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# Price Cannibalization Effect on Long-Term Electricity Prices and Profitability of Renewables in the Baltic States

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**Abstract:** This paper aims to evaluate price cannibalization effects in forecasts of long-term electricity prices and substantiate their relevance on the profitability of renewables in the Baltic States from 2024 to 2033. Statistical data analysis, literature review, scenario method, and PLEXOS modeling were applied. Five scenarios were analyzed for developing renewable energy sources (RES) and load in Lithuania. In contrast, scenarios for Estonia and Latvia were based on assumptions derived from the countries' national RES strategies. The results showed that the increase in RES capacities will halve electricity market prices from around 130 EUR/MWh in 2024 to 58 EUR/MWh in Latvia, 60 EUR/MWh in Estonia, and 60–77 EUR/MWh in Lithuania in 2033. In time-waving, the absolute and relative price cannibalization effects of renewables were found. In 2033, the loss of revenue from solar photovoltaic (PV) generators was estimated to be 5.5–17.0 EUR/MWh in Lithuania, 7.1 EUR/MWh in Latvia, and 5.6 EUR in Estonia. The case of onshore wind demonstrated revenue losses of 10.5–22.0 EUR/MWh in Lithuania, 12.0 EUR/MWh in Latvia, and 10.0 EUR/MWh in Estonia. After 2029, revenues received by RES electricity generators could not guarantee project profitability; therefore, market flexibility options will be required. The key innovative strategy to mitigate the price cannibalization effect is the demand-side response when leveraging demand flexibility. Typically, this is achieved by sending price signals to the consumers who, if they have any, shift their demand to lower price periods. This is easily applied within HVAC systems, smart electric vehicle charging, and smart home appliance usage. Such behavior would allow the price cannibalization effect to be decreased.

**Keywords:** renewables; scenario method; price cannibalization effect; profitability; Baltic States



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## 1. Introduction

In pursuing a sustainable future, the global energy market is shifting towards green energy generation. This shift is caused by the concerns over climate change, the decreasing fossil fuel reserves, and the obligation to mitigate the adverse effects of traditional energy generation methods. Lithuania, Latvia, and Estonia, together with many nations, have committed to achieving net-zero carbon emission targets by the year 2050, which aligns with the Paris Agreement's aim to limit the global warming effect [1–4]. The Baltic States have been actively working on their energy strategy and policies towards transition to renewable energy sources (RES). According to the National Energy Independence Strategy (NEIS) [1], 45% of Lithuania's total electricity consumption is expected to be produced by RES in 2030. RES production is projected to increase to 80% of the total national load in 2050, making it the main source of electricity. Considering that electricity generated by

RES accounted for 21% of country's total electricity consumption in 2021 [5], a significant RES capacity growth can be assumed. Similarly, Latvia [3] aims to produce 50% of its total electricity from RES, and Estonia [4] seeks to achieve an RES energy share of 42% of the total final consumption by 2030.

As RES experience a rise in capacity across the Baltic States, and a steady trend in growth is expected in future, a phenomenon known as the price cannibalization effect [6] is emerging and impacting electricity prices [7]. Under favorable weather conditions, wind and solar electricity generators oversupply the grid, and this surplus influx of energy floods the market, causing a supply–demand imbalance [7,8]. While advantageous from a sustainability perspective, the oversupply tends to drive down wholesale electricity prices due to merit order effect [8]. In some cases, prices dip below zero, making RES electricity financially detrimental [8]. In Lithuania, only 8 h of negative electricity prices were registered from 2021 to 2022; however, 45 h of negative electricity prices have already been recorded in the first 8 months of 2023 [9]. Latvia and Estonia both registered 7 h of negative electricity prices from 2021 to 2022 and, respectively, 53 and 80 h of negative electricity prices so far in 2023 [9].

The Baltic States must ensure the profitability for the RES electricity generation in order to achieve their energy strategy targets. Historically, profitability ratios achieved by RES technologies in the Baltic States were higher than they were in other energy industries [10] but lower in comparison to other EU countries, especially in case of solar photovoltaic (PV) systems [11]. The results of a low fuel price scenario [11] demonstrated that the profitability of solar PV systems would be around 5.5% lower in comparison to the baseline scenario and even negative in cases of onshore and offshore wind expansion. Expected reductions in and lack of profitability will make it difficult or even impossible to finance solar and wind energy projects in the future, as they might be detrimental. Therefore, electricity producers should be informed about the price cannibalization effects of renewables and their impact on profitability to take the right investment decisions.

The issue of the price cannibalization effect of renewables has earned attention among scientists in recent years worldwide. It was analyzed and discussed by Prol et al. (2020) [8], Blume-Werry et al. (2021) [12], Peña et al. (2022) [13], the Institute for Energy Research (2023) [14], Jones and Rothenberg (2019) [15], and others by introducing categories of unit revenue (UR) (capture price, CP) and value factor (VF) in the analysis. Prol et al. (2020) [8] estimated historical absolute and relative price cannibalization effects from solar and wind energy penetration in the Californian wholesale electricity market. They found that increasing solar and wind energy penetration reduced their UR by 19.9 USD/MWh and 13.0 USD/MWh, respectively. Furthermore, in 2013, solar electricity was worth 5.5% more than the average unit of electricity, while in 2017, its value was 14.3% lower than the average unit of electricity. However, the worth of wind energy in comparison to the average unit of electricity increased by 3 percentage points from 99% in 2013 to 102% in 2017. Blume-Werry et al. (2021) [12] investigated developments in wind and solar VF and CP in the context of changing solar PV and wind installations, natural gas, coal, and carbon prices as well as the availabilities of wind and solar in Europe over the following thirty years. The results of the scenarios modelled revealed that higher natural gas and carbon prices will result in lower wind and solar VF and vice versa, while the impact of coal prices will be limited. Furthermore, increasing solar PV production was found to strongly impact solar VFs in Spain in comparison to Poland, while wind VFs were actually independent of solar PV production. Considering the historical data of the Spanish electricity market, Peña et al. (2022) [13] evaluated the price cannibalization and depredation effects of renewables. Scientists found that due to wind and solar penetration, the market remuneration for solar and wind technologies as well as hydro, gas, nuclear, and coal technologies reduced. Moreover, it was estimated that remuneration volatility to coal and nuclear technologies was increasing. The Institute for Energy Research (2023) [14] stated that a rapid increase in solar capacity "eats" the profit of utilities, as surplus power from solar reduces wholesale electricity prices, which results in decreasing utilities revenues. They observed that this is due to a shift in prices, which are increasingly set not by producers using natural gas but by producers using RES. The latter will almost halve VFs in Europe and California over the next decades and, therefore, will necessitate solutions, including battery storage, that could help to alleviate the effect. Jones and Rothenberg (2019) [15] performed one of the most detailed evaluations of the price cannibalization effect of renewables in Germany, France, Spain, and the United Kingdom (UK). By comparing the estimated CPs to the levelized cost of energy (LCOE) of respective RES technologies, they addressed the issue of the financial viability of RES projects in the future. Their findings suggested that if countries reach their 2030 targets for RES capacity, governments will need to provide subsidies for new RES installations.

In relation to the questions of RES targets and policies in the Baltic States and which power systems have no flexible production capacities and the conclusions of studies conducted on the price cannibalization effect and a request for the financial viability of RES projects, this paper solves the scientific problem defined by the following question: How can we evaluate the price cannibalization effect of renewables in long-term electricity price forecasts and substantiate its impact on changes in the profitability of RES technologies in the Baltic States?

Responding the scientific problem, this paper aims at understanding the impact of intensive RES penetration on the long-term price changes and profitability of RES technologies in the Baltic States up to 2033.

Seeking to implement the aim, the following tasks were determined:

1. Determine the possibilities of long-term electricity price forecasting methods and models to evaluate the price cannibalization effect of renewables;
2. Forecast long-term electricity market price and estimate RES CP and RES VFs in the Baltic States until 2033;
3. Provide insights of development in the profitability of onshore wind and solar PV in the Baltic States up to the year 2033.

This paper makes the following contributions to the existing literature. Firstly, for the first time, the price cannibalization effect on long-term electricity prices and profitability of renewables in the Baltic States' market is analyzed by using actual market data. Secondly, the modelling results provide economic evidence for the need to rapidly develop flexibility services to ensure the profitability of RES electricity generators in order to meet the net-zero carbon emission target. From a practical point of view, the contribution of this paper is in the fact that RES electricity generators' decisions regarding investment in RES technologies in the future are supported by the estimated long-term electricity prices, which include the price cannibalization effect, as well as enriched by insights of profitability of RES technology in the long-term perspective.

The rest of the paper is organized as follows. Section 2 reviews the literature on the possibilities of long-term electricity price forecasting methods and models to evaluate the price cannibalization effect of renewables. Section 3 shortly introduces the method of research, i.e., the PLEXOS model, scenarios considered, assumptions taken, and indicators estimated. Section 4 presents the results of the research, including developments in long-term electricity market price, RES CP and VF, as well as insights on profitability. Section 5 discusses the results achieved. Finally, in Section 6, the conclusions are drawn.

## 2. Literature Review

Developments in electricity prices are evaluated by applying different electricity price forecasting methods. There exists rich literature on electricity price forecasting, which has been widely studied by Aggarwal et al., 2009 [16]; Bobinaite and Zuters, 2016 [17]; Shah et al., 2022 [18]; and Leal et al., 2023 [19]. Its analysis shows that electricity price forecasts are prepared for short-, medium-, and long-term periods, with extremely different electricity markets studied, resolutions of collected input data, and methods or methodologies used to address each of these timeframes. Scientists (García-Martos et al., 2015 [20]; Ziel at al., 2018 [21]; Shah et al., 2022 [18]) have observed that while research on short-term electricity price forecasting is sufficient and methodologically well addressed, studies on long-term forecasting are scarce, although long-term forecasts are requested, as they are linked to the way bilateral contracts are negotiated and are often used for risk management and planning determinations. Therefore, the paper aims to fulfill the existing literature gap by focusing on long-term electricity market price forecasting. It was found (García-Martos et al., 2015 [20]) that short-term forecasting methodologies do not suit an extended forecasting horizon. Ziel et al. (2018) [21] argued that the literature on long-term forecasting is not comprehensive because of issues related to correctly selected electricity price factors and uncertainty about them in the long term but not the models themselves. Responding to the request for long-term forecasts for policy and business investment decision making, which no longer falls within the field of the short-term research carried out so far, the task of this review is to find out how to forecast the long-term prices, especially drawing attention to the evaluation of national conditions and price factors. For the time being, we limit ourselves to a review of the key literature sources, which demonstrate some diversity in the methodologies applied. Observed variety is presented in a systematic manner based on the price forecasting method used, country studied, price factors evaluated, and the results achieved.

Long-term electricity price forecasting is performed by applying time series and fundamental methods based on the classification of Aggarwal et al. (2009) [16]. Within a group of time series, neural networks (NNs) and regression and causal analysis are used. NNs demonstrate potential to deal with noisy, volatile, and non-linear environment of electricity market prices (Leal et al., 2023) [19]. The method was applied by Santos et al. (2021) [22], Wagner et al. (2022) [23], Dombi and Dulai (2022) [24], and Leal et al. (2023) [19]. In the work by Wagner et al. (2022) [23], the method was employed to forecast long-term electricity price profiles in the German electricity market by considering calendar information. They applied sinusoidal and dummy approaches. The results demonstrated that NN are better than benchmarking methods to establish long-term profiles of electricity prices. Similarly, Dombi and Dulai (2022) [24] analyzed the impact of various structures of deep NNs on forecasts of electricity prices in Hungary. They found that in markets with low volumes of RES, the meteorological factors are not useful to forecast electricity prices, as they return high errors. Instead, electricity prices in univariate models and electricity prices in combination with the time- and date-related data in multivariate models should be used to provide short- to long-term forecasts. Furthermore, a deep NN with one ConvLSTM encoder was found the most precise for problem solving. Continuing the research in NNs application to forecast long-term electricity prices and focusing on energy and climate plans requesting high volumes of RES, Santos et al. (2021) [22] estimated that the growth in RES electricity and the decrease in non-renewable electricity in the Iberian market will lead to a significant decrease in the market price of electricity of 18.279 EUR/MWh in 2030, and solar PV generation will be responsible for this decrease the most. Following up, Leal et al. (2023) [19] analyzed the impact of increased volumes of RES on the Iberian electricity market prices in 2030 in the context of a set of other price factors, including electricity generation, energy sources other than RES, demand, coal and natural gas prices, the price of $CO_2$ allowances, and nuclear variable cost. For the purpose, feedforward NN and long short-term memory (LSTM) algorithms were applied, and daily data were used. Authors found that NN models performed worse than the persistence model, but their quality improved subject to the inclusion of an optimum number of previous days of electricity prices. The results showed that in 2030, the average electricity price will be reduced in the Iberian market in comparison to 2015–2019. The observed reduction was described by the expected penetration of RES electricity and the related reduction in the fossil fuel contribution in the future.

Regression and causal methods have been tailored to forecast long-term electricity market prices by Ziel and Steinert (2018) [21], Fereira et al. (2019) [25], Gabrielli et al. (2022) [6], and Česnavičius and Konstantinavičiūtė (2023) [26]. Ziel and Steinert (2018) [21] proposed to apply the time series method referred to causal and autoregressive analysis to forecast high-resolution (hourly) electricity prices from several months up to three years ahead in Germany and Austria. The structure of the proposed model considered market structure and took into account a detailed day-ahead market bidding structure. It was also able to detect probabilities for price spikes. The findings suggested that a proposed model could be used in parallel to fundamental ones. A multivariate regression model was applied to forecast long-term electricity prices on monthly basis in the Iberian market by Fereira et al. (2019) [25]. The interest of market participants for causal forecasts was the motivating factor for the type of method selected. Authors found that demand for electricity, ambient conditions, volume of production of goods, hydroelectric production, fossil fuel prices, penetration of RES, and import of electricity have a significant contribution to the electricity price change in Portugal and Spain; therefore, they were included in the model. The results demonstrated that models approximated electricity prices well with an increasing error in a longer forecasting horizon. They estimated that the highest electricity prices were in the winter, and lower prices were in the summer, while the lowest were found in spring. A regression model was applied to forecast long-term electricity market prices in Lithuania by Česnavičius and Konstantinavičiūtė (2023) [26]. From a set of factors of electricity prices, natural gas price was found to be the most relevant one. It explained up to 83% of the variations in electricity prices. It was forecasted that due to changes in natural gas price the electricity market price will be halved in 2023 and vary in the range of 72–117 EUR/MWh from 2024 to 2030. Seeking to address the issues of the combination of extensive time horizons and fine time resolutions as well as out-of-sample electricity prices or shifts in the pricing regime, which was not observed in the past, Gabrielli et al. (2022) [6] developed a six-step data-driven model for long-term electricity price forecasting. In the model, electricity generated using natural gas and solar energy as well as oil and natural gas prices were the key drivers of the electricity price model. The single-output GPR model was found as the optimal regression model, as it had the lowest error. The out-of-sample issue was solved by coupling data-driven and market-based models. The results demonstrated a trend towards higher electricity prices. The trend was mostly driven by an increase in natural gas price and solar electricity generation. A combination of methods was adapted by Fraunholz et al. (2021) [27]. These scientists proposed a methodology for electricity price forecasting in a number of European countries from 2020 to 2050 at an hourly resolution based on machine learning and agent-based modelling (PowerACE). The results showed that naive approaches perform poorly. The linear regression performed reasonably well, but it was outperformed by the NN approach.

In contrast, Ercan and Soto (2011) [28] developed an optimization theory referred to a single-reservoir hydro-production model to forecast long-term electricity prices in France. A deterministic approach used to understand load profiles, reservoir limits, or generation patterns was supplemented by a stochastic approach, which encompassed uncertainty in yearly water inflows. Responding to the recent energy crisis and high electricity prices, Wrake et al. (2022) [29] assessed the available measures of reduction in electricity demand, the addition of RES in electricity generation, and the removal of coal use restrictions as well as an increase in electricity transmission capacity impact on the development of electricity prices in Europe. They applied EPOD for 2022–2023 as well as the power system model Balmorel to optimize dispatch for 2022–2025. Under the baseline scenario, prices were found to remain high but reduce to around 100 EUR/MWh; Norway and Sweden were predicted to pose lower prices compared to the rest of Europe. If electricity demand across Europe reduces by 1%, electricity price in SE4 will decrease by one-third. Under the scenario of RES buildout (210 GW of wind and 4 GW of solar), electricity price will reduce by 20%. Additional fossil fuel generating capacity would help mitigate the highest electricity prices but increase GHG emissions. Increased electricity transmission capacity in Sweden assures lower electricity prices in the south and higher ones in the north in Europe. It is worth mentioning the work by Afman et al. (2017) [30], who adapted a PowerFlex simulation model to derive electricity prices up to 2030. They found that the average electricity price level depends on prices for coal and gas and $CO_2$ emissions. Increases in RES electricity decrease the prices, but this effect is actually during 900–1800 h, when the price is low. Over time, the volatility of the electricity price is expected to increase notably. The high-RES scenario for 2030 showed that with 28 GW of wind and 20 GW of solar PV, there is a clear need for demand response that could absorb the oversupply of resources. Finally, Jones and Rothenberg (2019) [15] studied the impact of RES cannibalization on electricity prices in Germany, France, Spain, and the UK by applying a long-term pan-European power price forecasting model (ICIS Power Horizon). They found that the price captured on the market by solar or onshore wind generators reduces over time and by 2030 will be below the respective technology LCOE.

Thus, in the extensive existing literature covering theoretical and empirical studies on long-term electricity price forecasting methods the price cannibalization effect of renewables, scientists have applied forecasting models of varying complexity and detail to demonstrate that RES development, subject to the defined electricity demand level, decreases electricity market prices in long-term and thus the revenue to all electricity producers. However, it remains unclear how strongly the electricity market prices and the revenues will be affected by different RES development rates and subject to various levels of electricity demand. Furthermore, the scientists rarely distinguish how RES-influenced decreases in electricity prices would affect the revenue of non-RES electricity producing technologies and whether they, being sustainable, will also be profitable in the future and what the differences in profitability will be as well as what novel technical solutions should be applied to solve the arising profitability issues. Furthermore, the review of the literature revealed that there is a lack of scientifically based knowledge about how, in the context of RES development, not only the revenue to RES will change but how also the income to conventional energy producing technologies will be altered. Thus, with our research, we contribute to the global scientific research on the evaluation of the price cannibalization effect of renewables in forecasts of long-term electricity prices influenced by rapid penetration of RES technologies subject to different levels of electricity demand, justifying both the RES profitability issue and the increasing need for flexibility development in the regions. We focus on the adaptation of a fundamental model, the actual data, the LCOE method, and the case of the Baltic States in such a way that highlights profitability challenges for solar and wind energy as well as emphasizes an increasing interest in flexibility in the future power systems supplied with high shares of RES.

## 3. Materials and Methods

The research was carried out following the steps summarized in Figure 1.

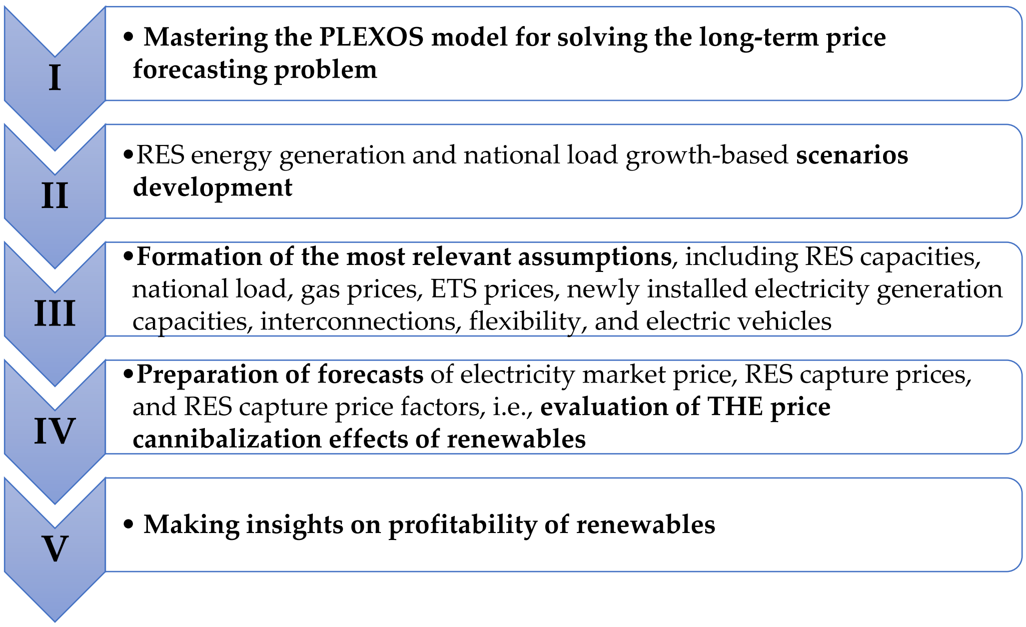



**Figure 1.** Steps of research carried out (source: authors).

In the subsections below, the research steps are explained in detail.

### 3.1. Model

The PLEXOS Integrated Energy Model was applied to forecast long-term electricity prices. It is a power system modeling tool used for electricity market modeling. PLEXOS is a commercial modeling tool developed and commercialized by Energy Exemplar Pty Ltd registered in Australia with the registered office at 17 Bagot Street, North Adelaide, South Australia 5006, and used by industry and academic researchers throughout the world. PLEXOS has been used in numerous peer-reviewed publications covering relevant topics [31–36].

This is a bottom-up model, which is mainly used for investment and operation decision making [32]. PLEXOS solves the optimization task for the power system over a variety of time scales from the short term (less than 1 year) to the long term (1–40 years) [33]. Alternatively, it minimizes an objective function subject to the expected cost of electricity dispatch given a number of constraints, including load, availability, and the operational characteristics of generating plants, fuel costs, network constraints, and market information [33] (Figure 2).

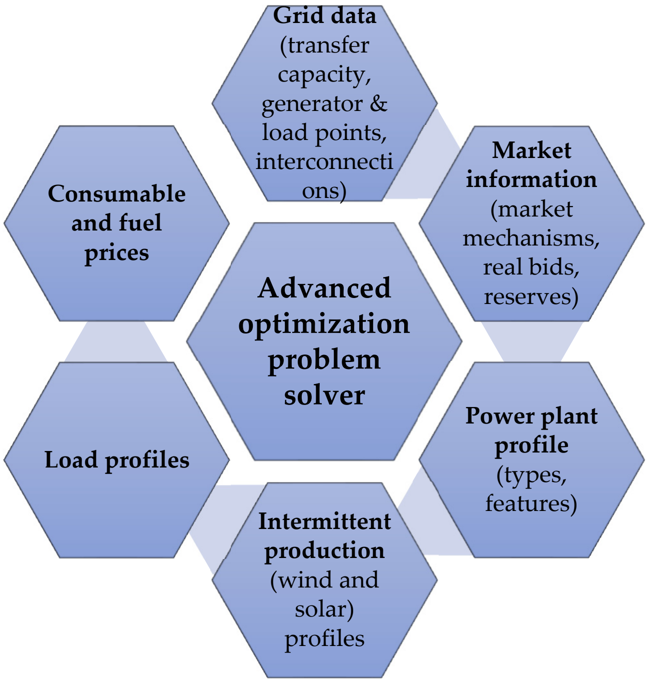



**Figure 2.** Structure of PLEXOS model [34,35].

In this research, PLEXOS solves one optimization problem for each time slot and determines the lowest market price for the zone, including the decision of which generator to start up, when to start up, where the flows go, etc. It simulates a separate merit order curve for each hour. The minimized system cost using the PLEXOS model can be simplified by the following equation [35]:

$$\text{System Cost} = \sum_{i=1}^{n} (\text{Fuel off take} \times \text{Fuel Price}) + (\text{Generation} \times \text{O\&M}) + (\text{Start Cost} \times \text{Units Started})$$

where i represents each generator in the power system.

The PLEXOS model minimizes the system cost considering the key parameters presented in Table 1.

**Table 1.** Key parameters of PLEXOS model [34,35].

| | |
|---|---|
| Technical parameters | • Installed capacity<br>• Input/output fuels<br>• Efficiencies<br>• Min. stable generation<br>• Up/down ramp rates/reserves<br>• Min. up/down times<br>• Maintenance rates<br>• Repair time |
| Economic parameters | • Fixed O&M costs<br>• Variable O&M costs<br>• Fuel costs<br>• Start-up costs<br>• Emission costs |
| Environmental parameters | • Emissions ($CO_2$, $SO_x$, $NO_x$, etc.) |

The superiorities of PLEXOS in a list of 74 other models were identified in [32]. The key advantages of it that are relevant for this research are the following:

- It assesses the impact of other countries' consumption a d generation availability (price) on Lithuania and does not use fixed flows;
- It allows to manage the assumptions;
- It has a high resolution (1 h): if necessary, 15 min;
- It is the most popular modeling tool among EU utilities.

The disadvantages are as follows:

- Germany is not modeled, which has a significant influence on Lithuania through its connection with SE4, which has a NordBalt connection with Lithuania;
- It cannot predict the availability of commercial flows between countries because it does not have the information (a separate technical model is needed);
- It is a marginal cost model, i.e., the model does not evaluate the price offered by each generating unit but determines it based on the technical parameters and fuel price.

### 3.2. Energy System

A detailed description of the energy system in the Baltic States and its development was given by Sliogeriene (2014) [37]. In Table 2, the latest data on electricity generation volume and installed capacity are provided.

As is shown in Table 2, the power system of the Baltic States consists of 10,284 MW of installed capacity in the power plants (PPs), from which 1405 MW consists of wind PPs, 1382 MW of solar PPs, and 382 MW of biofuel PPs. Further, 3033 MW are installed in PPs consuming fossil fuels. In Estonia, 1330 MW are installed in PPs using domestic shale. The power system generates 16,651 GWh, but the economy consumes 26,790 GWh of electricity. The coverage of national consumption by local generation differs between the Baltic States—88.3% in Latvia, 47.9% in Lithuania, and 60.8% in Estonia. However, last year's ratio of 62.2% for the Baltic States as a whole is the highest since 2018. The Baltic States have completely withdrawn from Russian and Belarusian electricity; therefore, no more electricity was imported from these countries starting in 2023, resulting in 0 GWh of imports [38]. Electricity imports come from neighboring regions through the interconnectors, the capacity of which is given in Table 3.

As is presented in Table 3, electricity imports come through interconnections with Sweden, Poland, and Finland. Moreover, the Baltic States are interconnected well in between. Estonia currently has a 1.4 GW interconnection capacity with Latvia, consisting of three 330 kV lines. Latvia and Estonia plan to build a new interconnector of 1 GW [39].

**Table 2.** Installed capacity and electricity production volume in the Baltic States in 2023 [38].

| | Lithuania | | Latvia | | Estonia | |
|---|---|---|---|---|---|---|
| | **Electricity Produced, GWh** | **Installed Capacity, MW** | **Electricity Produced, GWh** | **Installed Capacity, MW** | **Electricity Produced, GWh** | **Installed Capacity, MW** |
| Wind | 2524 | 947 | 268 | 141 | 684 | 317 |
| Solar | 633 | 572 | 128 | 300 | 693 | 510 |
| Biomass | 124 | 62 | 346 | 130 | 1062 | 153 |
| Biogas | 103 | 37 | 200 | - | 2.6 | - |
| Hydro | 446 (+520 Pump-storage) | 128 (+900 Pump-storage) | 3778 | 1570 | 24.6 | 7 |
| Fossil fuels | 1311 | 1555 | 1363 | 1270 (2021) | 314 | 208 |
| Waste-to-energy | - | 70 | - | - | 140 | 17 |
| Shale | - | - | - | - | 1988 | 1330 |
| Total | 5664 | 4271 | 6083 | ~3471 | 4904 | 2542 |
| Electricity consumption, GWh | 11,833 | | 6887 | | 8070 | |

**Table 3.** Interconnection capacity in the Baltic States [38].

| Interconnector | Capacity, MW |
|---|---|
| LT—SE | 700 |
| LT—PL | 1000 |
| LT—LV | 1500 (to LT); 1200 (to LV) |
| LV—EE | 1400 |
| EE—FI | 1000 |

### *3.3. Scenarios*

The potential scenarios for RES capacity and national load growth were outlined based on the national energy targets for 2030. Five different scenarios were defined for Lithuania, taking into account high, middle, and low values of key indicators, namely RES capacity and national load. The first scenario refers to Lithuania's energy strategy data in 2030. The last scenario reflects a pessimistic view of the RES sector development. Other cases fill in the gaps to provide a broader range of the price development and dependencies from RES capacity. Scenarios were prepared based on short-term (from 2022 to 2026) projects, which are already announced, and in order to reach the 2030 target capacity of each scenario, several potential future projects were added. In addition, Lithuania's Transmission System Operator (TSO) forecasts of final electricity demand were taken [40]. As for Latvia and Estonia, the RES capacities and national loads represent their energy strategy targets in 2030 as presented in [3,4,10,41]. The assumed RES capacities and national loads for each scenario are shown in Table 4.

**Table 4.** Scenarios considered: RES capacities and national loads in 2030 (source: authors).

| Country | Scenario | Load, TWh | Solar, GW | Wind Onshore, GW | Wind Offshore, GW |
|---|---|---|---|---|---|
| Lithuania | High RES and High Load | 17.5 | 3.0 | 3.6 | 0.7 |
| | High RES and Low Load | 14.5 | 3.0 | 3.6 | 0.7 |
| | Mid RES and Mid Load | 16.0 | 2.0 | 3.0 | 0.7 |
| | Low RES and High Load | 17.5 | 1.5 | 2.0 | 0.7 |
| | Low RES and Low Load | 14.5 | 1.5 | 2.0 | 0.7 |
| Latvia | Conventional | 8.6 | 0.4 | 1.3 | 0.5 |
| Estonia | Conventional | 8.9 | 0.6 | 1.5 | 0.5 |

### *3.4. Assumptions*

#### 3.4.1. Gas Prices

The natural gas commodity price considered historic seasonal volatility by assuming a daily price profile from 2020 scaled according to monthly average values [42]. The short-term natural gas price was based on the Dutch TTF futures [43] until 2026. From 2030 onwards, an influx of new liquified natural gas (LNG) capacity from Qatar, the USA, and others was assumed to lead to the normalization of gas prices in the long term. The base yearly average was assumed to be the long-run marginal cost (LRMC) of USA LNG [44] at around 29–32 EUR/MWh.

#### 3.4.2. ETS Prices

The EU emissions trading system (ETS) price [45] is expected to increase due to a faster decrease in overall emission allowances (2.2% p.a. vs. 1.74% until 2021) and a larger number of unused allowances put into the Market Stability Reserve. Additionally, free allowances will be discontinued in the medium term (from 2026 to 2027). The mid-term prices were forecasted by calculating the difference in marginal costs (MC) of coal and gas generation in order to set an allowance price to incentivize switching to RES generation. Long-term prices were forecasted by calculating the difference in using natural gas and blue hydrogen in industrial heat processes to incentivize the use of blue hydrogen.

#### 3.4.3. Newly Installed Generation Capacities

Lithuania's ongoing and planned electricity generation expansion projects and plans have a significant role in forecasting future market prices. In 2022, the Maritime Spatial Development Plan [46] was approved in Lithuania. It lays the foundation for the development of 1400 MW of offshore wind capacities by 2030. However, due to a large gap between the current capacity and projected demand for the offshore wind components [47], the analysis assumed 700 MW operational in 2028 and the second operational in 2031. Furthermore, the planned Kruonis Pumped Storage Hydroelectric Power Plant 5th expansion unit was assumed to enter operation in 2027, with a 110 MW rated capacity and a typical efficiency ratio of 78.6% for the novel Francis hydro turbine [48]. No fossil fuel power plant capacity expansion was assumed. Central power plant capacity will decrease by 650 MW in 2030 due to plant decommissioning [49]. The Kaunas Combined Heat and Power Plant is planned to have 50 MW decommissioned in 2026, and Elektrenai Power Plant blocks 7 and 8 with 300 MW each are planned to be decommissioned no earlier than 2030 [50].

#### 3.4.4. Interconnections

According to the Ten-year Network Development plan [45], no additional interconnection capacity is foreseen up to 2030 except for the 700 MW Harmony Link interconnector with Poland [51]. Due to project procurement delays, with the initial project delivery in 2025, the project is delayed until 2028. This means that Lithuania is expected to have

950 MW connection with Latvia via 330/132 kV lines, 500 MW via LitPol Link with additional 700 MW via Harmony Link connections with Poland, and 700 MW interconnection with SE4 via NordBalt.

#### 3.4.5. Flexibility

The hydrogen market will grow to develop 243 MW in 2027 and 1243 MW in 2032 of electrolysis capacity. It was estimated that after a support scheme for pilot hydrogen electrolysis-based production is initiated, 30–35 MW will be attracted. The largest fertilizer producer in the Baltic States plans to develop 213 MW of electrolysis capacity to produce green hydrogen for industrial processes [52]. By 2030–2032, a green hydrogen hub system with the estimated capacity of 1000 MW is expected for facilitation of market decarbonization.

A utility-scale battery energy storage system (BESS) is planned to enter the market on a commercial basis with 200 MWh in 2027 and grow to 350 MWh in 2030. TSO will develop 200 MW/200 MWh BESS through the EnergyCells project [53], which will be fully developed in 2024, but commercial operation is scheduled for no earlier than 2027, when Harmony Link and synchronization with continental Europe is established. Development of prosumer scale batteries is planned to start in 2027 and grow to 3 MW in 2030 [54]. Demand Side Response [54] is expected to become available as a service allowing the capacity to grow to 40 MW in Lithuania in 2030.

#### 3.4.6. Electric Vehicles

Electric vehicles (EV) are estimated to grow to 230 thousand units in Lithuania in 2030. However, historic EV registrations and scarce EV charging points identified in the Alternative Fuels Law in the Republic of Lithuania [55] do not support this claim. Further, the private sector engagement in the EV sector is low due to technical EV parameters and convenience factor [56]. For the reasons mentioned, it was decided to adopt a much more realistic approach and consider the EV number to be closer to 60,000 units in 2030.

#### 3.4.7. Other

All variables and assumptions were incorporated and used in an hourly optimization problem where the objective was to dispatch generators according to their marginal cost to minimize the total system cost for every hour. The RES intermittency was accounted by simulating three historic climate years, which provide a system price sensitivity depending on RES generation level. The resulting prices were estimated on real basis, meaning that inflation index was not accounted for the simulation.

### *3.5. Estimated Indicators*

Absolute and relative price cannibalization effects of the penetration of solar and onshore wind technologies were assessed based on Prol et al. (2020) [8]. For this purpose, the CP, which is the equivalent to UR, and the capture price factor (CPF), which is equivalent to VF, were estimated.

The CP is defined as the solar and wind generation-weighted electricity prices, which reveal how much income solar and wind producers receive per electricity unit [8]. It is the ratio between the amount of revenue and total quantity of forecast generation of solar and wind technologies over a certain period, be it a day, week, month, or year [8]. The CP was calculated by Equation (1):

$$CP_{t;S} = \frac{\sum_{h=1}^{8760} P_h \times Q_{h;S}}{\sum_{h=1}^{8760} Q_{h;S}} \text{ and } CP_{t;W} = \frac{\sum_{h=1}^{8760} P_h \times Q_{h;W}}{\sum_{h=1}^{8760} Q_{h;W}} \quad (1)$$

where $CP_{t;S}$ and $CP_{t;W}$ is the capture price of solar (S) and wind (W) technologies in year t, EUR/MWh; $P_h$ is the electricity market price during hour h, EUR/MWh; $Q_{h;S}$ and $Q_{h;W}$

are the quantity of forecast generation of solar (S) and wind (W) technologies during an hour h, MWh.

The comparison of the $CP_{t;S}$ or the $CP_{t;W}$ with the average electricity market price ($\overline{P_t} = \sum_{h=1}^{8760} P_h : 8760$) demonstrates an absolute price cannibalization effect of solar and wind technologies, respectively. Subject to an absolute price cannibalization effect, the $CP_{t;S}$ or the $CP_{t;W}$ is less than the $\overline{P_t}$.

Based on [8,12], the CPF is estimated by dividing the CP by the average electricity market price, which historically was decided by the power plants using natural gas [12], by Equation (2):

$$CPF_{t;S} = \frac{CP_{t;S}}{\overline{P_t}} \text{ and } CPF_{t;W} = \frac{CP_{t;W}}{\overline{P_t}} \quad (2)$$

The $CPF_{t;S}$ or the $CPF_{t;W}$ reveal the relative price cannibalization effects of solar and wind technologies. If $CPF_{t;S} < 1$, or $CPF_{t;W} < 1$, then it is said that relative price cannibalization effect is equivalent to $1 - CPF_{t;S}$ or $1 - CPF_{t;W}$.

The indicators were calculated by PLEXOS model and Excel 2019.

### *3.6. Principle for Profitability Evaluation*

The profitability of RES technologies was decided by comparing the income generated by that RES technology with their cost [10]. The income generated by solar and wind technologies is equivalent to the estimated $CP_{t;S}$ or the $CP_{t;W}$, respectively. Based on research carried out by [15], the LCOE of solar and wind was taken as a measure. In this study, we referred to the LCOE estimates provided in [52]. In this way, solar and wind technologies are considered profitable if the $CP_{t;S}$ or the $CP_{t;W}$ is above the LCOE of respective technologies in the long term.

## **4. Results**

### *4.1. Electricity Market Prices*

The average electricity market price in Lithuania was found to follow a decreasing trend with growing RES capacity over the years (see Figure 3).

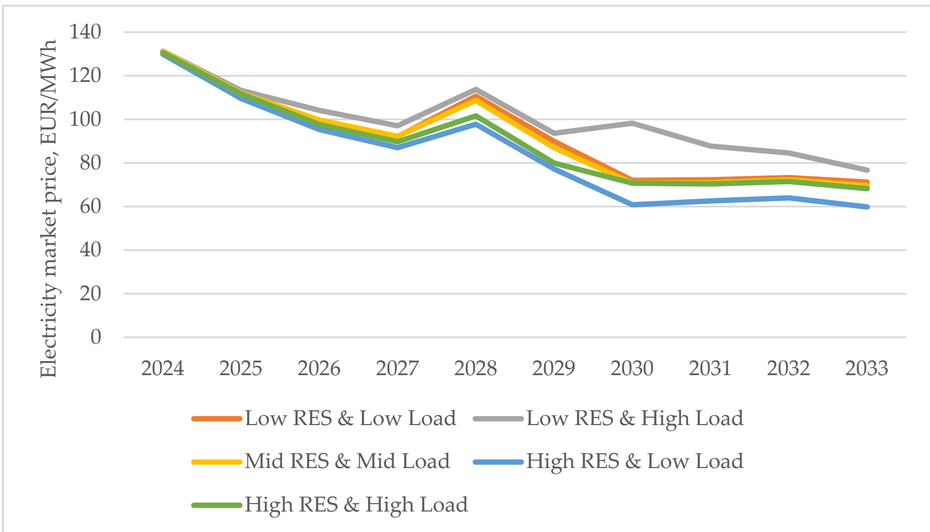



**Figure 3.** Electricity market price forecast in Lithuania from 2024 to 2033 (own estimations).

As shown in Figure 3, for low-RES and mid-RES scenarios, the average electricity market price was estimated to be around 130 EUR/MWh in 2024 and only 70–98 EUR/MWh in 2030. For high-RES scenarios, the average electricity market price was projected to change from 130 EUR/MWh in 2024 to 60 EUR/MWh if the load is low or 70 EUR/MWh if the load is high in 2030. In 2028, a significant price increase of 12–20% was registered due to the expected introduction of the Harmony Link, which will provide electricity export opportunities to Poland and create additional electricity demand, increasing the average price to 98–114 EUR/MWh. In the low-RES and low-load scenario, local generation was found insufficient to cover the local electricity demand in Lithuania; therefore, the electricity market price was formed by imports from Poland or Latvia.

Considering the average electricity market price in Latvia and Estonia, a similar price trend can be observed, which is illustrated in Figure 4.

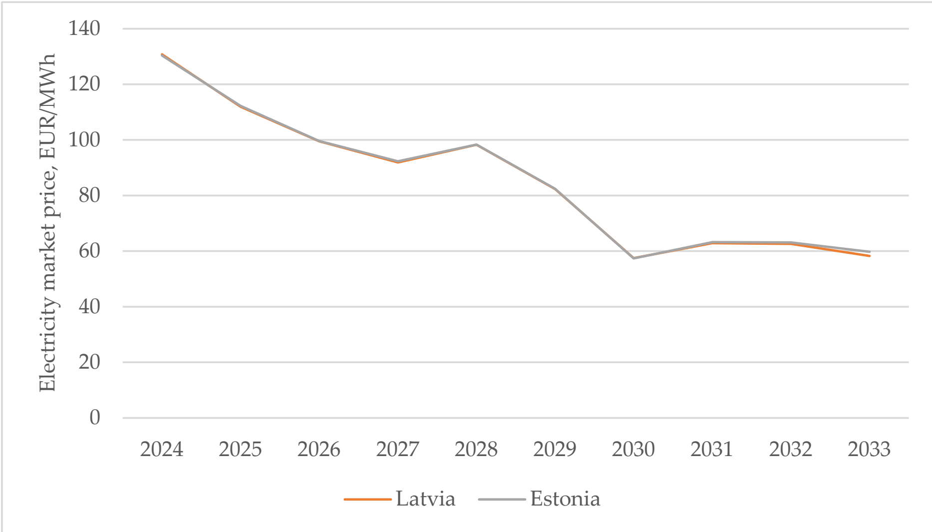



**Figure 4.** Electricity market price forecast in Latvia and Estonia from 2024 to 2033 (own estimations).

As shown in Figure 4, if both countries achieve their national energy strategy targets, the average electricity market price will steadily decrease from around 130 EUR/MWh in 2024 to 58 EUR/MWh in 2030. An increase of 7% in the electricity market price was forecasted for 2028; however, from 2029 onwards, a sharp drop of 10% a year is expected. Minor differences in electricity market prices are expected in Latvia and Estonia.

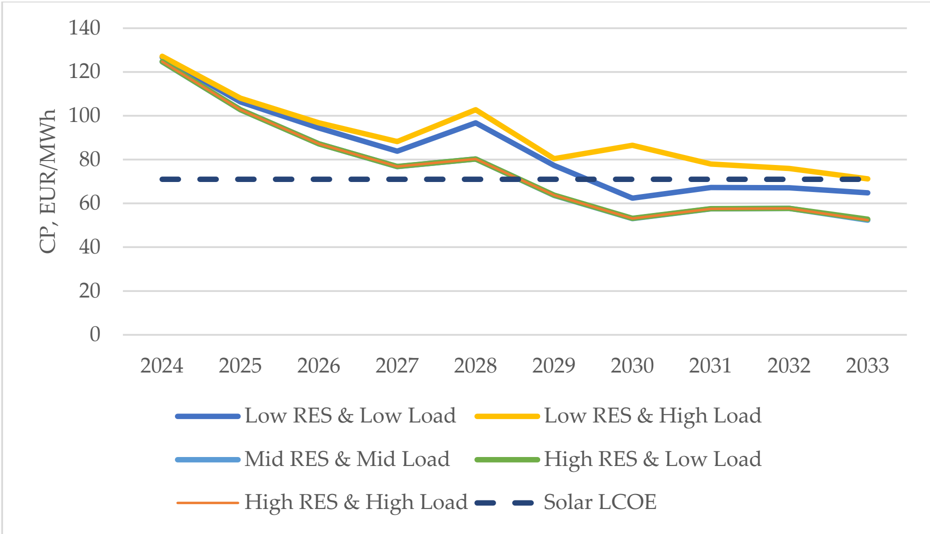
### *4.2. Assessment of Price Cannibalization Effects and Profitability Issues*

#### 4.2.1. Solar PV

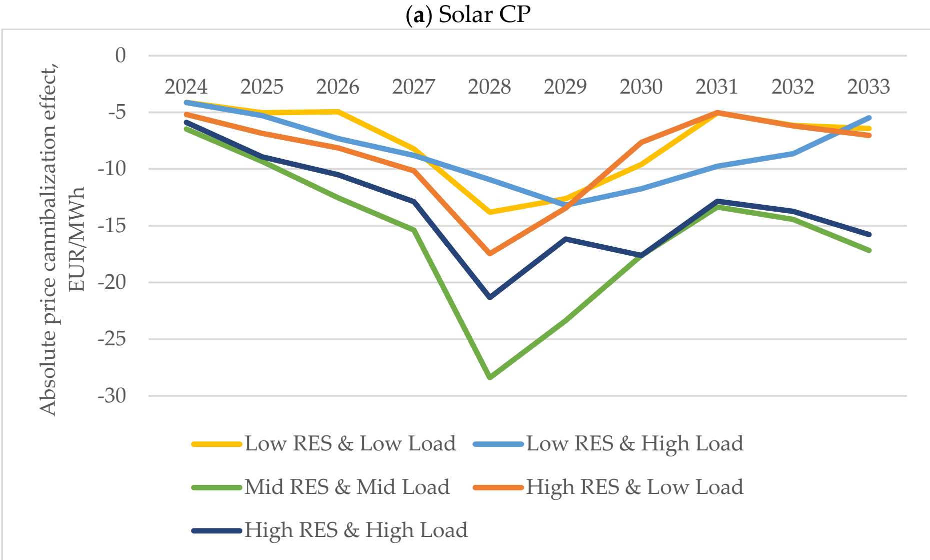
Increasing solar capacity in Lithuania will cause absolute and relative price cannibalization effects in the country during the following decade (Figure 5).

Figure 5a shows that due to solar penetration in electricity market, its electricity CP decreased significantly from 125 EUR/MWh in 2024 to 71 EUR/MWh in the low-RES and high-load scenario and reached as low as 52 EUR/MWh in the mid-RES and high-RES scenarios in 2030. The differences in solar CPs in the mid-RES and the high-RES scenarios are minor. Considering that the LCOE of solar PV is 71 EUR/MWh [57], it becomes obvious that solar PV projects will be less profitable in long-term. Moreover, only the low-RES and high-load scenario guaranteed profit in the year 2030 and onward, whereas under the mid-RES and high-RES scenarios, solar PV generators were projected to suffer losses during 2029–2034.

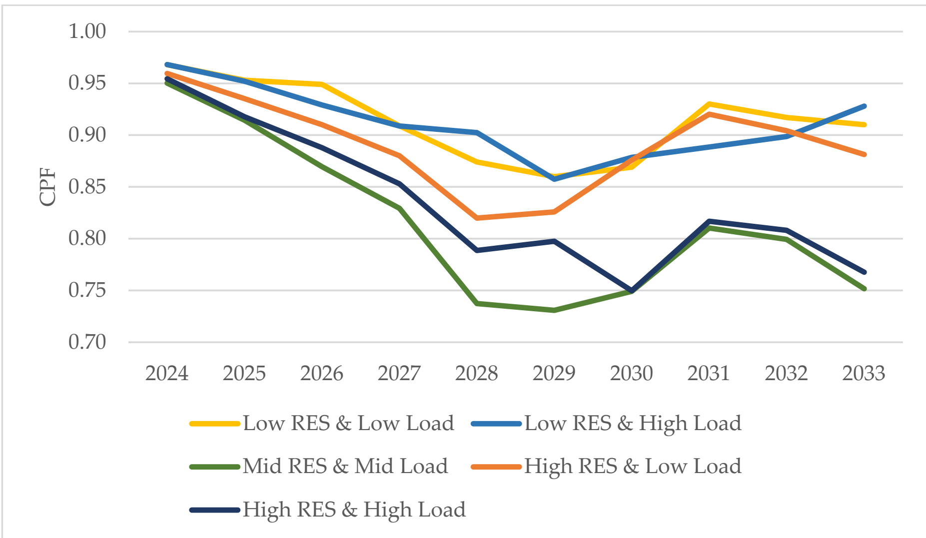
A significant decrease in CP over time will lead to an absolute price cannibalization effect for solar (Figure 5b). for 2024, the absolute price cannibalization effect was estimated to be around 4.1–6.5 EUR/MWh under all scenarios considered, but for 2029, it will be relevant—from 10.9 EUR/MWh under the low-RES and high-load scenario to 28.4 EUR/MWh under the mid-RES and mid-load scenario. Later on, an absolute price cannibalization effect will exist, but its scale will reduce to 5.5 EUR/MWh under the low-RES and high-load scenario and to 17.2 EUR/MWh under the mid-RES and mid-load scenario. This means that solar PV generators will lose their revenue by the estimated monetary value due to solar electricity supplied to the market.




(**a**) Solar CP




(**b**) Difference between electricity market price and solar CP

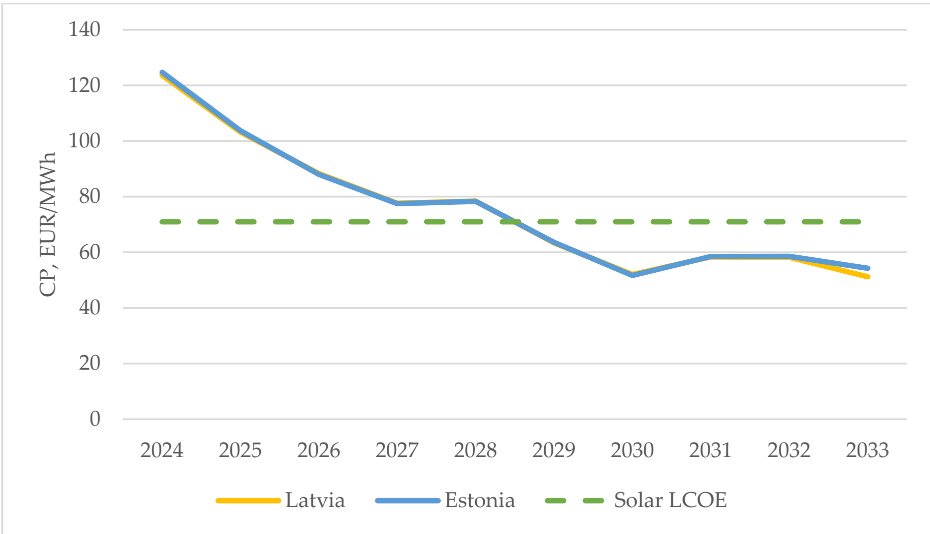



(**c**) Solar CPF

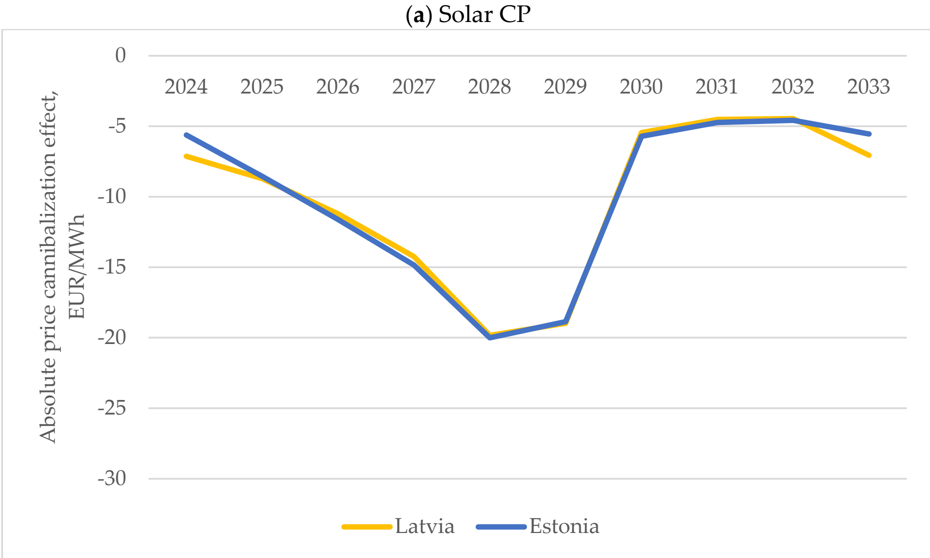
**Figure 5.** Developments in solar PV power capture prices and capture price factors in Lithuania under different scenarios from 2024 to 2033 (own estimations).

Furthermore, a relative price cannibalization effect will be fixed but at a different size (Figure 5c). The low-RES scenarios will achieve a relatively high CPF of around 93% of the average yearly price in 2033, while the mid-RES and the high-RES and high-load CP will reach 77% and 75% in CPF, respectively, in 2033 due to high RES penetration but insufficient local load. The latter estimates show that during the time the electricity market is supplied with solar electricity, its generators will receive by 23–25% less revenue in comparison to the case when the electricity market price is decided by other types of generators. The irregular behavior of the high-RES and low-load scenario having a relatively high CP of 88% in 2033 can be explained by the increased electricity export of 12 TWh compared to the mid-RES and mid-load scenario that exports 10.5 TWh. The lowest values of CPF were found between the years 2028 and 2029 due to the LT1 offshore wind park and Latvia's offshore park starting operations, Harmony Link, and the introduction of hydrogen electrolysis and BESS.

The expansion of solar PV capacity in Latvia and Estonia is forecasted to lead to a substantial reduction in solar PV CP, too (Figure 6a).

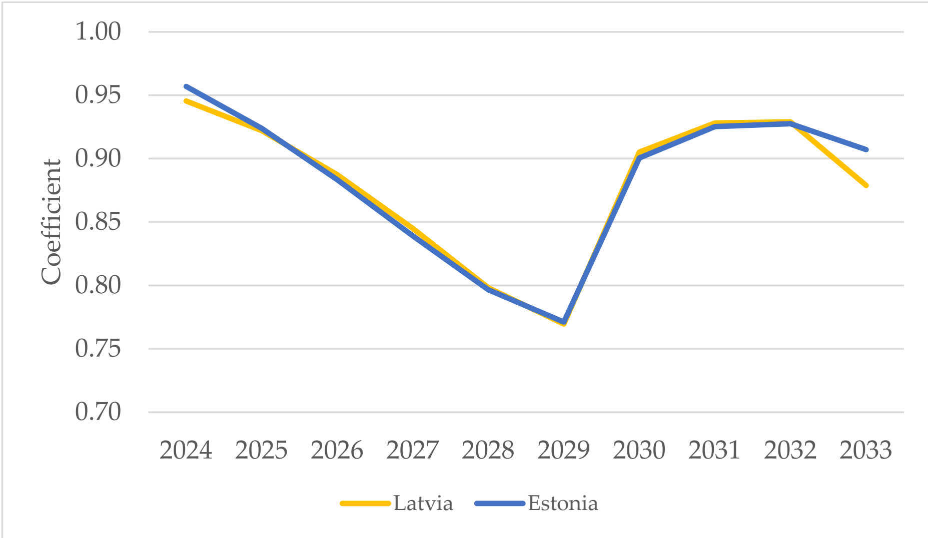



(**a**) Solar CP




(**b**) Difference between electricity market price and solar CP

**Figure 6.** *Cont*.




(**c**) Solar CPF

**Figure 6.** Developments in solar PV power capture prices and capture price factors in Latvia and Estonia from 2024 to 2033 (own estimations).

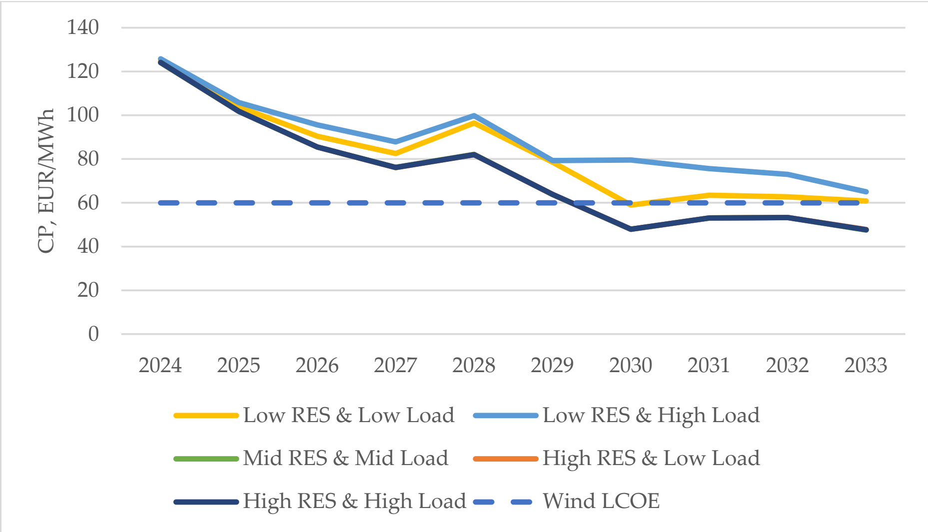
As is shown in Figure 6a, the CP, representing the revenue of solar PV generators, will decline from the initial 123–124 EUR/MWh in 2024 to as low as 52 EUR/MWh in 2030. The differences in the CP are minor in Latvia and Estonia. From mid-2028, the solar CP will be below the solar LCOE in these countries, suggesting losses suffered by the solar electricity generators (Figure 6b). The losses will be as high as 20 EUR/MWh in Latvia and 17 EUR/MWh in Estonia in 2033. The absolute price cannibalization effect of solar will be fixed (Figure 6c). It will amount to 20 EUR/MWh in 2028 but, later on, will reduce to 7.1 EUR/MWh in Latvia and 5.6 EUR/MWh in Estonia in 2033. In 2029, the revenue of solar PV generators will reach only 77% of the amount the other generators will receive (Figure 6c), but in 2033, the revenue of different kinds of generators will become more even; i.e., the gap in revenue will account for 10–12%.

4.2.2. Onshore Wind

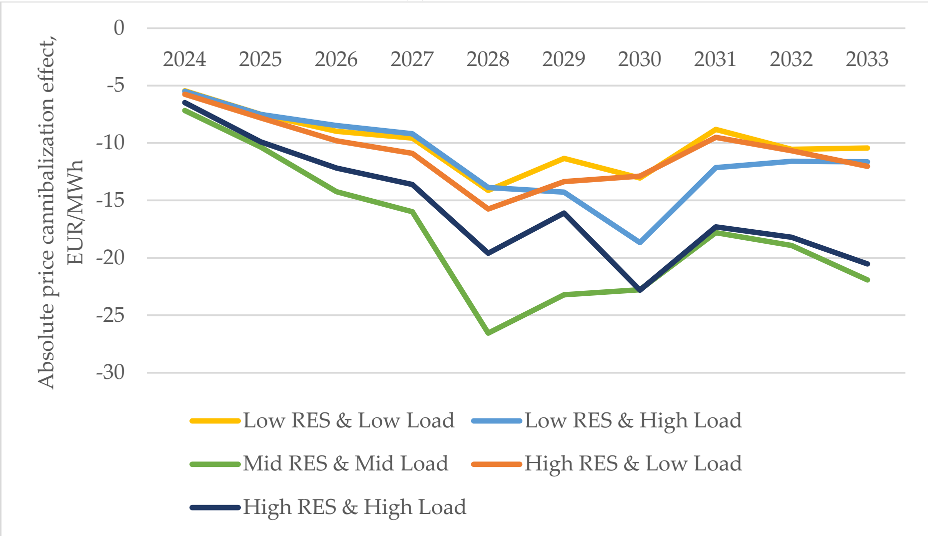
Similarly, onshore wind power will encounter a decline in its CP and CPF in Lithuania (Figure 7).

As is illustrated in Figure 7a, increasing onshore wind capacity in Lithuania will halve its CP from 124–125 EUR/MWh in 2024 to 60–65 EUR/MWh under low-RES scenarios and will reach 48 EUR/MWh under mid- and high-RES scenarios the differences in the CP between the latter scenarios are found insignificant. Only low-RES scenarios will ensure profitability to onshore wind electricity generators during each year in the period. Profit is expected to reach only 1.0 EUR/MWh in 2033 in comparison to 65 EUR/MWh in 2024. Under the mid- and high-RES scenarios, onshore wind electricity generators will suffer losses of up to 12 EUR/MWh from 2030. The absolute price cannibalization effect of onshore wind is estimated at 27 EUR/MWh under the mid-RES scenario, 20 EUR/MWh under the high-RES and high-load scenario, and 14–16 EUR/MWh under the remaining scenarios in 2027 (Figure 7b). Although during the following five years, loss of revenue by onshore wind generators will decline, the issue will be relevant in numbers, i.e., 10–22 EUR/MWh in 2033. Low-RES scenarios will achieve a relatively high CPF of around 85% of the average yearly electricity market price, while the mid-RES and high-RES and high-load CPF will reach 68–80% in 2030 due to high RES penetration but insufficient local load (Figure 7c).

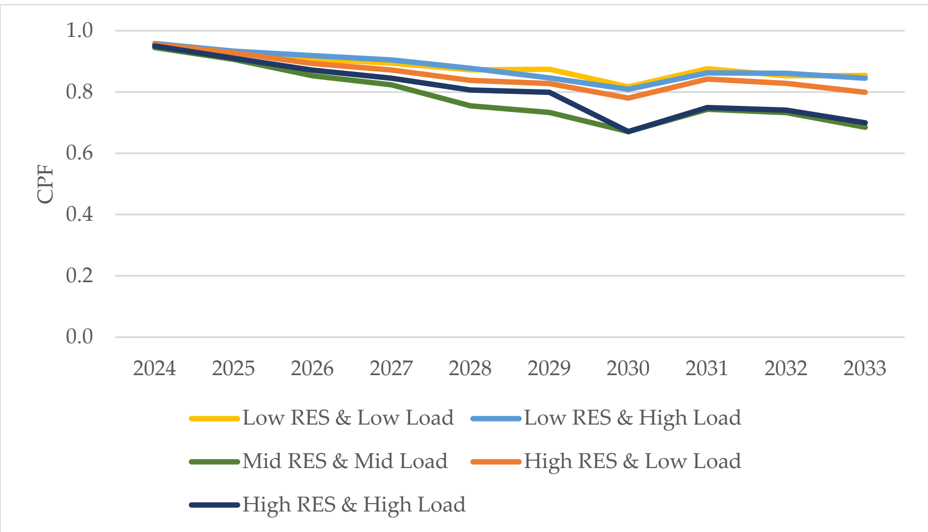
The scenarios prepared for Latvia and Estonia demonstrate similar results (Figure 8).




(**a**) Wind CP

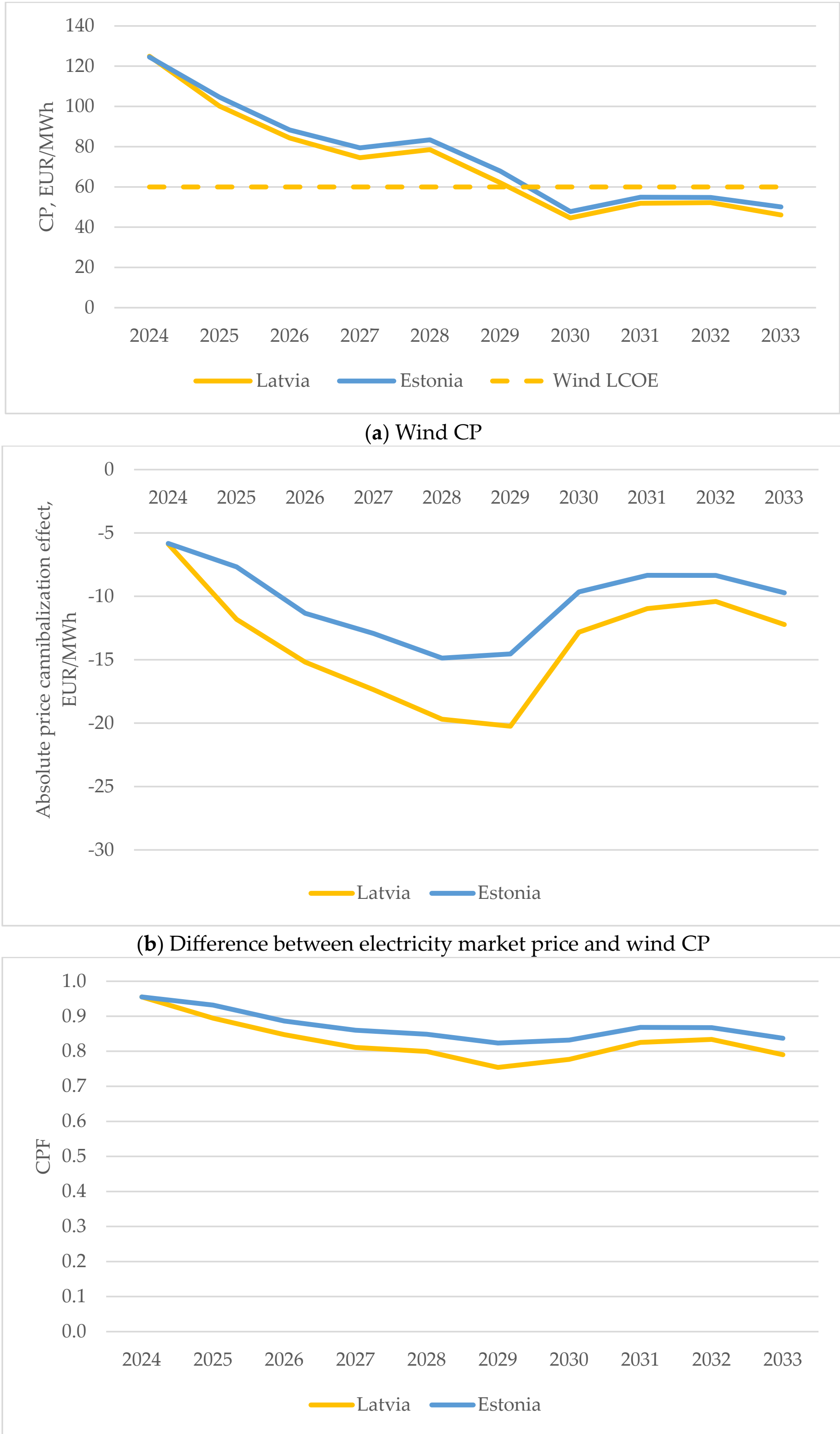



(**b**) Difference between electricity market price and wind CP




(**c**) Wind CPF

**Figure 7.** Developments in onshore wind power capture prices and capture price factors in Lithuania from 2024 to 2033 (own estimations).




(**a**) Wind CP



(**b**) Difference between electricity market price and wind CP



(**c**) Wind CPF

**Figure 8.** Developments in onshore wind power capture prices and capture price factors in Latvia and Estonia from 2024 to 2033 (own estimations).

Figure 8a demonstrates that onshore wind CP will dip below the wind LCOE value of 60 EUR/MWh in 2029 after a steady decline from a CP of 127 EUR/MWh in 2024. This suggests wind electricity profitability issues after 2029. In 2033, onshore wind electricity generators will suffer losses of 14 EUR/MWh in Latvia and 10 EUR/MWh in Estonia. The absolute price cannibalization effect of onshore wind will deepen from 2024 to 2029 (Figure 8b). In 2029, wind electricity generators will have a loss of revenue of 20 EUR/MWh in Latvia and 15 EUR/MWh in Estonia. At the end of the period, the loss of revenue will be smaller but relevant, i.e., 12 EUR/MWh and 10 EUR/MWh, respectively. In 2033, subject to the CPF of 79% for Latvia and 84% for Estonia, the loss of revenue will account for 21% in Latvia and 16% in Estonia (Figure 8c).

## 5. Discussion

The study carried out demonstrated that the implemented energy and climate policy measures will result in a halved wholesale electricity price in the Baltic States during the following decade, which, in agreement with [8], will push other forms of generation out of the market. It also substantiates that the absolute and relative price cannibalization effects of renewables will appear on the electricity market in these countries in the long term, suggesting that expansion of RES capacity will assure both low wholesale electricity prices for consumers as well as result in reducing revenue to RES generators and causing profitability issues for them. The findings are in line with the results achieved by Prol et al. (2020) [8], who found absolute and relative cannibalization effects, which, inter alia, were found stronger for solar. In our research, the penetration of onshore wind technologies was found to result in larger price cannibalization effects of renewables than that of solar PV. It is consistent with results achieved by Peña et al. (2022) [13], who found evidence of significant cannibalization in the Spanish electricity market and a stronger non-linear effect of wind when its penetration exceeds 30–40%. Our results go beyond this in that we can assess the effect of demand changes on the price cannibalization effect of renewables. The effect of load becomes significant only when subject to low-RES penetration. If RES penetration is higher, the load does not affect the price cannibalization effect of renewables. The most relevant cannibalization effect is achieved subject to medium RES penetration and medium electricity demand as well as high-RES penetration. The Institute for Energy Research (2023) [14] expects the capture rate for Germany to decline from its current 94% to 80% by 2026 and dip below 50% by summer 2029. In relation to this research, our results demonstrate moderate declines in wind and solar CPF, which are estimated to decrease to 70% and 78% by 2033 under the high-RES and high-demand scenario for Lithuania. Major effects on the capture price and cannibalization effect of renewables are interconnected with high-liquidity market zones, installed capacities, and the forecasted system demand.

The price cannibalization effect of renewables can be mitigated by implementing flexible energy sources, which shift the energy utilization in time. BESS utilizes the peak generation periods and reduces the need to curtail energy from RES by storing it and using it during hours of high electricity demand [58]. Pumped energy storage systems and flow batteries operate in a similar manner—this shift of RES generation allows to maintain the necessary synchronous generation in the network and to utilize the price arbitrage while ensuring the security of the grid. Cross-border interconnections in a case study performed in [59] showed a reduction in the critical excess energy production (CEEP). The increase in interconnection capacity between neighboring regions significantly reduced the CEEP for the same percentage of wind and solar penetration in the grid. This allows distribution of the excess renewable generation to regions with higher electricity demand and increases RES penetration in the system. Other optimal flexibility options in the power system could be applied, too [60]. Thus, the study's findings suggest a strong focus on system flexibility, which should be incorporated within the national strategies. The contracts for difference (CfDs) mechanisms might also help to mitigate the cannibalization risk for RES developers; however, if overall system flexibility is not improved, this could be a very pricey solution.

The flexibility options mentioned above can already be implemented in the Baltic electric power system. Each of the options has distinct working mechanisms and parameters that need to be taken into consideration when evaluating their optimal integration within the system. Therefore, further analysis is necessary to determine the most effective and economically viable flexibility solution to tackle the price cannibalization effects of renewables in the Baltic States.

## 6. Conclusions

The results of the literature review revealed that various approaches could be applied to forecast long-term electricity prices in the context of increasing RES development worldwide. They significantly differ in the electricity markets studied, resolutions of collected input data, and methods or methodologies used to address each of these timeframes. The group of fundamental models, which describe the power systems comprehensively and in detail, was identified as the most valuable one, as it allows both forecasting electricity market prices and detecting the price cannibalization effect of renewables. A fundamental model, which is the PLEXOS model, was applied to carry out a perspective analysis of the power system development in the Baltic States from 2024 to 2033.

The modelling results demonstrated that electricity market prices will decrease in the future in the Baltic States due to RES development. The most significant decreases are expected in Latvia (55%), Estonia (54%), and Lithuania (40–50%), revealing reducing revenue to all electricity producing technologies. It is expected that in 2033, electricity market prices will account for 58 EUR/MWh in Latvia, 59 EUR/MWh in Estonia, and 60–78 EUR/MWh in Lithuania. The estimated CP and CPF demonstrated that the price cannibalization effect of renewables will appear in the Baltic States' electricity market in the long term. It will grow stronger over time but at the end of period will drop. The price cannibalization effect of wind will be more noticeable than that of solar, as the differences between the electricity market price and the CP show. The absolute price cannibalization effect of onshore wind is estimated to be 10–21 EUR/MWh in Lithuania, 12 EUR/MWh in Latvia, and 9 EUR/MWh in Estonia in 2033. The same was calculated to be 6 EUR/MWh in Estonia, 7 EUR/MWh in Latvia, and 6–16 EUR/MWh in Lithuania for solar in 2033.

The findings of this research outline a challenging future for the economic viability of solar PV and onshore wind energy projects in 2033. The detrimental impact of the price cannibalization effect of renewables is a substantial obstacle that leads to a lack of profitability of RES technologies. In 2030, only the low-RES and high-load scenario in Lithuania was found to ensure a profitable CP; otherwise, electricity producers will lose money on every megawatt hour of RES electricity generated, as the LCOE will be higher than the CP. In detail, only under the low-RES and high-load scenario was the solar CP estimated at 71.21 EUR/MWh and onshore wind at 65.1 EUR/MWh when LCOE is 71 and 60 EUR/MWh, respectively. The same issue is visible across the entire Baltic zone, as Latvia and Estonia are both expected to encounter a financially detrimental CP of RES electricity in 2030. Particularly, wind CP was calculated to be 46 EUR/MWh in Latvia and 50 EUR/MWh in Estonia in 2033 when LCOE is 71 EUR/MWh; solar CP was estimated at 51–54 EUR/MWh in 2033 when its LCOE is 60 EUR/MWh.

The results are useful for policymakers, as the power system's flexibility should be incorporated within the national strategies in the Baltic States. Innovative strategies can address this problem by increasing market flexibility and re-establishing the financial viability of RES. Various flexibility service providers have the potential to restore the financial profitability of RES projects by increasing the demand for electricity and raising the overall price. Solutions such as energy storage systems with charging and discharging options, electric vehicles with grid-to-vehicle and vehicle-to-grid modes, demand response programs for cost-optimal energy, as well as green hydrogen production at peak electricity generation times, the establishment of expanded electricity export interconnections, and other solutions are essential. Therefore, the main area for future research would be to determine the most effective and economically viable flexibility solutions in the Baltic States.

**Author Contributions:** Conceptualization, P.K.; Validation, S.G. (Saulius Gudzius) and A.J.; Formal analysis, I.K., S.G. (Saule Gudziute) and G.G.; Investigation, P.K., V.B. and G.G.; Resources, A.J.; Data curation, I.K.; Writing—original draft, P.K.; Writing—review & editing, V.B. and S.G. (Saule

Gudziute); Visualization, I.K.; Supervision, P.K. and S.G. (Saulius Gudzius); Project administration, P.K. All authors have read and agreed to the published version of the manuscript.

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