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Technical potential of solar energy in buildings across Norway: capacity and demand

Hassan Gholami [a,b,*]

[a] University of Stavanger, Norway
[b] Solar, BESS and Smart Grid Consultant, Multiconsult AS, Norway

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ABSTRACT

This research study delves into the solar energy potential and capacity in Norway, aiming to assess the viability of solar power integration in the country's urban landscape. Through a comprehensive analysis, historical data, and PVsyst simulations, the study reveals that solar photovoltaic (PV) systems offer significant promise in contributing to Norway's renewable energy goals.

The study uncovers a seasonal variation in solar energy production, with peak generation during the summer months due to extended daylight hours and more intense sunlight. However, winter months experience lower solar energy production due to limited daylight hours and weaker solar radiation. To fully exploit solar energy potential, effective energy management strategies such as energy storage, smart grid technologies, and demand response mechanisms are crucial.

Moreover, the research highlights the relationship between energy consumption and solar energy production, emphasizing the importance of efficient energy management and capacity planning. Bridging the gap between supply and demand requires optimized solar energy utilization aligned with consumption patterns.

A key finding of this study is the identification of a pivotal threshold: up to 36% of the feasible solar power, equivalent to 31 GWp, can be integrated into the grid to match daily production and consumption. However, exceeding this threshold leads to challenges in peak production times, necessitating exports or additional strategies to accommodate the excess energy.

In conclusion, this study underscores the promising prospects of solar energy integration in Norway. By leveraging solar power's potential, implementing effective energy management measures, and addressing challenges, Norway can work towards a more sustainable and resilient energy future, reducing reliance on fossil fuels and making significant strides in combating climate change.

1. Introduction

Solar energy has emerged as a prominent source of renewable energy, offering significant potential for countries to reduce their carbon emissions and transition towards a sustainable future. It is now the cheapest and most competitive source of new electricity generation in most markets worldwide according to IEA's recent report [1]. This has resulted in a consistent rise in the adoption of solar photovoltaic (PV) and solar thermal (ST) technologies, with an average yearly global growth rate of 36 % for PV and 10.5 % for S T [2].

According to the International Energy Agency, solar energy is referred to as the "new king of electricity" production and is projected to satisfy nearly one-third of the future energy demand by 2030 [3]. Cities are expected to be the primary drivers of this energy demand, accounting for over 75 % of global energy consumption and more than 70 % of associated carbon dioxide (CO2) emissions [4]. Incorporating solar energy into urban settings can play a significant role in advancing the 17 United Nations' Sustainable Development Goals (SDGs) [5].

The solar energy generation market is currently dominated by large-scale ground-mounted plants situated outside cities due to their

Abbreviations: **BAPV**, Building-Attached Photovoltaics; **BIPV**, Building-Integrated Photovoltaics; **FGD**, File Geodatabase; **GIS**, Geographic Information System; **GWh**, Gigawatt-hour; **GWp**, Gigawatt peak; **IEA**, International Energy Agency; **kWh**, Kilowatt-hour; **kWp**, Kilowatt peak; **LCCA**, Lifecycle Cost Analysis; **LCOE**, Levelized Cost of Electricity; **m^2**, Square meters; **MWp**, Megawatt peak; **NVE**, Norwegian Water Resources and Energy Directorate; **PV**, Photovoltaic; **SDGs**, Sustainable Development Goals; **SSB**, Statistics Norway; **ST**, Solar Thermal; **STC**, Standard Test Conditions; **TWh**, Terawatt-hour.

* Corresponding author at: University of Stavanger, Norway.
E-mail address: hassan.gholami@uis.no.

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extensive land requirements. However, these installations have raised environmental concerns, as they often cause ecosystem damage and significant land-use changes [6–9].

To address these issues, smaller-scale solar systems in urban areas where the energy can be produced when and where it is needed have gained popularity and market share [10]. These systems offer several advantages, which is discussed in detail in section 1.2. The European Solar Rooftop Initiative, part of the EU Solar Energy Strategy, aligns with these trends by promoting solar-ready new buildings, renewable-based communities, simplified installation permits, and economic support through the REPowerEU plan [11].

Despite the benefits, there are challenges in implementing solar systems in urban environments. The proximity and shape of buildings can hinder the integration of active solar systems and affect daylight accessibility both outdoors and indoors [12]. The choice of materials and colors also plays a crucial role in determining daylight availability and energy generation, considering factors like reflectance and specularity, which influence the contribution of reflected solar irradiation [13,14]. Moreover, achieving visual acceptability is essential for solar systems, especially when integrating them into visually exposed surfaces or in historically sensitive or protected urban areas, where technical and aesthetic design considerations become critical. The challenges and barriers of roll out of solar energy in urban areas is elaborated in detail in [15].

Norway as a country located in high latitudes, expariences significant seasonal and day length variations. Summer days boast abundant sunlight, lasting up to 24 h beyond the arctic circle (approximately 66.3°N), while winters endure prolonged darkness. The low sun angles intensify overshadowing effects and contribute to colder temperatures across these regions. Moreover, the counrty experience higher sky coverage, a greater proportion of diffuse solar radiation, and increased rainfall and snowfall [16,17].

Contrary to common perception, the distinctive features of high latitudes offer promising opportunities. Abundant summer sunlight enhances photovoltaic (PV) generation, with surplus energy export to the grid. The low sun angles create favorable conditions for building-integrated PV (BIPV) [10,18]. The unique production profile facilitates increased self-consumption of energy and enables peak-shaving strategies [19].

Moreover, the presence of snow during winter ensures a higher energy yield, particularly for vertically mounted solar systems [20] and improves outdoor [21] and indoor [22] visual conditions due to increased reflection levels. Additionally, low air temperatures benefit the efficiency of photovoltaic (PV) systems [23], while wind and precipitation naturally cleanse PV surfaces from dirt and dust [24]. Solar accessibility in the built environment in Norway, therefore, is a complex subject, presenting challenges, barriers, and opportunities, accentuating certain aspects while unveiling new possibilities. Thus, extensive research is necessary, especially during early design phases, to develop effective strategies for evaluating and enhancing solar accessibility in high-latitude locations.

Norway, renowned for its abundant natural resources and dedication to environmental preservation, has significantly integrated solar energy into its renewable energy portfolio in recent years. By May 2024, Norway's cumulative installed solar power capacity had reached 661 MWp [25]. This impressive growth was particularly evident in 2023, when the total solar capacity doubled from 300 MWp to 600 MWp. This expansion is a critical step towards Norway's ambitious goal of achieving 8 terawatt hours (TWh) of solar energy by 2030, indicating a promising future for the market [26].

Fig. 1 illustrates the monthly cumulative installed solar PV power in Norway from January 2021 to May 2024, based on data from the Norwegian Water Resources and Energy Directorate (NVE). The data, measured in kilowatt-peak (kWp), reflects the total solar PV capacity added to the national grid each month. KWp denotes the peak power the solar panels can generate under Standard Testing Conditions (STC). The graph shows a steady increase in cumulative installed solar PV power over the observed period. Notably, there was a significant surge in growth from mid-2022 onwards, highlighting a growing interest in solar energy adoption.

As Norway seeks to diversify its energy mix and reduce its reliance on fossil fuels, solar energy has gained increasing prominence. Historically known for its vast hydropower resources, Norway now recognizes the importance of solar energy as a complementary source of renewable electricity generation. With the rapidly declining cost of solar photovoltaic (PV) systems and advancements in solar technology, the viability of harnessing solar energy in Norway's diverse landscapes, including urban areas, farmland, and industrial sites, has improved significantly.

The convergence of cold weather, low solar angles, and reflection from snow in Scandinavian countries like Norway offer significant advantages for power production in solar systems, particularly those integrated into building facades [17,28]. The cold climate helps maintain optimal operating temperatures for solar panels, reducing energy losses due to heat dissipation. Simultaneously, the low solar angles, characteristic of higher latitudes, enable solar panels mounted on facades to capture sunlight more effectively, maximizing energy absorption.

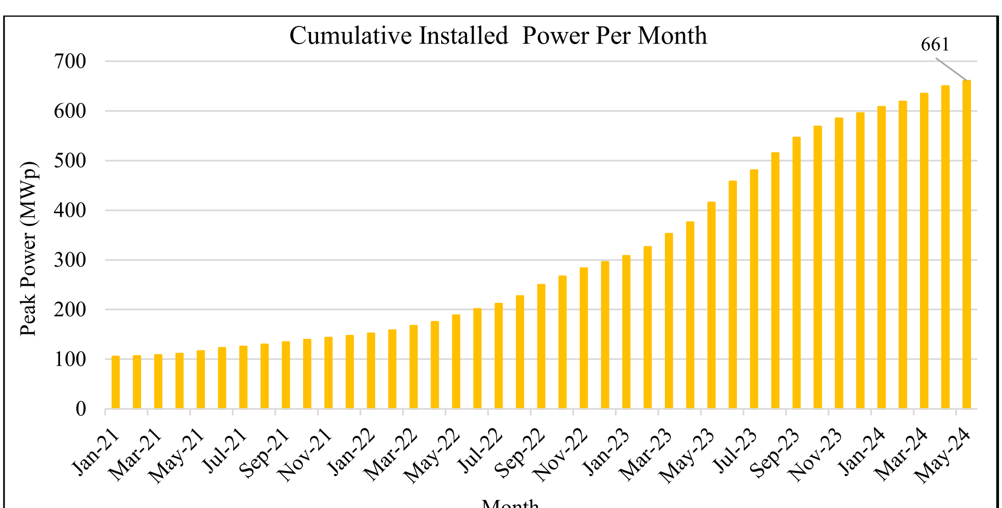

Fig. 1. Cumulative Installed Solar PV Power Per Month (Source of data:[27]).

Moreover, the reflection of sunlight from snow-covered surfaces further enhances the overall solar irradiance received by the panels. This increased irradiance, combined with the efficient functioning of the panels in cold conditions, significantly improves the power production of solar systems in Norway. As a result, solar energy solutions integrated into building facades benefit from enhanced efficiency and output, making them an attractive and viable option for sustainable power generation in the country's snowy environment.

Fig. 2 illustrates the land cover categories in Norway based on data obtained from the Norwegian statistical agency, Statistics Norway [29], for the year 2023. The total land area of Norway is approximately 323,779 square kilometres, with each land cover category representing a specific percentage of the total area. The largest land cover category is forests, accounting for 37 % (119,867 square kilometres) of the country's land area. Open firm ground, including grasslands and barren areas, comprises 34.5 % (111,803 square kilometres) of the land. Agricultural land covers 3.5 % (11,208 square kilometres), while built-up areas occupy 1.8 % (5,694 square kilometres). Bogs, bare rock, gravel, and blockfields represent 6.1 % (19,907 square kilometres) and 10 % (32,239 square kilometres) of the land area, respectively. Permanent snow and glaciers account for 0.9 % (2,862 square kilometres), and inland waters make up 6.2 % (20,197 square kilometres) of the land area. This comprehensive representation of land cover categories provides valuable insights into the distribution and composition of Norway's natural and human-altered environments, essential for understanding land use patterns and environmental management strategies.

Solar energy integration on buildings presents a compelling solution for sustainable energy production in Norway, considering that only 0.39 % of the land area in the country is covered by buildings. This paper aims to delve into the potential of this limited area for solar energy utilization as well as the grid capacity for such a potential.

This study utilizes two distinct datasets to examine the solar potential of buildings and assess the compatibility of the power grid for solar power integration in Norway. The first dataset, derived from GIS analysis carried out by Multiconsult AS and published by The Solar Energy Cluster of Norway [30], provides valuable information regarding the total surface areas and types of buildings. This dataset serves as a fundamental resource for investigating the potential of solar power on buildings, as it offers insights into the physical characteristics and spatial distribution of structures across the study area. By leveraging this dataset, the research aims to identify buildings with suitable surface areas and orientations that are conducive to effective solar energy generation.

The second dataset, obtained from Nord Pool AS [31], comprises historical data pertaining to power production, consumption, import, and export in Norway. This dataset provides a comprehensive overview of the energy dynamics within the Norwegian power grid. By analysing this dataset, the study aims to evaluate the capacity of the power grid to accommodate solar energy generation. This analysis will shed light on the potential implications and feasibility of incorporating solar power into the Norwegian energy system, paving the way for informed decision-making regarding sustainable energy transitions.

1.1. *Solar system on buildings*

Integrating solar technology into building skins has gained attention for its potential to revolutionize energy use and enhance modern architecture. This is achieved through Building-Integrated Photovoltaics (BIPV) and Building-Attached Photovoltaics (BAPV) [32]. These methods allow buildings to incorporate solar elements seamlessly, utilizing space to generate renewable electricity and promoting a sustainable future.

1.1.1. *BIPV*

BIPV integrates solar photovoltaic (PV) elements into building envelopes like roofs, facades, and windows, generating clean electricity while enhancing aesthetics and functionality. This technology promises sustainable architecture by enabling buildings to generate and use green energy. BIPV systems also offset traditional construction materials and electricity costs, making them a sustainable and cost-effective alternative. They have potential applications in various industries, such as shipping, and are viable in most European countries [18,33].

1.1.2. *BAPV*

BAPV involves adding solar panels onto existing buildings without major architectural changes, unlike BIPV. These systems provide a practical and cost-effective way to generate solar energy from unused surfaces, aiding in the expansion of sustainable energy infrastructure without significant architectural alterations.

1.2. *Solar energy utilization in urban areas: Impacts and prospects*

By leveraging building surfaces to harness solar power, a range of advantages can be achieved, including minimal environmental impact, localized power generation, synergy with hydropower, water

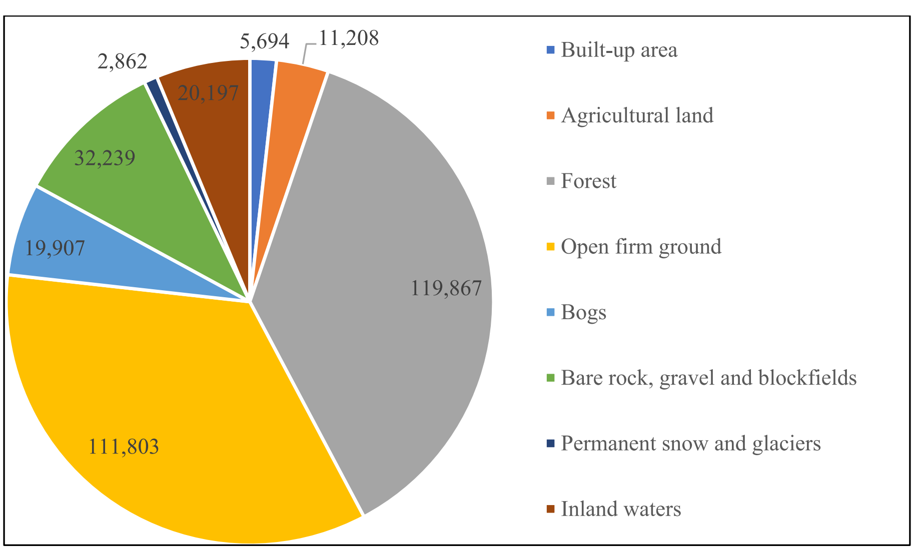

Fig. 2. Land cover by category in Norway (Source of data: [29]).

management solutions, enhanced power production, aesthetic appeal, and citizen engagement. These factors collectively highlight the significance of solar energy integration in Norwegian buildings as a crucial pathway towards achieving a greener and more energy-efficient future.

1.2.1. Minimal environmental impact

One notable advantage of solar energy integration on buildings is its minimal environmental footprint. Solar PV systems in urban areas leave the natural environment undisturbed by utilising already occupied land surfaces. This nature-neutral approach reduces the need for additional land usage and minimizes the ecological impact associated with traditional power generation methods [34,35].

1.2.2. Localized power generation

The deployment of solar power on buildings allows for power generation at the point of consumption, eliminating the need for extensive transmission infrastructure. This localized approach enables efficient energy utilization and reduces transmission losses, contributing to a more reliable and cost-effective energy supply mostly when and where it is needed [10,28].

1.2.3. Synergy with hydropower

Solar energy integration complements Norway's existing hydropower infrastructure, which currently supplies over 90 % of the country's power demand. By harnessing solar energy during the summer months, when hydropower availability is typically lower, solar systems can help offset the seasonal variability in energy production and reduce dependency on hydropower resources [36,37].

1.2.4. Water management solutions

Solar energy integration also presents a solution to address challenges associated with behind-the-dam water management in Norway. By utilizing solar power during the summer, when hydropower resources may be stretched, the strain on water resources can be alleviated. This strategic energy diversification contributes to more efficient water management and supports the sustainability of hydropower operations.

1.2.5. Distributed power production

The versatility of solar installations on buildings enables power production throughout the day, taking advantage of different tilts and orientations (different facades for example). This distributed power generation approach ensures a spread of energy production during daylight hours (power production from east façades in the morning and west façades in the afternoon and evening), optimizing solar yield and reducing reliance on peak production times, such as noon. Consequently, solar energy integration enhances overall power production efficacy by matching the production with consumption.

1.2.6. Aesthetic appeal

Advances in BIPV solutions offer opportunities for customized designs, enabling solar systems to blend seamlessly into building facades. The ability to achieve a wide range of colours and patterns enhances the aesthetic aspects of buildings, encouraging wider acceptance and integration of solar energy technologies [38,39].

1.2.7. Citizen engagement

Solar energy integration in buildings empowers citizens to actively participate in the energy transition. By enabling individuals to generate their own clean electricity, solar systems promote a sense of ownership and engagement in sustainable energy practices. This direct citizen involvement contributes to the democratization of energy and supports the transition to a more decentralized and resilient energy system [40,41].

1.2.8. Peak shaving

Solar energy helps building owners practice peak shaving by generating on-site electricity during high-demand periods, reducing grid reliance, and lowering electricity bills. This eco-friendly solution enhances grid stability and fosters a sustainable energy future [42].

1.2.9. Energy independence and economic growth

Solar energy integration enhances energy security by reducing the need for fossil fuel exports. This transition stimulates economic growth through job creation and the development of solar technology manufacturing within the region.

1.2.10. Environmental benefits

Solar energy reduces air pollution and greenhouse gas emissions, providing environmental and public health advantages. It plays a vital role in carbon offsetting, particularly in urban areas with higher emissions, contributing to climate change mitigation.

1.2.11. Resilience and technological advancements

Solar energy, when combined with energy storage solutions, enhances resilience during power outages and natural disasters, ensuring essential services are maintained. Additionally, investment in solar technology drives advancements, making solar systems more efficient and cost-effective in the long term.

1.2.12. Export opportunities and awareness initiatives

Excess solar energy generated can be exported to neighboring regions, creating opportunities for revenue generation and energy trade. Solar energy integration also serves as an educational tool, raising awareness about renewable energy and sustainable practices in communities and schools.

1.2.13. Urban improvement and Government support

Solar panels mitigate the urban heat island effect, improving urban comfort and energy efficiency. Government incentives, such as tax credits and feed-in tariffs, encourage solar adoption and investment, promoting the transition to cleaner energy sources in urban areas.

1.3. Categorization of solar energy in urban areas

In urban areas, evaluating solar energy's potential for sustainable development requires a systematic categorization. This section delves into the essential framework for classifying solar energy, encompassing theoretical, geographical, technical, and economic potential. Understanding these categories is crucial for the effective integration of solar energy systems, ensuring optimal utilization of solar resources in urban environments [10].

1.3.1. Theoretical potential

Theoretical potential represents all solar radiation received in an area without any technical or geometrical limitations. Solar irradiation maps fall into this category, and it includes both direct and diffuse irradiance.

1.3.2. Geographical potential

Geographical potential refers to the portion of the theoretical potential that is suitable for solar energy systems. For example, in a city, the geographical potential would be the solar radiation available on all available surfaces of buildings.

1.3.3. Technical potential

Technical potential is the power produced by the BIPV system in a region, taking into account technology and efficiency. It can be calculated from the geographical potential, considering the efficiency of the BIPV modules used.

1.3.4. Economic potential

Economic potential represents the portion of the BIPV technical potential that is economically feasible. This aspect involves various parameters such as technology, market price, energy tariffs, subsidies, system degradation rate, etc. A life cycle cost analysis (LCCA) is typically adopted to study the economic potential of BIPV systems in urban areas.

This study is dealing with the technical potential of solar energy in urban areas in Norway. In the subsequent chapters, this research delves deeper into various aspects of solar energy in Norway. Chapter 2 outlines the databases and methodology used for assessing solar energy potential. Chapter 3 examines PV system performance and the technical potential of solar power on different building types. Chapter 4 explores the grid capacity for solar power. Finally, Chapter 6 concludes by summarizing findings and implications for policymakers.

2. Data interpretation and methodology

Two utilized datasets in this study are introduced in this chapter.

2.1. GIS data

One of the significant advantages of solar power is its versatility in installation, as solar installations can be deployed in various locations. The effectiveness of solar power generation relies on the availability of sunlight. In Norway, the annual solar irradiation received exceeds the country's total energy consumption, making it particularly intriguing to evaluate the solar power potential in areas deemed suitable. The aim here is to assess the potential for solar power by considering suitable areas, primarily encompassing solar panels installed on buildings. However, it is worth noting that solar cells can also be implemented on the ground, integrated into noise barriers, deployed along roads and tracks, utilized in parking lots, or combined with agricultural activities. It is important to note that the potential presented here is solely the technical potential, without considering the economic feasibility of fully realizing it. Economic viability would depend on various factors such as system component costs, installation expenses, electricity prices, etc. Nevertheless, as the cost of solar plants continues to decline and electricity prices rise, the economically feasible potential is expected to increase.

In this article, the technical potential of solar power on buildings in Norway is assessed by estimating the available roof and wall area suitable for the installation of solar cells. The evaluation takes into account generic calculations of production potential corresponding to different power spot price zones in Norway.

There are five price zones in Norway: Eastern region (NO1), Southern region (NO2), Central region (NO3), Northern region (NO4) and Western region (NO5). This is illustrated in Fig. 3.

The calculations are based on extensive map data, providing area measurements for all buildings[43] in the country. Consequently, this dataset forms the most precise and comprehensive mapping endeavour conducted in Norway to date. By utilizing this accurate and detailed foundation, the study aims to provide a robust evaluation of the technical potential for solar power generation on buildings throughout the country.

The calculation of available roof area in Norway relies on utilizing the building footprints as a measure. It is commonly assumed that the footprint of a building serves as a reliable approximation of its total roof area. To obtain the footprint data for buildings in Norway, geographic map data was collected using ArcGIS Pro software. The data sets utilized for this analysis were in the Matrix Building Surface format, stored in the FGD (File Geodatabase) file format commonly used for storing geographic information system (GIS) data. These data sets encompass the building surfaces, or footprints, of all buildings in Norway. From these data sets, the "shape length" attribute, representing the perimeter of each building, was extracted. Furthermore, each building in the dataset is associated with a comprehensive set of attribute values, as presented in Table 1[44], providing additional information for the analysis of available roof area for solar power installation.

Fig. 3. The map of different power spot price zones in Norway [43].

The standard for building type/cadastre [45] presents a classification of buildings with building type codes and building type names based on the function of the buildings. This classification has been linked to the building footprints using the building type codes as a linking key. This means that each building footprint is assigned a building type name according to the standard for building type/cadastre.

The total roof and wall area for buildings in Norway, divided by different building types, are presented in Table 2. Further calculations consider the distribution of this data across various price zones. Geometric data extracted from building models, which serve as the foundation for energy framework requirements in TEK17, have been utilized. These data include floor height, window area proportions, ceiling angles, and length-to-width ratios. They are employed to calculate areas for walls, flat roofs, and sloping ceilings in the subsequent analyses. The number of buildings per building type is also included, allowing for the calculation of average values. This enables the derivation of the average footprint, number of floors, and perimeter for each building type.

2.2. Assumptions

The practical utilization of roof and façade areas for solar power generation is limited by various technical factors associated with

Table 1
Relevant attribute values with description in Cadastre Building Surface.

Name	Description
Built-up area [m^2]	The built-up area is the total area of the "footprint" of the entire building. The information from the cadastre is used where available. The area is sourced from other geospatial data sources in cases where it is missing in the cadastre.
Building Type Code / Building Group	Code value for building type. This code indicates whether it is a school building, private residence, etc.
Number of floors	Specifies the number of floors in the building

Table 2
The total footprint and wall area for buildings in Norway divided into different building types/building groups).

Build Type	Building code	Footprint [m^2]	Number of buildings	Wall area [m^2]
Detached house	11	172 355 113	1 169 830	338 185 777
Semi-detached house	12	20 224 195	170 618	42 861 465
Townhouses, chain houses, other small houses	13	21 424 951	172 724	38 345 353
Large residential buildings	14	18 827 313	41 745	35 317 727
Building for cohabitation	15	2 389 811	5 315	2 466 974
Holiday home	16	43 854 895	458 017	57 190 368
Koie, farmhouse and the like	17	2 147 128	40 400	1 288 644
Garage and outbuildings for housing	18	64 540 906	1 284 358	76 837 787
Other residential building	19	1 256 839	7 342	1 295 720
Industrial building	21	31 792 078	37 142	6 473 491
Magazine	23	19 242 891	39 449	4 097 390
Fisheries and agricultural building	24	74 743 120	440 886	11 903 242
Office building	31	10 358 594	15 209	6 942 261
Business building	32	19 394 789	21 969	8 564 574
Exhibition and Congress Building	33	164 096	106	130 893
Expedition building, terminal	41	1 936 317	2 133	1 285 828
Garage and hangar building	43	1 807 268	2 871	1 575 054
Road and traffic supervision building	44	318 520	1 149	322 934
Hotel building	51	1 774 521	2 209	1 388 470
Building for accommodation	52	2 205 414	23 061	1 393 540
Restaurant building	53	1 326 675	4 846	844 630
School building	61	13 344 404	17 230	5 272 057
University and University College Building	62	1 239 696	931	649 526
Museum and library building	64	1 029 172	5 160	366 152
Sports building	65	5 420 213	8 632	4 075 762
Cultural centre	66	2 422 805	7 038	1 072 832
Building for religious activities	67	1 897 589	6 959	783 542
Hospital	71	1 019 497	480	635 981
Nursing home	72	3 683 192	3 517	2 022 942
Primary health building	73	826 880	1 509	481 370
Emergency building	82	419 364	860	160 303
Sum		543 388 246	3 993 695	654 232 591

buildings. For instance, many detached houses have chimneys, roof structures, wind conditions, and shaded areas. Similarly, commercial buildings often have equipment such as fans and refrigeration plants occupying their roofs. As a result, the actual available area for solar power production is significantly smaller than the total roof and façade areas. Ideally, it would be desirable to estimate the solar power potential in Norway by assessing the technical potential of each individual building. However, considering the approximately 4 million buildings in the building stock, this would be an excessively extensive calculation task within the scope of this study. To address this, certain simplifications and assumptions have been made based on Multiconsult's experience [46] in converting total roof and façade areas to areas suitable for solar power. The following assumptions and simplifications have been employed:

2.2.1. Roof slope and orientation

- Small houses (detached houses, semi-detached houses, holiday homes, garages, etc.) are assumed to have inclined roofs with an average slope of 25 degrees.
- For apartment buildings, it is assumed that 50 % have sloping roofs and 50 % have flat roofs.
- Commercial buildings are assumed to have flat roofs.
- The total area of sloping roofs is evenly distributed in each cardinal direction (on average).

2.2.2. Roof utilization

- Sloping roofs facing north are not utilized for solar cells.
- It is assumed that 30 % of sloping roofs cannot be used for solar cell installation due to factors such as chimneys, air ducts/hoods, roof ladders, snow fences, and small or unsuitable roof surfaces (e.g., rolled roofs).
- For flat roofs, it is assumed that 50 % are equipped with solar cells, divided equally between east-facing and west-facing orientations at a 10-degree angle.
- For flat roofs, it is assumed that 25 % of the area cannot be utilized due to factors such as distances to the roof edge because of national standards, air ducts/hoods, skylights, and technical installations like ventilation systems or dry coolers. However, in industrial/warehouse/expedition buildings/hangars, only 10 % of the area is assumed to be unavailable for solar power utilization.
- The estimation of solar power potential does not consider roof load-bearing capacity. Although limitations in load-bearing capacity may reduce the utilization rate, the potential can still be realized by using solar cells with a snow-melting function to automatically clear the roof or lightweight solutions.

2.2.3. Wall area

- The total wall area is evenly distributed among each cardinal direction (on average).
- Wall areas facing north are not utilized for solar cells.
- Wall areas of small houses are not used for solar cells.
- For apartment buildings, it is assumed that 50 % of the wall area cannot be utilized due to factors such as balconies, window reframing, sunshade solutions, and small or inaccessible areas.
- For most commercial buildings, it is assumed that 20 % of the wall area cannot be utilized due to window areas, sunshade solutions, company logos/advertisements, technical installations, or irregular areas.
- In industrial/warehouse/expedition buildings, it is assumed that only 10 % of the wall area cannot be utilized.
- The estimation of solar power potential does not consider the load-bearing capacity of the walls. Limitations in load-bearing capacity may reduce the utilization rate.

Based on the dataset from the cadastre and the processing described above, the available area for solar cells is divided by building types, as depicted in Table 3, and further categorized by price zones, as shown in Table 4.

Table 3
Summarized available areas for solar cells on buildings in Norway divided into building categories.

Building type	Available Facade areas [million m^2]	Available roof areas [million m^2]
Detached house	0.0	99.8
Semi-detached house	0.0	14.6
Townhouses, chain houses, other small houses	0.0	15.5
Large residential buildings	13.2	12.0
Building for cohabitation	0.9	1.5
Holiday home	0.0	31.8
Koie, farmhouse and the like	0.0	1.6
Garage and outbuildings for housing	0.0	46.7
Other residential building	0.0	0.7
Industrial building	4.4	28.6
Magazine	2.8	17.3
Fisheries and agricultural building	7.1	56.1
Office building	4.2	7.8
Business building	5.1	14.5
Exhibition and Congress Building	0.1	0.1
Expedition building, terminal	0.9	1.7
Garage and hangar building	1.1	1.6
Road and traffic supervision building	0.2	0.2
Hotel building	0.8	1.3
Building for accommodation	0.8	1.7
Restaurant building	0.5	1.0
School building	3.2	10.0
University and University College Building	0.4	0.9
Museum and library building	0.2	0.8
Sports building	2.4	4.1
Cultural centre	0.6	1.8
Building for religious activities	0.0	1.0
Hospital	0.4	0.8
Nursing home	1.2	2.8
Primary health building	0.3	0.6
Emergency building	0.1	0.3
Sum	51	379

Table 4
Summarized available areas for solar cells on buildings in Norway divided into price zones.

Price zone	Available Facade areas [million m^2]	Available roof areas [million m^2]
NO1	20	136
NO2	11	98
NO3	9	71
NO4	5	40
NO5	5	34
SUM	51	379

2.3. Nord Pool AS

This section utilizes a comprehensive historical dataset obtained from Nord Pool AS, covering the period from 2013 to 2021. The dataset consists of hourly resolution data on power production, exported power and spot prices across all five price zones in Norway. The objective of this research is to examine the grid capacity implications of solar power production on building skins in urban areas. By analyzing the historical trends and dynamics within the electricity market, this study aims to assess the feasibility and potential of integrating solar PV systems into urban environments, with a focus on understanding the impact on grid capacity and the efficient utilization of electricity grids.

The availability of historical data spanning from 2013 to 2021 provides a valuable opportunity to investigate the grid capacity considerations associated with solar PV production on building skins in urban areas. By analysing the hourly resolution data, including power production, exported power, and spot prices, this research aims to identify temporal patterns and spatial variations in solar energy generation, as well as their implications for electricity supply and demand. The comprehensive nature of the dataset, encompassing all five price zones in Norway, allows for a detailed examination of regional variations and their impact on grid stability. By leveraging this historical data, this study seeks to contribute to the understanding of capacity limitations, grid integration challenges, and potential opportunities for the successful integration of solar PV systems on building skins in urban settings. The findings from this research can inform policymakers, urban planners, and energy system designers in making informed decisions to effectively manage and optimize electricity grids in the face of increasing solar PV penetration in urban areas.

Fig. 4 represents the annual electricity consumption of Norway from 2013 to 2021, measured in terawatt-hours (TWh). It shows a relatively stable trend with a remarkable growth in consumption. The consumption ranged from approximately 125.9 TWh in 2014 to 138.9 TWh in 2021. There was a slight increase in electricity consumption from 2013 to 2016, followed by a relatively flat trend until 2019. In 2020, there was a slight dip in consumption, but it rebounded in 2021 to reach the highest level in the reported years.

Fig. 5 displays the electricity consumption pattern in Norway throughout the year. The x-axis represents the days of the year, starting from January 1st to December 31st, and the y-axis shows the electricity consumption measured in GWh (Gigawatt-hours). The graph indicates fluctuations in electricity consumption over the year by depicting the maximum, minimum and average hourly consumption of each day. Consumption is generally higher during colder months (winter) and lower during milder months (summer). There are visible peaks in electricity usage during certain periods, possibly reflecting increased heating and energy demands during colder weather. Additionally, there are relatively lower points during the summer months when energy consumption typically decreases due to less heating needs (electricity is yet the major resource for heating in Norway).

Fig. 6 represents the maximum and minimum electricity consumption in Gigawatt-hours (GWh) for each hour of the day, as well as the average consumption for each hour of the day, in Norway throughout the year. The data is organized by month, day, and hour. For instance, in January, the maximum consumption recorded during hour 00 was 21.2 GWh, the minimum consumption was 14.3 GWh, and the average consumption for that hour was approximately 17.5 GWh. The data spans each month of the year, and for each hour, it shows how electricity consumption varies, with higher consumption typically occurring during colder months and lower consumption during warmer months. Fig. 7 illustrates the average hourly consumption of each month.

3. Solar potential on the building

The subsequent section delves into a comprehensive analysis of the solar photovoltaic (PV) potential on buildings in Norway, utilizing the dataset derived from the previous section that entailed GIS analyses of surface areas of buildings across the country.

3.1. Pvsyst simulation

The PVsyst simulation tool facilitates the assessment of solar power production in different price zones at specified locations. Each price zone is represented by either the most population-dense area or an intermediate location between the two most populated regions, ensuring a reference simulation for each zone. The simulations are based on climate data obtained from the Meteonorm 8.0 database, providing a robust foundation for the analysis.

Given that areas with higher population density are likely to have a greater concentration of solar installations, the climate data from these regions is considered to be representative of the entire price zone for

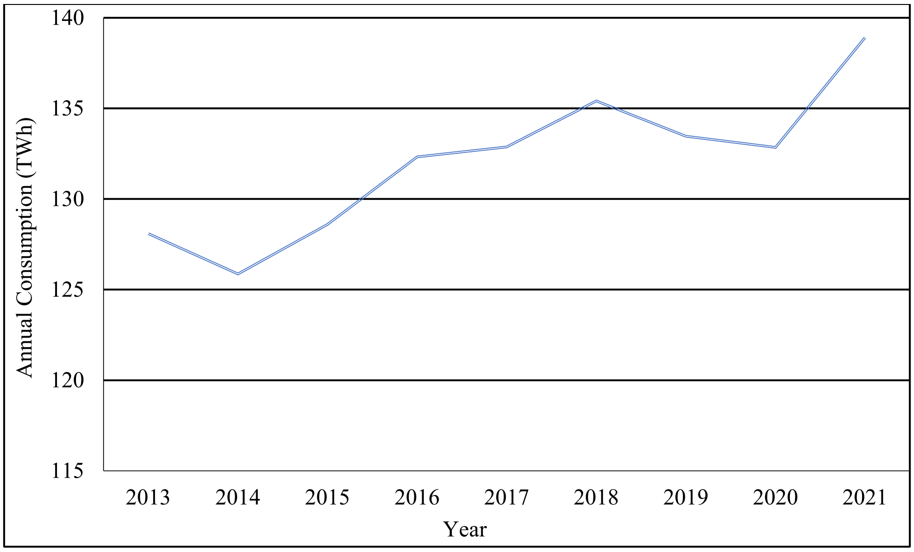

Fig. 4. Historical data of Norway's annual electricity consumption.

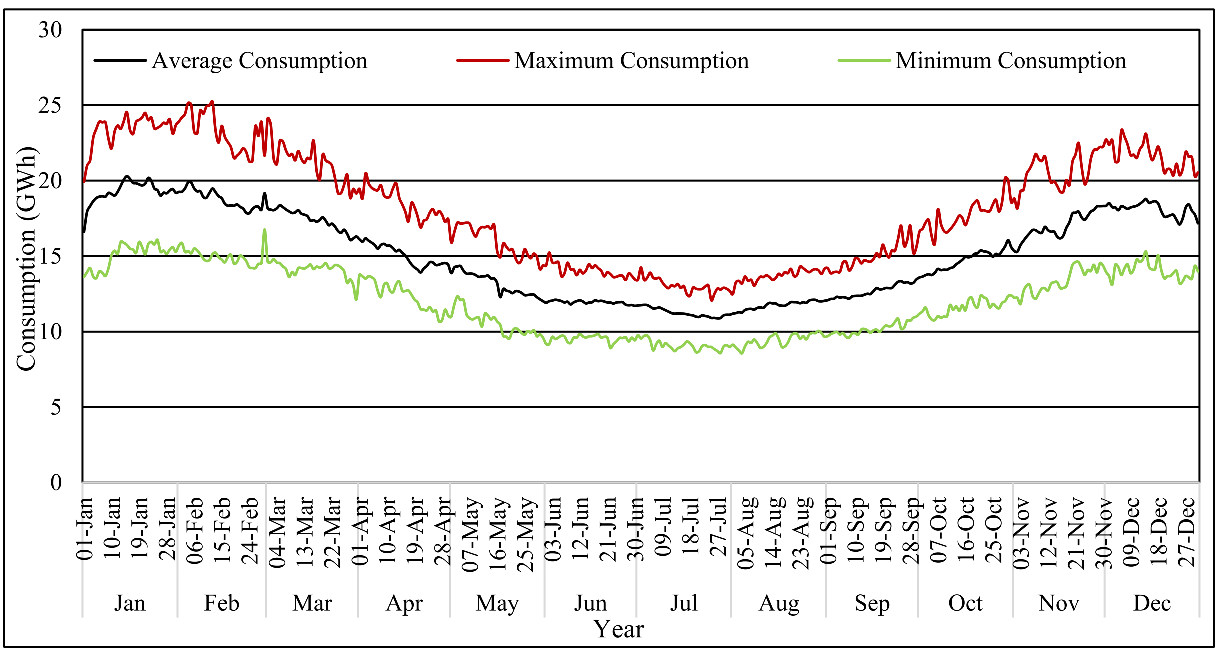

Fig. 5. Average, Minimum and Maximum of hourly power consumption per day.

solar system installed on buildings.

By using this methodology, we can accurately estimate the solar power production capacity and potential across various price zones in a given region. The simulations encompass solar panels installed on walls, flat roofs, and sloping roofs, with a range of slopes and orientations, as outlined in Table 5. The solar panels are aligned with the inclination and orientation of the walls and ceilings. However, in the case of flat roofs, the panels are configured in an east–west orientation with a slope of 10 degrees. REC solar panels (72 cells) are utilized in the simulations, with an individual panel capacity of 405 Wp and a modular efficiency of 20.2 %.

The selection of regions with higher population density as representatives is grounded in the expectation that such areas are likely to host a greater concentration of solar installations. Consequently, the climate data from these representative regions is deemed to be reflective of the overall price zone for solar cells installed on buildings.

The adapted location for each price zones is as follows:

- NO1: Oslo
- NO2: Bortelid
- NO3: Trondheim
- NO4: Narvik
- NO5: Bergen

During the calculation of solar power production, the values for albedo (reflection) comply with **Multiconsult's best practices** [46] (refer to Table 6), while losses resulting from dirt and snow are considered based on NS3031-2016 guidelines (refer to Table 7). Notably, for façade applications, losses due to dirt and snow are assumed to be 3 %.

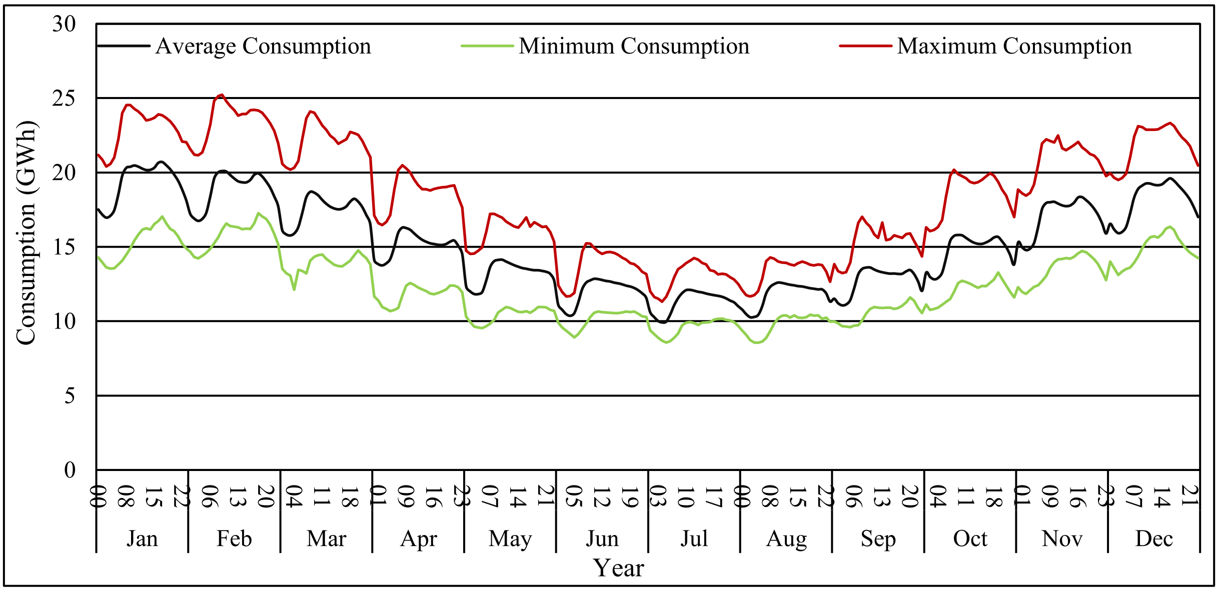

Fig. 6. Average, Minimum and Maximum hourly power consumption per month.

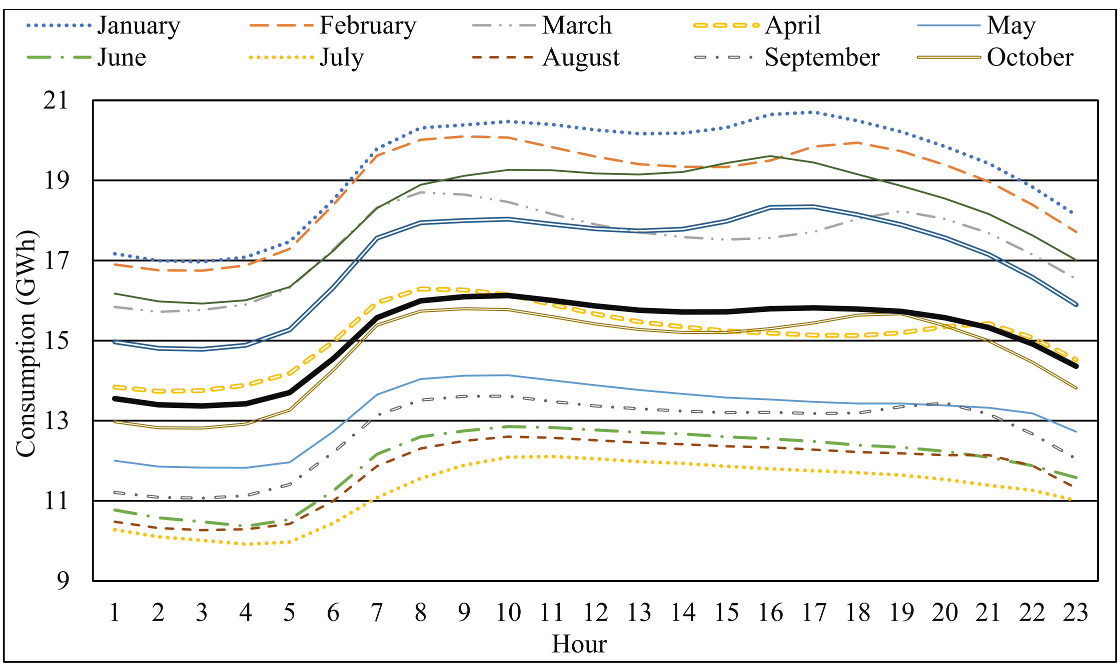

Fig. 7. Average hourly consumption of each month.

Table 5
Selected slopes and orientations for solar panels on walls, flat roofs and sloping roofs used for simulations in PVsyst.

Areal	Slope [degrees]	Orientation [degrees]
South-facing façade	90	0
East-facing façade	90	−90
West-facing façade	90	+90
Flat roof	10	−90, +90
Sloping roof to the south	25	0
Sloping roof to the east	25	−90
Sloping roof to the west	25	+90

3.2. Production potential per kWp

The resulting annual energy production and specific production per price zone shown in Table 8 and Table 9. Specific production or specific yield indicates electricity production (kWh) per kWp of solar PV system regardless of the rated power of the solar plant.

3.3. Production potential in buildings

3.3.1. Production potential per building type

The overall technical production potential is obtained by multiplying the available roof and facade areas of buildings with specific solar power production. The potential is shown distributed across building types in Table 10 and as an average per building in Table 11. Table 10 shows that

Table 6
Albedo/reflection used in the PVsyst simulations according to Multiconsult's best practice.

Month	NO1	NO2	NO3	NO4	NO5
January	0,8	0,8	0,8	0,8	0,8
February	0,8	0,8	0,8	0,8	0,8
March	0,7	0,6	0,8	0,8	0,7
April	0,4	0,3	0,5	0,5	0,4
May	0,2	0,2	0,2	0,2	0,2
June	0,2	0,2	0,2	0,2	0,2
July	0,2	0,2	0,2	0,2	0,2
August	0,2	0,2	0,2	0,2	0,2
September	0,2	0,2	0,2	0,2	0,2
October	0,2	0,2	0,2	0,2	0,2
November	0,2	0,2	0,2	0,2	0,2
December	0,6	0,5	0,7	0,7	0,6

the total technical potential is highest in the building category of detached houses. Table 12 provides the total and average potential per building type.

3.3.2. Production potential per price zone

The technical potential is presented per price zone in Table 13 and Table 14. The technical potential is approximately 87 GWp in total in Norway, with the highest technical potential in the Eastern region (NO1).

Fig. 8 presents the potential of monthly power production of solar energy in Norway. The values are given in Tearwatt-hours (TWh), representing the total amount of solar energy generated each month. The highest solar energy production occurs in June, with 11.3 TWh, followed by July with 10.7 TWh and May with 11 TWh. These months are during the peak of summer when Norway experiences long daylight hours and more intense sunlight, leading to optimal conditions for solar energy generation. Conversely, the winter months, specifically December with 290 GWh and November with 904 GWh, have the lowest solar energy production due to the limited daylight and weaker solar radiation during this period. The grand total for the entire year sums up to 65.6 TWh, illustrating the annual solar energy output. This data underscores the seasonal variation in solar energy production, emphasizing the significant impact of changing daylight hours and sun intensity throughout the year.

3.3.3. Uncertainty

Uncertainty is inherent in the calculations conducted to determine Norway's maximum technical potential, as presented in the preceding sections. In the context of roof and facade areas, specific assumptions have been employed concerning the practical usability of the total surface area for solar panels. These assumptions primarily draw from Multiconsult's expertise [46] and building models, which may introduce deviations from actual real-world scenarios (refer to Section 2.2 Assumptions for detailed insights into the assumptions made). It is essential to acknowledge and address these uncertainties to ensure a robust and reliable assessment of Norway's solar energy potential.

It is also essential to acknowledge that our focus has been on determining the maximum technical potential for solar energy, but real-world solar panel installations typically do not utilize the entire available roof surface. For instance, our calculations estimated a maximum potential of 20.2 GWp (16.2 TWh/year) for detached houses, corresponding to an average installed capacity of 17.3 kWp per detached house. However, in practice, most solar PV systems on detached houses are sized according to household energy consumption, leading to lower utilization of the roofs.

Furthermore, various factors may hinder the full utilization of the maximum available area for solar panels, leading to a potentially

Table 8
Annual energy production (kWh/m^2) per price zone for walls and roofs with selected slopes and orientations.

	NO1 [kWh/m^2]	NO2 [kWh/m^2]	NO3 [kWh/m^2]	NO4 [kWh/m^2]	NO5 [kWh/m^2]
South façade	169	177	162	158	123
East façade	125	130	115	117	95
West façade	126	131	115	117	97
Flat roof	150	159	140	108	129
Tilted roof to the south	195	200	185	159	154
Tilted roof to the east	158	161	147	127	128
Tilted roof to the west	157	162	147	126	129

Table 9
Specific production (kWh/kWp) per price zone for walls and roofs with selected slopes and orientations.

	NO1 [kWh/kWp]	NO2 [kWh/kWp]	NO3 [kWh/kWp]	NO4 [kWh/kWp]	NO5 [kWh/kWp]
South façade	836	873	799	780	608
East façade	619	640	569	579	471
West façade	621	648	568	577	478
Flat roof	742	787	691	533	635
Tilted roof to the south	965	990	915	784	761
Tilted roof to the east	779	797	727	629	634
Tilted roof to the west	777	800	724	621	637

Table 7
Loss due to dirt/snow used in the PVsyst simulations according to NS3031-2016 indicated as a percentage. For façade, losses due to dirt/snow are set at 3%.

Month	NO1		NO2		NO3		NO4		NO5	
Slope	10°	25°	10°	25°	10°	25°	10°	25°	10°	25°
January	60	20	45	30	60	20	75	25	15	5
February	75	25	75	50	75	25	75	25	30	10
March	60	20	45	30	45	15	75	25	15	5
April	2	2	2	2	8	3	75	25	2	2
May	2	2	2	2	2	2	2	2	2	2
June	2	2	2	2	2	2	2	2	2	2
July	2	2	2	2	2	2	2	2	2	2
August	2	2	2	2	2	2	2	2	2	2
September	2	2	2	2	2	2	2	2	2	2
October	2	2	2	2	2	2	30	10	2	2
November	15	5	2	2	15	5	45	15	2	2
December	45	15	38	25	53	18	60	20	23	8

Table 10
Summarized potential for solar power on buildings (walls + roofs) distributed by building type.

Building type	Potential (GWh/year)
Detached house	16,264.1
Semi-detached house	2,389.4
Townhouses, chain houses, other small houses	2,529.2
Large residential buildings	3,626.0
Building for cohabitation	353.6
Holiday home	5,143.3
Koie, farmhouse and the like	251.3
Garage and outbuildings for housing	7,601.4
Other residential building	107.1
Industrial building	4,734.8
Magazine	2,873.9
Fisheries and agricultural building	9,064.5
Office building	1,695.5
Business building	2,786.7
Exhibition and Congress Building	28.9
Expedition building, terminal	366.2
Garage and hangar building	375.9
Road and traffic supervision building	60.1
Hotel building	297.4
Building for accommodation	343.2
Restaurant building	209.9
School building	1,862.7
University and University College Building	182.9
Museum and library building	139.4
Sports building	916.0
Cultural centre	342.6
Building for religious activities	162.1
Hospital	161.2
Nursing home	558.4
Primary health building	127.0
Emergency building	57.5
Sum	65,612

Table 11
Average potential for solar power per building type.

Building type	Solar power on walls per building [kWh/year]	Solar power on roofs per building [kWh/year]
Detached house	0.0	13,902.9
Semi-detached house	0.0	14,004.3
Townhouses, chain houses, other small houses	0.0	14,642.9
Large residential buildings	42,850.8	44,011.0
Building for cohabitation	23,518.8	43,006.9
Holiday home	0.0	11,229.4
Koie, farmhouse and the like	0.0	6,219.1
Garage and outbuildings for housing	0.0	5,918.5
Other residential building	0.0	14,592.3
Industrial building	15,971.2	111,507.7
Magazine	9,470.2	63,380.5
Fisheries and agricultural building	2,200.3	18,359.4
Office building	37,241.2	74,237.6
Business building	31,616.3	95,230.0
Exhibition and Congress Building	100,480.0	172,392.5
Expedition building, terminal	54,761.1	116,932.6
Garage and hangar building	49,995.8	80,925.3
Road and traffic supervision building	22,712.1	29,594.1
Hotel building	49,947.7	84,687.3
Building for accommodation	4,787.7	10,095.0
Restaurant building	14,115.6	29,206.1
School building	24,798.9	83,311.9
University and University College Building	54,536.0	141,866.2
Museum and library building	5,682.3	21,328.2
Sports building	38,360.5	67,751.7
Cultural centre	12,298.1	36,374.6
Building for religious activities	0.0	23,291.5
Hospital	106,796.0	229,036.6
Nursing home	46,436.1	112,328.2
Primary health building	25,882.7	58,283.1
Emergency building	15,099.1	51,808.7

achievable solar power potential lower than indicated by our calculations. Nevertheless, the progress in technology and ongoing advancements in construction practices are expected to counterbalance this effect. Our calculations assumed a module efficiency of 20.2 %, and it is noteworthy that the technical production potential will naturally increase with improved efficiency. Continuous enhancement in efficiency is pivotal for the solar power industry as it contributes to reducing system costs, and it is anticipated that efficiency will continue to improve in the years to come. These factors add to the dynamic nature of the solar energy landscape, influencing the real-world implementation of solar PV systems and emphasizing the significance of considering both technical and practical factors in assessing solar energy potential.

4. The grid capacity for the solar power

Fig. 9 represents the average hourly potential of solar power production in Norway for each month. The values indicate the amount of solar energy, measured in Gigawatt-hours, that can be generated on an average hourly basis for different hours of the day throughout the year. The data shows that as expected, solar power production is relatively low during the winter months (January and February) due to the limited daylight hours and the low sun angle. As spring and summer arrive (March to August), solar production starts to increase significantly, with June and July being the peak months for solar energy generation. During these months, the long daylight hours and higher sun angle contribute to a substantial increase in solar energy output. As autumn approaches (September to November), solar production gradually declines, and it reaches its lowest point during the winter months again.

Fig. 10 shows the minimum, maximum and average hourly potential of solar power production for a day of each month in Norway.

Fig. 11 provides a comprehensive view of the diurnal variation in solar energy production throughout the year. It allows for a detailed understanding of how solar energy generation fluctuates during different hours of the day within each month. The average hourly values give insights into the typical trend of solar energy production at specific hours, while the minimum and maximum values represent the lowest and highest points of solar energy generation during those hours. By examining this data in conjunction with the monthly power production figures, it becomes evident how the combination of daily and seasonal variations influences the overall solar energy output in Norway.

Fig. 12 presents the cumulative monthly consumption (based on data from 2013 to 2021) and potential solar power production of electricity in Norway, with the values given in terawatt-hours (TWh). The data indicates that the average total consumption per month ranges from 8.60 TWh in June to 14.27 TWh in December. Conversely, the potential solar production per month shows a distinct seasonal pattern, with the highest production occurring in June at 11.33 TWh and gradually decreasing towards the end of the year, reaching its lowest point in December at 0.29 TWh. The average of potential solar power production per month is approximately 6.84 TWh. This data highlights the disparity between electricity consumption and production in Norway, emphasizing the importance of efficient energy management, renewable energy integration, and capacity planning to ensure a sustainable and reliable energy supply for the country.

Based on the figures provided, there is a clear relationship between energy consumption and the potential of solar energy production in Norway. The data shows that solar energy production experiences significant seasonal variation, with peak generation occurring during the

Table 12
Solar power potential on buildings, summed and averaged.

	Total Energi [GWh/year]			Peak Power [MWp]			Average Energy [kWh/year]			Average Peak Power [kWp]		
Building type	Wall	Roof	Sum	Wall	Roof	Sum	Wall	Roof	Sum	Wall	Roof	Sum
Detached house	0	16,264	16,264	0	20,200	20,200	0	13,903	13,903	0	17	17
Semi-detached house	0	2389	2389	0	2963	2963	0	14,004	14,004	0	17	17
Townhouses, chain houses, other small houses	0	2529	2529	0	3139	3139	0	14,643	14,643	0	18	18
Large residential buildings	1789	1837	3626	2681	2428	5109	42,851	44,011	86,862	64	58	122
Building for cohabitation	125	229	354	187	308	496	23,519	43,007	66,526	35	58	93
Holiday home	0	5143	5143	0	6425	6425	0	11,229	11,229	0	14	14
Koie, farmhouse and the like	0	251	251	0	315	315	0	6219	6219	0	8	8
Garage and outbuildings for housing	0	7601	7601	0	9456	9456	0	5918	5918	0	7	7
Other residential building	0	107	107	0	134	134	0	14,592	14,592	0	18	18
Industrial building	593	4142	4735	885	5789	6674	15,971	111,508	127,479	24	156	180
Magazine	374	2500	2874	560	3504	4064	9470	63,380	72,851	14	89	103
Fisheries and agricultural building	970	8094	9065	1446	11,343	12,789	2200	18,359	20,560	3	26	29
Office building	566	1129	1695	843	1572	2415	37,241	74,238	111,479	55	103	159
Business building	695	2092	2787	1040	2943	3984	31,616	95,230	126,846	47	134	181
Exhibition and Congress Building	11	18	29	16	25	41	100,480	172,393	272,873	150	235	385
Expedition building, terminal	117	249	366	176	353	528	54,761	116,933	171,694	82	165	248
Garage and hangar building	144	232	376	215	329	544	49,996	80,925	130,921	75	115	190
Road and traffic supervision building	26	34	60	39	48	88	22,712	29,594	52,306	34	42	76
Hotel building	110	187	297	169	269	438	49,948	84,687	134,635	76	122	198
Building for accommodation	110	233	343	169	335	504	4788	10,095	14,883	7	15	22
Restaurant building	68	142	210	103	201	304	14,116	29,206	43,322	21	42	63
School building	427	1435	1863	640	2025	2666	24,799	83,312	108,111	37	118	155
University and University College Building	51	132	183	79	188	267	54,536	141,866	196,402	85	202	287
Museum and library building	29	110	139	44	156	201	5682	21,328	27,010	9	30	39
Sports building	331	585	916	495	823	1318	38,361	67,752	106,112	57	95	153
Cultural centre	87	256	343	130	368	498	12,298	36,375	48,673	19	52	71
Building for religious activities	0	162	162	0	202	202	0	23,291	23,291	0	29	29
Hospital	51	110	161	77	155	232	106,796	229,037	335,833	161	322	483
Nursing home	163	395	558	246	559	805	46,436	112,328	158,764	70	159	229
Primary health building	39	88	127	58	125	184	25,883	58,283	84,166	39	83	122
Emergency building	13	45	58	19	64	83	15,099	51,809	66,908	23	74	97
Sum	6890	58,723	65,612	10,319	76,744	87,063						

Table 13
Summarized solar power potential for solar power on buildings (walls + roofs) distributed across price zones.

	Total solar power potential [GWp]		
Price zone	Wall	Roof	Sum
NO1	4.0	27.6	31.6
NO2	2.3	19.9	22.2
NO3	1.9	14.4	16.3
NO4	10.9	8.1	9.1
NO5	1.0	6.8	7.9
SUM	10.3	76.7	87.1

Table 14
Summarized solar power production potential on buildings (walls + roofs) distributed across price zones.

	Total solar power potential [TWh/year]		
Price zone	Wall	Roof	Sum
NO1	2.8	22.0	24.8
NO2	1.7	16.5	18.2
NO3	1.2	10.7	11.9
NO4	0.7	5.0	5.7
NO5	0.5	4.5	5.1
SUM	6.9	58.7	65.6

summer months due to extended daylight hours and more intense sunlight. Conversely, solar energy production is at its lowest during the winter months when daylight hours are limited. In contrast, energy consumption tends to follow a more stable pattern, driven primarily by factors such as population and industrial demand, with an annual growth rate. To fully harness the potential of solar energy and bridge the gap between supply and demand, effective energy management strategies are essential. Energy storage solutions, smart grid technologies, and demand response mechanisms can help optimize solar energy utilization and balance consumption throughout the year. By aligning solar energy generation with consumption patterns, Norway can work towards a more sustainable and resilient energy future.

Shifting part of the solar power production during peak production times (with BESS solution for example) and when the production is more than consumption can significantly improve the matching of energy demand and supply. By doing so, it addresses two main challenges in the energy industry: the intermittency of renewable energy sources and the need to match energy generation with consumer demand.

During peak production times, solar power plants will produce more energy than is needed (if the maximum technically feasible capacity installed), leading to a surplus. By shifting this excess energy to times of higher demand, such as during the evening when energy consumption typically increases, the utilization of solar power could be maximized. This approach optimizes the use of renewable energy and reduce the reliance on conventional power sources during peak demand periods.

Table 15 presents the first 30 critical hours throughout the year that limit the maximum PV capacity. Based on the data analysis and Table 15, integrating photovoltaic (PV) capacity up to 36 % of the calculated capacity, which will be 31 GWp, allows smooth incorporation of solar power into the grid, effectively matching production with consumption. Within this range, the grid efficiently absorbs the generated solar energy, ensuring stability and sustainability. However, exceeding the 31 GWp threshold leads to a divergence between production and consumption in peak production times in summer, resulting in potential losses or necessitating exports to other regions. Although anticipating future electricity demand growth could absorb excess solar power, accurate projections are challenging. Achieving a balanced and sustainable energy system requires careful evaluation of optimal PV capacity limits, considering regional consumption patterns, interconnectivity, and innovative energy management and storage solutions. Policymakers and grid operators must strike the right balance to foster an

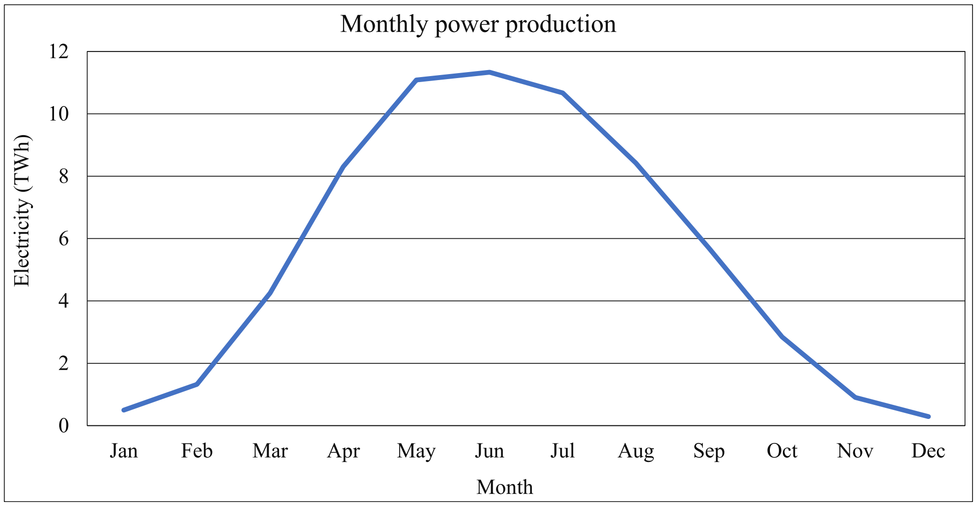

Fig. 8. The potential monthly power production of solar energy in Norway.

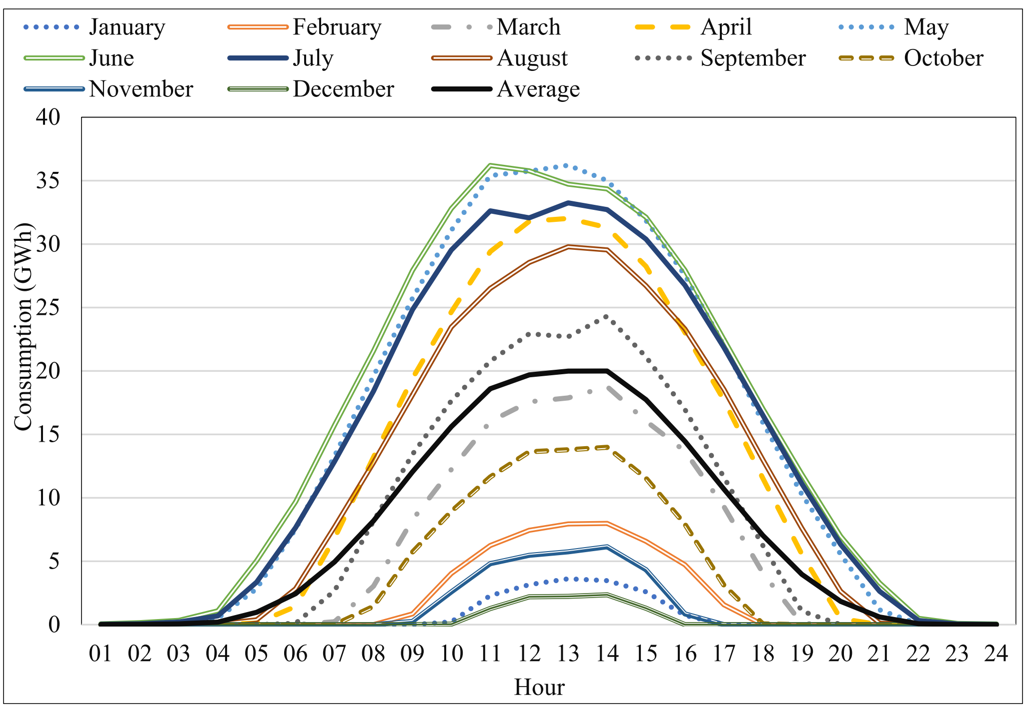

Fig. 9. The average hourly production of the solar system for a day of each month in Norway.

environmentally and nature friendly and economically efficient energy landscape.

Therefore, only 36 % of the technically feasible solar power can be practically integrated into the grid due to electricity consumption levels in the associated hour. While this threshold ensures a balanced match between production and consumption on a hourly basis, it falls short when considering the annual energy requirements. The annual power production from the technically feasible solar PV system, amounting to 65 TWh, remains less than half of Norway's average annual consumption of 132 TWh. This discrepancy underscores the challenges posed by intermittency and highlights the need to explore additional strategies to increase demand matching, including a comprehensive approach that integrates various renewable energy sources, grid enhancements, energy storage technologies, and potential interconnection with neighboring countries to optimize energy utilization and create a sustainable and resilient energy system.

5. Conclusion

The research on solar energy potential and capacity in Norway presents a compelling case for integrating solar photovoltaic (PV) systems as a pivotal component of the country's renewable energy strategy. Through the analysis of historical data, PVsyst simulations and GIS analysis, the substantial promise of solar power in contributing to Norway's sustainable energy objectives becomes evident.

The study underscores the seasonal variation in solar energy production, with peak generation during summer and reduced production in winter. This variation underscores the need for effective energy management strategies to optimize solar energy utilization throughout the year.

Furthermore, the assessment of solar PV potential on buildings reveals a significant technical capacity, particularly in the Eastern region. Although uncertainties and real-world limitations may influence

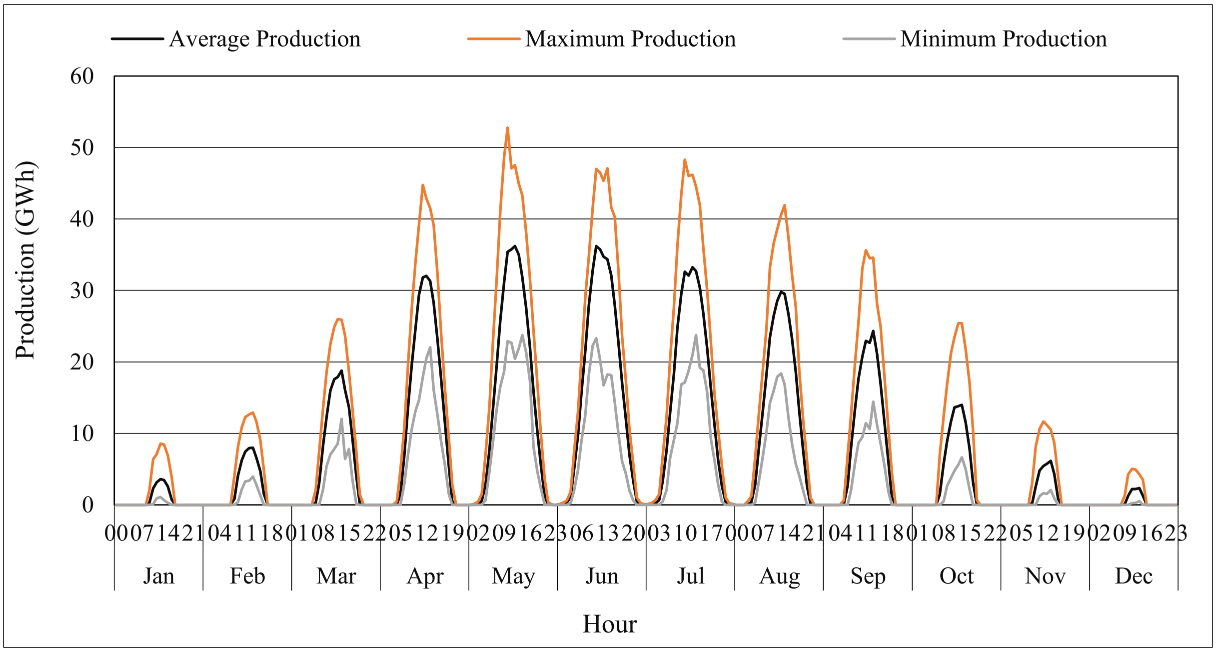

Fig. 10. The minimum, maximum and average hourly production of the solar system for a day of each month in Norway.

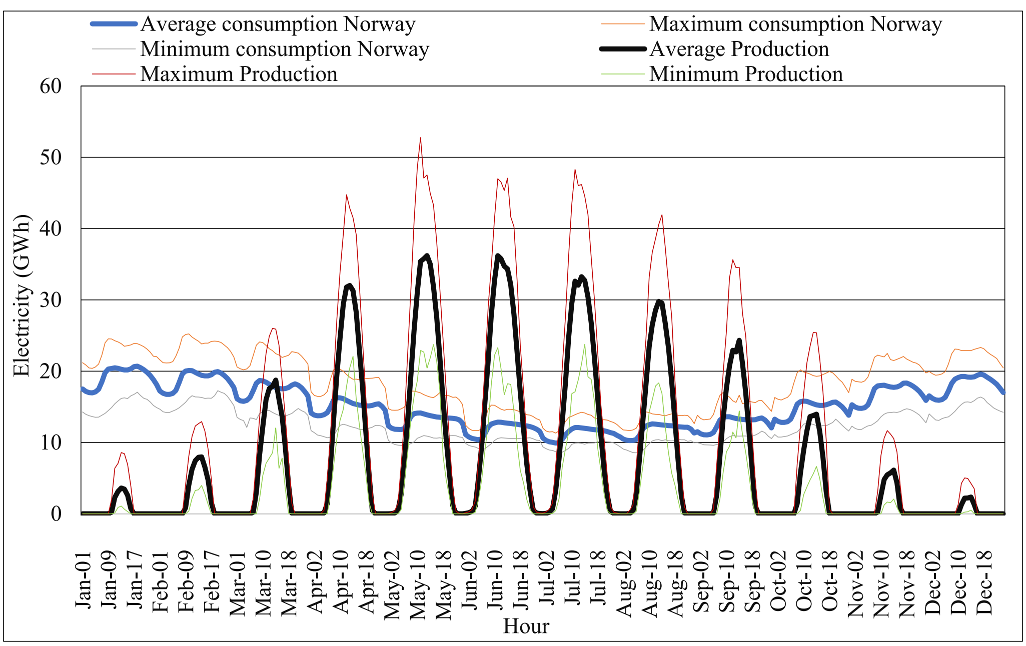

Fig. 11. The minimum, maximum and average hourly potential of solar power production and power consumption for a day of each month in Norway.

practical implementation, ongoing technological advancements are expected to enhance solar energy utilization.

The research highlights the critical relationship between energy consumption and solar energy production. A key discovery is the identification of a crucial threshold: up to 36 % of the feasible solar energy, roughly 31 GWp, can be integrated into the power system to match daily generation and consumption. However, surpassing this threshold presents challenges during periods of high production, necessitating exports or alternative approaches to manage surplus energy.

In conclusion, this study advocates for exploring and adopting solar energy solutions within Norway's energy landscape. By harnessing solar power potential, implementing effective energy management practices, and addressing challenges, Norway can transition toward a more sustainable energy future. Embracing solar energy will not only reduce the country's carbon footprint but also contribute to global endeavors in mitigating climate change. The research findings offer valuable insights for policymakers, urban planners, and energy system designers aiming to advance sustainable energy practices and unlock the full potential of solar power in Norway.

CRediT authorship contribution statement

Hassan Gholami: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

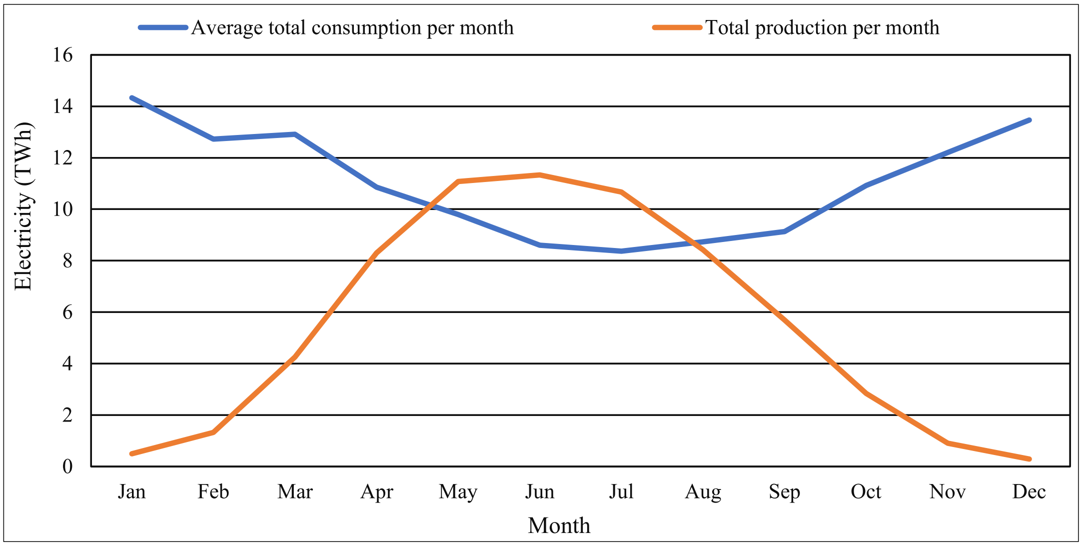

Fig. 12. Monthly solar energy potential and the electricity consumption in Norway.

Table 15
PV capacity limit in the first 30 critical hours of the year.

Month/ Hour	Average consumption (GWh)	Average PV Production (GWh)	Max PV Capacity (%) of 87 GWp meeting demand
Jun-11	12,853	36,197	36 %
Jun-12	12,832	35,771	36 %
May-13	13,886	36,212	38 %
Jun-13	12,771	34,717	37 %
May-12	14,009	35,756	39 %
Jun-14	12,708	34,350	37 %
May-11	14,136	35,405	40 %
May-14	13,767	35,003	39 %
Jul-13	12,053	33,249	36 %
Jul-14	11,979	32,718	37 %
Jul-11	12,091	32,622	37 %
Jun-10	12,748	32,785	39 %
Jul-12	12,108	32,065	38 %
Jun-15	12,672	32,120	39 %
Jul-15	11,936	30,391	39 %
May-15	13,668	31,859	43 %
Jul-10	11,891	29,525	40 %
Aug-13	12,511	29,786	42 %
Aug-14	12,453	29,546	42 %
May-10	14,122	31,086	45 %
Apr-13	15,667	32,022	49 %
Aug-12	12,575	28,559	44 %
Apr-12	15,902	31,792	50 %
Apr-14	15,473	31,308	49 %
Jun-16	12,595	27,954	45 %
Jun-09	12,599	27,913	45 %
Jul-16	11,861	26,764	44 %
Aug-15	12,413	26,722	46 %
May-16	13,578	27,547	49 %
Aug-11	12,602	26,501	48 %

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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