{c}} \\
\text{s.t.} \quad & \sum_{s} P_{s,c} + \sum_{j\neq c} T_{j,c} - \sum_{j\neq c} T_{c,j} = D_c \quad \forall c \quad \text{(Demand Constraint)} \\
& 0 \le P_{s,c} \le K_{s,c} \quad \forall s,c \quad \text{(Capacity Constraint)} \\
& 0 \le T_{c1,c2,t} \le L_{c1\to c2} \quad \forall c_1, c_2, c_1 \neq c_2 \quad \text{(Transmission Constraint)} \\
& \sum_{t,s\in \text{Renewable}} P_{s,c} \ge r\sum_{t,s} P_{s,c} \quad \forall c \quad \text{(Renewable Constraint)}
\end{aligned}
$$

Equation 5: LP constraints and objective functions

The variables are defined below:

Variable	Description
α	Scaling factor for total cost.
β	Scaling factor for total carbon emission.
$C_{s,c}$	Cost of producing energy source s at country c, in MWh.
$P_{s,c}$	Production of energy source s at country c, in MWh.
$T_{c_1 \to c_2}$	Power transmission from country c_1 to country c_2, in MWh.
$Q_{c_1 \to c_2}$	Transmission cost from country c_1 to country c_2, in euros per MWh.
E_s	Carbon intensity per MWh energy produced for source s.
D_c	Demand for electrical power in country c.
$K_{s,c}$	Maximum power production for source s at country c, in MWh.
$L_{c_1 \to c_2}$	Capacity for transmitting power from country c_1 to c_2, in MWh.
r	Goal for percentage of power produced from renewable sources.

Table 5: Variable Definitions for Trade Optimization Model

α and β are free variables we set, $C_{s,c}$ and $T_{c_1 \to c_2}$ are decision variables, and all others are parameters estimated from historical data. Methods of parameter estimation are described in section 5-3.

The objective function consists of two terms: a cost term and a carbon emission term, each scaled by a constant (α and β, respectively). The cost term consists of the cost of energy production (first term) and the cost of transmission (second term). When α = 1, β could be interpreted as the **carbon tax** since it measures the euro equivalent of CO_2 emission.

There are four constraints to the LP:

1. **Demand Constraint.** The sum of total production and total import minus the total export must exceed the electricity demand in the country.
2. **Capacity Constraint.** There is a maximum value as to which energy source can produce how much electrical power.
3. **Transmission Constraint.** There is a maximum transmission load from any country to any other country.
4. **Renewable Constraint**. Countries can have policies that demand a percentage of all energy produced must be from renewable sources.

We use the pyomo package in python to solve the LP. To construct the LP, we create a ConcreteModel, input the decision variables and constraints, and solve it with the CBC (Coin-or Branch and Cut) solver. The solver takes an average of 17ms for our program.

5-2 Assumptions and Limitations

Our LP model is based on the following simplifying assumptions:

- **Linearity:** The model assumes linearity in both costs and carbon emissions, meaning they scale directly with energy production and transmission. This ignores economies of scale or nonlinear effects. We make this assumption for simplicity.
- **Aggregation and Homogeneity:** All energy from the same source is treated as identical, with no differentiation based on location or efficiency. Production and transmission are aggregated at the national level. We make this assumption because the Baltic countries are small in size.
- **Perfect Information:** The model assumes perfect knowledge of all parameters (e.g., production capacities, transmission limits, demand, and emissions) with no uncertainty or variability.
- **Static Optimization:** The LP is a static model, considering only one time period and ignoring dynamic factors like demand fluctuations, production ramping, or energy storage. However, we do perform the LP in different seasons with different capacity metrics.
- **Idealized Transmission:** Transmission is assumed to be lossless, with linear costs. This ignores real-world transmission losses and grid inefficiencies.
- **Market Behavior Assumptions:** The model assumes a centralized optimization, where countries cooperate fully. It ignores market behavior, competition, or political/regulatory barriers to energy trade. Implementing the results of the model would require cooperation among the Baltic countries as well as between them and the EU or the rest of the world.
- **Simplified Renewable Energy Policy:** The renewable energy share is modeled as a fixed percentage of total production, without considering variations in renewable sources or their specific impact.

5-3 Parameter Estimation

In order to solve the linear program, we need to estimate the parameters of the program. Now we explain how we obtained each of our parameters:

- **Demand:** We used historical demand data.
- **Production Capacity:** We calculated the production capacity *by season* due to seasonalities in renewable energy sources like solar and hydroelectric power. We calculated the capacity by taking the maximum production during the season and scaling it to three months.
- **Production Cost:** We looked up operational costs online through multiple news sources and operational reports[16].

[16] Data Sources: https://www.pv-magazine.com/, https://thundersaidenergy.com/downloads/wind-power-operating-costs/#:~:text=Wind%20power%20operating%20costs.,worth%20%3E$20bn%20per%20year,

- **Transmission Capacity:** We took the maximum transmission from one country to another and scaled it to three months. Note that since Lithuania and Estonia do not directly border each other, power from Lithuania/Estonia needs to pass through Latvia to reach each other.
- **Transmission Cost:** We looked up transmission costs online[17]. The price for 2023 is €13.29 per MWh transmitted.
- **Emission Data:** To estimate the carbon intensity for each energy source, we trained an ordinary least squares regression model on historical carbon emissions from electricity generation data. The predictors are the amounts of energy produced from each source in each country on each date, and the label is the total emissions in grams of CO_2 equivalent on the date. The slopes for the regression would indicate grams of CO_2 equivalent per MWh of source consumed.

The OLS for the emission data passed almost all assumptions (statistical significance, homoscedasticity, autocorrelation, multicollinearity) with *p*-value ≤ 0.05. The residuals are not perfectly normally distributed; however, a skew of 0.83 demonstrates a moderate skew, and the residual plot does not show extreme skew. Thus, we conclude that our model provides a credible estimation of the carbon intensity associated with each energy source.

$$\mathbf{Emissions} = \beta_1\mathbf{biomass}+\beta_2\mathbf{coal}+\beta_3\mathbf{gas}+\beta_4\mathbf{shale}+\beta_5\mathbf{peat}+\beta_6\mathbf{hydro}+\beta_7\mathbf{solar}+\beta_8\mathbf{wind}+\beta_9$$

Equation 6 - Parameter Estimation for emission per amount for energy types

We present the results relating to energy sources included in our LP:

Source	**Coefficient (g CO_2/MWh energy produced)**	***p*-value**	**2.5 percentile**	**97.5 percentile**
Biomass	$4.119 \cdot 10^5$	0.000	$3.78 \cdot 10^5$	$4.46 \cdot 10^5$
Coal	$3.485 \cdot 10^5$	0.000	$2.75 \cdot 10^5$	$4.22 \cdot 10^5$
Gas	$4.549 \cdot 10^5$	0.000	$4.47 \cdot 10^5$	$4.63 \cdot 10^5$
Oil Shale	$7.167 \cdot 10^5$	0.000	$7.08 \cdot 10^5$	$7.26 \cdot 10^5$

Table 6 - Summary of LP results for energy sources

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-HYDROPOWER.pdf

[17] Data Source: https://view.news.eu.nasdaq.com/view?id=b71d382988456ae8e71e42bbfa96dcb19&lang=en&src=listed

5-4 Results and Model Verification

To test that our model works, we performed tests on historical data to verify. The pie charts below, representing 2021 data show that our model predictions mostly match actual production data. In addition to annual statistics, our model successfully tracks seasonal variations in energy sources because of our control over production capacities.

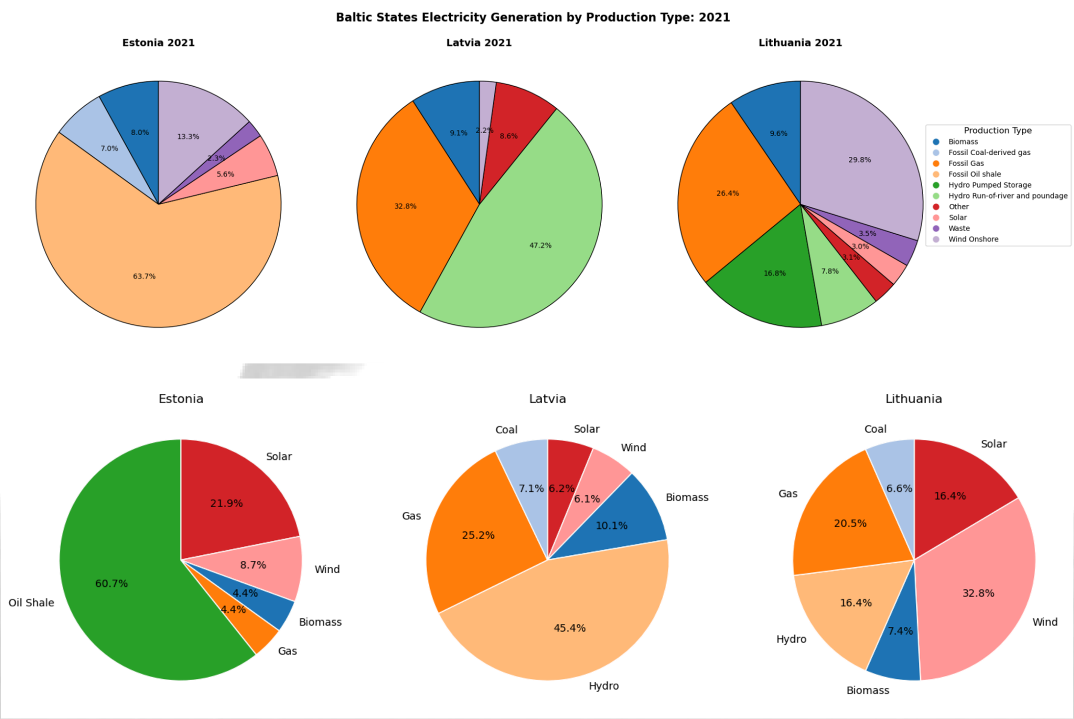


Fig 15- Actual production (top); LP Result for 2021 with 4 seasons combined (bottom)

Our model predicts that in fall 2024, there will be a total of 1.61 MWh of power produced by Lithuania, 1.37 MWh produced by Estonia, and 1.20 MWh produced by Latvia, as opposed to 1.83 MWh, 1.19 MWh, and 0.85 MWh in reality. In general, our model tends to overestimate total power generated for larger countries. We believe that with more advanced capacity and cost estimation techniques, we would be able to produce more accurate results that match reality closely.

5-5 Insights and Recommendations

The model produces the following insights:

1. Total cost and total emissions scale roughly linearly with demand, regardless of the type of energy source. This suggests that Baltic countries have **structural stability** -

i.e. disruptions in demand do not significantly impact total cost or emissions. For every 1% change in demand, there is roughly 1% change in total cost and emissions.

- **Recommendation:** Baltic countries should seek to expand their renewable energy infrastructure while keeping their current structural stability.

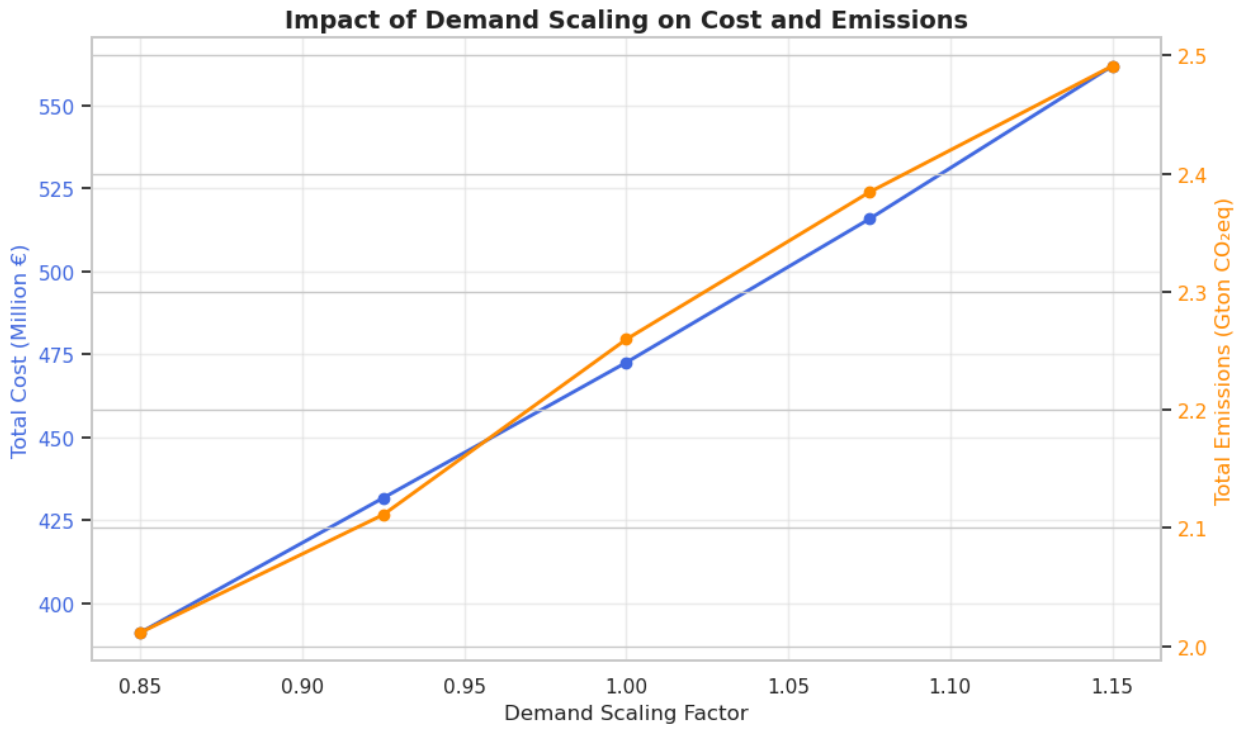
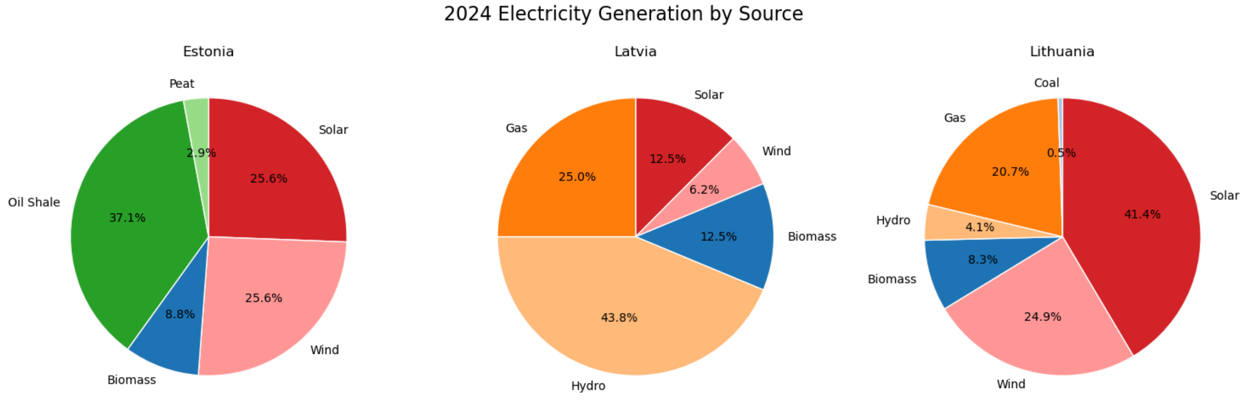


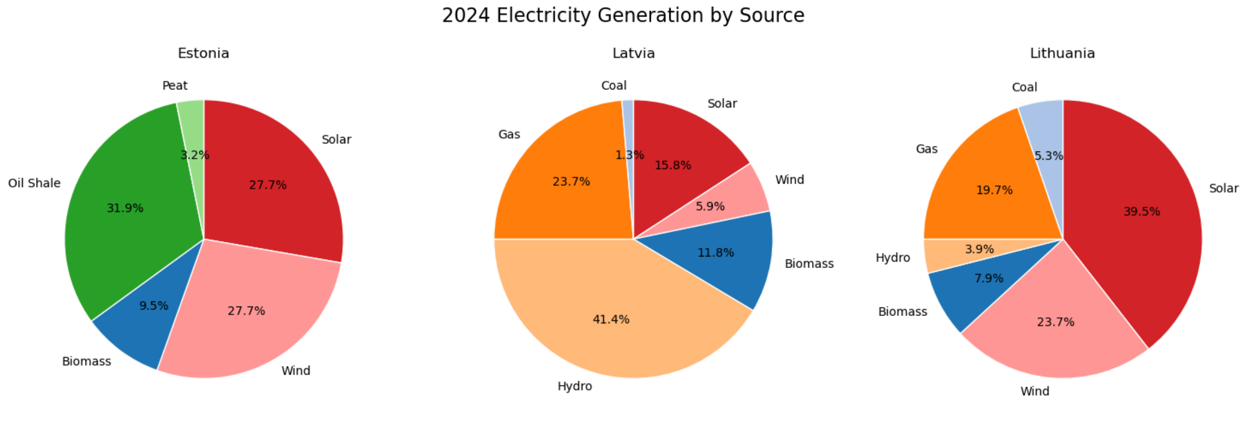
Figure 16 - Impact of Demand Scaling on Cost and Emissions

2. Carbon tax has a limited impact on fossil fuel production, as seen by how changing the β does not change the optimal balance of energy at all. Since the Baltic countries have limited capacities for renewable energy production, fossil-fuel-based energy is necessary for meeting electricity demand. However, once total renewable energy production capacity exceeds demand, increasing carbon taxes significantly decreases the total percentage of fossil fuel production. Our model predicts that, without increasing renewable facilities, increasing the carbon tax from €2×10^{-6}/g CO_2 to €2.5×10^{-5}/g CO_2 in Estonia does not impact oil shale production *at all*.
    - **Recommendation: Do not implement heavy carbon taxes** until renewable energy facilities are in place. They would only hurt consumers without having the desired effect of increasing renewable energy usage.
3. Renewable energy goals in one country could impact energy production methods in other countries. For example, all else equal, if Estonia unitarily increases its renewable energy percentage to 65% in winter 2024, Lithuania will need to increase coal production to 5.3% of total market share to meet its energy demands. Thus, although Estonian total emission would decrease by 29,000 metric tonnes CO_2

equivalent, Lithuanian total emission would increase by 46,000 metric tonnes CO_2 equivalent. This would be a net increase of 17,000 metric tonnes CO_2 equivalent. In essence, Lithuanians would be paying for Estonians going green.

- One reason for the phenomenon is that Lithuania is a net importer of energy. Our model predicts that Lithuania will import an average of 2TW energy from Estonia per year (which is also true in reality). Thus, rising cost of energy would encourage Lithuanians to produce more energy on their own.





Figs 17 and 18 - Impacts of Estonia increasing Renewable Energy Percentage

- **Recommendations:**
    i. The Baltic countries should **coordinate their renewable energy policies**, as they are connected to the same grid and their electricity markets are highly correlated. We suggest that Estonia, Latvia, and Lithuania adopt joint climate goals. Instead of each country having an individual target percentage for renewable energy sources, the three countries could share a single objective applicable to the entire region. Our model suggests that sharing joint climate goals and increasing power trade would decrease overall emissions from 2.4

million metric tonnes CO_2 equivalent to 2.1 million metric tonnes CO_2 equivalent for winter 2024, a 13% drop.

ii. To achieve coordinated goals, the Baltic countries will need to **increase their transmission capacities** to take advantage of their comparative advantages.

iii. Countries should also try to **minimize transmission cost**. Our model predicts an average of €28 million (8% total cost) spent on electricity transmission per quarter. Building high-quality cheap transmission systems could significantly reduce transmission costs.

4. Total emissions decrease roughly linearly with increasing renewable energy target percentage while total costs increase **exponentially**. Starting from a renewable target of 80%, the marginal cost for increasing renewable energy share changes from €1,000,000 per percent to €1,600,000 per percent; at 90%, the marginal cost becomes €2,000,000 per percent. Noticeably, the LP ceases to have a solution above 90%, meaning that the Baltic countries currently do not have enough renewable energy capacity to reach 90% renewable energy.

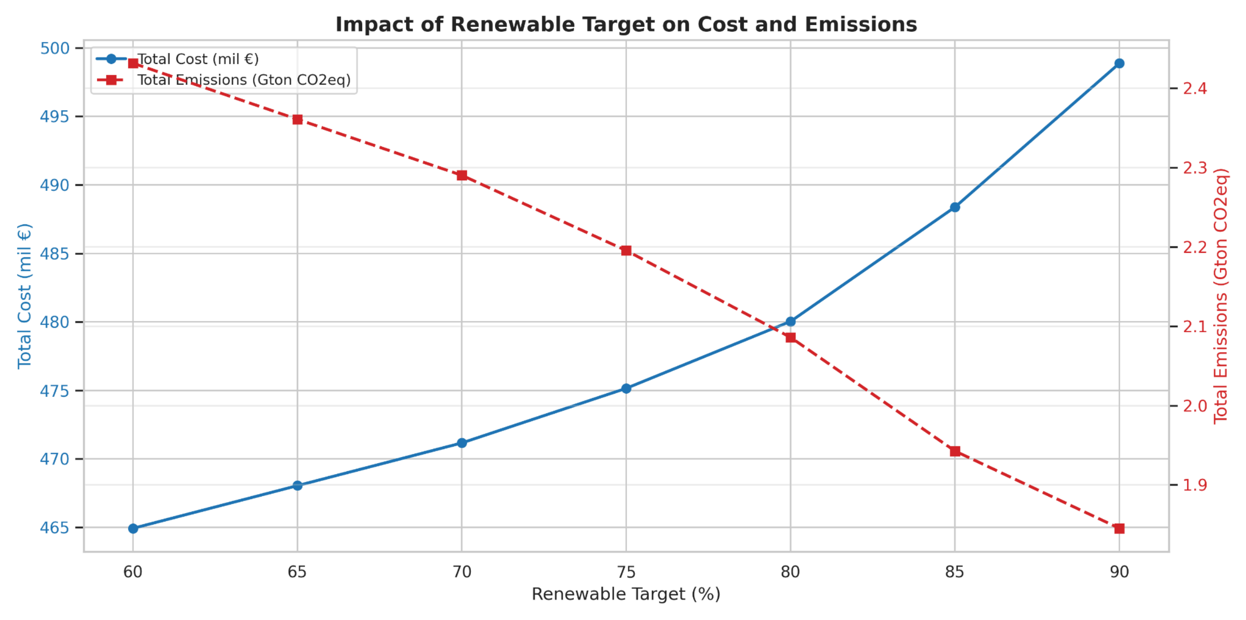


Figure 19- Impact of Renewable Target on Cost and Emissions

- **Recommendations:** The Baltic countries should currently target **a maximum of 80%** total energy produced through renewable sources to prevent excessive exponential costs.

6 - Conclusion

Estonia is strongly dependent on oil shale production for its economy and energy production. While Estonia has made significant progress in reducing carbon intensity and increasing renewable energy share, achieving 100% renewable electricity by 2030 through domestic measures alone is economically unfeasible.

Estonia's sustainability goals demand infrastructure investments far beyond Estonia's current fiscal capacity. Our solar energy feasibility analysis shows that the investment required (€4 billion) vastly exceeds available funding.

Our optimization model demonstrates that coordinated regional energy policy—leveraging Latvia's hydroelectric capacity and Lithuania's wind infrastructure—can maximize efficiency while minimizing both costs and emissions. The model shows that pursuing individual national renewable targets can increase regional carbon emissions through carbon leakage, while coordinated targets could reduce regional emissions by 13%.

We recommend that Estonia:

1. Advocate for integrated Baltic energy policies with shared renewable targets rather than individual national goals
2. Invest in expanded cross-border transmission capacity to enhance system flexibility
3. Target an 80% regional renewable energy mix by 2030 to optimize cost-effectiveness
4. Delay implementing heavy carbon taxes until sufficient renewable infrastructure is established
5. Develop clear transition plans for oil shale-dependent communities to ensure social sustainability

While Estonia's 100% renewable electricity goal by 2030 appears challenging through domestic measures alone, a coordinated Baltic approach offers a pragmatic path toward substantial decarbonization. By combining regional strengths and addressing the economic realities of energy transition, Estonia can make significant progress toward climate neutrality while maintaining energy security and economic stability.