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The Role and Impact of Rooftop Photovoltaics in the Norwegian Energy System under Different Energy Transition Pathways

Stine Fleischer Myhre and Eva Rosenberg*

This study focuses on investigating the impact and cost-competitiveness of solar power in a highly hydropower-driven northern energy system. The goal is to assess the role of rooftop photovoltaics (PV) in the Norwegian energy system toward 2050 under different energy transition pathways. Energy system analysis is conducted using the IFE-TIMES-Norway model, with an integrated detailed representation of rooftop PV based on the tilt and azimuth of existing rooftops in Norway. A thorough sensitivity analysis is conducted to illustrate how investment in rooftop PV varies under different system and parameter conditions and to disclose important barriers for PV in similar energy systems. The results show that when PV investments are facilitated, solar power can potentially stand for 56% of all new investments, resulting in a share of 10% of the total electricity generation. With less competition from onshore wind power and favorable investment parameters, especially lowering the demand for the rate of return, the investments in PV will be four times higher and reach their full potential in commercial and apartment buildings by 2050. Additionally, the results highlight that the cost parameter functions as a barrier to other solutions that facilitate increased PV investments, such as flexibility and energy storage.

1. Introduction

Renewable energy sources play a vital role in the ongoing transition to a low-emission society with reduced reliance on fossil energy sources. One of the most common and increasingly popular renewable energy sources is solar power, which accounts for a great share of renewable capacity worldwide.[1] The same trends are seen in Northern Europe.[2] However, since the amount of solar irradiation is limited in the Northern Hemisphere, solar power has not yet taken a large share of the total electricity production in some of the Nordic countries.[3] Norway has an almost entirely renewable-based electricity generation mix, highly dependent on hydropower.[4] Similar to many other countries, Norway is facing a future with uncertainties concerning power balance and the grid due to increased electrification.

Increased integration of renewable energy sources and solar power can have a positive impact on the energy system in terms of more local generation. Local generation is beneficial to limit the pressure of new transmission grid infrastructure. To further reduce the pressure on the energy system and optimize utilization, energy awareness of end-users is also important. With energy efficiency measures, increased self-consumption, or demand-side management, the pressure of the grid can be lowered and unfold opportunities for increased electrification of other sectors. Rooftop photovoltaics (PV) is a popular option for renewable energy sources in the end-user sector due to low maintenance and fast implementation time. Another advantage of rooftop PV is the ability to utilize existing building structures, hence limiting the impact on nature and area usage.[5] In addition, the technical potential of rooftop PV is large due to the high number of buildings in modern society.[6] However, since the end-user controls this potential, it is hard to facilitate a large deployment of rooftop PV. It is therefore important to investigate barriers and opportunities for increasing the technoeconomic feasibility of rooftop PV at the end-users.

In,[7] a review of barriers regarding building integrated PV is addressed. Since the systems are similar, many barriers are also applicable to rooftop PV. Here, barriers such as feed-in tariff implementation, public acceptance, lack of economic support and subsidies, and technical aspects are highlighted as common barriers. Similar barriers including cost and capacity of PV are also pointed out in[8] where a review of modeling of energy scenarios is conducted. This is supported by[9] where different energy transition pathways are investigated and compared. However, rooftop PV is not a focus of these studies. In,[10] a review of the future zero-emission energy system is conducted. Here, the cost of PV is also highlighted as one of the driving factors for increased PV penetration in the energy system. Furthermore, in,[11] a meta-analysis is conducted to investigate the adaption of residential PV.

S. F. Myhre, E. Rosenberg
Department of Energy System Analysis
Institute for Energy Technology (IFE)
Instituttveien 18, 2007 Kjeller, Norway
E-mail: stine.myhre@ife.no

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/aesr.202400184.

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DOI: 10.1002/aesr.202400184

A major concern of high penetration of PV in the distribution grid is the possibility of grid instabilities.[12] Solutions for assessing grid stability have been discussed in the two-part review[12,13] where demand side management is an important solution. This includes optimizing demand and generation and utilizing flexible assets such as energy storage systems. Both demand–response and increased end-use flexibility can accelerate investment in PV due to demand shifting, resulting in better demand and solar generation profiles.[14] Multiple studies have investigated the technoeconomic feasibility of PV and energy storage systems,[15] showing an increased value of residential PV when including energy storage systems. A self-sustaining off-grid energy system in northern climates is assessed in.[16] The system consists of a PV generation system, but to be self-sustained, an energy storage system is needed. Additionally, the paper points out the struggle with off-grid systems for northern climates to sustain the winter months. A similar off-grid solar energy system is investigated in[17] for a residential community in the Middle East. A technoeconomic analysis was conducted to investigate the performance of the system. The result of the study concludes that energy storage is necessary to sustain an off-grid operation. Similar results are presented in,[18] where an optimum design of a hybrid off-grid system based on solar power is investigated. Decoupled from the main grid, the studies aim to meet the entire system demand, indicating the need for large storage solutions to handle the peak hours and seasonal variations in solar power. In,[19] the impact of peak net load is investigated for energy systems with high penetration of PV and energy storage, showing that high penetration of PV shifts the peak net load hour to the evening. Additionally, the study investigates cases with a higher frequency of peak load hours during the summer, resulting in a system with high penetration of PV, shifting the peak load hours to winter time. This situation is similar to the conditions for regions in the Northern Hemisphere where the peak hours normally occur during the winter. In the study, energy storage is pointed out as a major contributor to the efficient utilization of high PV penetration.

Furthermore, there are multiple studies that investigate the feasibility of PV for local systems. In,[20] an optimization model is applied to minimize the cost of a PV and energy storage-based system for a household. Others have investigated optimal solutions for PV in residential urban areas,[21] optimization for solar PV and energy storage solutions in an energy community,[22] and PV-based microgrids.[23] The common solution is to optimize either based on minimizing cost or optimal utilization, usually in combination with energy storage systems. Additionally, some studies have focused on investigating the technoeconomic performance of PV from a system perspective. In,[24] a technoeconomic performance study is performed on a grid-connected renewable energy system including solar power on an island in Norway. Here, the HOMER software is utilized to simulate and analyze the technoeconomic performance. The study concludes that an energy system consisting of multiple renewable energy system sources could meet the demand of the island and ensure a reliable electricity supply. A similar study was conducted in[25] for Turkey, where HOMER is also utilized to perform the technoeconomic performance.

Few studies conducting energy system analysis focus on a detailed representation of rooftop PV in terms of the tilt and azimuth of existing rooftops combined with solar conditions in the northern hemisphere. Energy system analysis with correct representation for Nordic countries is important to not overestimate the solar power potential and to optimize the solar PV systems.[26] By including a detailed representation of rooftop PV in the energy system analysis of Norway, the role and impact of rooftop PV can be investigated. Using simplifications of rooftop PV modeling will result in overestimation of the solar potential of the Northern Hemisphere.[27] Additionally, studies have shown that tilt and azimuth affect greenhouse gas[28] reduction. By representing the different building categories with their technical potential, the impact of each building sector can be highlighted.

The literature is missing an exclusive focus on the role of rooftop PV in the future energy system for conditions similar to regions in the Northern Hemisphere that are highly hydropower-driven. Typically, energy systems in the Northern Hemisphere have high demands during winter when solar irradiation is low. An example of this is shown in **Figure 1** where the monthly demand and PV generation from Norway are illustrated.[29] This proposes a mismatch between the peak demand and the peak PV generation, lowering the utilization of PV generation when the demand is high. However, as discussed, solar power is an important measure to become zero-emission and could play a central role in the electrification of society. To increase the technoeconomic feasibility of PV in similar energy systems a thorough analysis is necessary to uncover the barriers and investigate how to improve the utilization of PV. This paper focuses on rooftop PV from an energy system perspective. To account for more representative modeling of rooftop PV without overestimating the technical potential, a detailed representation of rooftop PV accounting for tilt and azimuth is modeled in the energy system model in this study.

This paper aims to investigate the role of rooftop PV in the Norwegian energy system toward 2050. This is conducted through energy system analysis by utilizing the energy system model IFE-TIMES-Norway. The model is improved with more detailed modeling of rooftop PV based on calculations of the technical potentials for rooftop PV for different tilts and orientations. The energy system modeling is conducted by investigating two different sociotechnological energy transition pathways. In addition, a thorough sensitivity analysis for investigating the

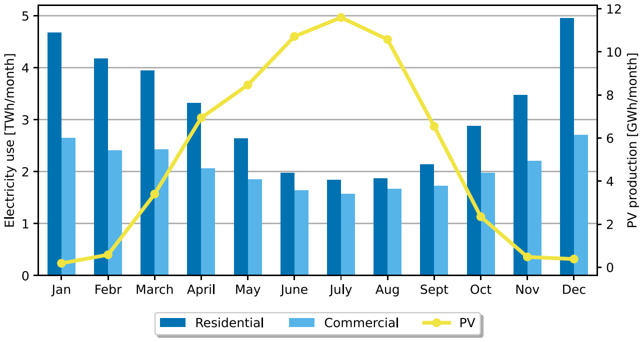

Figure 1. The monthly demand for residential and commercial buildings compared to the total PV production in Norway. The data is collected from Elhub, the Norwegian power industry's central IT system for the distribution of measured values and processing of market processes.[29]

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impact and cost competitiveness of rooftop PV in the Norwegian energy system under different transition pathways is conducted. The future energy transition pathways demonstrate two scenarios, one with low technology and socioinstitutional change and one with high technology and socioinstitutional change. A sensitivity analysis is conducted to illustrate the sensitivity of rooftop PV under different system and parameter conditions, such as investment cost, changes in grid fee, and new or limited potential for other energy sources. The paper highlights barriers and opportunities to increase the feasibility of rooftop PV for similar energy systems in the Nordic Hemisphere with a more detailed representation of the technical potential of rooftop PV. We aim to answer the following research questions: 1) How cost-competitive is rooftop PV in a hydropower-driven energy system in the Northern Hemisphere based on different future transition pathways? 2) How will rooftop PV impact and which role might it have in hydropower-driven energy systems in the Northern Hemisphere toward 2050? 3) How sensitive is the investment in rooftop PV to different system and parameter conditions and what are the key barriers to facilitating more PV?

The paper is structured as follows. Section 2 presents the energy system modeling, the energy transition pathways, and the approach for calculating the technical potential of rooftop PV. In Section 3, the results from the energy system analysis and sensitivity analysis are presented and discussed before the work is concluded in Section 4.

2. Methodology and Approach

This section will describe the methodology and approach used in this analysis. The methodology is divided into three main parts. First, the approach for calculating the input data to the energy system model is described. In this study, we have used a PV-design model (Helioscope) to first calculate the area potential of rooftop PV in Norway, described in Section 2.1. The performance of the rooftop PV is further calculated by utilizing the Photovoltaic Information System (PVGIS) tools, as described in Section 2.3. Based on this and an estimation of future building areas, the aggregated Norwegian technical potential is calculated. The second part of the methodology describes the utilized energy system model, IFE-TIMES-Norway, and the modeling approach for further improving the energy system model by integrating the calculated area potential for rooftop PV in Norway into the energy system model. This is described in Section 2.4. The integration of the area potential for rooftop PV in Norway is conducted to heighten the detail level of PV modeling in the energy system model and ensure more reliable results. The stepwise approach can be seen in **Figure 2**. The third part of the methodology describes the applied energy transition pathways and the sensitivity analysis and is presented in Section 2.5.

2.1. Technical Potential for Rooftop PV in Norway

This study has utilized a detailed modeling approach to highlight the effects of tilt and azimuth on the technoeconomic feasibility of rooftop PV in Norway. To accomplish a detailed representation of rooftop PV, we conducted a thorough analysis of the area utilization of Norwegian rooftops within eight different building categories.[30] The eight investigated building categories are commercial (COM) buildings, agriculture (AGR), industry (IND), warehouses, multifamily houses (MFH), single-family houses (SFH), garages, and leisure homes. An overview of the approach is presented in Figure 2. To facilitate the area utilization analysis, a detailed database regarding the Norwegian building stock is used to estimate the potential of PV on existing roofs. This database includes information about the roof area, azimuth, tilt, location, and building category. In the study, the rooftops have been distributed based on the location following the five bidding areas in Norway (NO1-NO5, see Figure 6) and the mentioned building categories. Furthermore, the rooftops are divided based on tilt and azimuth. Eight different azimuths, North, North–East, East, South–East, South, South–West, West, and North–West, and four different tilt categories, 10° (flat roofs), 20°, 30°, and 40°. The potential for PV on facades is not included in this study.

To account for areas inaccessible to PV panels, the technical potential is calculated by estimating the area utilization of the

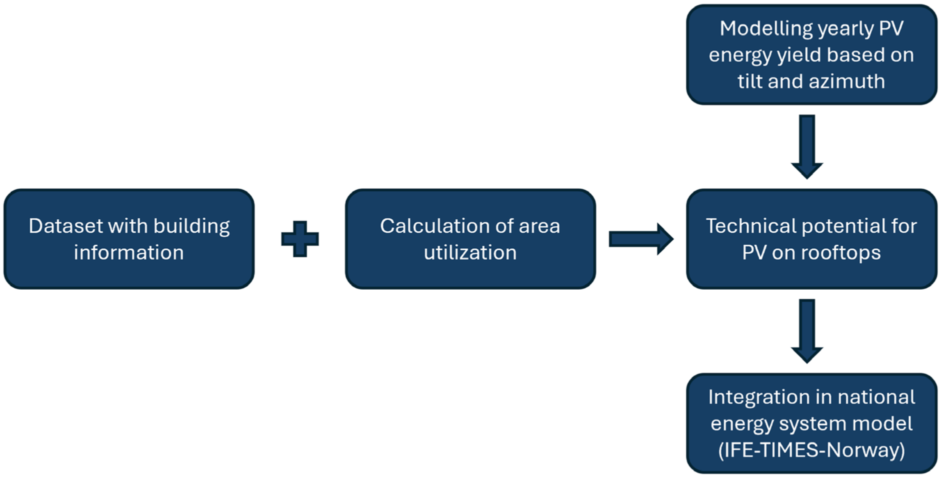

Figure 2. Overview of the approach for calculating the technical potential for rooftop PV in Norway and the integration in the national energy system model, IFE-TIMES-Norway.

rooftops in each building category. The total area utilization has been found by mapping the number of PV panels that technically can be installed based on the available rooftop area. The approach accounts for structures on the rooftop and spacing regulations. Since the dataset does not include any information regarding structures on the rooftops, a designing tool named Helioscope is used to calculate the area utilization since the tool gives an overview of the rooftop structure. Helioscope is a commercial software for planning PV panel layouts on buildings.[31] Since the dataset contains over five million buildings and the area utilization approach requires investigations of individual rooftops, a clustering methodology based on statistical information about each building category is used to select representative rooftops for investigation. The selection process is performed randomly based on statistical information on tilt and rooftop area for the buildings in each category. Rooftops with areas and tilts that are more frequent in the given building category have a higher probability of being selected for investigation. ≈20 buildings for each category were investigated.

The calculation of area utilization starts by adding a given building to Helioscope. Here, the roof area can be drawn, structures on the roof can be excluded, and specifications related to PV panel size and spacing can be added. This gives the available roof area for the placement of PV panels. An example is illustrated in **Figure 3**. The light blue area shows the boundary of the rooftop whereas the orange areas illustrate excluded construction on the rooftop. The dark blue rectangles show the placement of PV panels which together make up the total technical potential for PV panels on that given rooftop.

This procedure has been performed for all the investigated rooftops in a given building category. The total area utilization for a given building category was based on an average of the individually calculated area utilizations. Here, conservative estimates have been used to account for errors in the calculation. The estimated area utilization was further used to calculate the technical potential for PV panels for each building category

$$P_{\text{ins}} = A \cdot U \cdot \rho \tag{1}$$

where A is the sum of the area for all the rooftops in a given building category, U is the total area utilization for the given building category, and ρ is the energy density of the solar panels. The area utilization result and the technical potential for rooftop PV based on existing and future building stock can be seen in **Table 1**.

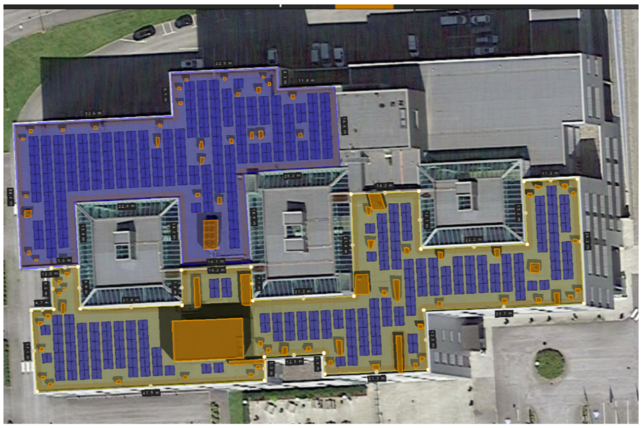

Figure 3. Example of rooftop with marked roof area in blue, solar panels, and excluded roof structure in orange.

Table 1. Overview of the area utilization, technical potential, and energy yield for the eight different building categories for existing rooftops in Norway including the change in 2050 when the future building stock is included. The values inside parentheses represent the change in the technical potential and energy yield due to the future building stock changes in 2050. More details can be found in ref. [30].

Area utilization	Capacity [GWp]	Generation [TWh year^{-1}]
30%[a)]	14 (16.4)[a)]	9.4 (11)[a)]
30%[b)]	1.8 (2.8)[b)]	1.2 (1.9)[b)]
60%[c)]	7.1 (8.3)[c)]	4.8 (5.6)[c)]
30%[d)]	3.9 (4.6)[d)]	2.6 (3)[d)]
30%[e)]	4.5 (5)[e)]	3 (3.4)[e)]
60%[f)]	2.3 (2.6)[f)]	1.6 (1.8)[f)]
30%[g)]	1.9 (2.1)[g)]	1.3 (1.5)[g)]
55%[h)]	9.1 (10.2)[h)]	6.1 (6.8)[h)]
–	44.6 (52)[i)]	30 (35)[i)]

[a)]SFH. [b)]Multifamily house. [c)]Garage. [d)]Leisure homes. [e)]COM. [f)]Warehouses. [g)]IND. [h)]AGR. [i)]Total.

2.2. Effect of Future Building Stock Changes on the Technical Potential

An estimation of the future building stock is considered in the study to include possible new potential of rooftop PV. The future building stock area is calculated based on the main alternative of population growth by Statistics Norway.[32] Important parameters derived from historical evolution used in the estimation of the future building stock are presented in **Table 2**. In situations where the building category diverges between the dataset, average parameters are used. An example is the commercial building category, which is an aggregation of multiple other building categories such as office buildings and schools. Here, average values for all subcategories are used to estimate the future increase in building stock for that given building category.

The calculation of future building stock results in increases in areas of 17% in single-family housing, 55% in multi-family housing, and 12% in commercial buildings and industry. The roof area is assumed to increase at the same rate as the building area, meaning that we assume a constant relationship between the roof and the building area. Thus, the technical potential for rooftop PV increases with a similar factor for each of the building categories. How this affects the technical potential for rooftop PV in 2050 can be seen in Table 1 (the numbers in the brackets).

2.3. Modeling of the Rooftop PV Energy Yield Based on Tilt and Azimuth

The hourly rooftop PV performance is simulated with the PVGIS tool (version 5.2) based on PVGIS-ERA5 solar irradiation

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Table 2. Parameters used for estimating future building stock areas of single-family, multi-family, and commercial buildings in 2020, 2030, and 2050.[32]

SFH	MFH	COM buildings
0.7% per year[a]	0.7% per year[a]	0.5% per year[a]
2% per year[b]	2% per year[b]	2% per year[b]
180 m^2/dwelling[c]	95 m^2/dwelling[c]	1.9 m^2/capita in avg.[c]
2.00[d]	2.00[d]	–
38.5%[e]	61.5%[e]	–
5.4 mill[f]	5.4 mill[f]	5.4 mill[f]
5.7 mill[g]	5.7 mill[g]	5.7 mill[g]
6.0 mill[h]	6.0 mill[h]	6.0 mill[h]
273[i]	4[i]	111[i]
290[j]	58[j]	117[j]
312[k]	72[k]	124[k]

[a] Demolition rate. [b] Renovation rate. [c] Area. [d] Number of persons per dwelling. [e] Share of new dwellings. [f] Population 2020. [g] Population 2030. [h] Population 2050. [i] Are mill. m^2 2020. [j] Are mill. m^2 2030. [k] Are mill. m^2 2050.

database (2005–2020).[33] PVGIS-ERA5 is chosen as the solar irradiation data due to its performance for northern latitudes where geostationary satellites have a reduced accuracy due to satellite angles and snow.[34]

As a basis for the yearly yield of the rooftop PV, a standard PV system consisting of a fixed tilt mounting solar system based on Cryst-Si module technology with 14% fixed losses and nominal power of 1 kWp is assumed. The investigated tilt angle and azimuth are based on the building stock characteristics as described in Section 2.1. The geographical locations are based on the largest city in each bidding area. Oslo for NO1, Kristiansand for NO2, Trondheim for NO3, Tromsø for NO4, and Bergen for NO5. In the data postprocessing, the energy yield data is normalized to represent capacity factors in each representative day. The normalization is performed by dividing the energy yield by the nominal power and averaging the hourly data within each meteorological season. Examples of capacity factors based on tilt angle and azimuth can be seen in **Figure 4** and **5**, respectively for some given tilts and azimuths. The calculated capacity factor time series is used as an input in the energy system analysis.

2.4. Energy System Modeling

This study utilizes energy system analysis to investigate the role of rooftop PV in the Norwegian energy system under different energy transition pathways. The analysis is performed using the Norwegian energy system model, IFE-TIMES-Norway, developed by our team based on the IEA-ETSAP tool TIMES. This model is further developed in this study, with more detailed modeling of PV rooftop systems, representing different orientations and tilts as presented previously in this section. IFE-TIMES-Norway is a linear programming model to analyze the long-term development of the Norwegian energy system.[35] As presented in **Figure 6**, the geographical scope of the model is Norway (incl. offshore wind power), which is divided into five regions representing the corresponding bidding areas (NO1-NO5). The model assumes perfect foresight within the years and perfectly competitive markets, providing investment decisions from 2018 to 2050 divided into 5 year periods from 2020 to 2050. The operational decisions in the model are captured by dividing the periods into 96 time slices where each meteorological season (fall, summer, spring, and winter) is represented by one day of 24 h. The model captures the interplay between sectors, trade between regions and neighboring countries, technologies, energy carriers, and emissions and has a detailed implementation of end-use divided into buildings, industry, and transport. The electricity spot prices in the bidding areas in Norway are endogenous, as those are the dual values of the electricity balance equation, while the electricity prices in the neighboring countries with transmission capacities to Norway are exogenous.

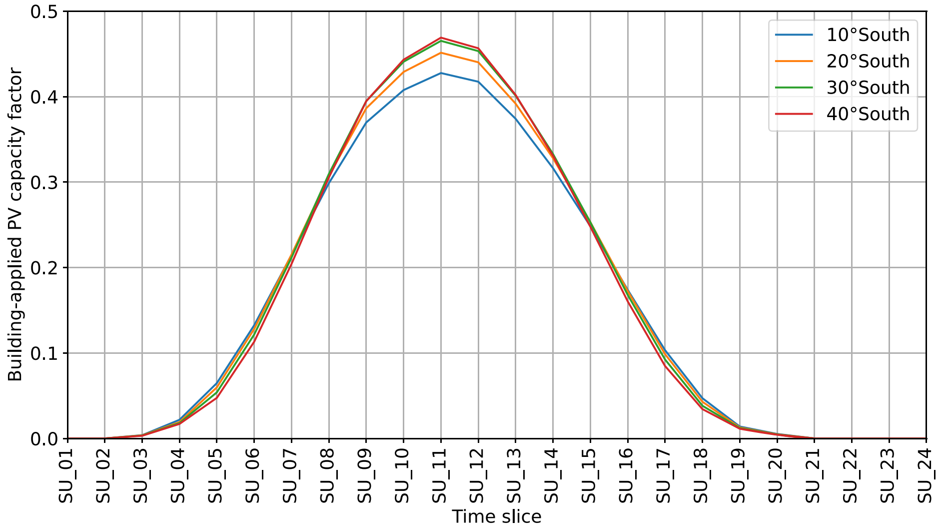

Figure 4. Example of capacity factors for solar irradiation based on tilt illustrated for summer in south orientation.

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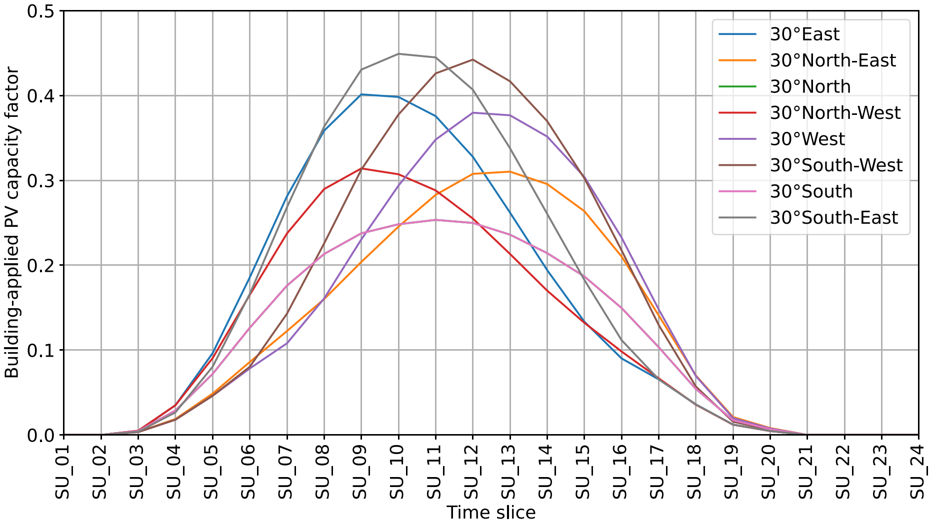

Figure 5. Example of capacity factors for solar irradiation based on azimuth illustrated for summer with a tilt of 30°.

The electricity generation implementation includes offshore wind, onshore wind, rooftop PV, solar PV parks, and regulated and run-of-river hydropower. Additionally, the model considers the possibilities of hydrogen, thermal storage, district heating, and energy storage. The cost assumptions regarding rooftop PV systems are based on the practices from PV installations in Norway prepared by Multiconsult[36,37] and are presented in **Table 3**. Furthermore, the cost of rooftop PV system on SFH includes a value-added tax (VAT) of 25%. The future costs are estimated based on the development of large-scale solar PV as presented by IEA in.[38] In this regard, the PV capital expenditures (CAPEX) are assumed to decrease by 42% between 2020 and 2030 and by 57% between 2020 and 2050. The fixed operational expenditures (OPEX) are assumed to be 0.5% of the CAPEX based on.[36,39] A detailed description of the model (including the technology cost assumptions) is presented in the IFE-TIMES-Norway documentation report.[35] Exchange rates for monetary values are retrieved from European Central Bank statistics[40] and are used to convert costs to the base year of 2020, with an average exchange rate of 10.7 NOK/€.

2.5. Scenario Description

To evaluate the role of rooftop PV in the Norwegian energy system, two different future transition pathways are applied. The transition pathways are based on the NTRANS socio-technical pathways as presented in.[41] In this study, the role of rooftop PV is investigated by utilizing the Incremental Innovation pathway (INC) and the Radical Transformation pathway (RAD). The difference between the two scenarios is that INC involves very limited discontinuity and is less challenging for incumbents. The RAD scenario, however, comes with a high degree of discontinuity and reflects a transition pattern with a high transformation of system architecture and institutions to fit the properties of novel core and architectural technologies. RAD is interpreted with a lower energy service demand with high flexibility, less central energy production, high technology learning rates, and a focus on local/national solutions with no new energy transmission and no net import of bioenergy. INC focuses on central energy production and unlimited trade of electricity and biofuels, with continuous increases in energy service demand without a focus on flexibility and with low technology learning rates. A selection of important parameters for the two scenarios is presented in **Table 4**. To increase understanding of the result, an explanation of the energy transition pathways is given.

2.5.1. Explanation of the Future Transition Pathways

Power generation: In Norway, the development of onshore wind power is highly debated based on environmental concerns and this is reflected in a low acceptance of new wind power in RAD and a high acceptance in INC. Thus, the maximum potential for onshore wind in the RAD scenario only consists of already existing wind power and wind power projects currently under construction. No new onshore wind is allowed. The high acceptance in INC results in a high maximum potential based on wind power applications[35] (See Table 4).

The high offshore potential in RAD is based on the Norwegian target of 30 GW by 2040, while in INC, only half of this potential is assumed due to lower technology development. In RAD, high technology learning is a condition and the investment cost of offshore wind power is reduced by 39% from 2020 to 2050 for bottom-fixed and by 49% for floating wind power plants. In INC, the low technology learning only reduces the investment cost by 21% and 30% respectively.

Transmission grid: The focus on local and Norwegian solutions in RAD results in assumptions of no new national or international transmission capacity. The assumption is rooted in the focus on protecting nature, as well as prominent regionalization with less global collaboration. In INC, there are no limits on neither national nor international transmission capacities. The grid power fee is expected to increase by 80% until 2050 while the grid energy tariff only increases by 5%. The self-consumption

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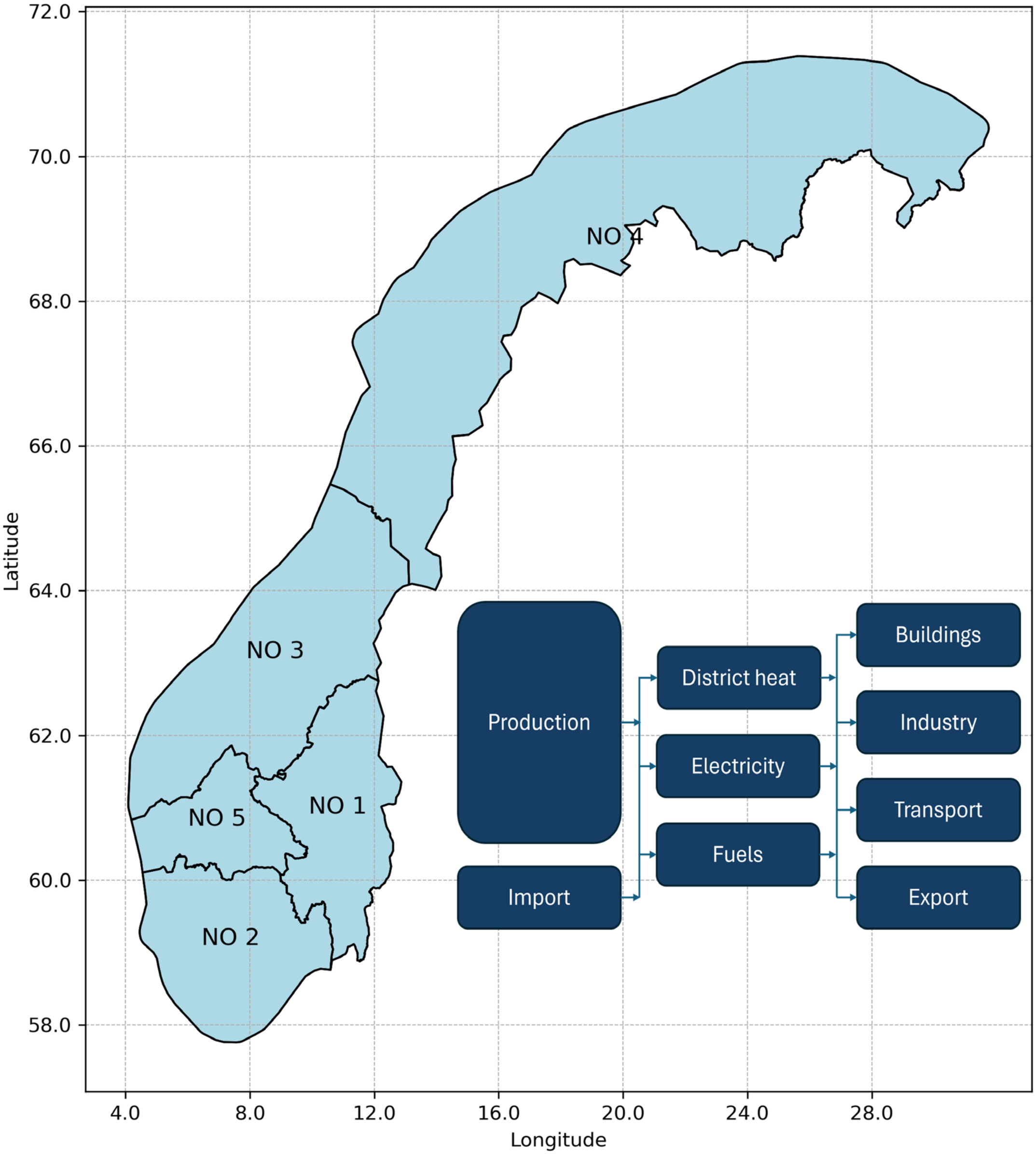

Figure 6. Geographical coverage and topology of the IFE-TIMES-Norway model with longitude and latitude including the five bidding areas in Norway (NO1-NO5) and the sector coupling. The boundaries of the bidding zones also include islands and offshore regions.

share of rooftop PV is important as the generated electricity that is not consumed by the building is sold to the grid. This results in added grid tariffs. The self-consumption is assumed to vary with season as the electricity use is typically high during winter and lower during summer when the production is higher in Norway (see **Figure 7**). In households, an average of 59% is used by the dwelling, divided into 96% during the winter, 64% in spring, 26% in summer, and 48% in fall. For commercial buildings, the average is 88% for all seasons but summer, where 50% of the produced electricity is used in commercial buildings.

Energy service demand: Energy service demand is an exogenous input to IFE-TIMES-Norway and in INC it assumes that the present trends continue to 2050, with little attention on energy efficiency or general reduced consumption. The energy service demand of all end-use sectors but petroleum increases, while the oil and gas extraction and belonging onshore industry decrease to 1/3 of the present level, in line with the official projections.[42] RAD has a constant development in the onshore industry and a total phase-out of oil and gas extraction by 2050. Energy efficiency plays an important role in RAD, resulting in a decrease in energy service demand in buildings of 19% despite increased building areas. In RAD, transport demand is decreasing and a modal shift from individual to public transport takes place for passenger transport and from road to sea and rail for freight transport.

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Table 3. Assumed capital, fixed operational expenditures, and lifetime of rooftop PV systems for different building categories in Norway until 2050. The OPEX is fixed at 0.5% of the CAPEX cost.[35]

SFH	MFH	AGR	IND and COM
495 € kW^{-1}[a]	889 € kW^{-1}[a]	889 € kW^{-1}[a]	889 € kW^{-1}[a]
869 € kW^{-1}[b]	514 € kW^{-1}[b]	514 € kW^{-1}[b]	514 € kW^{-1}[b]
646 € kW^{-1}[c]	383 € kW^{-1}[c]	383 € kW^{-1}[c]	383 € kW^{-1}[c]
0.5%[d]	0.5%[d]	0.5%[d]	0.5%[d]
30 years[e]	30 years[e]	30 years[e]	30 years[e]

[a] CAPEX 2020. [b] CAPEX 2030. [c] CAPEX 2050. [d] Fixed OPEX. [e] Lifetime.

Table 4. Selected characteristic parameters of the NTRANS scenarios RAD and INC. All numbers provided for 2050 or 2050 relative to 2020. For more information, see ref. [41].

	RAD	INC
Power generation		
Onshore wind	< 5 GW	< 15 GW
Offshore wind	< 32 GW low cost	< 16 GW high cost
Rooftop PV	< 41 MW	< 41 MW
PV parks	No	No
Transmission grid		
New grid investment	No new	Yes, no limits
Grid energy tariff (average season regions)	5.3 € MWh^{-1}	5.3 € MWh^{-1}
Grid power tariff (average)	50.7 € kW^{-1}	50.7 € kW^{-1}
PV self-consumption	59% in dwellings	59% in dwellings
	88% in COM	88% in COM
Energy service demand		
IND	0%	31%
Buildings	−19%	5%
Road transport	−10%	37%
Oil and gas extraction	Zero extraction	−63%
Flexibility		
EV charging	Peak shaving 90%	No
Electric water heater	Peak shaving 30%	No
Stationary batteries	Yes (low cost)	Yes
Other		
End-use technology (incl. rooftop PV) discount rate	4%	10%
CO2 fee	400 € tCO2^{-1}	400 € tCO2^{-1}
Biofuel	Norwegian resources	Unlimited (141 € MWh^{-1})
Electricity trade prices	Medium[43]	Higher and more volatile[43]

Flexibility: Another characteristic of RAD is a high demand flexibility. Here, the possibility to change the electric vehicle charging by allowing a peak power variation of ±90% per hour and a moving of up to 30% of the daily power demand for electric hot water heating are included.

Other specifications: The high degree of behavior changes and citizen involvement in RAD is modeled as a lower rate for investments in end-use technologies compared to INC.

Norway is a country rich in bioenergy resources and in RAD it is assumed that these resources must be enough to supply the Norwegian use of different biomass-based products in total. Thus, no net import of biofuel, biogas, bio coal, or biomass is allowed in RAD, in contrast to INC that has unlimited volumes of bioenergy products available.

Another important exogenous input to IFE-TIMES-Norway is the electricity trade prices with neighboring countries. A medium price set based on a bidirectional linking with the power-marked model EMPIRE[43] is applied in RAD and a high price set with more volatile prices is applied in INC.

2.5.2. Sensitivity Analysis Description

Some of the discussed parameters for the two scenarios are varied in the sensitivity analyses. An overview of the parameter variations is presented in **Table 5** and **6** for both scenarios. The parameter variations vary slightly between the INC and RAD due to their differences in concept. The sensitivity analysis is divided into three main topics, power generation, cost and grid tariff, and demand-side management. For power generation, the largest difference is the limitation of new onshore and offshore wind power and the inclusion of PV parks. Investment in solar parks is set to start in 2030, here the cost is 280 € kW^{-1}.[35] For cost and grid tariff sensitivities, the conducted changes in investment cost and power and energy tariffs are equal for both scenarios. Here, a double price of the energy and power tariff means that the basis value of the energy and power tariff as seen in Table 4 is doubled. This results in a high increase in the grid tariffs. A constant power tariff means that the power tariff stays constant on the price from 2020 and does not increase toward 2050 as it does in the scenario basis. For reduced investment costs, three cases are applied as seen in Table 5 and 6. A high number of cases is included to investigate possible breaking points of investments for the two scenarios. Additionally, for INC, a case with a reduced hurdle rate is included.

Demand side management includes increased or decreased flexibility To investigate the effect of flexibility on rooftop PV investments, the opportunity for flexibility is removed in RAD. In addition, an increased flexibility solution is added. Here, an increased opportunity for electric vehicle chairing at work is added. This is also applied to INC. To investigate the effect of self-consumption, a reduced self-consumption rate is applied at 50% for all categories.

3. Results and Discussion

3.1. Transition Pathways Scenario Results

The total electricity generation mix for Norway toward 2050 is illustrated in **Figure 8** for the Incremental transition pathway and in **Figure 9** for the Radical transition pathway. The figures divide the different electricity generation technologies, the total electricity demand, and the net electricity import to the country from 2020 to 2050. There are clear differences in the energy mix

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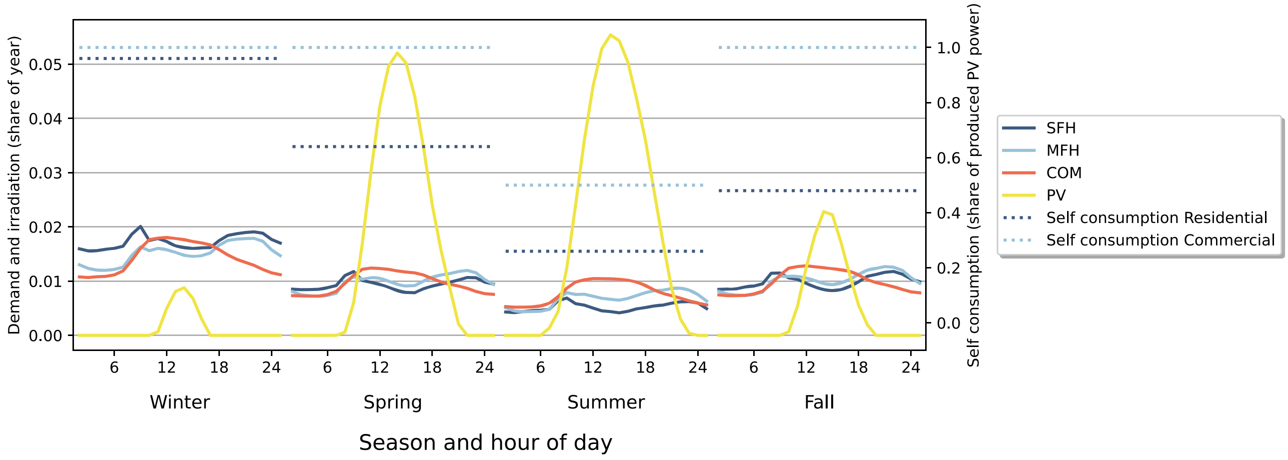

Figure 7. The daily seasonal electricity demand for SFH, MFH, and COM buildings against the solar irradiation and self-consumption of the residential and commercial buildings.

Table 5. Sensitivities for INC scenario.

Sensitivity	Description	Name
Energy generation	Allow investments in PV parks	PV park
	Double investment cost of wind power	InvCost wind
	No new offshore wind power	No new wind
Power and energy tariff	Double energy tariff	Double power fee
	Constant energy tariff	Constant energy fee
	Double power tariff	Double power fee
Investment cost	10% reduction	InvCost-10
	25% reduction	InvCost-25
	50% reduction	InvCost-50
Investment cost, power, and energy tariff	10% reduction in investment cost + double power tariff	InvCost + Power fee
	10% reduction in investment cost + double energy tariff	InvCost + Energy fee
Flexibility	Allow for flexibility	Flex
Self-consumption	Less self-consumption of PV (50%)	Own PV
Hurdle rate	Reduced hurdle rate of PV (4%)	Hurdle rate 4%

Table 6. Sensitivities for RAD scenario.

Sensitivity	Description	Name
Energy generation	Allow investments in PV parks	PV park
	Allow new investment in wind power	New wind
Power and energy tariff	Double energy tariff	Double power fee
	Constant energy tariff	Constant energy fee
	Double power tariff	Double power fee
Investment cost	10% reduction	InvCost-10
	25% reduction	InvCost-25
	50% reduction	InvCost-50
Investment cost, power, and energy tariff	10% reduction in investment cost + double power tariff	InvCost + Power fee
	10% reduction in investment cost + double energy tariff	InvCost + Energy fee
Flexibility	No flexibility	No flex
	Increased flexibility	Flex
Self-consumption	Less self-consumption of PV (50%)	Own PV

between the two transition pathways. Firstly, in the INC scenario with low social and technical development, the electricity demand will increase by over 40% toward 2050 and stabilize at below 190 TWh year^{-1}. This increase in demand is mainly met by high investment in offshore and onshore wind generation. Additionally, due to no limitations in investments in the new transmission grid, the export (shown as a negative import) to other countries increases by over 300%. In the INC scenario, the investment in rooftop PV accounts for only 2% of the total electricity generation in 2050 compared to wind that accounts for over 36%. The higher investment in wind compared to rooftop PV is a result of allowing new investment in onshore wind and the high discount rate for end-use technologies such as PV technology. This result illustrates the price sensitivity of the technologies and the competition between wind and solar power.

Figure 10 illustrates the investment of rooftop PV distributed based on the different building categories, AGR, COM, SFH, MFH, and IND compared to the technical potential. When investigating only investments in rooftop PV for the INC scenario, the differences are more explicit as seen in Figure 10. The largest investment in rooftop PV occurs in COM followed by MFH, but only a marginal investment occurs before 2040. No

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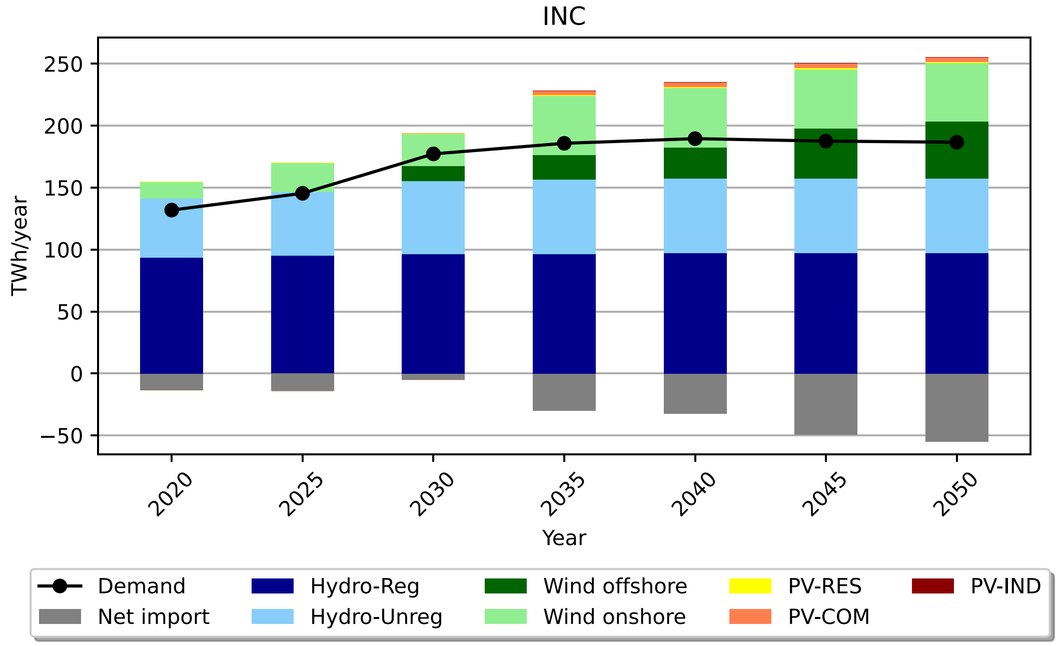

Figure 8. The electricity mix for the incremental energy transition pathway. PV-RES is rooftop PV in the residential sector, PV-IND is rooftop PV for industry, and PV-COM is rooftop PV in commercial buildings.

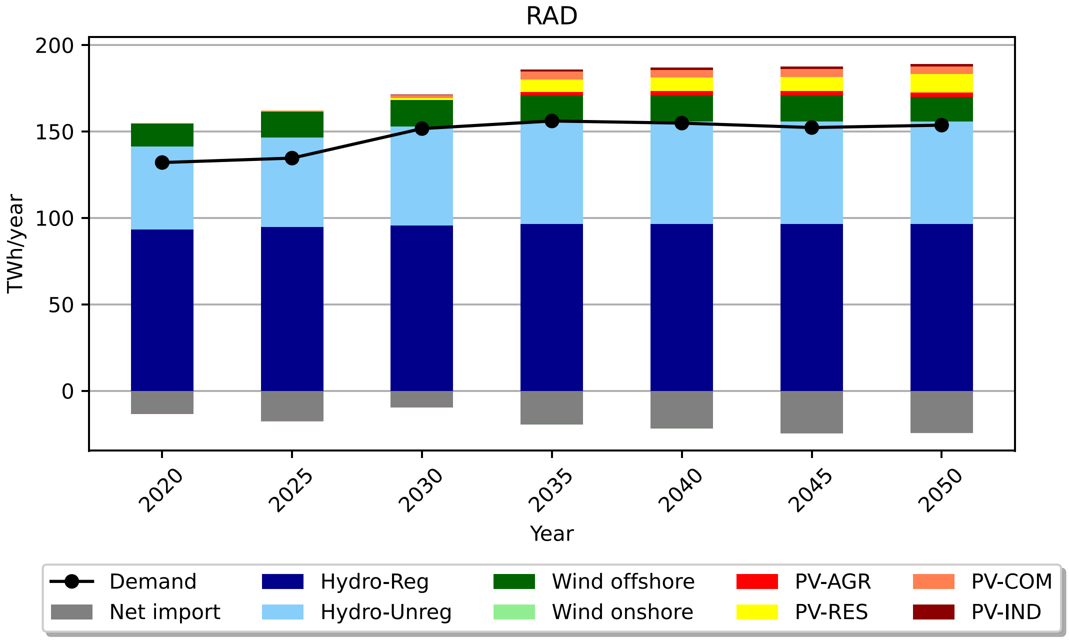

Figure 9. The electricity mix for the radical energy transition pathway. PV-RES is rooftop PV in the residential sector, PV-IND is rooftop PV for industry, PV-AGR is rooftop PV in agriculture, and PV-COM is rooftop PV in commercial buildings.

investment occurs in SFH and AGR. The reason for this is the combination of the added discount rate, relatively low self-consumption as seen in Figure 7, and the additional VAT for SFH increasing the investment cost compared to the other building categories. Additionally, rooftop PV is more beneficial in COM due to a greater match between generation and demand resulting in increased self-consumption as seen in Figure 7. For MFH, rooftop PV is beneficial to reduce the total energy demand. In 2050, the investment of rooftop PV in COM and in MFH will reach 76% and 78% respectively of available capacity.

In the RAD scenario, no new onshore wind or transmission is allowed. This can be seen by no investment in onshore wind and

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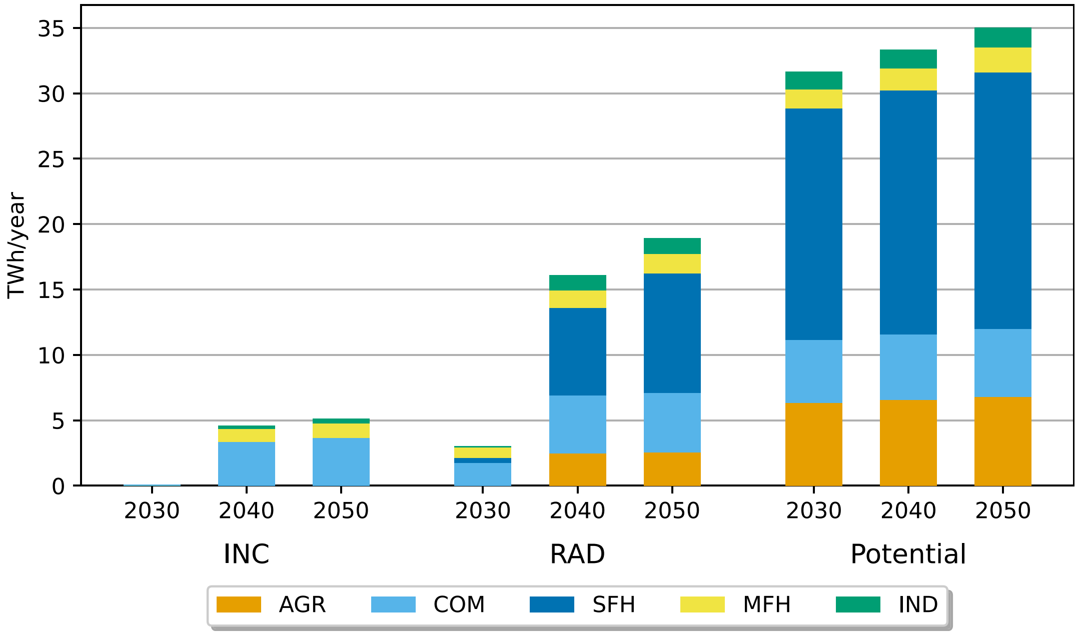

Figure 10. The distribution of rooftop PV investment based on building category compared to the technical potential for each building category.

lower exports. Additionally, the total electricity demand is lower, only increasing by 16% and stabilized at a little over 150 TWh year^{-1}. Concerning new generation, offshore wind and rooftop PV are used. Total new generation from offshore wind power and rooftop PV stands for 18% of total generation (excluding hydropower). Here, 44% is from offshore wind and 56% from rooftop PV, resulting in PV standing for 10% of the total electricity mix in the Norwegian energy system in 2050. This is a significant increase compared to the INC scenario. Additionally, rooftop PV now has a considerably larger role in the energy system and is the most attractive technology for new investments. This effect illustrates the importance of price and the competition between rooftop PV and onshore and offshore wind technologies.

Figure 10 highlights how the invested rooftop PV is distributed based on building category. Firstly, there is an increase in investment already from 2030 compared to the INC scenario. This is mainly from COM and MFH. In this scenario, there is a large investment in rooftop PV for SFH and AGR where a total of 52% and 40% of the available capacity is utilized respectively. Additionally, SFH stand for almost half of the generation from rooftop PV. Including AGR, this is more than 60%. SFH followed by AGR have the highest technical potential in Norway, illustrating the importance of facilitating for increased feasibility of rooftop PV for these building categories. Close to all the technical potential for MFH and COM are invested in.

The impact of more PV in the Norwegian energy mix is studied with INC by comparing the electricity trade and electricity prices in the sensitivity analysis with a lower hurdle rate (4%) to the base case with a hurdle rate of 10%. The net electricity export increases almost as much as the increased PV production, by 90% in 2030 and by 21% in 2050; see **Figure 11**. The cost of electricity at the distribution level increases by up to 3.5% on an annual average. The prices in summer and spring become more volatile and more hours with zero prices are observed; see **Figure 12**. Some small curtailment is observed during summer peak hours when the rooftop PV capacity increases and zero prices are obtained (2% of the annual PV production). The electricity use increase in total by 1%, mostly in transport and in 2050 also for hydrogen production.

3.2. Sensitivity Analysis

The sensitivity analysis aims to illustrate how the investment in rooftop PV is affected by changes in input parameters. The investigated parameters can be seen in Table 5 and 6 for the INC and RAD scenarios, respectively. The result is shown in **Figure 13** and **14**. The figures highlight the percentage change in rooftop PV compared to the base as presented in Figure 10 for each of the different rooftop PV technologies in 2030 and 2050. A negative change means the investments decrease while a positive indicates that the investments increase.

3.2.1. Investment Cost and Grid Tariff

Similar to findings in other research and as expected, investment cost and hurdle rate greatly impact the investment in rooftop PV. For the INC scenario (Figure 13), only investments in rooftop PV on COM, IND, and MFH will be affected in 2030. However, in 2050, AGR and SFH experience the highest changes in investments. The largest barrier is the hurdle rate of the technology. The total investment will increase by more than 4000% in 2030. This effect is also large in 2050. However, in 2050, the effect is largest for SFH and AGR because most of the potential for the other building categories are invested in. This highlights the impact of pricing the technology. With a lower rate of return, the technology is considered significantly more beneficial.

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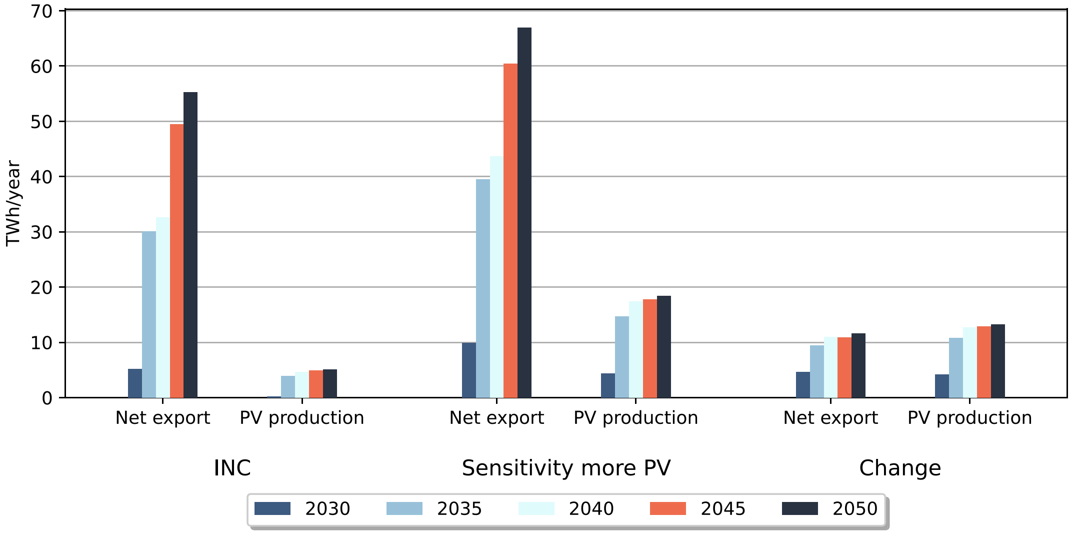

Figure 11. Net import compared to PV generation for INC base case against INC with lower hurdle rate (4%) with the differences between the scenarios.

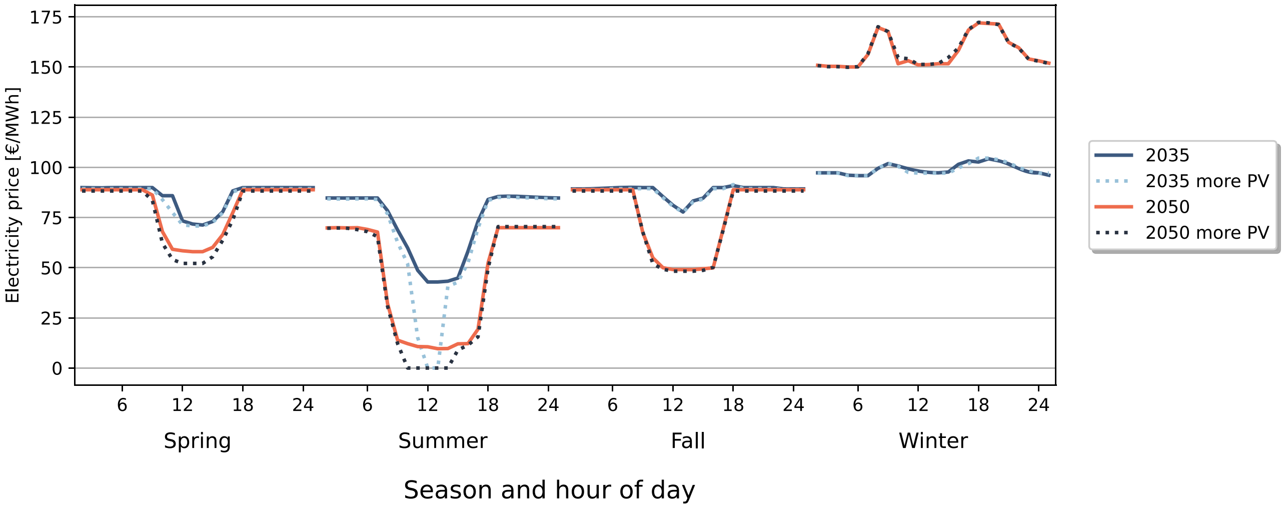

Figure 12. The electricity price in 2030 and 2050 for INC base case (thick line) compared to INC with lower hurdle rate (4%) (dashed line).

A reduction in investment cost does not affect the investment in rooftop PV in a comparable range in 2030. This shows a breaking point of price compared to investment. The hurdle rate affects the interest rate of all the end-user technologies, which results in increased utilization of, for example, heat pumps and batteries in addition to rooftop PV. This combination results in very beneficial rooftop PV. In 2050, an investment cost reduction of 50% results in close to a 300% increase in investment. This comes as an addition to the already decreased prices of rooftop PV toward 2050, making this the most beneficial solution. A combination of lower investment costs and the low hurdle rate would further increase the profitability of rooftop PV, especially in SFH and AGR where the potential is largest, as well as having the highest barrier regarding price. There is no similar hurdle rate sensitivity in RAD. However, a reduction in investment cost results in a significant effect on investment in rooftop PV. In 2050, the investment cost will have the largest impact on SFH and AGR since the technical potential of the other building categories was almost reached in the base case as seen in Figure 10. Similar to INC, the investment cost impacts mostly single-family homes and AGR. The investment cost is a larger barrier in these categories mainly due to the added VAT in SFH and the match of demand and generation profiles as seen in Figure 12.

The effect of grid tariffs is the largest in 2030 for both INC and RAD. A doubling of the power and energy fees has a positive impact on investments since it results in higher grid tariff prices for consumption from the grid, hence increasing the benefits of own produced power. Similarly, a constant power fee will result in decreased investment since the power fee will decrease compared to the base cases. For INC in 2030, this results in no investment in rooftop PV. The energy fee has no impact on RAD since

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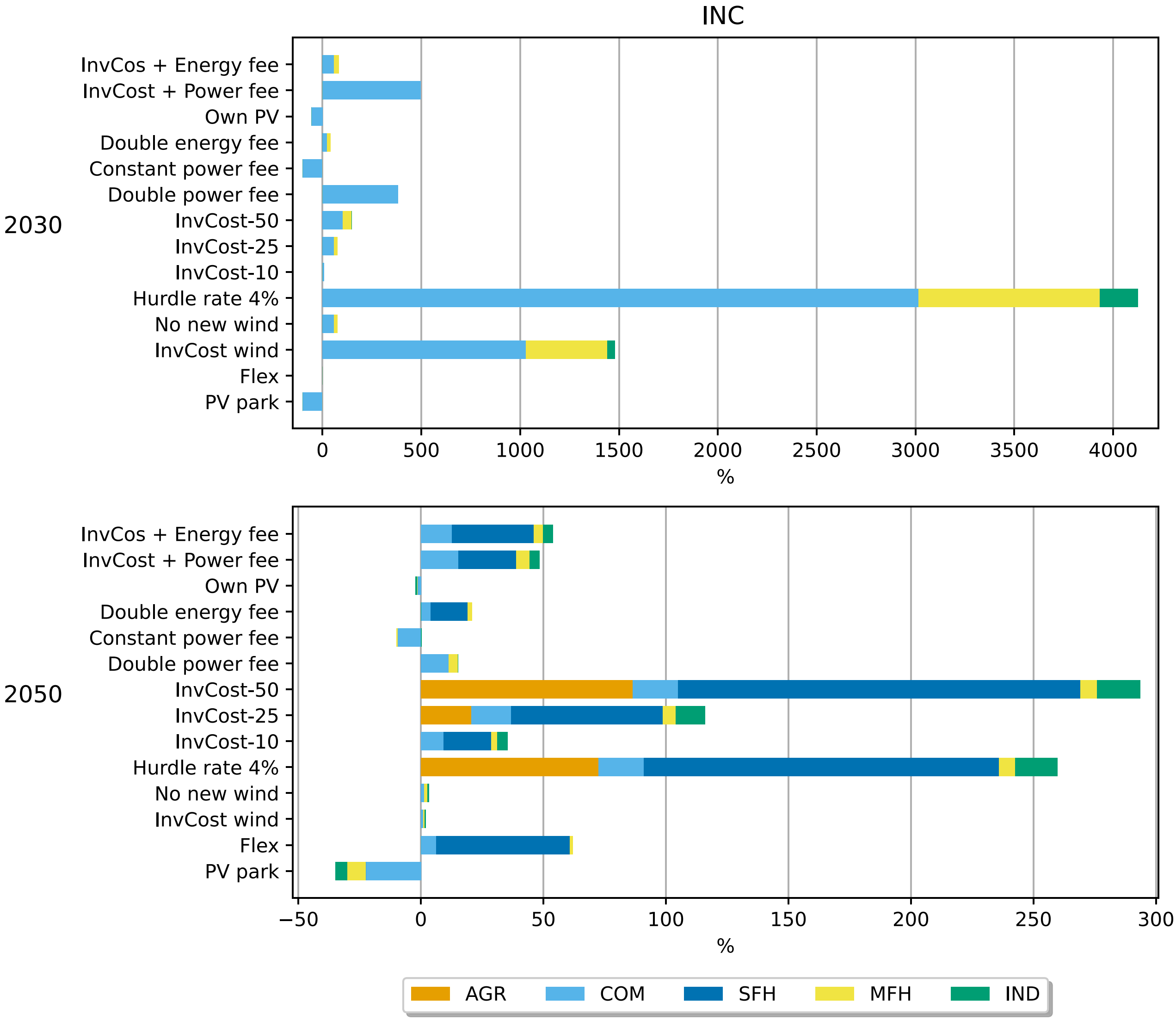

Figure 13. The percentage change of investment in rooftop PV based on different sensitivities compared to INC base case.

the increase in energy fee only results in a small increase in the electricity bill overall, compared to the increased power fee, which results in a larger increase in the electricity bill. However, a combination of increased energy and power fees with a lower investment cost gives a great effect on the investment for both INC and RAD.

3.2.2. Power Generation

The results from the sensitivity analysis illustrate a clear competition between rooftop PV and investment in other energy sources. An increase in the investment cost for wind results in an increase of investment in rooftop PV with close to 1500% in 2030 for INC. However, with still high hurdle rates of rooftop PV and the fact that a great portion of the capacity for MFH and COM is invested in 2030, the effect is lower in 2050. This illustrates the competition between the different generation technologies and that wind power competes strongly against rooftop PV in COM and MFH buildings.

Allowing for new wind and PV parks has a direct negative impact on the investment in rooftop PV. For the INC scenario, in 2030, the investment in rooftop PV is reduced by 100%, resulting in investments in PV parks instead. The effect is somewhat lower in 2050 when the investment cost of rooftop PV has decreased. For RAD, the option for PV park investment has the strongest negative effect. The competition between rooftop PV and ground-mounted PV parks is important in RAD while it has less impact in INC, due to the more tense electricity balance in RAD compared to INC (scenario with fewer limitations to wind and grid development). Investment in PV parks solely has a negative correlation with investment in rooftop PV, where SFH and AGR are strongly affected since the demand can be covered by a cheaper technology with better solar irradiation data since the PV parks are easier to optimize based on tilt and azimuth compared to the rooftop PV that needs to follow the orientation

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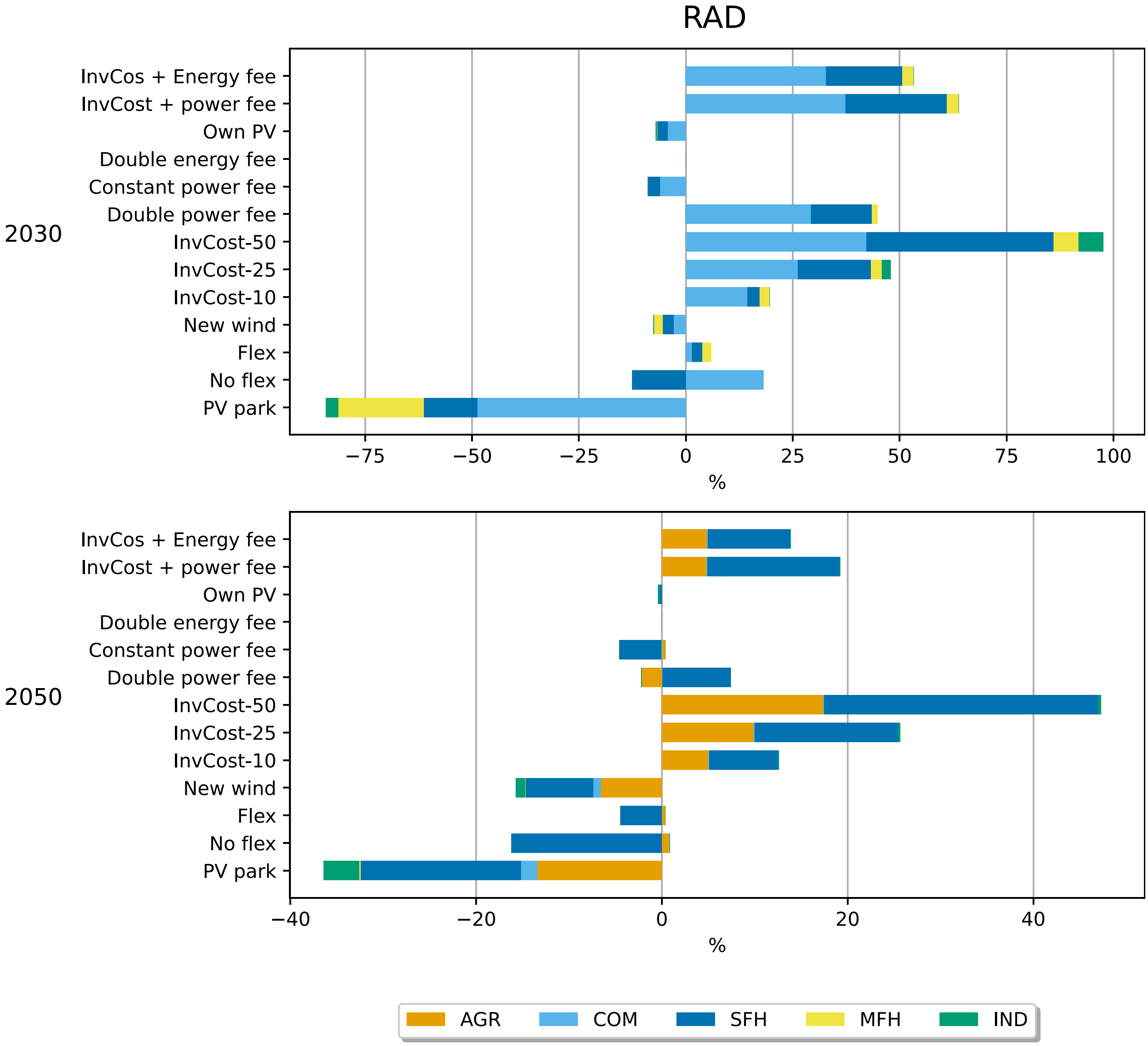

Figure 14. The percentage change of investment in rooftop PV based on different sensitivities compared to RAD base case.

and tilt of the roof. The inclusion of new wind also results in a reduction of rooftop PV, but the effect is smaller than when introducing PV parks.

3.2.3. Demand Side Management

The option for increased flexibility has a positive effect on investment in rooftop PV, especially for SFH. The negative effect seen in RAD in 2050 is a result of the high opportunity of charging electrical vehicles at work, resulting in a small reduction in SFH. However, comparing the result to the sensitivity without flexibility, the impact of flexibility on the investment of rooftop PV is visual. The effect of flexibility is greater in 2050 for INC, illustrating the effect of investment cost. Decreased self-consumption has no significant effect on the investments in rooftop PV, except for INC in 2030 where it reduces the investment in COM by 50%. However, since the investments are low in 2030 for INC, the effect is low in RAD, and in 2050, the self-consumption rate has little effect on PV investments.

3.3. Discussion

The results from the analysis contribute to a thorough understanding of the role of rooftop PV from an energy system perspective for northern regions. The utilized energy transition pathways illustrate two extremities and the results highlight the higher sensitivity in the INC scenario with lower sociotechnological development. The largest barrier is the price of the technology. This has also been shown indirectly through the other parameters, where the impact of multiple noncost related parameters had a greater impact in 2050 compared to 2030 when the investment cost of rooftop PV has decreased. Furthermore, a

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combination of lower investment costs and doubling of the grid tariffs indicates a dependency between technology cost and other parameters. The calculation of the technical potential of rooftop PV shows that the greatest technical potential is in SFH followed by AGR. The results have shown that the barrier to investing in rooftop PV is larger for these building categories compared to others having a coherence with low self-consumption in addition to being price sensitive. To increase the technoeconomic feasibility and increase the utilization of rooftop PV, support schemes and incentives for rooftop PV could be beneficial.

Additionally, the use of stationary batteries in buildings is higher in RAD than in INC, due to lower investment costs and more invested rooftop PV. The use of batteries increases with more rooftop PV production, with higher power fees or less demand flexibility. The use is highest in dwellings and the increase is also observed to be highest in dwellings with the highest increase in rooftop PV in the sensitivity analyses. The reason for this is that energy storage increases the self-consumption of PV for the dwellings. However, a disadvantage of the modeling approach is the low temporal resolution. The benefits of flexibility and energy storage in combination with rooftop PV would be greater with a higher temporal resolution that could account for higher variability and the operation of energy storage systems.

Another interesting result is that rooftop PV is a direct competition with other energy sources. A disadvantage of rooftop PV is its dependency on more or less following the rooftop tilt and azimuth. A high degree of the rooftops in Norway, especially for single-family homes, are oriented in a Northern orientation. This is to have the large wall areas facing south to utilize the solar irradiation and heat in the house. This is one of the barriers to fully utilize the technical potential of rooftop PV and is one of the reasons for not having higher differences between the sensitivities and the base cases. In addition, the study does not consider technological development of PV technology such as increased efficiency other than a reduced cost. Including more detail on technology development could facilitate increased technoeconomic feasibility of PV in northern countries. However, a great benefit of rooftop PV is the utilization of already existing built areas compared to PV parks and onshore wind. Land area utilization for renewable energy is a highly debated topic, and it is predicted that becoming zero-emission will require large land areas.[44] This is an important argument for policymakers and politicians to lower the barriers of rooftop PV in society which could reduce the need for large deployment of other renewable energy resources.

4. Conclusion

This study has aimed to investigate the role of rooftop PV from an energy system perspective for an energy system highly dependent on hydropower in Northern conditions. To investigate different energy transition pathways, we illustrated a pathway with low sociotechnological development and a scenario pathway with high development. Additionally, we performed a thorough sensitivity analysis to investigate the sensitivity of rooftop PV under different system and parameter conditions to identify important barriers to the technoeconomic feasibility of rooftop PV in similar energy systems. The analysis was conducted using IFE-TIMES-Norway, where a detailed representation of the technical potential distributed based on tilt and azimuth following the rooftops in Norway was implemented to highlight the effect of rooftop PV. The results indicate clear differences in PV penetration in the energy system based on the two energy transition pathways. If the energy system experiences low sociotechnological development, rooftop PV will only contribute a small portion of the total energy mix toward 2050. Additionally, the large technical potential of rooftop PV in residential buildings is not utilized. With higher development and technology learning, rooftop PV will play a central role in the electrification of a largely hydropower-driven energy system.

The results from the sensitivity analysis highlight barriers and opportunities for increasing the technoeconomic feasibility of rooftop PV. The cost of PV is the largest hurdle concerning the high deployment of rooftop PV followed by the competition with other renewable energy sources. Additionally, the investment cost of rooftop PV has been shown to affect how some of the other parameters impact the investment in rooftop PV, such as grid tariffs and competing energy sources. This highlights the importance of considering multiple factors when investigating possible measures to increase utilization such as incentives. Reduced investment costs could then facilitate indirect growth in rooftop PV through other measures being implemented.

For further work, a higher temporal resolution of the energy system model to better account for the impact of flexibility and energy storage systems is of high interest. For increasing knowledge regarding the effects, different system parameters have on the investment of rooftop PV, a full factorial sensitivity study could be interesting to investigate the interdependencies of parameters. Additionally, including optimization of tilt and azimuth could give further insight into how to increase the technoeconomic feasibility of rooftop PV.

Acknowledgements

We would like to thank He Riise and Mari Øgaard for their great input and discussions related to the project. This work was financially supported by the Research Council of Norway, funding received from ENERGIX-Stort program energi (KSP SUn in Norway: POtential and INTegration of the solar energy resource) (grant no. 320750).

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

energy system analyses, energy transition pathways, renewable energy sources, sensitivity analyses, solar power generations

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Received: June 23, 2024
Revised: September 13, 2024
Published online:

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