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# Impacts of High PV Penetration on Slovenia's Electricity Grid: Energy Modeling and Life Cycle Assessment

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**Abstract:** The complexities of high PV penetration in the electricity grid in Slovenia based on targets proposed in national energy and climate plan were explored. Scenarios modeled an increase in installation power from 1800 MW in 2030 to 8000 MW in 2050. They were analyzed using energy modeling and life cycle assessment to assess the technical and environmental aspects of high PV grid penetration. The results showed that the increase in PV production from 2200 GWh (2030) to 11,090 GWh (2050) showed an unfavorable course of excess electricity in the system, resulting in the need for short-term and long-term storage strategies and exports of electricity. LCA analysis showed that penetration of a high share of PV results in a decrease in the impact category of global warming, which is higher in 2050 green scenarios that phase out coal and lignite electricity sources (80.5% decrease) compared to the 2020 baseline scenario. The increase in mineral resource scarcity can be observed with an increase in PV share when comparing the 2030 (50%) and 2050 (150%) BAU scenarios with the baseline scenario (2020). Factors such as environmental impacts, technical challenges, and the impact on the grid must be considered when implementing a decarbonization strategy.

**Keywords:** photovoltaic electricity production; sustainable energy system; life cycle assessment; Slovenia; electricity production

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## 1. Introduction

The energy demand is increasing, and the energy generation processes are facing significant challenges such as sustainability, cost, security, and market price fluctuations [1–3]. The production and use of fossil fuels play an important role in global greenhouse gas (GHG) emissions, including $CO_2$. Renewable green energy transitions are crucial to mitigate climate change and reduce GHG emissions [4–6]. Critical technologies in the ascent of renewable technologies are hybrid and sustainable energy systems such as solar, wind, geothermal, and biomass [7]. Deploying large-scale renewable energy (RE) supply in energy systems could be an instrument to reduce emissions from fossil fuels, which is aligned with the United Nations' sustainable development goals (SDGs), especially SDGs for affordable and clean energy [8]. $CO_2$ emission reduction is one of the components of the energy trilemma [1]. The European Union (EU) aims to significantly reduce GHG emissions and become net-zero by 2050. Following the EU agenda, the member states have reformed their energy policy framework to reduce GHG emissions and use cleaner energy. Decarbonizing the energy sector is a crucial action to mitigate global warming [9,10]. It consists of several aspects—energy performance in buildings, energy efficiency, electricity market design, and most importantly, an increase in RES share. [11,12]. The energy system is transitioning from fossil-fuel-based generation sources towards adaptation of RES, including more local and distributed energy generation, with PV at the forefront [12]. At the same time, decarbonization also leads to the electrification of transport and buildings through electric vehicles and heat pumps, which leads to increased energy demand [13]. Although RES are considered sustainable energy sources, their installation presents environmental challenges that can be analyzed using life cycle assessment tools (LCA), quantifying environmental impacts in different categories [2,14,15].

The 100% RES concept is gaining momentum, and several papers on national energy systems powered 100% by RES have been published, focusing on different national systems, including Portugal, Denmark, Japan, Macedonia, Ireland, and Germany [8,16–23]. Most studies find that 100% RES is possible from a technical perspective. Few published studies argue against the possibility of 100% RES systems [24–26]. According to Heard et al., a 100% renewable electricity supply would demand a reinvention of the entire electricity supply-and-demand system to ensure that renewable supplies would be reliable [26]. RES generation includes more predictable non-intermittent hydropower, biomass, geothermal, and intermittent sources, mainly solar and wind power [27–29]. Although intermittent energy sources have advantages in decreasing dependence on fossil fuels and lowering GHG emissions, increased RES in the power grids has introduced new challenges: power system stability, security, and power quality, which must be addressed [27,30]. High penetration of grid-connected PV systems could result in a reverse power flow that could harm the distribution network's safety, dependability, and financial performance, resulting in voltage over-limits and increased power loss [31]. The penetration of RES in distribution networks requires a series of actions in planning and grid operation to ensure optimal utilization of RES. Wind and PV sources are notorious for their volatility, and they can severely affect the stability, security, reliability, and power quality of electric power systems. With an increased share of such RES, balancing the electricity supply and demand is becoming necessary and presents a severe challenge [12]. The transition to RES-based electricity generation challenges sovereignty as it increases demand for regional integration of electricity grids [32]. LCA could play an important role in developing national policies and recommendations, and findings could aid in policy decision-making for national energy sustainability and security [33]. LCA has been used to evaluate the impact of electrical country mixes with different scenarios regarding the introduction of RES in the energy sector in Italy, Spain, Portugal, the UK and Ecuador. The results showed that the effect on global warming is lower in scenarios with a higher share of RES [34–38]; however, to the best of the author's knowledge, there are no available data for Slovenia.

Slovenia committed in 2009 to achieve at least a 25% share of RES in the final energy balance by 2020 and a 39.3% share of RES in electricity generation; however, in 2020, the target value was not reached. The total percentage of RES was 23.5%, and the achieved share of RES in electricity generation was 34.7% [39–41]. EU member and accession countries have drafted and elaborated their 10-year integrated National Energy and Climate Plans (NECP) that will be implemented during 2021–2030 to achieve the EU's declared energy and climate targets [42]. Slovenia published the NECP in February 2020, setting national targets for Slovenia, which were revised in a draft for the updated NECP with new targets set for 2030 [23]. The 2030 targets aim to reduce GHGE compared to 2005 under the Effort Sharing Regulation by 40% and increase the share of renewable sources. Slovenia aims to achieve a 27% share of RE according to NECP targets, and 30–35% according to revised NECP targets with a focus on the higher share of PV [43–45].

The last available report on the energy situation in Slovenia from 2022 showed a decrease in RES electricity generation, with RES having more than 30% share, and the estimated share of RES in total gross final energy use is 23% [46]. The shares of net electricity production sources from 2022 are shown in Figure 1 [47].

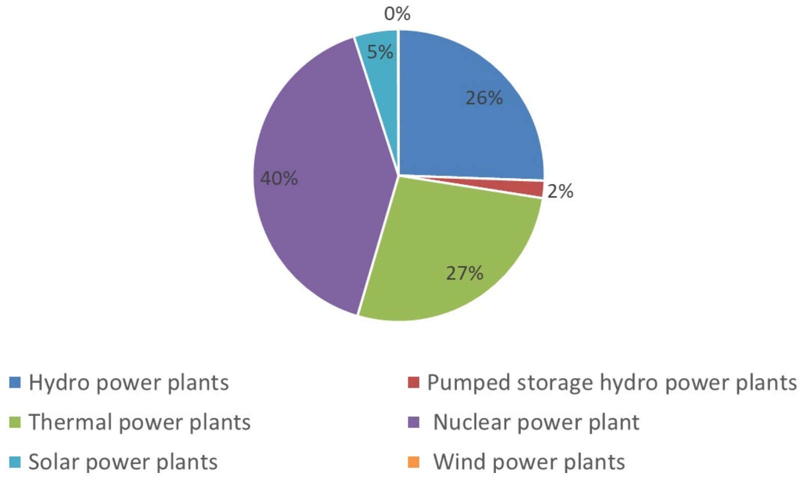


**Figure 1.** Shares of electricity production sources in net electricity generation in Slovenia for 2022 [47].

Primary energy RES in Slovenia are water flows, wood and other biomass energy, and solar irradiation [41]. It is expected that decarbonization will be achieved mainly through the reduction in fossil fuels, as well as incentives and subsidies for RES [48]. Relevant national circumstances regarding the future development of RE arise from environmental restrictions and the fact that numerous unrealized and planned hydro and wind projects are located in the protected Natura 2000 areas, which cover over 37% of all land territory in Slovenia, the largest share in Europe. Due to this, RE targets often come into collision with environmental targets [49]. The highest potential for an increase in RES is photovoltaics (PV) and minor water potential, as it is estimated that 47% of technical water potential is already exploited. Wind energy is considered to be inconsistent for commercial use [41]. The supporting laws and regulations are key factors in investing in the economic feasibility of PV plants. In 2021, over 396 million euros in energy subsidies were allocated in Slovenia. A total of 26% of all energy subsidies were incentives for energy production from fossil fuels and the use of fossil fuels. Subsidizing production from RES significantly increased, as 74% of all incentives were allocated for energy efficiency measures, co-generation, and RES [50]. In previous years, a net-metering system and a feed-in tariff system were established in Slovenia to encourage households to install PV systems [51,52]. The electricity production in 2019 within the subsidies scheme amounted to 947.5 GW, rising by 1% from the year 2018 [48]. In 2020, amendments to the Rules on Support for Electricity Generated from Renewable Energy Sources and High-Efficiency Co-generation were adopted, which introduced obligations for investors to provide adequate insurance for the performance of installations (up to 5%). A Decree on Small Installations for the Production of Electricity from Renewable Energy Sources or Through High-Efficiency Co-Generation also came into force, which specifies that the types of installations for energy production from renewable energy sources and high-efficiency co-generation that do not require a building permit were specified as solar power plants with a maximum power of up to 1 MW, simplifying investing in renewables [48]. On the other hand, in 2024, a new regulation came into effect that abolishes the concept of net-metering for new installations, as well as the requirement that household users be required to pay a network fee for all the electricity derived from the distribution grid, bringing significant changes in Slovenia's network tariffs causing households to wonder about the profitability of investments [51]. The dynamic-price tariff system is planned to be introduced in July 2024, putting customers at the center of the electricity systems and coordinating the grid users and the network to foster more efficient network development [13].

The evaluation of Slovenian national RES potential has predicted total national end-use energy use in 2050 to reach 41 TWh, while the total solar potential is estimated at 25.8 TWh/annually, showcasing the potential for an increase in the utilization of solar power [53]. The increase in the use of solar energy is regarded as one of the most effective approaches to reducing $CO_2$ emissions. However, its intermittent nature challenges its reliability. This could be partly solved by power storage, geographic dispersion, load control, and the implementation of forecasting algorithms. The challenges of significant impacts on solar energy grid integration remain [54] due to overvoltages and voltage unbalance in the distribution network [55].

Several studies have investigated the impact of the predominant share of RES on power systems. The principal investigative lines related to the high share of distributed renewables in power systems are:

- Stability challenges in smart grids [56,57]
- Smart grids and renewable energy sources [58]
- Smart grid technology [59]
- Artificial intelligence with Blockchain distributed technology is used as a tool for studying renewable energy and related power automation [60]
- Bio-inspired optimization applications in renewable-powered smart grids [61]
- Changes in consumer behavior in case they purchase distributed solar photovoltaics and/or electric vehicles [62]
- Storage challenges and optimization [63]
- Data management related to consumer behavior [64].

An assessment of the feasibility of 100% RES power systems must include an analysis of both their long- and short-term reliability. An important aspect of PV installations is that their electricity consumption is mostly during hours of low consumption, while in hours of high consumption, the electricity production of the PV installation is low. Due to this, a mismatch of production and consumption occurs, which can result in oversized installations and electricity curtailments [65]. In the short term, technical limitations may result in power plants being unable to ramp quickly enough to keep supply and demand in balance, leading to challenging grid parameters. Additionally, some years can be less sunny in the long term, meaning that photovoltaic installations cannot be relied upon to produce the same amount of electricity each year [66]. In a 100% RES power system, any residual demand that variable RES does not power, must be provided by dispatchable RES generation technologies or storage [67], which can increase the environmental footprint [68].

Energy system models are used to analyze national energy systems and predict potential future scenarios [69]. Using energy system modeling with hourly energy modeling enables optimized use of technologies reflecting their resource complementarity and storage options hour-by-hour in current energy systems and possible future energy system scenarios [8]. A tool most commonly used for evaluating systems with high shares of RES is EnergyPlan [19,70–72]—other available tools, such as DynEMo. E4Cast, ENSYSI, ESME, IKARUS, and MARKAL are reviewed in the article by Fattahi et al. [73].

Several studies have been published on national systems with a high share of distributed renewables and an analysis of the situation. The literature review shows a gap in the available data for hourly analysis of different scenarios with high penetration of PV small energy systems that are location-constrained, such as the Slovenian electro-energetic system. At the same time, there is no available data on the environmental impact of Slovenian electricity decarbonization scenarios from the LCA perspective.

The research aims to simulate the Slovenian national energy system hourly with the modeling tool EnergyPlan and present the challenges of a high share of PV in the mix. The difficulties expected for a power system with a high share of distributed renewables with low annual equivalent operating hours will be presented and discussed. The National Energy and Climate Plan (NECP) 2030, 2040, and 2050 scenarios will be modeled. The challenges when the share of distributed renewable resources represents most of the final energy use will be discussed, and the impact of excess power in the system will be presented.

The second aim of the research is to assess the environmental impact of introducing a high share of distributed RES in the power system using LCA to determine the environmental impact of an electricity mix containing a high share of PV. NECP 2030, 2040, and 2050 electricity generation scenarios with a larger deployment of PV and decreased production from non-renewable primary sources will be investigated, and the environmental impact assessment results will be presented. The research roadmap is presented in Figure 2.

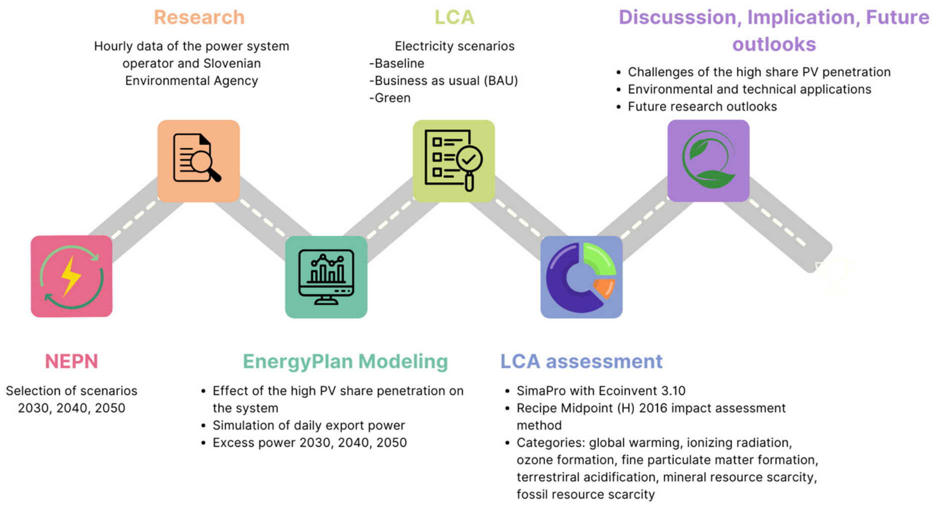


**Figure 2.** Research roadmap.

The study provides valuable insights into the technical aspect of high PV penetration in the electro-energetic system in Slovenia and its environmental impact, which can provide valuable information for future policy and strategy planning.

## 2. Materials and Methods

### *2.1. Research Roadmap*

The research has followed steps that are shown in detail in Figure 2 and further explained in Sections 2.2 and 2.3:

1. Selection of scenarios based on targets and data from NECP
2. Energy system modeling with EnergyPlan
3. LCA of electricity generation scenarios
4. Interpretation of the results

### *2.2. Analysis of the Power Systems*

Software EnergyPlan was used as a tool for analyzing energy systems. EnergyPlan is a system commonly used to analyze energy systems with a high share of RES. It simulates the operation of national energy systems on an hourly basis. The Sustainable Energy Planning Research Group develops it at the Aalborg University (Denmark) [72,74]. Hourly data of the system operator of the electric power system [75,76] and the Slovenian Environmental Agency were used for the hourly analysis of the system [77].

The next step was assessing the required energy to mitigate the excess energy and evaluating the additional required RE to achieve the same share of RE in the final energy use. A comparison of capacities between different energy sources and their impact on the socio-economic acceptability of an individual path to achieve carbon neutrality was performed.

The excess power expected based on the scenarios from valid NECP [43,78] and a further increase in installed renewables to the level where PV generation would reach up to 9 TWh in 2050 with an expected final energy use of 41 TWh was simulated with EnergyPlan modeling tool. The scenarios that will be evaluated are:

- 2030 scenario: by 2030, an installation power of PV is 1800 MW and production of electricity is 2200 GWh
- 2040 scenario: by 2040, an installation power of PV is 5000 MW and production of electricity is 6160 GWh

- 2050 scenario: by 2050, an installation power of PV is 8000 MW and production of electricity is 11,090 GWh

*2.3. Life Cycle Assessment of the High Share of Photovoltaics in the Electricity Production*

Life cycle assessment (LCA) is a methodology regulated by the 14040 and 14044 ISO standards that allows the quantification of the potential environmental impact of products, processes or activities through the whole life cycle stages The functional unit of the assessment used was 1 kWh of low-voltage supply on the grid. The software SimaPro and Ecoinvent 3.10 database were used for modeling. Ecoinvent is a comprehensive life cycle inventory database [35,79]. The LCA analysis has four main steps: definition of the goal and scope of the study, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation [35].

This LCA uses Ecoinvent data about electricity generation in Slovenia to report environmental data about the impact of producing 1 kWh of electricity in Slovenia. For the calculation of environmental impacts, the ReCiPe midpoint method was used. On the whole, Slovenia has three major primary energy sources: nuclear energy plants, hydroelectric power plants and thermal power plants.

The study's main goal is to evaluate and compare the potential environmental impact of the different electricity production mix scenarios for Slovenia, as described below. The second goal is to assess and interpret the results of this study based on the energy and decarbonization strategies highlighted in the NECP.

Eight scenarios were considered for the evaluation of Slovenian electricity production. The first group is business as usual (BAU) scenarios that retain production from other sources and increase production by photovoltaics for 2030, 2040, and 2050 scenarios. The second group considered are green scenarios that model an increase in photovoltaics and a decrease in fossil fuel sources for 2030, 2040, and 2050 projections. In total, eight scenarios were modeled:

1. Baseline 2020 scenario: Total production of electricity is 16,289.6 GWh. PV share of electricity is 2.6%.
2. BAU 2030 scenario: Total production of electricity is 18,121.6 GWh. PV share of electricity is 12.1%.
3. BAU 2040 scenario: Total production of electricity is 27,001.6 GWh. PV share of electricity is 27.9%.
4. BAU 2050 scenario: Total production of electricity is 18,121.6 GWh. PV share of electricity is 41.1%.
5. Green 2030 scenario: Total production of electricity is 16,289.6 GWh. PV share of electricity is 13.5%. The scenario considers a 45.7% decrease in the production of electricity from lignite compared to the baseline scenario.
6. Green 2040 scenario: Total production of electricity is 17,282.8 GWh. PV share of electricity is 35.6%. Compared to the baseline scenario, the scenario assumes phasing out electricity production from lignite by 2040.
7. Green 2050 scenario with nuclear power plant in operation: Total production of electricity is 22,212.8 GWh. PV share of electricity is 49.9%. Compared to the baseline scenario, the scenario assumes phasing out electricity production from fossil-based fuels.
8. Green 2050 scenario with phased out nuclear power plant (NPP) by 2050: Total production of electricity is 16,146.4 GWh. PV share of electricity is 68.7%. Compared to the baseline scenario, the scenario assumes phasing out electricity production from fossil fuels and closing down nuclear power plant by 2050.

This LCA uses primary data about the net electricity generation in Slovenia in the different scenarios (BAU, Green). Secondary environmental data (that generally are previously published data about the unit impacts generated by the processes) are derived from the Ecoinvent Database 3.10. The environmental data retrieved from the Ecoinvent Database 3.10 consider different types of plants (and reactors, in the case of nuclear) for producing electricity (thermal, nuclear and renewable) to represent all the types of available plants in

Slovenia. Secondary data have also been used for the electricity generation in Slovenia to assess the impacts of the 2030, 2040, and 2050 scenarios modeled by Dimnik et al. [44] and the Slovenian NECP report [43]. System boundaries are cradle to grave for the different electricity generation systems (thermoelectric, nuclear, and renewable) and include raw material extraction and fuel supply, construction and plant operation, end-of-life disposal for thermoelectric plants, hydroelectric, solar PV, and wind power plants.

## 3. Results and Discussion

### *3.1. Simulation of the Daily Import and Export of Photovoltaic Power*

The simulation of the daily import and export of photovoltaic power using the EnergyPlan presented in Figure 3. shows the need to import and export electricity for the system's 8000 MW of photovoltaic power plants on a summer day. The production from solar power plants is below 20% of the final energy use. The excess energy that must be exported during daylight exceeds the need for energy, which must be imported during darkness. The results showcase the known challenge of the volatility of PV penetration and its supply variability, as seasonal and daily fluctuations may not be aligned with power demand. To cope with this, the electricity grid will require significant backup capabilities in the form of dispatchable power or energy storage and the necessity for storage in the form of pumped hydro storage, batteries, and hydrogen storage. Another possibility is storage on the demand side, conversion to synthetic hydrocarbons and smart energy systems. Costs and electricity generation predictions are important concerns when choosing between different dispatchable power sources and other flexibility options [67].

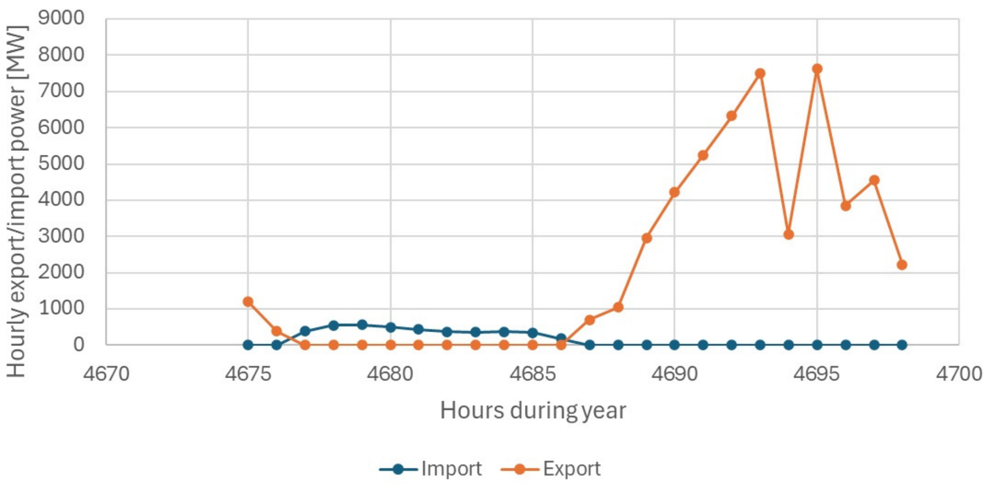


**Figure 3.** Hourly simulation of daily import–export power on a typical summer day.

In the case of reliance on cross-border electricity exchange, high fluctuations in electricity prices can be expected, which could be mitigated only by storing surplus electricity or making long-term electricity purchases. Dimensioning the production of a temporary carrier to the capacity that is reached for a few hours a day in a few months of the year is not economically justifiable. In producing synthetic temporary energy carriers, all energy conversions needed to have adequate energy available in time must be considered. Excess energy (Figure 4) must be evenly distributed by short-term storage to optimize the plant's capacity for converting electricity into a temporary carrier or, if the final energy is used as hydrogen or synthesis gases, the capacity for synthesized gases. Another option is electricity system integration with neighbors, as it would be easier to cost-effectively satisfy the flexibility needs of RES-based energy systems [32]. The Slovenian grid is strongly interconnected with neighboring grids, with a physical capacity that exceeds the peak demand for electricity from the grid. If neighboring grids would operate in a coordinated manner, neighboring countries without significant production capacity on the domestic grid could be drawn. Market coupling would also reduce commercial risks for professional investors in RE development [32].

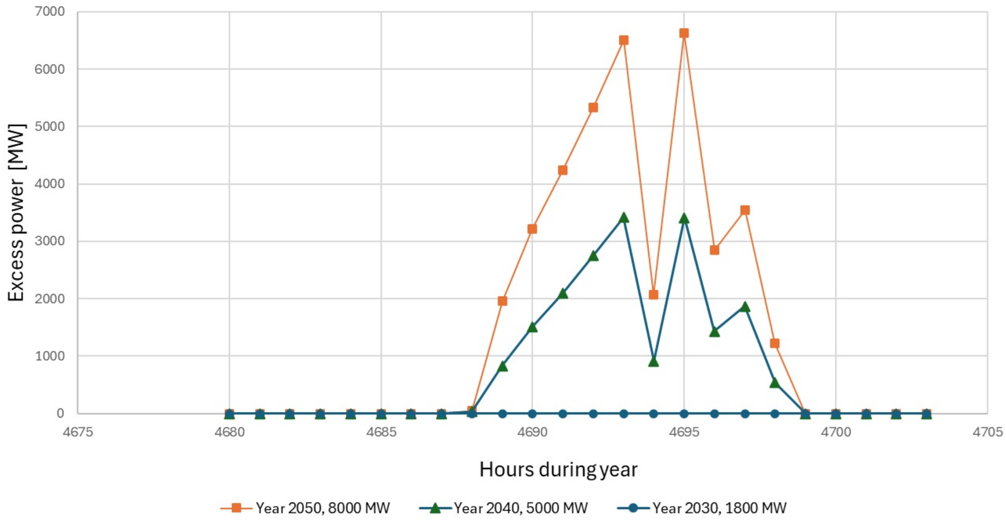


**Figure 4.** The year 2030, 2040, 2050 Excess power based on installed PV power on a typical summer day.

### 3.2. Simulation of Excess Power of the Photovoltaic System

Solar power is a RES with the highest public acceptability [80], and solar system installation subsidies have been available [51]. Public acceptance favors photovoltaics in Slovenia, while other renewables either lack sufficient natural endowments (wind power) or are not acceptable to the public [81]. However, a higher percentage of photovoltaics can be applied if excess energy can be stored or exported to neighboring systems. The excess power resulted from an increase in installed renewables with PV generation of 9 TWh by 2050; final energy use is expected to be 41 TWh.

The simulation results of the situation in the power system showed a somewhat unfavorable course of excess electricity in the system with the increase in the installed PV power due to the direct link between the production of electricity from the sun and the sun irradiation and the modest connection between solar irradiation and the electricity demand. As a result, the need for short-term, daily, and long-term annual storage of electricity is significant. Short-term storage requires capacities that exceed the capacities of hydropower pump plants and, given the high share of energy from distributed sources in final energy use, also available cross-border capacities. This can be solved by increasing import dependency or by converting excess electricity into a temporary energy carrier that can be stored long-term. Similarly, Bonilla-Campos et al. modeled energy scenarios with the integration of high-share RES for Spain, and the three analyzed energy scenarios returned extensive periods in which the energy generation exceeded the expected energy requirements of the Spanish grid even with the assumptions of a synchrony on the integration of the expected imports/exports and the expected storage scenarios. Two techno-economic approaches are proposed to balance the grid needs—thermal storage in thermally retrofitted plants and reversible hydrogen plants [82].

The challenge of high values of excess electricity in the Slovenian grid could be solved by renewable sources, such as pumped-hydro storage plants, which coincide more with the electricity demand. As the future growth of variable RES will require short- and long-term storage alternatives, the coordination of intermittent power systems with hydropower can improve efficiency and economy. Utilizing a pumped-hydro storage system can improve supply reliability in both the energy and water sectors [83–85]. Although water-based RES have promising potential, considering the severity of negative environmental impacts, hydroelectric power plants are found to be the most hazardous amongst all RES [86]. Further penetration of hydropower in Slovenia collides with environmental targets, as 37% of Slovenia's territory is in Natura 2000 [49].

Further increasing the share of photovoltaics to 100% of final energy use exhausts export capacities and natural resources for hydro storage of surplus electricity. Only short-term, intra-day, and long-term, seasonal storage of surplus electricity remains available in the country. Short-term storage with batteries has a relatively good efficiency comparable to storage in hydropower plant basins. Currently, the only pumped storage hydropower plant in Slovenia (Avče) is sufficient for the limited amount of RES electricity through 2030. Due to an expected rapid increase in electric energy storage demand, it is anticipated that the new pumped storage hydropower plant will have to be installed; however, according to the NECP, the increase in the installed hydropower will be modest (3%) [87]. The daily storage capacity required is expected to reach 10 GWh by 2040, which exceeds the current and planned pump hydro storage capacity of the country's hydro reservoirs. In this case, the share of photovoltaics does not reach half of the electricity end-use, and the share in total energy end-use is even lower [44]. Given Slovenia's central location in Europe, PV in the country has relatively modest annual equivalent operating hours, and the country does not have sufficient natural potential to store surplus energy in hydroelectric basins. Self-sufficient energy production with photovoltaic systems cannot be achieved because snow covers the panels during the winter and shuts down the energy production [88]. Conventional RES such as hydropower are exposed to extreme weather events, such as drought, which can impact electricity production [68,89].

Other long-term storage measures would need to be exploited, such as improving the functionality of the hydropower plants or converting surplus electricity into a temporary energy carrier, such as hydrogen or green synthetic hydrocarbon, with the possibility to use the temporary carrier directly in the final energy use or to convert it back into electricity [87,90]. Integration of local PV panels with hydrogen cells has been suggested; however, from an economic point of view, such systems are accessible for commercial use due to the high cost of hydrogen storage tanks [91]. In the production of synthetic temporary energy carriers, all energy conversions need to have adequate energy available in time, which must be considered. Excess energy from the figure (Figure 4) must be evenly distributed by short-term storage to optimize the plant's capacity for converting electricity into a temporary carrier or, if the final energy is used as hydrogen or synthesis gases, the capacity for synthesized gases. Additionally, storage systems to resolve the supply intermittency of RES can result in a higher environmental footprint than fossil power plants [68,92].

Currently, PVs annual equivalent operating hours are just over 1000 h. If a fossil source with up to 8000 equivalent yearly operating hours is to be replaced, PVs capacity must be up to 8 times higher than the fossil source that has been abandoned. As long as the capacity of PV in the system is lower than the capacity of fossil resources dedicated to system services, we do not observe any significant impact of distributed renewable sources on the energy system. As the PV capacity of the system grows, there are two choices [44]:

- either conservation of some of the fossil resources used to provide system services and exporting the surplus energy or storage of the surplus energy
- or reduction in fossil energy generation and leave system services to other generation sources.

When decarbonizing the national energy system, it is assumed that PV power plants will generate most of the electricity. In the case of a territorially small country such as Slovenia, the high generation of all distributed PV resources does not allow the spatial distribution of PV to improve the excess power scenario in Figure 4. The prevailing decarbonization with a one-of-a-kind resource, which mainly operates in accordance with solar irradiation and has low equivalent annual operating hours, should be avoided, as this results in high values of excess electricity, which results in extensive measures to control excess energy. Another aspect is the supply security concerns of operating electricity systems based on fluctuating RE [32,93]. Recently, Thaler and Hofmann (2023) highlighted the energy policy trade-offs that countries that expand RE production and are part of cross-border electricity systems are facing. They established the concept of an impossible energy trinity, noting that many states cannot simultaneously achieve energy security, sustainability, and sovereignty [32]. Countries must contend with several interdependencies. If a country produces ever higher amounts of fluctuating renewable electricity, it remains dependent on neighboring countries to provide electricity balancing [94]. According to Thaler and Hofmann (2023), the countries have three options to cope with the challenge of intermittent electricity productions [32]:

1. To base or reserve electricity-generating capacity from non-sustainable sources (non-sustainable);
2. To accept system stability risk and/or higher electricity prices (insecurity);
3. To cede control over domestic energy rules to pursue integration with neighboring electricity grids and markets (non-autonomous).

### *3.3. LCA of Electricity Production Scenarios*

Figure 5 shows the share of electricity production sources in the LCA-modeled scenarios. The share of electricity produced in 1 kWh is shown. In BAU scenarios, only PV production increases, resulting in a higher share of PV in the 1 kWh of electricity produced in Slovenia. In green scenarios, along with an increase in PV, a decrease in fossil fuel sources is modeled, with the phasing out of lignite power plants in 2040 and 2050 green scenarios.

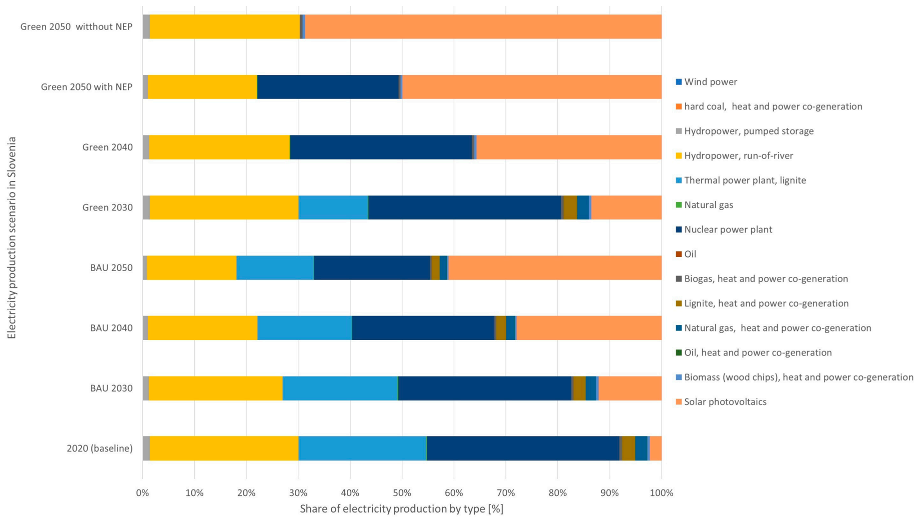


**Figure 5.** The share of electricity production sources in modeled scenarios.

The life cycle impact assessment results for the categories considered are presented in Table 1. In total, eight scenarios were modeled following NECP targets. The plans to increase the share of PV are underway and have been highlighted as NECP scenarios expect that RES will account for 27% of the total energy use. Decarbonization will be achieved through the reduction in fossil fuels, incentives, and subsidies for non-conventional energy sources. The foreseen steps are a reduction in coal electricity use by 30% by 2030 and phasing it out by 2050 [48].

The impact on category global warming decreases by introducing a higher share of PV in the system. If the production follows the BAU scenarios with only PV increasing while the other sources remain the same, the reduction achieved will be 30.3% by the year 2050. In the green scenarios, the values decrease by 80.5% compared to the baseline 2020 scenario due to the phasing out of coal and lignite. A study by Gárcia-Gusano et al. demonstrated that an increase in PV in Spain resulted in a lower global warming potential of 61.7% or 86.4% based on the 2014 baseline, depending on the scenarios selected—BAU or an 80% reduction of $CO_2$ by 2050 with respect to 2005 levels [95]. An LCA study of the electricity generation of French overseas territories showed that the territories with a higher share of fossil energy had a higher impact on global warming. French Guyana had the lowest global warming impact due to its high share of RES [96].

**Table 1.** Lifecycle impact assessment for categories considered for Slovenian electricity production scenarios (1 kWh of produced electricity).

| Impact Category | Unit | Baseline 2020 | BAU 2030 | BAU 2040 | BAU 2050 | Green 2030 | Green 2040 | Green 2050 | Green 2050 without NPP |
|---|---|---|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | 0.3626 | 0.3345 | 0.2899 | 0.2526 | 0.2361 | 0.0663 | 0.0706 | 0.0687 |
| Ionizing radiation | kBq Co-60 eq | 0.2635 | 0.2375 | 0.1960 | 0.1614 | 0.2626 | 0.2482 | 0.1945 | 0.0083 |
| Ozone formation, Human health | kg NOx eq | 0.0009 | 0.0008 | 0.0007 | 0.0006 | 0.0006 | 0.0002 | 0.0002 | 0.0002 |
| Fine particulate matter formation | kg PM2.5 eq | 0.0020 | 0.0018 | 0.0015 | 0.0013 | 0.0012 | 0.0003 | 0.0003 | 0.0002 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 0.0009 | 0.0008 | 0.0007 | 0.0006 | 0.0006 | 0.0002 | 0.0002 | 0.0002 |
| Terrestrial acidification | kg $SO_2$ eq | 0.0062 | 0.0057 | 0.0048 | 0.0040 | 0.0038 | 0.0007 | 0.0007 | 0.0005 |
| Mineral resource scarcity | kg Cu eq | 0.0004 | 0.0006 | 0.0008 | 0.0010 | 0.0006 | 0.0010 | 0.0012 | 0.0014 |
| Fossil resource scarcity | kg oil eq | 0.0787 | 0.0729 | 0.0637 | 0.0560 | 0.0525 | 0.0153 | 0.0166 | 0.0168 |

Although PV causes negligible environmental impacts during the use phase, other phases, particularly manufacturing, entail environmental burdens [97]. An increase in the impact categories of mineral resource scarcity and land use can be observed. In BAU scenarios, the increase in the category of mineral resource scarcity is 50% in 2030 and 150% in 2050 compared to the 2020 baseline scenario, which can be attributed to the necessary material acquisition and consumption of metals in the construction phase [34]. In the case of green scenarios, where the share of PV in the system is even higher, the impact on mineral resource scarcity is higher than in BAU scenarios, which can be attributed to the higher share of PV in the production mix, which reaches 68.7% in the case when fossil fuel electricity production is phased out and nuclear plants are closed down. The last scenario is theoretical and does not align with the notion of increased self-supply, as shutting down nuclear power plants would result in the need to import more electricity, especially as electricity use is expected to rise in the next few years due to the electrification of transport and heating.

The phasing out of coal and lignite electricity sources in the green scenarios results in lover values for impact category fossil resource scarcity. The decrease from 0.08 kg oil eq. in the baseline to 0.17 g oil eq in the green 2050 scenario, can be observed. The decrease in fossil resource impact was also observed in a study conducted by Ghisellini et al. (2023), where "cleaner electricity mixes" in Italy were assessed [35]. The results demonstrated that fossil resource scarcity and global warming impacts can be reduced by substituting coal-based electricity generation [98], which is in agreement with results from our study, where an 80.5% reduction in global warming was observed when the 2020 baseline scenario and the green 2050 scenario with nuclear power plants were compared. Due to the higher share of PV in the BAU scenario, a 35.5% reduction in the terrestrial acidification impact category was observed in the BAU 2050 scenario compared to the 2020 baseline scenario. The reduction was higher in green electricity scenarios due to the modeled phasing out of fossil fuel sources, with an 88.7% decrease in the green 2050 scenario compared to the 2020 baseline scenario. The reduction in acidification and eutrophication, as well as ozone layer depletion, was observed in an LCA study of electricity mix in Portugal due to the installation of desulphurization and denitrification in coal power plants, as well as the phase-out of large fuel oil power plants [37].

The decrease in freshwater eutrophication can be observed when comparing BAU and green scenarios. The decrease is higher in green scenarios than BAU due to the phasing out of coal power sources. A higher decrease in green scenarios is also observed in the impact categories of fine particulate particle formation and ozone formation, as the main contribution is associated with coal and lignite power plants [34]. The decrease in ionizing radiation is the highest in green scenarios without nuclear power plants, as the main contributor to the impact category is nuclear power plants [34].

The decarbonization scenarios result in lower environmental impacts in most categories, notably global warming. However, decarbonization faces several challenges and costs when transitioning to low-carbon technologies and infrastructure, developing necessary infrastructure, and gaining strong political will and commitment from governments and other actors. Technological limitations are still significant challenges, not least with the intermittency of most RES and the challenges of the storage of surplus energy [99]. Among RES, there are multiple competing factor: land use for bioenergy, health and safety risks of nuclear waste disposal from decommissioning of nuclear power plants, as well as power price rise from hydropower during drought and power supply/price instability due to RES supply intermittency. The land requirement for GHG capture and sequestration to achieve net zero differs between electricity technologies, which can be measured by soil organic carbon sequestration analysis (SOC). Recently, Sadhukhan (2022) analyzed different electricity generation options, showing the differences between the systems in terms of the additional land needed. The RES system options would need 0.19–2.57 $m^2$ (based on 280 kg $CO_2$ sequestration per Ha forest) for neutralizing GHG from 1 kWh electricity generation, lowest for hydro run-of-river, highest for geothermal, followed by their GWP ranking [68].

## 4. Conclusions, Implications, and Future Outlooks

The energy transition requires a reduction in GHG emissions through decarbonization. For Slovenia, the most viable option for increasing the RES share in the system is solar PV, with a total solar potential estimated at 25.8 TWh/annually. The introduction of solar PV can be an effective approach to reducing $CO_2$ emissions. It is also the approach that public acceptance favors. This study modeled scenarios with a high share of PV in the Slovenian national energy system, where electricity production from PV rises from 2200 GWh in 2030 to 11,090 GWh in 2050. The simulation results of the situation in the power system showed an unfavorable course of excess electricity in the system with the increase in the installed PV power due to the direct link between the production of electricity from the sun and the sun irradiation and the modest connection between solar irradiation and the need for electricity, resulting in the need for short-term and long-term storage of electricity.

National, EU, and IRENA guidelines put increasing PV share at the forefront of decarbonization measures. From a technical perspective, increasing the share of PV has a beneficial effect on the system parameters. PV reduces peak demand during daylight hours and reduces the need to operate fossil sources, either coal or gas, which have traditionally covered peak demand. Further increases in the PV share (2050 scenario with 8000 MW installed power) result in the need to reduce the operation of other renewables, increase exports at economically unfavorable times of the day, ensure adequate storage capacity, or a combination of these. While this impacts the economics of such an approach, in technical terms, such a system is still manageable.

The LCA of electricity production scenarios was conducted to assess the environmental impact. With the increase in PV in BAU scenarios, the reduction in impact category global warming by 2050 is 30.3% and 80.5% in the green scenarios compared to the 2020 baseline scenario. The higher decrease in the green scenarios can be attributed to the phasing out of coal and lignite electricity production sources. This is also the reason for a decline in the impact category of fossil resource scarcity. Although PV causes negligible impacts during the use phase, the increase in PV results in higher values for the impact category of mineral resource scarcity, which increases when the share of PV in electricity production increases. With the advancement in research on End-Of-Life, the possibility of PV recycling could reduce the impact in this category. To achieve a net zero GHG energy system, soil organic carbon sequestration analysis (SOC) should also be considered, as it considers the land required to neutralize residual GHG from electricity generation systems, further showcasing the trade-offs between electricity mix/technology in different scenarios.

Several factors should be considered for sustainable net-zero transitioning, including environmental, technological, and socio-economic factors. Among them, electricity use, electrification of mobility, technology mix, resource availability, energy storage, environmental impact, economic consideration, social impact, grid integration, infrastructure development, and policy and regulation will have to be taken into account to maximize benefits and minimize trade-offs. This paper looks forward to the next turning point, when PV exceeds demand, export capacity, and hydro storage, with constraints in hydro storage, exports, and the need to store surplus energy in liquid or gaseous energy carriers. Very low efficiencies would force further increases in the capacity of distributed renewables and the installation of additional storage capacities, which in sub-optimal solutions can result in a shift away from the primary goal of carbon neutrality.

Further research work will include the development of new scenarios, which will be based on state-of-the-art technical developments and evaluated with LCA, as well as the analysis of socio-economic indicators, which are important aspects of just and green transition.

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