Türkiye can expand solar by 120 GW through rooftops

Türkiye's rooftop solar potential is close to ten times its current installed solar capacity - enough to meet 45% of electricity consumption.

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Translation

About

This study considers potential for expanding solar rooftop capacity in Türkiye, alongside potential benefits and routes towards policy implementation.

Analysis of high resolution satellite images is used to assess what solar panels can be installed on rooftops, outside the 11 provinces of Türkiye declared as disaster areas. By calculating the capacity and electricity production potential for each province, this then demonstrates the extent to which electricity consumption can be met through expanded rooftop solar. The analysis concludes with policy recommendations for Türkiye, taking into consideration global policies regarding rooftop solar energy, as well as the context of electricity tariff subsidies in Türkiye.

Highlights

120 GW

Technical potential of solar power on Türkiye's rooftops

45%

The share of total electricity consumption in Türkiye that can be met from rooftops

$3.6 bn

Subsidies for residential power that can be reduced by rooftop solar

Executive Summary

Rooftops offer a path to solar goals

Rooftop solar is an invaluable tool in expanding clean power. It does not require land and generates power at the point of consumption, making it more affordable and efficient. It will play a critical role in the economy by mitigating the EU carbon border levy's impact on Turkish exports, and will underpin development efforts by providing people with the opportunity to produce their own electricity. The future of rooftop solar will also have an important impact on fiscal policies by reducing the need for subsidies in electricity tariffs.

01 Türkiye's rooftop solar power potential is at least 120 GW

Türkiye's rooftop solar potential is close to ten times its current installed solar capacity. The top three provinces for total rooftop solar potential are Istanbul (10.4 GW), Ankara (10.1 GW) and Izmir (9.3 GW), the provinces with the highest population. As flat roofs are usually found on industrial facilities, industrialized provinces such as Kocaeli (2.5 GW), Manisa (3.1 GW) and Tekirdağ (1.9 GW) ranked just behind large provinces in flat roof potential despite not being as populous. Housing types also affected the results. Despite being the 31st province by population, Afyon ranks fourth in pitched roof potential with 2.8 GW, as more than half of the population resides in buildings with two or fewer floors. In terms of roof suitability rates, Central and Central Western Anatolian provinces such as Uşak, Afyon, Eskişehir and Kütahya stand out with rates above 40%.

02 Rooftop potential can meet 45% of total electricity consumption

Potential generation from 120 GW of rooftop capacity can cover 45% of Türkiye's 2022 electricity consumption. With its production potential of 11.4 TWh, Istanbul is behind Ankara (12.5 TWh) and Izmir (12.4 TWh), which have higher solar potential. Konya (8.6 TWh) follows the three major provinces, followed by Manisa (6.4 TWh), Bursa (5.4 TWh), Afyon (5.3 TWh) and Balıkesir (4.7 TWh), similar to the capacity ranking. When looking at the ratio of rooftop electricity generation potential to billed electricity consumption, provinces such as Afyon, Çorum, Iğdır, Kırşehir and Yozgat stand out with a potential more than twice their electricity consumption. The rooftop electricity generation potential of metropolitan cities such as Konya (113%), Ankara (88%) and Izmir (76%) is also high relative to billed electricity consumption.

03 Rooftop installations worldwide reached half of new solar capacity

A total of 239 GW of new solar capacity was added worldwide in 2022, with nearly half of this (118 GW) installed on rooftops. Newly installed rooftop solar power plants in 2022 increased by 49% compared to the previous year. Solar generation among leading countries is driven by rooftop installations. In Australia, top for solar capacity per capita as of 2022, one in every three houses has rooftop solar. The Netherlands sources 40% of solar generation from residential rooftops. In Germany, third for solar capacity per capita globally, over 60% of newly installed solar power plants each year are set up on rooftops, or in some years over 80%. In the European Union, as of the end of 2022, 66% of installed solar capacity was on rooftops.

04 Rooftops in Türkiye could reduce residential subsidies, currently funded at $3.6 billion

Rooftop solar expansion would see increased self-consumption, replacing the need for use of electricity from the grid, which is currently subsidized, per official statements. The potential for solar to reduce the need for this support is particularly impactful for residences, which have the lowest electricity tariff due to subsidies. The subsidy amount reached approximately $3.6 billion from September 2022 to August 2023. Domestically produced solar, especially in residences, could reduce fossil fuel imports and reduce the real cost of electricity in the country.

Rooftops are prioritised in energy transition policies across the world - and for good reason. Türkiye, which has ambitious solar targets, has a rooftop potential almost ten times its installed solar capacity. In addition to the current potential of roofs, tens of thousands of new buildings are being constructed every year in Türkiye with the rebuilding effort in the earthquake zone raising this figure even higher. Introducing rooftop solar obligations for new buildings and public buildings, and the tendering of suitable apartment building roof areas by municipalities can both help Türkiye achieve its energy targets and enable people to generate their own electricity cheaply.

Ufuk Alparslan
Regional Lead
Ember

Widespread benefits from rooftop solar power

Solar generation from rooftops is not only important in terms of energy and environmental policies; expansion can also benefit Türkiye in terms of industry, growth, development and fiscal policies.

Solar's share lags behind its potential

Although Türkiye has a higher solar energy potential than most European countries, this has not yet been reflected in electricity generation. The share of solar in electricity generation in Türkiye increased to 4.7% in 2022, lagging behind northern European countries such as the Netherlands (14%), Estonia (6.3%) and Denmark (5.8%), which have lower potential and smaller surface area compared to Türkiye.

This remained true in the first half of 2023. From January to June, the share of solar generation in Türkiye increased to 5.7% compared to the same period last year. However, it lagged behind a northern country, Poland, in the same period (6.6%). Poland, which had a share of solar electricity production below 1% in 2019, managed to surpass Türkiye in 2023.

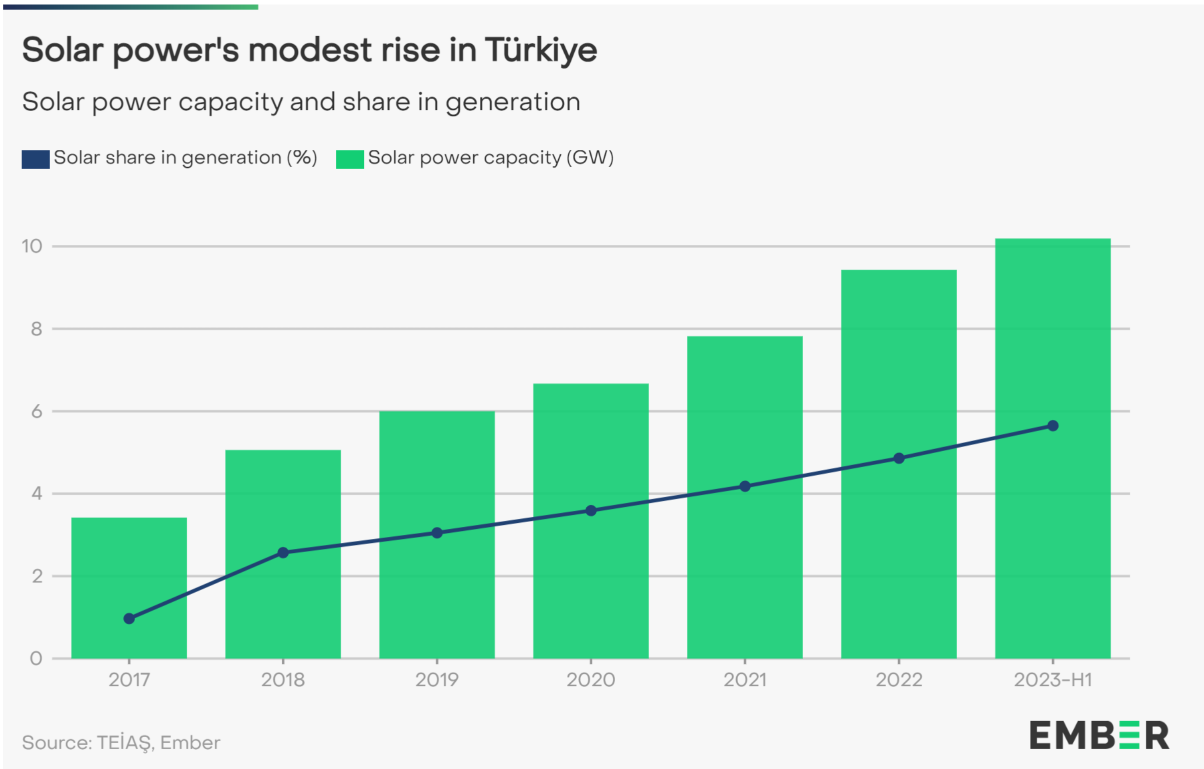
Status of rooftop solar in Türkiye

The installed capacity of rooftop solar power plants (SPPs) in Türkiye is not included in official statistics. Although information on the share of unlicensed solar power plants for self-consumption is available, these plants can also be ground-mounted. Looking at the total solar installed capacity, an average of 1.2 GW has been added annually for the last five years. In 2023, a new solar capacity of 1.8 GW was commissioned as of the end of November, bringing the total solar installed capacity to 11.2 GW.

Rooftop SPPs facilitate the management of the electrical system network due to electricity production at the same point as consumption and proximity to population centers where electricity demand is high. For this reason, in many countries, steps are being taken to pave the way for roofs to produce electricity. The monthly net-metering regulation published in

Türkiye in 2019 has been one of the important factors opening the door for rooftop solar power.

With the change in regulation, solar power plants established for self-consumption are exempt from the obligation to obtain a production license or establish a company, provided that they are on residential roofs. In addition, it became possible to earn extra income by selling excess electricity at the consumer rate through monthly net metering. However, this regulation, which limited self-consumption oriented panels to roof and facade applications, has not generated new momentum in the increase in installed solar capacity.



Impact on industry

Türkiye's energy landscape will be affected by the introduction of the Carbon Border Adjustment Mechanism (CBAM), which came into effect with a pilot application in October 2023. It will impose financial obligations on companies in certain sectors that export to the European Union countries, depending on their emissions, starting from 2026. The CBAM will initially cover cement, iron and steel, aluminum, fertilizer, electricity and hydrogen.

In order to avoid the cost from CBAM and not be at a disadvantage compared to competitors in the sector, industry will need to plan to decarbonize production processes where possible.

Where this can be achieved most rapidly will be by bringing down emissions from electricity use, which already has cost effective low carbon alternatives available.

Emissions from electricity consumption, which are indirect emissions included in the Scope 2 category, are set to be included in the scope of the cement and fertilizer sectors once the CBAM transition period is completed. In addition to including indirect emissions, the possibility of increasing the number of sectors initially determined will be considered during the CBAM transition period, so the impact could widen in future.

For a facility's electricity consumption to be considered as sourced from clean energy within CBAM's rules, it must be produced within the relevant facility or purchased through a bilateral agreement. This means that the electricity production of unlicensed power plants established outside the facility land will be taxed as if consumed from the grid. Rooftop solar power plants installed within facilities therefore offer one route forward for industry to avoid penalties from CBAM.

The critical role of housing

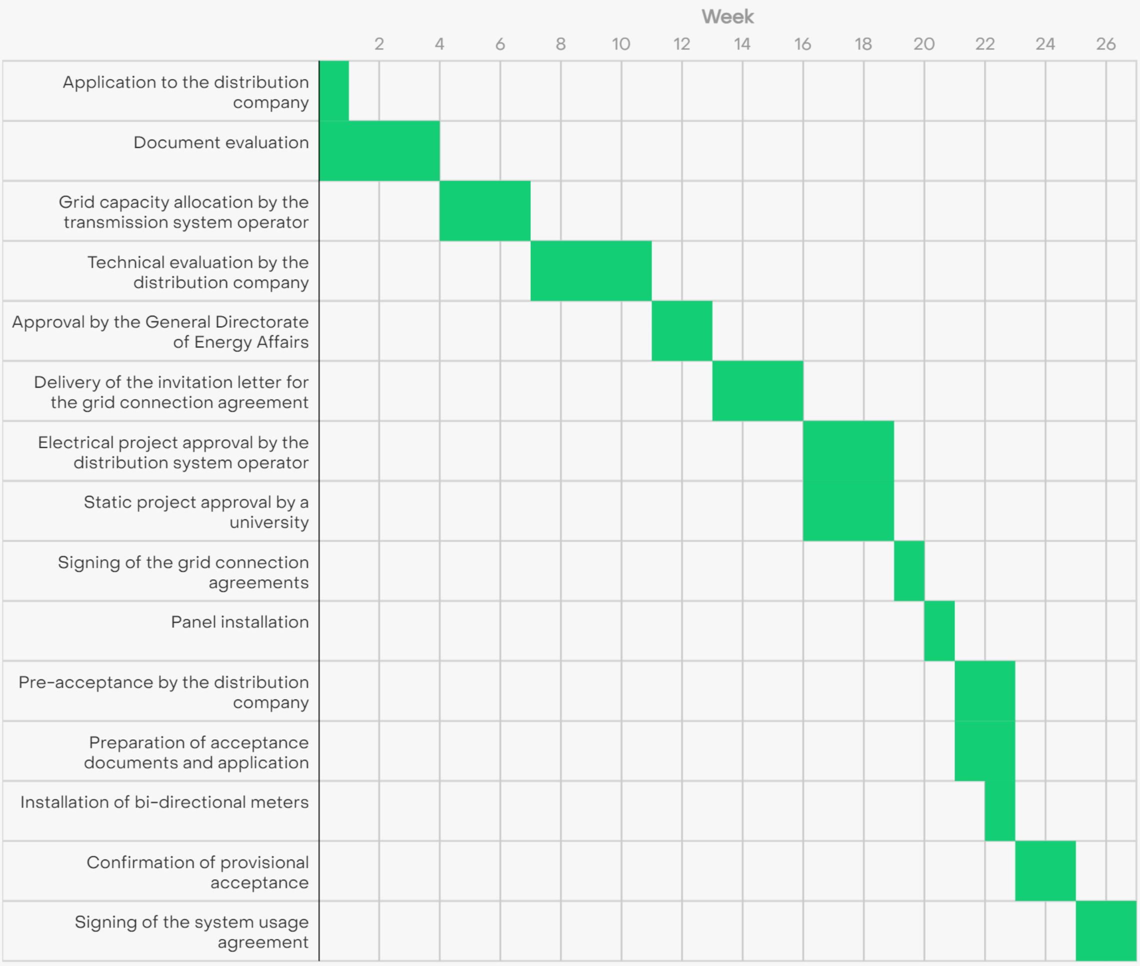
Rooftop solar also offers benefits to households. From the perspective of individual homeowners, rooftop solar power plants stand out as the first choice for those who want to be part of the energy transition, given their accessibility and affordability. However, ownership of a house is a pre-requisite in order to install a rooftop solar power plant. Apartment dwellers face limitations on the installation of solar panels for personal energy generation. Instead of household consumption, solar panels installed on the roof of an apartment building are typically used for shared electricity consumption purposes such as elevators and lighting.

In Türkiye, residential consumers who want to generate their own electricity by installing rooftop solar systems must undergo a lengthy bureaucratic process. Approval must be obtained from different organizations, such as the distribution company responsible for the region where the system will be installed, the transmission system operator (TEİAŞ), the General Directorate of Energy Affairs, the distribution system operator (TEDAŞ) and universities.

This process introduces substantial delays. According to a study by the solar energy association Solar3GW, it takes 27 weeks to complete a residential rooftop solar system from application to installation. Of those 27 weeks, only one is spent installing the panels. Therefore, even those who want to install just one panel on their roof must go through a minimum 26-week application process.

Rooftop solar permitting and installation process takes 27 weeks in Türkiye

Number of weeks it takes for each step



Source: Solar3GW

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There are obstacles to residential rooftop solar power installation other than the bureaucracy of the application process. According to the 2021 Population and Housing Census statistics of the Turkish Statistical Institute (TÜIK), 60.7% of households in Türkiye own the house in which they live. According to TÜİK's 2021 Building and Housing Qualifications Survey, only 11.7% of households living in residences reside in single-story buildings.

Electricity generated on residential rooftops could help reduce the need for energy subsidies. According to official statements, national electricity tariffs in Türkiye are subject to subsidies of up to 50%. However, keeping electricity rates low does not reduce the cost of electricity —

meeting that gap creates a burden on the treasury budget. Residences, where one quarter of the country's electricity consumption occurs, receive the highest level of support. As more residences use electricity directly from solar panels, they will depend less on the subsidised power, therefore lessening the cost burden to the treasury.

A robust understanding of Türkiye's rooftop solar power potential will serve as a guide for determining how much of the country's planned future solar capacity can be installed on rooftops. Since rooftop solar power systems stand out as a clean energy alternative that can benefit all sectors, decisions taken on rooftop solar expansion will have an impact in industrial, residential and governmental areas. Understanding the potential for rooftop solar generation nationwide can help inform not only Türkiye's energy and environmental policies, but also to navigate the impact and opportunities of CBAM, the development potential from prosumers and impacts on the treasury budget due to subsidies in electricity tariffs.

Rooftop potential

The path to solar targets is through rooftops

With a potential exceeding 120 GW and able to meet 45% of electricity consumption, rooftop solar will play a critical role in Türkiye's energy transition.

Analysing rooftop solar potential across Türkiye

Definitions of potential

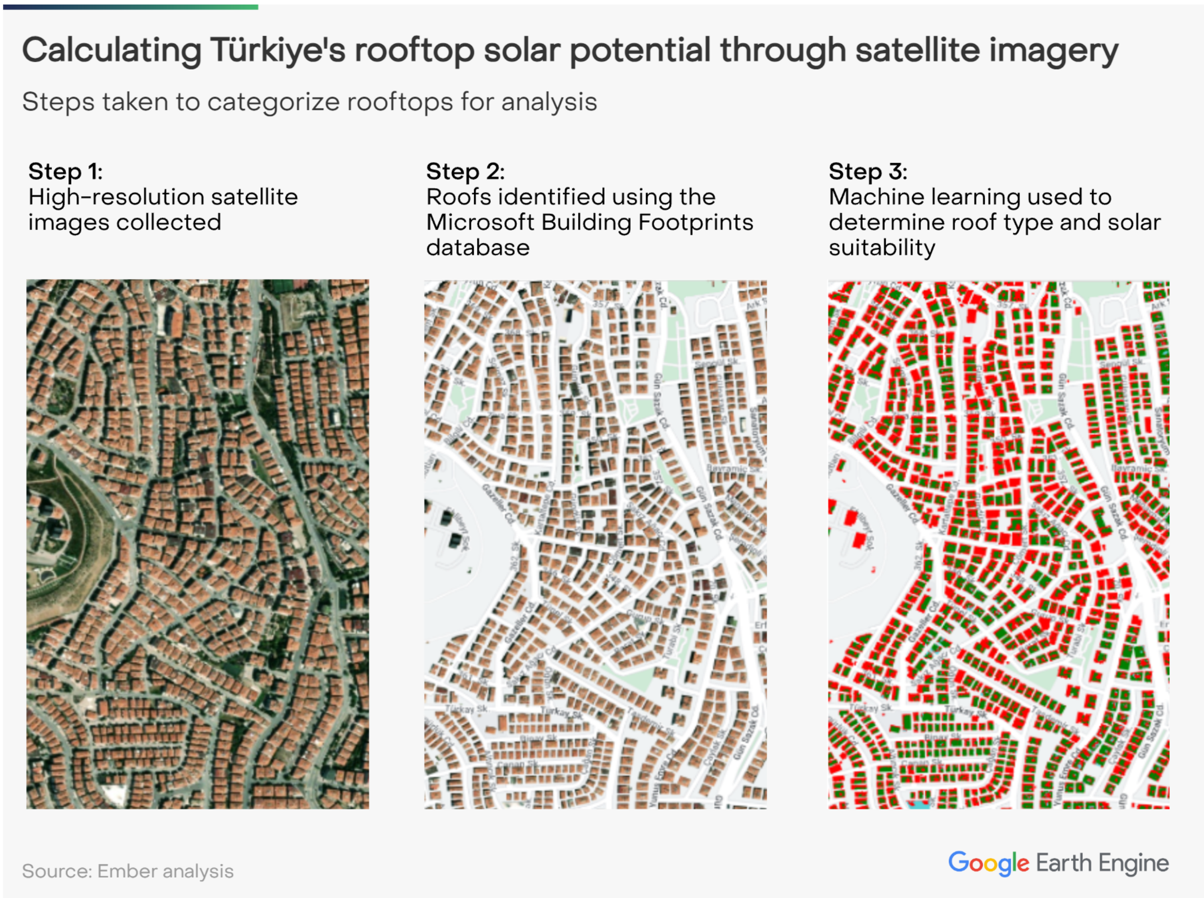
There are multiple definitions of potential for renewable energy sources: theoretical, technical, economic and market potential.

Theoretical potential for rooftop solar is the broadest category. It is calculated by assuming that all building roof areas have solar panels, regardless of their suitability. To determine the technical potential, the roof's suitable areas are taken into account as well. For economic potential, the profitability of potential projects is also considered, while market potential adds additional factors such as grid constraints, market competition and investment climate.

Technological changes, economic conditions and regulations all impact potential. For example, improvements in solar panel efficiency increase the panel capacity per unit area, thus improving all four potentials. On the other hand, panel prices, financing costs, regulatory changes, electricity prices and tariffs directly affect economic potential. Economic potential can therefore change rapidly depending on market and regulatory conditions. For this reason, technical potential provides more stable results - the clearest indication of how much capacity could be installed on roofs if all the suitable area was filled.

Data and scope

This study calculates Türkiye's rooftop solar technical potential by analyzing high-resolution satellite images. Apart from the 11 provinces declared disaster areas following the earthquakes in February 2023, satellite images of the roofs of the remaining 70 provinces were analysed and classified according to their suitability for rooftop solar power systems.



Roofs across the country were identified using the Microsoft Building Footprints database. This publicly available database scans high-resolution satellite images of the earth at regular intervals, using deep neural network methods to publish the coordinates of the detected rooftops. By computing the roof areas of 70 provinces using the coordinates covering Türkiye, the study found a total roof area of 2.8 billion m2.

Google Earth Engine (GEE) software was used to analyse satellite images. Operating through the browser, GEE allows users to process and analyse satellite images via its integrated coding editor. Roof images obtained by cropping roof coordinates from satellite images in GEE were classified into three separate categories (flat suitable roof, pitched suitable roof, and unsuitable roof) with the Random Forest machine learning method.

During the classification of roofs based on their suitability, elements that occupy roof spaces, such as chimneys, antennas, solar collectors, solar panels, in addition to greenhouse roofs for covered cultivation were classified as unsuitable. Accordingly, the total flat and pitched roof area classified as suitable amounted to 772 million m2. In other words, 27.6% of the total roof area was classified as suitable.

To determine the potential solar capacity from suitable roof areas, calculations relied on assessments from rooftop solar installers and rooftop solar projects recently installed in Türkiye. The highest area requirement for a 1 kW rooftop solar power plant installation, 6.4 square meters, was assumed for the estimations. Additional information about the capacity potential calculation is provided in Methodology.

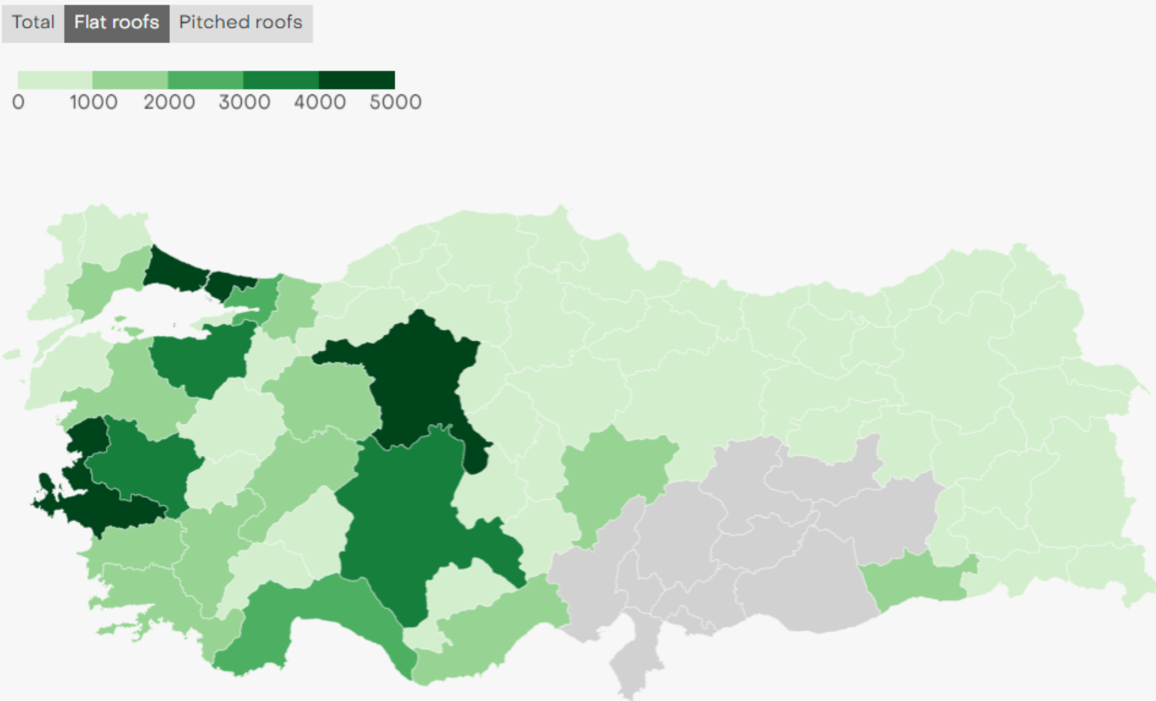
More than 120 GW potential

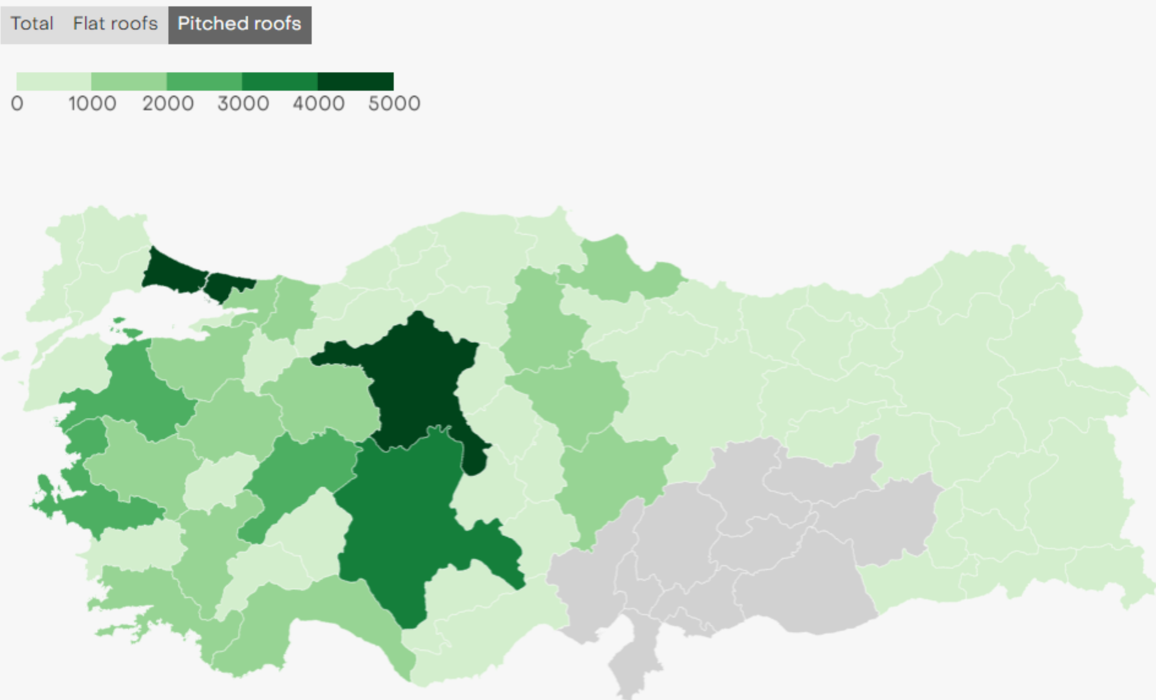
Total rooftop solar capacity potential is estimated at 120 GW, based on the flat and pitched roof areas classified as suitable in 70 provinces of Türkiye. Since the earthquake zone was not taken into account and the potential calculation was done by estimating the rooftop area that would be covered with relatively low-efficiency panels, it is likely that the true technical potential across the country even exceeds 120 GW.

Among the provinces with the highest rooftop solar capacity potential, those that stand out are the three most populated provinces: Istanbul (10.4 GW), Ankara (10.1 GW) and Izmir (9.3 GW). However, the capacity potential of Istanbul, despite its population of 15.9 million, is comparable to Ankara (population 5.8 million) indicating a low potential relative to its population.

Türkiye has at least 120 GW rooftop solar potential

Rooftop solar capacity potential, MW





Source: Ember analysis
Note: Earthquake region is excluded and colored in gray

Taking into account roof types reveals nuances in potential among regions. Izmir ranks first in flat roofs (6.7 GW) out of a total potential of 61.7 GW. Izmir is followed by the other metropolitan cities Istanbul (4.7 GW), Ankara (4.7 GW) and Bursa (3.3 GW). As flat roofs are usually found on industrial facilities, provinces in the top 10 in terms of industry's contribution to the gross domestic product such as Kocaeli (2.5 GW), Manisa (3.1 GW) and Tekirdağ (1.9 GW) ranked just behind large provinces in flat roof potential despite not being as populous.

Outside of the three major cities, Konya stands out in terms of its high potential from flat roofs (3.3 GW) and sloping roofs (3.2 GW). Considering the flat, expansive land area and high solar potential of Konya, the city is one of the most suitable locations for solar energy in the country. Indeed, Konya is home to Türkiye's largest solar power plant with an installed capacity of 1 GWac/1.35 GWdc.

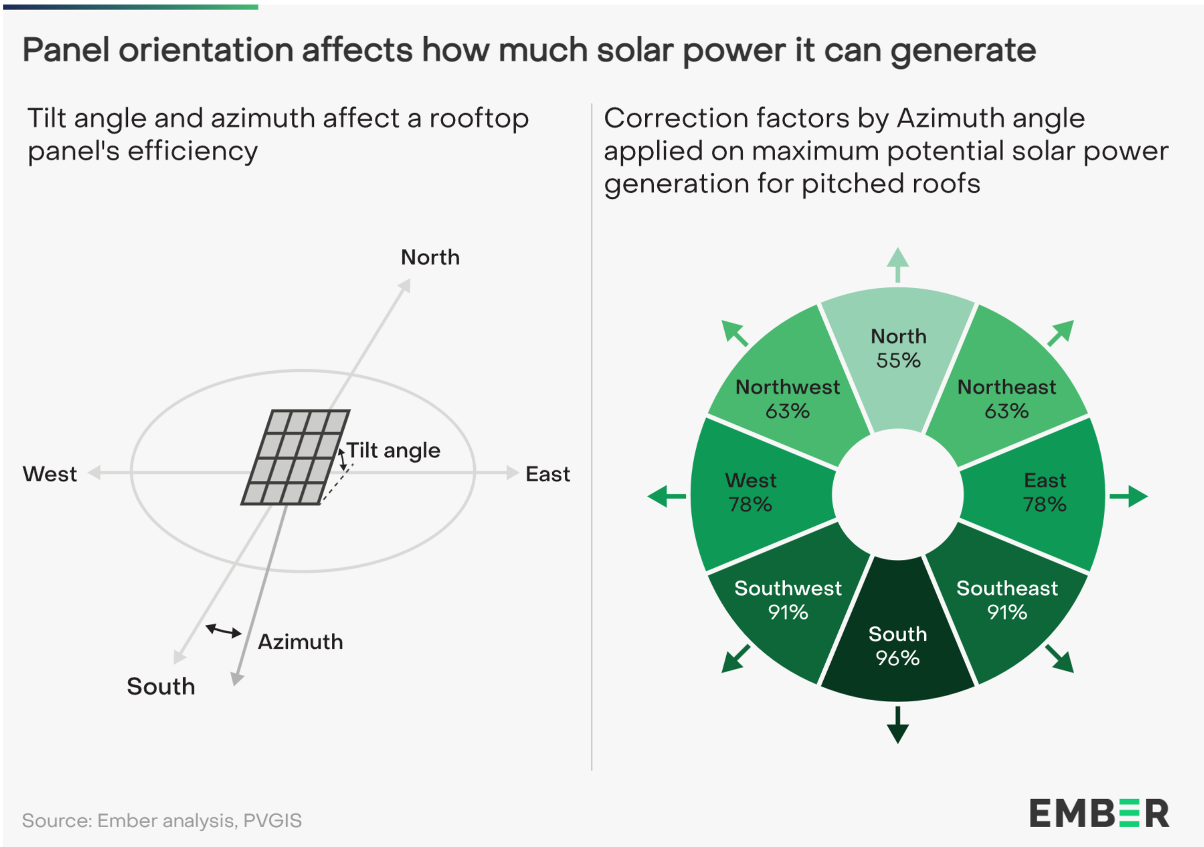
Istanbul (5.7 GW) and Ankara (5.5 GW) hold the highest shares in the country's pitched roof potential of 58.9 GW. The building types where households live also affect the results. While multi-story apartment buildings generally have flat roofs, single-story and detached houses have pitched roofs. For example, Antalya, the fifth most populous city in Türkiye, where 75% of the population is concentrated in multi-story apartment buildings, does not rank among the top 10 in pitched roof potential. On the other hand, although it is the 31st province in terms of population, Afyon, where more than half of the population lives in buildings with two or fewer floors, ranks fourth in this category with a pitched roof potential of 2.8 GW. Another province that stands out in terms of pitched roofs is Balıkesir (2.3 GW).

As for the suitability rate of roofs, Central and Central Western Anatolian provinces such as Uşak, Afyon, Eskişehir and Kütahya stand out with rates exceeding 40%. Afyon, Kütahya, and Kırşehir are notable for their particularly suitable pitched roofs, while Mardin and Siirt rank high due to their flat roofs.

Effect of angles on solar electricity generation

Determining the tilt angle, which represents the inclination of the solar panels, and the azimuth angle, representing the angle relative to south, enables the estimation of electricity production from the capacity potential. Although there are tilt and azimuth angles that optimize the production of electricity from the sun based on the location of a panel, it may not be possible to choose the optimal angle on roofs. On pitched roofs, for example, the slope of the roof determines the tilt angle. Similarly, even though an azimuth facing south is the optimal angle in the northern hemisphere, the direction a pitched roof faces will determine the azimuth of the rooftop solar system.

In production potential calculations, a tilt angle of 0 degrees is assumed for flat roofs. A 10-degree angle in the east-west direction, which can provide higher capacity, or a south-facing installation with an optimal angle for producing the highest electricity per unit capacity can also be considered. Each option has advantages and disadvantages. For pitched roofs, a slope of 33 degrees is assumed. The previously used roof coordinates database was used to calculate the direction that the pitched roofs face, giving the azimuth.



The azimuth angle calculated for each sloping roof is classified into eight equal portions of 45 degrees according to direction: north, northeast, east, southeast, south, southwest, west, northwest. Analysis of satellite images shows that most of the roofs in Türkiye are oriented in the north-south direction. The share of roofs facing north-south varies between 45-60%, depending on the province. The capacity potential of just the south-facing sloped roofs is 15.2 GW.

The type and direction of the roofs determine the angle of panels. As a result, the electricity produced by a rooftop solar power plant is less than the maximum production of an optimally positioned power plant of the same capacity.

In analysing solar generation potential, the maximum production that the estimated capacity potentials could produce at optimal angles was first calculated at the district level, followed by applying correction factors according to roof type. For example, a flat roof with a zero tilt angle can produce 84% of the electricity that would be produced at an optimal angle. The correction factors applied for the eight pitched roof types according to the direction they face are summarized in the figure above. More detailed information on the production estimation process can be found in the Methodology.

Potential reaches 45% of electricity consumption

Applying the correction factors to the generation potential of optimal-angle roof types for each roof in 70 provinces provides an annual rooftop solar power generation potential of 148 TWh. This amount corresponds to 45% of Türkiye's total electricity consumption in 2022.

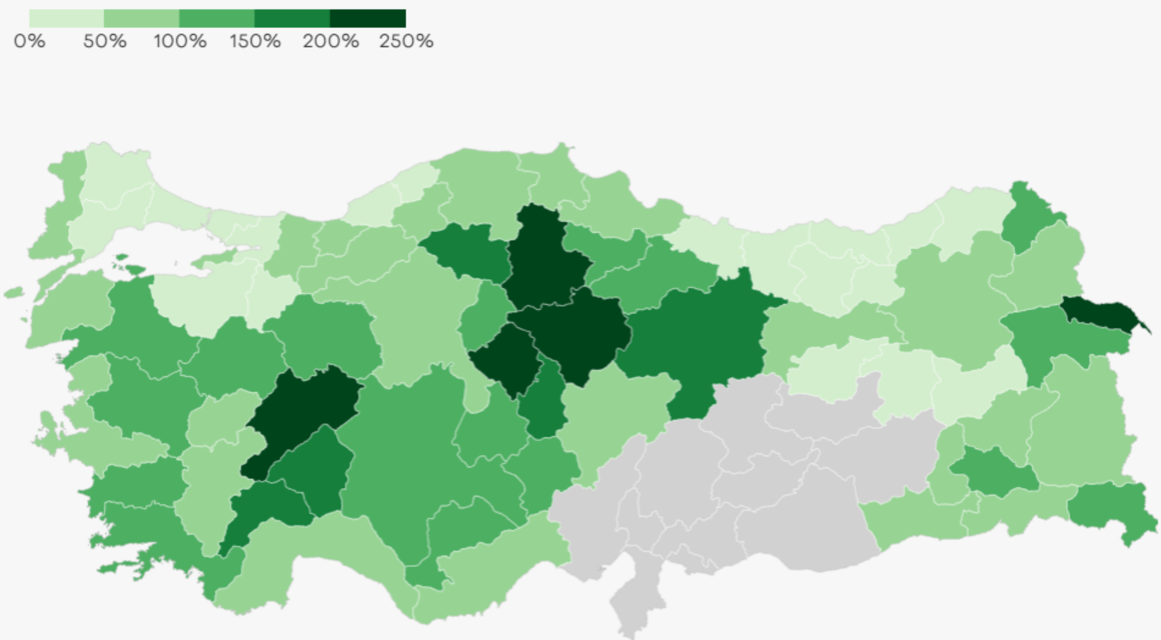
Although it ranks first in capacity potential, Istanbul, with its production potential of 11.4 TWh, lags behind Ankara (12.5 TWh) and Izmir (12.4 TWh), both of which have higher solar potential. Konya (8.6 TWh) follows the three largest cities. Manisa (6.4 TWh), Bursa (5.4 TWh), Afyon (5.3 TWh) and Balıkesir (4.7 TWh) follow, in line with their capacity potential rankings. The other two provinces in the top 10 regarding electricity production, Antalya (5.5 TWh) and Muğla (4.5 TWh), are ranked higher here compared to their capacity potential ranking because of their high solar potential.

When we look at the ratio of rooftop solar power generation potential to billed electricity consumption by province, those with potentials more than twice their electricity consumption such as Afyon, Çorum, Iğdır, Kırşehir and Yozgat stand out. Among these provinces, the low electricity consumption of Iğdır (0.22 TWh) and Kırşehir (0.53 TWh), the high roof suitability rate (46%) of Afyon, and the low per capita electricity consumption of Çorum and Yozgat contribute to their high ratios of rooftop solar power potential to electricity consumption.

Metropolitan cities like Konya (113%), Ankara (88%) and Izmir (76%) have significant rooftop solar generation potential relative to their billed electricity consumption. However, in northern, less sunny, industrialized cities like Istanbul (27%) and Bursa (42%), which have high electricity consumption, rooftop solar generation potential remains low. Antalya, another densely populated province, has a ratio of 59% despite its southern location due to the low suitability rate of its roofs.

Rooftop solar can cover 45% of electricity consumption in Türkiye

Rooftop solar potential as a percentage of electricity consumption by province (2022)



Source: Energy Market Regulatory Authority (2022 Invoiced electricity consumption by province), Ember analysis
Note: Earthquake region is excluded and colored in gray

The rooftop solar potential of the western provinces is significantly higher compared to eastern provinces. Although population density and industrialization are higher in the western provinces, the exclusion in this report of major industrialised eastern cities declared disaster areas such as Adana and Gaziantep as well as metropolitan cities such as Şanlıurfa, Diyarbakır, Hatay and Kahramanmaraş also affected this result. The 11 provinces outside the scope of the study comprise 16% of the total population.

The role of roofs in capacity targets

According to the National Energy Plan published by the Ministry of Energy and Natural Resources at the end of 2022, Türkiye plans to increase its solar power capacity to 52.9 GW by 2035. The 12th Development Plan published in October 2023 foresees a solar capacity target of 30 GW to be achieved by the end of 2028. In other words, the aim is to install 3.8 GW of solar power plants every year between 2024 and 2028.

Although targets highlighting solar energy have been announced in the National Energy Plan and the 12th Development Plan, no information has been provided regarding the types of solar power plants that will contribute to these targets. It is therefore not clear what planned capacity will be installed on rooftops, land or water surfaces.

Türkiye's technical potential of at least 120 GW of rooftop solar capacity indicates that rooftops will play an important role in achieving the country's solar energy capacity targets. Given the absence of land requirements, the ability to generate electricity in the same place as consumption, and the potential for participation from individuals across all sectors, future goals should include the development of appropriate policies to help rooftops actively contribute to energy transition and economic development.

Global examples

Rooftop solar incentives are expanding worldwide

The need for clean and reliable electricity is driving countries to take advantage of their rooftops.

Rooftop solar is supported by a multitude of policies

Many countries, from the Netherlands to China, from Montenegro to South Africa, implement policies that support the installation of solar power plants on rooftops. These practices include net metering, feed-in tariffs, tax incentives and subsidy policies. Regulations also include installation obligations and requirements for construction suitable for rooftop solar power plants.

Countries that have successfully implemented these policies have seen accelerated installation of solar power plants on rooftops, surpassing land-based installations in some cases (China, for example). On the other hand, in some countries such as South Africa, where energy supply security is not guaranteed, there have been spontaneous shifts by the public toward rooftop solar, followed by policy support or regulatory frameworks.

Virtual net metering for apartment rooftops

Countries aiming to expand electricity production on roofs first introduce net metering. With net metering in place, electricity produced by solar panels is periodically deducted from the amount consumed. The consumer then pays a lower bill aligned with the degree to which they cover their own consumption. If production exceeds consumption, the consumer can also profit by supplying extra electricity to the grid.

With physical net metering, a separate meter is needed for each consumption point to measure the electricity taken from and supplied to the grid. In buildings with more than one household, such as apartment buildings, virtual net metering is used to proportionally offset the production with the consumption for each meter. In this practice, where there is no physical connection between consumer meters and the power plant, the electricity produced is fed into the grid after being offset by the consumption of common areas. Then, financial netting is performed on the bill based on the electricity used by consumers from the grid.

In California, which has been using the net metering system since 1996, virtual net metering programs initiated in 2008 have led to the completion of 87.2 MW of solar power installations on apartment roofs as of October 2023. California has implemented fixed subsidies to facilitate the installation of solar power plants under the programs. High incentives ($1.8/W and $3.5/W) have been provided to systems where the generated electricity is netted with household consumption instead of common areas, with the aim of maximizing the benefits of rooftop solar systems for building residents.

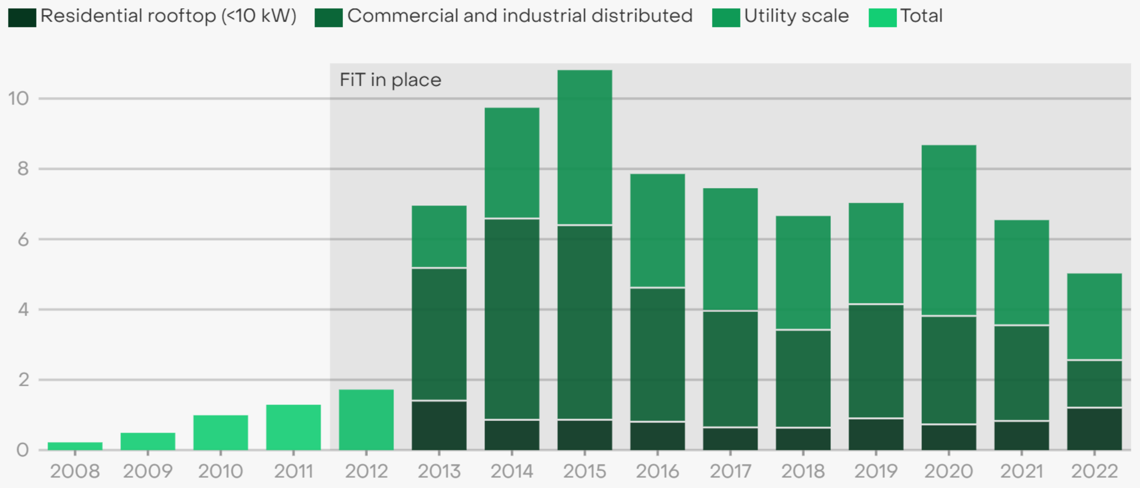
Feed-in tariffs

A feed-in tariff is an incentive method in which all the electricity produced is supplied to the grid at a price determined before installation. As part of this policy, the state provides rooftop solar owners with a power purchase guarantee at a price higher than the retail electricity price for long periods, such as 10 or 20 years.

Japan's breakthrough in solar energy began in 2012 with the introduction of a feed-in tariff for use by both self-consumption and commercial projects. The distributed solar capacity installed by residential, commercial and industrial consumers for self-consumption has been greater than grid-scale installations every year since 2013, except for 2020. As a result, Japan, which has the third-largest solar capacity in the world, derived approximately 60% of its 83 GW installed solar capacity from distributed solar projects in 2022.

Distributed solar has made up over half of Japan's solar capacity additions since 2013, spurred by feed-in tariff

Solar capacity additions by segment (GW)



Source: IEA PVPS, Japan Photovoltaic Energy Association
'Commercial and industrial distributed' category may include ground-mounted systems smaller than 500 kW. Segment breakdown before 2013 not available.

Roof leasing method for post-earthquake housing

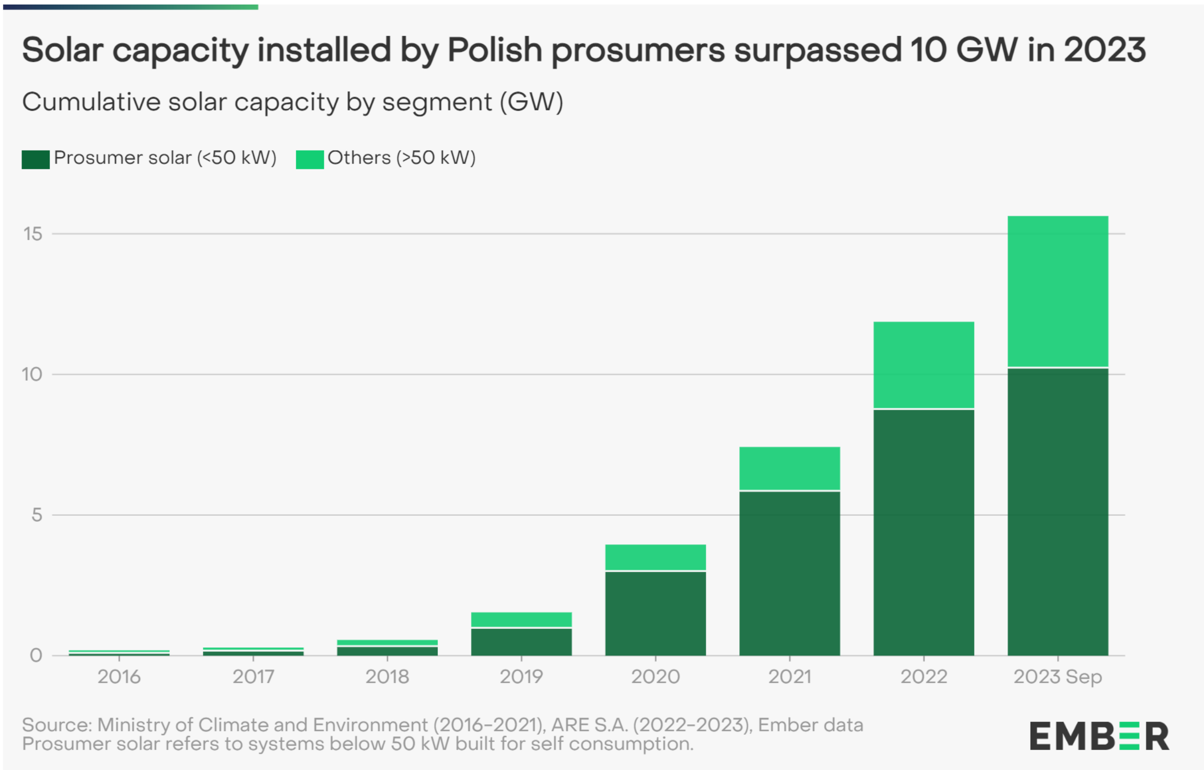
Another exemplary rooftop solar energy system application in Japan is the use of the roof leasing model in social housing built after the 2011 earthquake. In Miyagi, one of the prefectures most affected by the earthquake, the local government leased the social housing roofs built for earthquake victims to project developers for the installation of solar power plants with a total power of 4.3 MW.

In the rooftop leasing model, the project developer earns income by selling the electricity generated from the rooftop power plant directly to the grid while paying rent to the building owner. What makes this business model viable is that the income from electricity sold to the grid through the feed-in tariff is higher than the rent paid for the roof. Through this approach, building occupants can benefit from solar energy without having to bear installation costs.

Small-scale installations in Poland almost match Türkiye's installed solar capacity

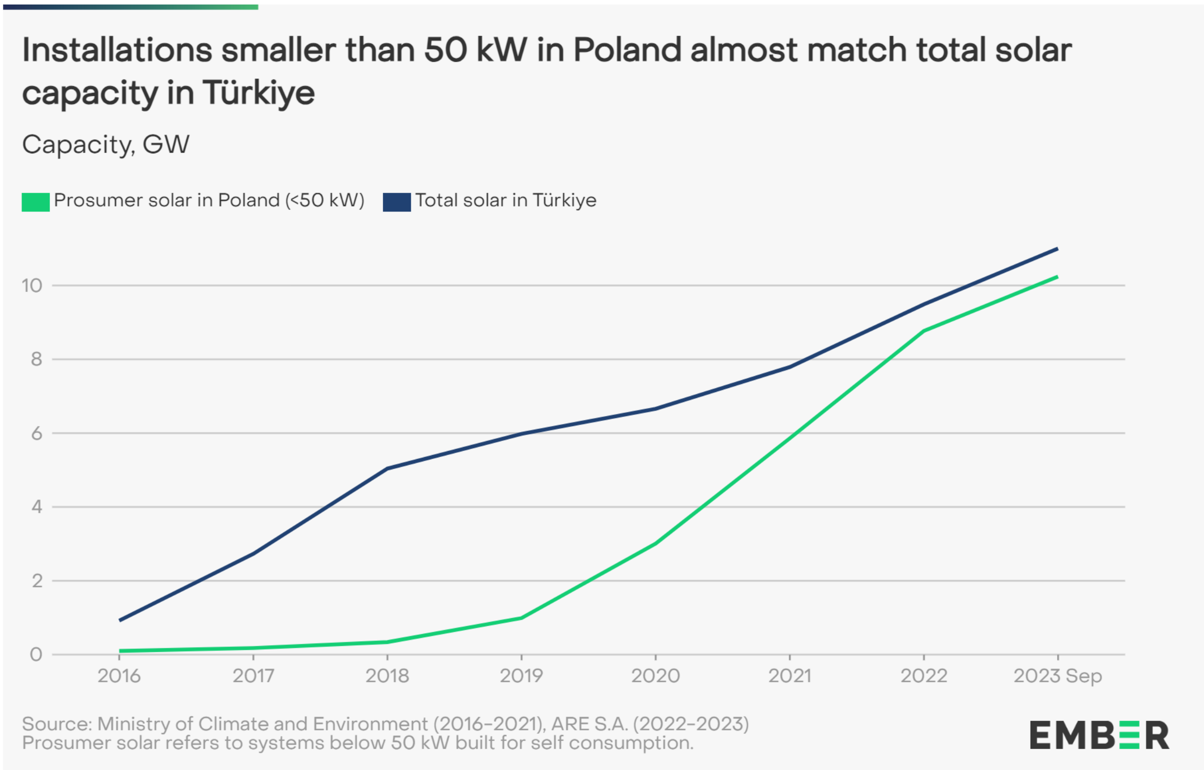
Direct subsidies and tax reductions can also reduce rooftop solar power costs. There are fixed payment policies per unit capacity to alleviate equipment costs and shorten the return on investment period for rooftop solar power projects. In addition, to encourage investment, there are practices such as reducing the value added tax (VAT) on solar panels and deducting expenses for rooftop solar installation from income tax.

A subsidy program called *My Electricity*, which came into effect in Poland in 2019, is a successful example of direct subsidies. Under the program, equipment and installation costs for rooftop solar power systems from 2 to 10 kW are subsidised up to PLN 7,000 ($1,745). As another supportive policy, the VAT applied to residential solar power plants was reduced from 23% to 8% in 2019.



Households and small businesses with systems of 50 kW and below, called prosumers, could benefit from net metering with the grid in Poland until 2022. The number of rooftop solar power plants increased from approximately 51,000 in 2018 to over 1.2 million by the end of 2022, thanks to a more than threefold increase in electricity prices between 2018 and 2022, the My Electricity program and the favourable net metering scheme. Three quarters of the 12 GW solar capacity installed during this period were rooftop power plants.

By the end of 2022, prosumer solar power plants in Poland had reached a capacity of 8.8 GW. With another 1.4 GW capacity added by August 2023, Poland's micro solar capacity was nearly on par with Türkiye's total solar capacity of 11 GW.



Another state policy that aims to reduce system costs through subsidies is the Solari program launched by Montenegro in 2021. Montenegro, with a solar installed capacity of 2.6 MW at the end of 2021, aims to install 70 MW rooftop solar power plants through Solari, with the government undertaking 20% of the solar power plant investment cost. Additionally, VAT on solar panels was reduced from 21% to 7% in January 2023, further lowering installation costs.

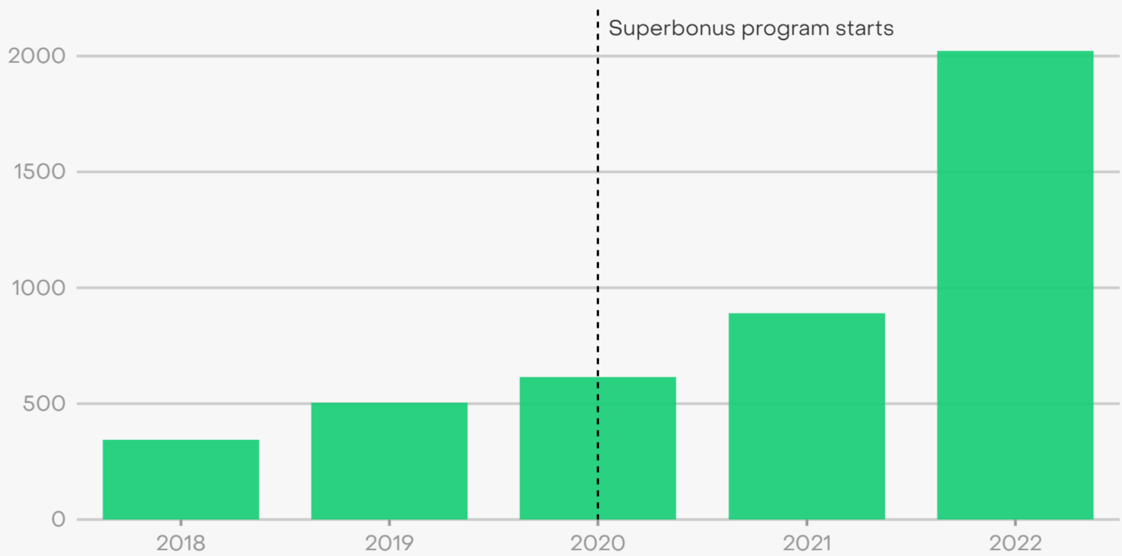
One of the features that make Solari attractive is that program participants can pay the investment cost to the public electricity company in monthly instalments without any payment upfront. The instalment amounts are set not to be higher than the monthly electricity bill of the participants. Since rooftop solar power plants are also subject to annual net metering, participants can become rooftop solar power plant owners without incurring any increase in monthly costs as long as they are able to meet their annual consumption from their rooftops.

Renovation incentives can pave the way for rooftop installations

Policies that support rooftop solar installations together with building renovations are another possible approach. The Superbonus program, started in Italy in 2020, allows for almost all of the investment amount for solar installations to be deducted from taxes when renovations and rooftop solar power installations are undertaken together with the aim of increasing energy efficiency in buildings. 63% of the 890 MW of distributed solar power capacity installed in 2021 consisted of power plants benefiting from the Superbonus. In 2022, distributed solar installations exceeded 2 GW.

Italy's distributed solar installations take off with the Superbonus rebate

Distributed solar capacity additions (MW)



Source: IEA PVPS, PV Magazine
Superbonus is an Italian tax rebate program for home renovations including rooftop solar.

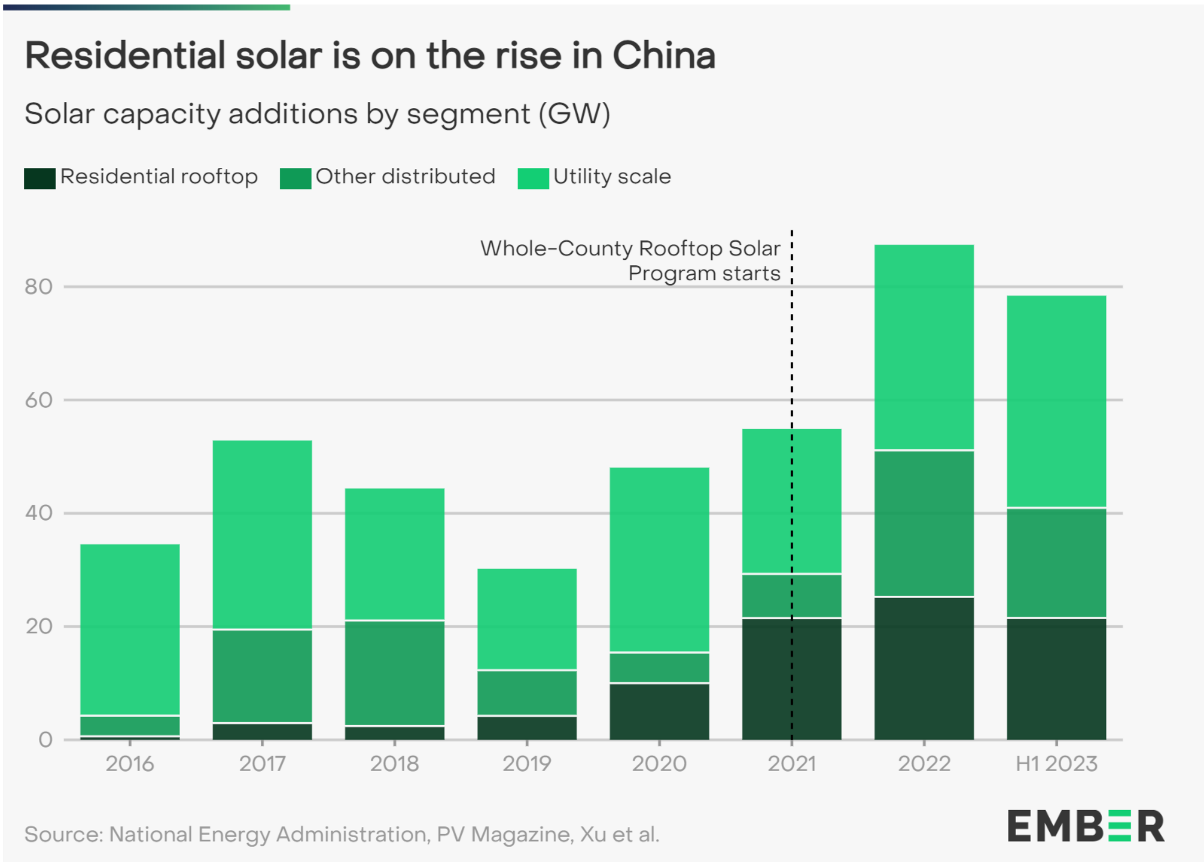
The fact that the renovation types eligible for Superbonus are compatible with rooftop solar plants also encourages installations. For example, including rooftop solar systems during roof renovations for insulation purposes allows both roofing works to be completed together. Moreover, the increased electricity demand resulting from the installation of a heat pump can be met by a rooftop solar power plant installed, at no cost through the Superbonus.

Superbonus also applies when rooftop solar installation and seismic strengthening are done together in residential buildings. In this way, solar energy is promoted while buildings are reinforced, thus providing energy security in case of a disaster.

Installation obligations

In addition to incentives, regulations that impose installation obligations are also used to accelerate the installation of solar power plants on rooftops. Examples of such regulations include building-scale emission reduction and self-consumption requirements. Obligations may vary in accordance with building type, roof area, and number of floors.

China's Whole-County Rooftop Solar policy, which introduced rooftop solar installation obligations, accounted for 53% of the 55 GW increase in solar installed capacity in 2021. Thus, the increase in distributed solar power surpassed that of grid-scale solar capacity for the first time. The momentum continued in 2022, with the commissioning of residential (25.3 GW) and other distributed solar power plants (25.9 GW) making up 58% of the total solar capacity increase.



In the Whole-County Rooftop Solar program, large project development companies are awarded rooftop solar installation tenders in certain districts. Tenders are based on power plant installation quotas determined by building type. Developers who win the tenders have the obligation to install rooftop solar power plants in half of public buildings, 40% of schools and hospitals, 30% of industrial and commercial buildings, and 20% of rural residences.

Complementary policies can further accelerate installations

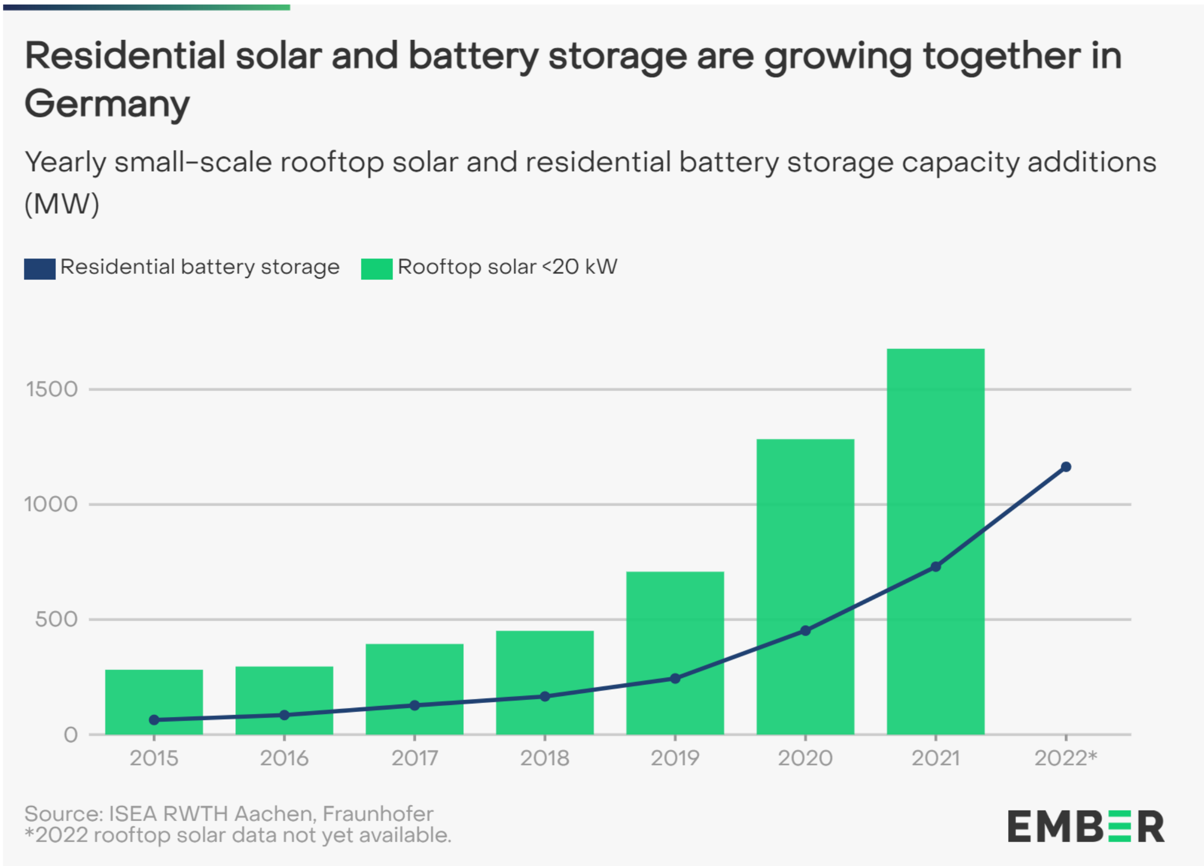
Implementation of multiple mutually supportive policies is key to popularising solar rooftops. One example is the Netherlands, which, despite its small surface area, is the leader in solar generation in Europe. Through a combination of policies including net metering, subsidies, feed-in tariffs and tax incentives, rooftop installations in the Netherlands are approaching 3 GW per year. In addition, there are plans to impose a solar energy installation obligation on non-residential buildings with a roof area of less than 250 m 2 starting in 2025.

In the Netherlands, residential roofs stand out among other installations. Although they could only benefit from net metering prior to the elimination of VAT on solar panels in 2023, solar was still an attractive option due to the average residential electricity tariff remaining higher than the cost of electricity generation from solar. Another factor that encouraged households to install solar power plants has been that, as part of net metering, all excess generation could be fed back to the grid at no cost for later use. Because of this, solar installations on residential roofs increased by an average of 1 GW per year from 2017 to 2022, constituting 44% of the Netherland's new solar power plant installations in 2022 (approximately 4 GW).

The rapid spread of rooftop solar energy in the Netherlands has also resulted in the curtailment of excess solar energy when demand is low. Grid operators can reduce the amount of solar power that is sent to the grid within the net metering framework to maintain system balance. This situation occurred 1,074 times in the distribution region hosting 43% of the Netherlands' solar capacity (8 GW) in the first half of 2022, and 3,476 times in the same period of 2023.

Policies promoting self-consumption and energy storage emerge as solutions to avoid this problem. In Germany, which has the fourth highest solar capacity in the world at 67 GW, the electricity produced by rooftop solar power plants is either used for self-consumption or fed back to the grid through feed-in tariffs. As the feed-in tariffs for residential solar power plants have remained below the electricity price since 2011, self-consumption has become more attractive.

Residential battery storage systems, which enable self-consumption during hours with no generation, increased significantly between 2014 and 2020 with a 71% reduction in costs. The annual growth in residential battery storage capacity paralleled the installation of new rooftop solar systems smaller than 20 kW. Commissioned residential solar power capacity was 1.2 GW in 2020, and battery storage systems saw their first gigawatt-scale increase in 2021, at 1.1 GW.



Self-consumption through rooftop solar power systems and batteries is also supported by incentive programs. For example, in Germany, the government implemented a policy from 2013 to 2018 supporting 30% of the battery cost on a residential scale with low-interest loans. A government-supported program continues to provide loans for rooftop solar and storage, with the condition that no more than half of the electricity produced is fed back to the grid.

Roofs can be a solution to energy insecurity

While rooftop solar installations have accelerated in many countries thanks to proactive policies as part of energy strategies, people have turned to rooftop solar as a solution in countries where energy supply security was hit by crises or war. For example, in Lebanon, where there have been cuts in fossil fuel imports due to the economic crisis since 2021, rooftop solar power installations grew from 14 MW in 2020 to 663 MW in 2022.

South Africa is another example where energy supply insecurity has driven consumers to rooftop solar. In the country, where more than 80% of the electricity production is sourced from coal, the number of days with at least one hour of power outage increased from 14 in 2018 to 181 in the first half of 2023. As self-consumption proved to be a feasible way of overcoming grid unreliability, rooftop solar capacity in South Africa increased more than fourfold from March 2022 to October 2023, surpassing 4.8 GW. This progress, which stemmed from consumer initiative, has started receiving support from the government through policies such as a tax deduction of one-fourth of the panel costs and loan guarantees.

In summary, a salient point in energy transition policies implemented worldwide is the prioritized utilisation of the solar potential on rooftops in electricity generation. When looking at the results of these policies and experiences in different countries, the electricity generated from rooftops is notable not only as a clean energy solution, but also in ensuring energy supply security.

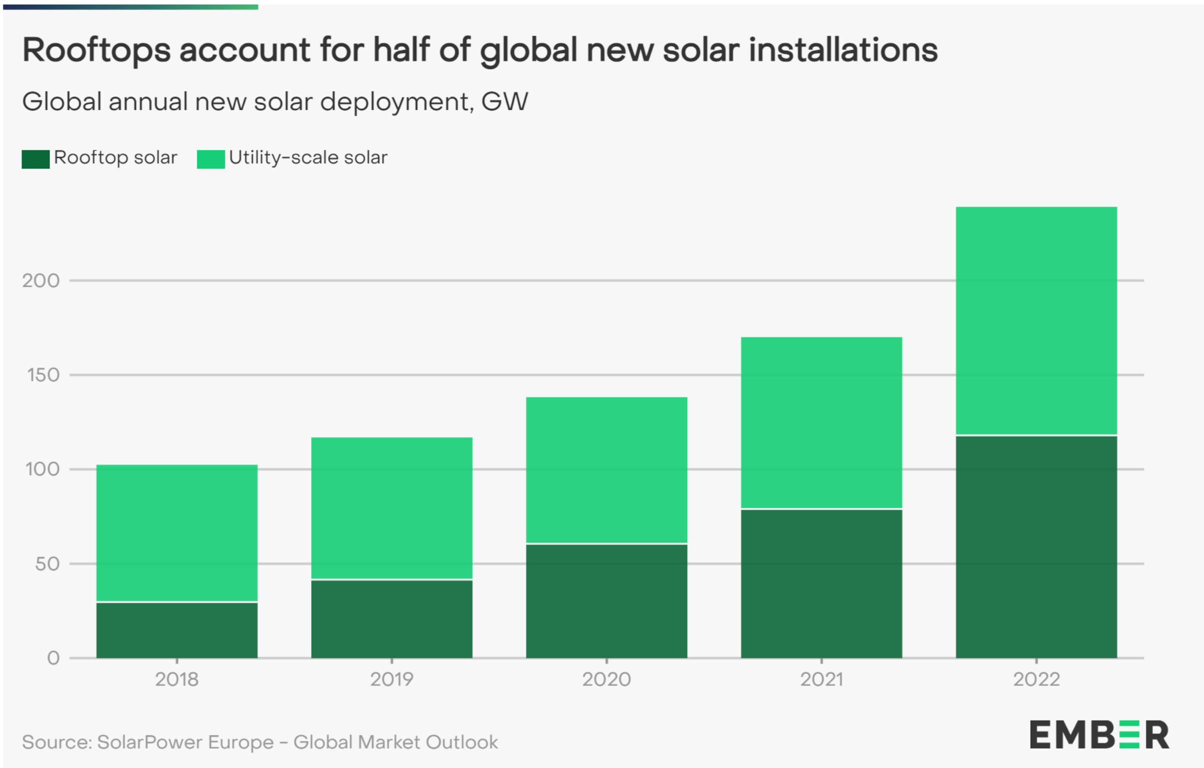
Conclusion

Roofs stand out globally

With installation on roofs being given priority in many countries around the world, the share of roofs in new solar installations worldwide reached 50% as of 2022.

Half of the world's new solar installations are on rooftops

A total of 239 GW of new solar capacity was added worldwide in 2022, and nearly half of this capacity (118 GW) was installed on rooftops. Thus, newly installed rooftop solar power plants in 2022 increased by 49% compared to the previous year. In 2021, the rooftop solar power capacity added worldwide was 79 GW. This is the first time rooftops have attained such a high share of total installations.

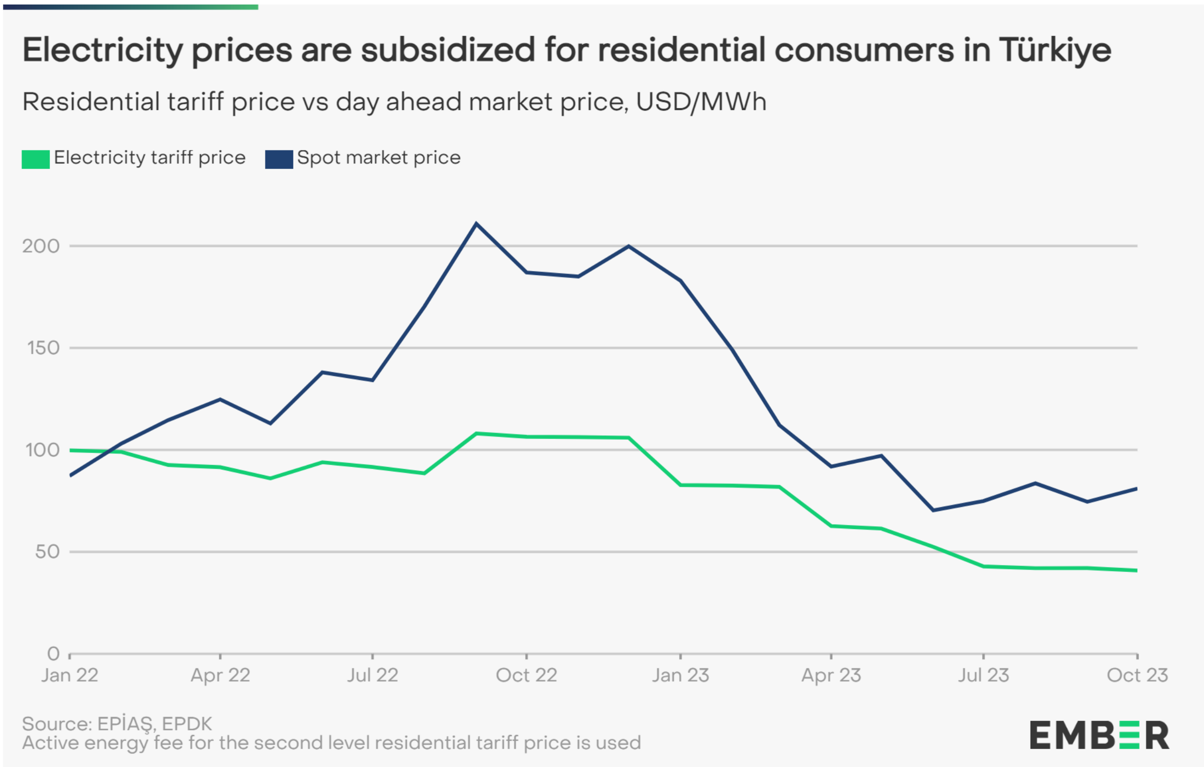


Roofs play an important role in countries that are solar energy leaders around the world. For example, in Australia, the world leader in solar capacity per capita as of 2022, one in every three homes has a solar power plant on its roof. In the Netherlands, which is right behind

Australia, 40% of solar electricity production is obtained from residential rooftops. In Germany, which ranks third in solar capacity per capita, over 60% of the new solar power plants installed each year are on roofs, and in some years this rate can exceed 80%. EU countries stand out in this regard, with 66% of total solar installed capacity on rooftops. Meanwhile, China, where mandatory requirements for rooftop solar installations are in place, installed one in every five solar panels globally in 2022.

Impact of electricity prices on installations

The global energy crisis that emerged from Russia's invasion of Ukraine and the escalation of electricity prices also motivated consumers to generate their own electricity. Particularly in 2022, monthly average electricity prices in wholesale markets in Europe, which reached over 500 EUR/MWh, played a significant role in increasing the number of rooftop installations, as evidenced by the rising share of rooftops in global installations that year. Therefore, the price of electricity can itself be a significant factor in turning a crisis into an opportunity.



Keeping the price of electricity low creates a vicious circle by discouraging consumers from producing their own electricity. Per official statements, subsidies are applied in Türkiye to prevent the energy crisis from directly affecting the electricity prices paid by end consumers. In residences, the consumer type with the lowest electricity tariffs in Türkiye, the subsidy

amount reached approximately 3.6 billion dollars in the 12-month period from September 2022 to August 2023.
Türkiye is dependent on foreign sources for electricity production. As of 2022, 42% of electricity production is derived from imported fossil resources. There are years when this rate approaches 50% due to drought reducing hydroelectric production and increasing electricity demand from year to year. Considering this, policies that promote the widespread use of rooftop solar power plants in Türkiye, particularly in residences, will help reduce the real cost of electricity in the country by reducing its dependence on imported fossil-fuel resources.

New building construction can be turned into an opportunity

The construction industry is an important sector in Türkiye, with approximately 130,000 new building permits issued every year. This number is expected to increase even further in the context of reconstruction following the February 2023 earthquake. According to an announcement by the Ministry of Environment, Urbanization and Climate Change in August, the goal is to reconstruct 319,000 buildings in the region within a year. Although beyond the scope of this study, consideration should be given to rooftop solar potential in structurally sound buildings in earthquake-prone areas. In addition, there are 400,000 urban transformation projects across the country involving the reconstruction of old buildings, particularly in cities at risk of earthquakes.
Türkiye can turn this reconstruction process into an opportunity to reduce foreign energy dependence and ensure supply security. As seen in the example of China, mandating solar installations on rooftops is a quick way to increase the share of rooftops in electricity production. Introducing obligations to install rooftop solar power plants on newly constructed buildings in Türkiye could lead to rooftop solar power plant installations at the gigawatt level in just one year. Mandatory installations for new buildings can be reinforced by policies supporting rooftop installations on public buildings.

Removing obstacles can turn into an incentive

In Türkiye, 88.3% of the population lives in multi-story buildings. However, the current situation has hindered the development of electricity production on apartment rooftops due to shared rooftop ownership and obstacles posed by lengthy decision-making and application processes.

To promote widespread installation of solar power plants on apartment roofs, regional rooftop solar power programs can be designed by the responsible municipality or distribution company in the area. After determining the rooftop solar power potential of the apartments that choose to be part of this program, the total capacity in each region can be converted into a single rooftop solar power tender. While the electricity generated in excess of consumption from the solar power plants to be commissioned continues to be supplied to the grid, the income resulting from excess electricity production can be shared among the apartment residents in proportion to their legal shares on the roof, utilizing a virtual net metering system. The government can support such installations through tax deductions.

While incentives have made a significant contribution to the spread of rooftop electricity production around the world, the removal of obstacles can also have a stimulating effect. In Spain, for example, where the share of solar in electricity production was 11.5% as of 2022, the Solar Tax applied to solar power plants installed for self-consumption was one such obstacle. The removal of this tax in 2018 led to a rapid increase in the country's solar capacity. In fact, the installed rooftop capacity doubled for two consecutive years and reached 3 GW in 2022. Despite being far behind in rooftop solar power potential, Türkiye's policies could likewise lead to a rapid increase in rooftop solar installations.

Methodology

Calculations of capacity potential

In the analysis, the publicly available Microsoft Building Footprints database, which contains more than 1 billion roof coordinates stored as polygons, was used to identify roofs in Türkiye. For this study, the May 2022 update, stored as a "Feature Collection" in the Google Earth Engine, was used. The dataset contains 18,058,257 polygons within the borders of Türkiye, including all kinds of structures with roofs.

More than one source was examined regarding the surface area a 1 kW solar power plant installed on the roof will occupy. According to a UK-based company that lists the most suitable solar panel options for homeowners and enables them to get price quotes, the required roof area is calculated as 6.4 m 2 per kW, assuming panels with less than 20% efficiency and with a capacity of 260 watts. According to a US-based website established to assist consumers in the solar energy sector, and an Australian service provider that lists solar panel suppliers to facilitate obtaining price quotes, the roof area required for 1 kW with panels of 330–400 watts and an efficiency of at least 20%, is from 4.1 to 5.6 m2. When ten random rooftop SPP projects completed in Türkiye in 2021-2022 were examined using satellite images, it was observed that the average area required for 1 kW of rooftop SPP capacity was 6.3 m2. Therefore, taking a conservative approach for the calculations, it was assumed that a 1 kW panel would cover an area of 6.4 m2.

The process of classifying roofs into three separate categories started with a training set including all three types identified in a satellite image containing only roofs for a selected province. In creating the training set, a sufficient number of randomly selected roof images were manually labeled according to the three roof types (flat empty/pitched empty/full). The decision to create a sufficient number of training sets was made using a validation set created completely independently of the training set. The validation set, selected from eight different regions of Türkiye, required the manual labelling of thousands of points in each region according to whether they were flat/pitched/full. Then, a visual classification algorithm designed on Google Earth Engine (GEE) was run to calculate accuracy rates in the validation set, and the training set was expanded and improved to maximize accuracy. The training set was created in Ankara, and the provinces covered by the validation set included Istanbul, Ankara, Izmir, Antalya, Konya, Erzurum, Trabzon and Şırnak. During validation, the final model achieved accuracy scores of 97% for empty pitched roofs, 83% for empty flat roofs, and 89% for full roofs.

Some corrections were applied to the roof areas following classification into three separate categories. The first correction was to reclassify areas with insufficient space for a panel as unsuitable roofs. Another adjustment was made for regions such as Antalya and Mersin, where greenhouse cultivation is common. For these regions, the coordinates of greenhouse roofs were manually identified and likewise classified as unsuitable.

Calculation of production forecasts

To determine the azimuth angles of pitched roofs in each province, roofs with an area between 150 and 500 m² in the Microsoft Building Footprints database were first filtered. This is because the majority of pitched roofs are found among roofs of this size. Assuming that the line dividing a roof into two sloping sides will run parallel to the long side of the roof, the angle between the long side of each rectangle obtained after filtering and the north-south axis was calculated and accepted as the azimuth angle of the roof. The calculated azimuth angles were then classified into categories based on directions, divided into eight equal parts of 45 degrees.

The maximum electricity production for the capacity potential of each district was calculated using the solar potential map published by Solargis (kWh/kWp). To achieve this, the Solargis potential map was uploaded to GEE and the pixel values were averaged for each district. The potential calculation provided by Solargis in this map was made based on the assumption of the production potential of an independent plant with optimum angles. It was thus used as a maximum production estimate. In the Solargis assumptions, inverter efficiency is 98%, loss due to dusting is 3.5%, DC-related loss is 2.3%, and AC-related loss is 0.9%. Correction factors applied to average district kWh/kWp potentials obtained from Solargis were calculated using the PVGIS solar energy production estimation model. For this purpose, tilt and azimuth angles for nine roof types in different parts of Türkiye were selected in PVGIS to calculate the degree to which the production estimate decreased compared to an independent solar power plant. These ratios were then used as correction factors in the analysis. As a final step, the capacity potential calculated for each district in GEE was multiplied by correction factors based on the average maximum production potential for the district and the roof category.

Subsidy calculations

In subsidy calculations for electricity tariffs, the active energy fee applied for low voltage - single rate second tier (above 8 kWh/day) in the Invoice-Based Tariff Tables published by the Energy Market Regulatory Authority (EPDK) was used. Monthly foreign exchange rates of the Central Bank of the Republic of Türkiye were used to convert tariff prices into US dollars. For the wholesale electricity market price, the prices reported in USD/MWh in the Day Ahead Market on the EPİAŞ Transparency Platform were used. The monthly subsidy amount was calculated by multiplying the monthly consumption of residential consumers published in EPDK's monthly reports by the price difference between the two.

Acknowledgements

Thank you

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Image credit

Mikel Bilbao / Alamy Stock Photo