UPPSALA
UNIVERSITET

Master thesis in Sustainable Development
Examensarbete i Hållbar utveckling

A stakeholder-based analysis of potential photovoltaic systems' contributions within the German government's capacity addition plans to 2030

Felix Rüsseler

DEPARTMENT OF
EARTH SCIENCES
INSTITUTIONEN FÖR
GEOVETENSKAPER

Master thesis in Sustainable Development
Examensarbete i Hållbar utveckling

A stakeholder-based analysis of potential photovoltaic systems' contributions within the German government's capacity addition plans to 2030

Felix Rüsseler

Supervisor: Maryna Henrysson
Subject Reviewer: Daniel Adshead

Contents

1. Introduction 1

2. Background 3

2.1. Literature Review 3

2.1.1. Global Studies 3

2.1.2. Studies focusing on Germany 4

2.2. What is energy? 5

2.3. What is renewable energy? 5

2.4. Photovoltaics 6

2.4.1. Technical background and functionality 6

2.4.2. Different solar PV power plants 7

2.5. Solar PV in Germany 9

2.5.1. The energy transition 9

2.5.2. The Up's-and Down's of the German PV market 9

2.5.3. The latest EEG and its regulations for PV 11

2.5.4. PV electricity costs 11

2.5.5. PV environmental compatibility 13

3. Methodology 14

3.1. Research problem and motivation for research 14

3.2. Data collection procedures 14

3.2.1. Conducting the semi-structured interviews 15

3.2.2. Literature analysis to support interviews 17

3.2.3. Data analysis with Grounded Theory Methodology (GTM) 18

3.2.4. Comments on limitations, reciprocity and reflexivity 19

4. Results 20

4.1. Recent dynamics in the PV branch 20

4.1.1. Overall market development 20

4.1.2. Impacts of the EEG amendment 21

4.2. Feasibility of the capacity addition targets 22

4.3. The role of Integrated PV 23

4.4. Contribution of different PV systems for 2030 PV mix 26

5. Discussion 29

6. Conclusion 32

6.1. Possible future work 33

7. Acknowledgement 34

8. References 35

Appendix A – Interview Guide 39

Appendix B – Coding Documentation 46

List of figures and tables

Fig 1. Electricity mix in Germany in 2022 (Own illustration based on Bundesnetzagentur, 2023) 1

Fig. 2. Illustration of solar cells (Mertens, 2014, p.13) 6

Fig. 3. Annual installed PV capacity (Own illustration based on Quaschning, 2023 and BMWK, 2023) 10

Fig. 4. LCOE of different energy technologies in Germany (Own illustration based on Kost et al., 2021) 12

Fig. 5. Stakeholder opinions on whether the long-term PV mix will align with the area potential for different PV systems (Own illustration) 27

Fig. 6. Certificate "Gute Planung" as a best practice approach for ground-mounted systems (bne, 2023) 28

Table 1. Criteria for interview partners (own illustration) 15

Table 2. Stakeholder categorization (own illustration) 15

Table 3. Major challenges to reach the governmental target of 215 GW installed capacity (Own illustration) 22

Table 4. Comparison of positive and negative aspects of integrated PV (Own illustration, values for potential based on Wirth et al., 2021)...24

Abbreviations

Agri-PV	Agriculture photovoltaics
BIPV	Building-integrated photovoltaics
C&I	Commercial and industrial
CO_2	Carbon dioxide
EEG	„Erneuerbare-Energien-Gesetz“ (German Renewable Energy Sources Act)
e-Mobility	Electro mobility
FIT	Feed-in tariffs
GMS	Ground-mounted systems
GW	Gigawatts
IPV	Integrated photovoltaics
kW	Kilowatts
kWp	Kilowatt-Peak
kWh	Kilowatt-hours
LCOE	Levelized Costs of Electricity
MW	Megawatts
PPA	Power-Purchase-Agreement
PV	Photovoltaics
RE	Renewable Energy/Renewable Energies
RIPV	Road-integrated photovoltaics
RTS	Roof-top systems
W	Watts

A stakeholder-based analysis of potential photovoltaic systems' contributions within the German government's capacity addition plans to 2030

FELIX RÜSSELER

Rüsseler, F., 2023: A stakeholder-based analysis of potential photovoltaic systems' contributions within the German government's capacity addition plans to 2030. *Master thesis in Sustainable Development at Uppsala University*, No. 2023/19, 49 pp, 30 ECTS/hp

Abstract: The ongoing energy transition in Germany foresees significant increases in the share of renewable energies in the country's electricity mix until 2030. A share of 80% is targeted and photovoltaics should have a major contribution with a total capacity of 215 Gigawatts aimed to be installed. Since the beginning of the energy transition in Germany, the Renewable Energy Sources Act (EEG) has played a key role with its regulations and support measures. The latest amendment of the EEG in January 2023 includes updated capacity addition targets and regulatory measures. In recent years, the solar branch in Germany has experienced growth after a period of drought from 2013 to 2017. The governmental plans are the basis to enable further growth, but challenges and uncertainties remain if the targets can be reached under the present and anticipated future constraints. This paper presents an evaluation of the feasibility of the capacity addition targets for photovoltaics and outlines the potential contribution of different photovoltaics system types within the installation plans. Through the conduction of semi-structured interviews with different stakeholders of the solar branch in Germany, a large variety of knowledge, experiences, perspectives and assessments is combined to theory which provides answers to the research questions. The results of the data analyses show, that the governmental targets are theoretically feasible but it is doubtful whether they will be reached in practice. Two of the main challenges which will need to be overcome are lacking installation capacities in form of skilled workers and hindering bureaucratic processes regarding planning, approvals, operations and accounting of photovoltaics plants. Moreover, the results indicate that the share of large-scale systems should increase, as scale-effects make them more cost-efficient and more capacity can be installed in the same amount of time. Most of these systems will be ground-mounted, but industrial roof-top systems will also contribute to a certain extent. Furthermore, integrated photovoltaic applications will increase in importance, due to the scarcity of areas and potential synergies. However, most of the stakeholders do not see a major contribution of such systems until 2030, as costs are too high, specific regulations are missing and market awareness is still low. Despite the dominance of large-scale systems, the segment of residential roof-top photovoltaic systems also has a high potential and consumers will want to produce their own electricity due to high energy prices and supply uncertainties.

Keywords: German Energy Transition, Photovoltaics, Photovoltaics System Types, Renewable Energy Policies, Stakeholder Interviews, Sustainable Development

Felix Rüsseler, Department of Earth Sciences, Uppsala University, Villavägen 16, SE- 752 36 Uppsala, Sweden

A stakeholder-based analysis of potential photovoltaic systems' contributions within the German government's capacity addition plans to 2030

FELIX RÜSSELER

Rüsseler, F., 2023: A stakeholder-based analysis of potential photovoltaic systems' contributions within the German government's capacity addition plans to 2030. *Master thesis in Sustainable Development at Uppsala University*, No. 2023/19, 49 pp, 30 ECTS/hp

Summary: Germany has ambitious plans to increase the share of renewable energies in their mix of electricity production to 80% until 2030. As one of the renewable energy sources, solar energy should have a major contribution. More precisely, the technology photovoltaics is meant in that context, through which electricity can be produced.

The governmental plans are included in the newest amendment of the Renewable Energy Sources Act called "EEG", which has been the central policy instrument for renewable energies in Germany. In this 2023 version, a capacity of 215 Gigawatts of photovoltaics plants is targeted to be installed until 2030 and different measures should support this development.

However, it is unclear today whether this target is reachable in practice and also which of the different photovoltaics power plants should contribute to what extent. In this paper, the feasibility of these targets and the anticipated contribution of different photovoltaics plants is evaluated through the conduction of semi-structured interviews with stakeholders of solar energy in Germany. These include representatives from different industry sectors, political- and academic institutions.

The results of the study show that the targets could be reached in theory, but in reality, several challenges still need to be overcome and the targets are not quite realistic. Two of the main challenges derived from the analyses are lacking skilled workers, especially electricians and assemblers, as well as bureaucratic hurdles within planning, approvals, operations and accounting of photovoltaics plants. Regarding the contribution of different system types, the importance of large-scale plants is expected to increase, because of the scale-effects they provide. This means that more ground-mounted photovoltaics plants on fields and large roof-top systems on industrial buildings will be built in the future. Besides, small-scale residential roof-top plants will also remain important, as there is still a great potential and the financial attractiveness of such systems for consumers is high. Furthermore, there are new integrated solutions that include building photovoltaics plants on lakes, agricultural fields, parking lots or in facades. These are only expected to have small contributions until 2030, as they are still too expensive and no certain regulations are in place as of today.

Keywords: Photovoltaics, Renewable Energies, Renewable Energy Policies, Solar Energy, Stakeholder Interviews, Sustainable Development

Felix Rüsseler, Department of Earth Sciences, Uppsala University, Villavägen 16, SE- 752 36 Uppsala, Sweden

1. Introduction

Transforming energy systems by increasing the share of renewable energy sources is part of the global Sustainable Development Goals published by the United Nations and adopted by member states in 2015. Within goal number seven, one of the three key targets is described as follows: “By 2030, increase substantially the share of renewable energy in the global energy mix” (United Nations, 2023).

The energy transition generally means a change from energy production and consumption based on fossil fuels to a state of decarbonization, by applying natural resources to generate renewable energy (S&P Global, 2020)

Germany has been at the forefront of this process early on. As a matter of fact, the term “Energiewende”, which is the German word for energy transition, has become popular even outside of Germany. There had been different actions before, but a milestone in the German energy transition was the initiation of the Renewable Energy Sources Act (“Erneuerbare Energien Gesetz”, abbreviation: EEG) in 2000. With that, Germany became the first country to have a governmental law aimed at renewable energies (Morris and Jungjohann, 2016).

Renewable energies are called this way, because the natural resources they rely upon are replenishable and, in contrast to fossil fuels, cannot be used up. Solar radiation causes the majority of all these primary energy sources such as wind, water flows or biomass production. A direct usage of solar energy is possible through solar thermal plants and photovoltaics (PV), a technology to generate electricity from sunlight (Demirel, 2016).

As can be seen in figure 1 below, Germany reached a share of almost 50% regarding the energy production from renewable sources in 2022. The second largest contributor with around 10% was PV (Bundesnetzagentur, 2023).

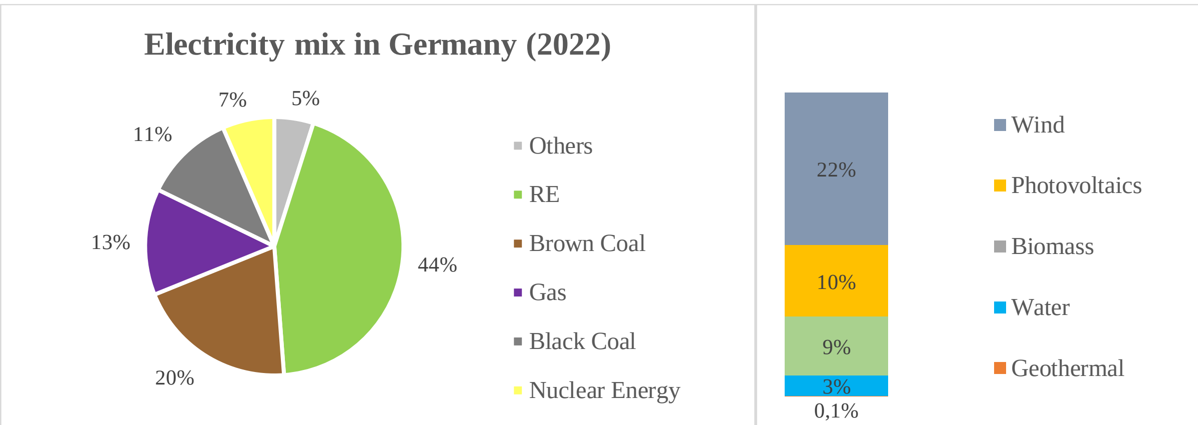


Fig 1. Electricity mix in Germany in 2022 (Own illustration based on Bundesnetzagentur, 2023)

Some of the key drivers of the energy transition are rising prices for fossil fuels, environmental concerns, especially related to climate warming, and security concerns from the society regarding nuclear power (Gründinger, 2017). Further dynamic comes from the significantly decreasing costs for renewable energy technologies, as a matter of fact “renewables are increasingly becoming the default source of least cost” (IRENA, 2022, p. 21).

In the past couple of years, energy security issues have also played a role in the acceleration of the energy transition. Electricity prices had already risen in 2021 in Europe due to import shortages. After the Ukraine war started in early 2022, the situation became even more intense, as energy supplies from Russia were stopped (World Economic Forum, 2023). Renewable energy (RE) produced in the regions where electricity is consumed can help to reduce import dependencies from traditional fossil fuel supplying countries.

The EEG maintains its importance in the German energy transition in 2023. On January 1st, an extensive amendment was published. With the overarching aim of becoming climate-neutral in order to limit climate warming to 1,5°C, an accelerated expansion of renewable energies is emphasised. Until 2030, renewables are planned to have a share of 80% in the electricity mix. For PV, there are ambitious capacity addition targets as well. In 2022, a capacity of 7 GW was installed in Germany. According to the EEG, this value should increase to 22 GW per year, a relative rise of roughly 300%, and a total of 215 GW should be installed until 2030 (BMWK, 2022).

PV can be applied in different power plants. Traditional applications are ground-mounted and roof-top systems. New concepts aim to integrate PV into sealed surfaces to prevent land-use conflicts, for example Agriculture-PV (Agri-PV), Road-integrated PV (RIPV) or Floating PV (Wirth *et al.*, 2021).

With this variety of different PV plants and the projected massive expansion of PV in the coming years, two decisive questions remain. At first, it must be evaluated if these installation plans from the government are actually reachable. Secondly, it is to be analysed to what extent the different PV plants should contribute to this expansion. When evaluating the different PV plants, factors such as the area potential, economic efficiency and environmental impact have to be taken into account. The potential indicates the foundation with available areas, but costs and impacts on existing landscapes, eco-systems and biodiversity of different PV systems can vary greatly on these areas. With the current theoretical basis in literature, it is not possible to give a profound answer to the contribution of different PV systems and to what grade the overall targets are reachable. However, for planning and decision-making from key stakeholders within politics and the industry, this is crucial information.

This study therefore aims to gather data on the PV market and different PV systems, by interviewing various stakeholders from the solar energy branch in Germany and support the data through literature research. Appropriate literature includes recent scientific studies on PV systems and market development as well as governmental publications.

The research is structured and guided with the following three research questions, focusing on the key areas of the research task.

- *Are the capacity addition targets by the German government of installing 215 GW of PV until 2030 reachable, with regards to policies and market structures?*
- *How much will different PV systems contribute to the planned capacity additions until 2030?*
- *What role will "integrated PV" play in the German PV mix in 2030?*

The results should provide an assessment of the governmental targets on the one hand, pointing out constraints and challenges in the solar energy branch. On the other hand, a comparison between the different PV plants based on the above-mentioned factors should also be enabled. This data can then be used to derive and estimate the contribution of the different PV plants within the planned capacity additions.

It must be noted, that this study is conducted under a set of limitations. The total available time for this project is only a few months as part of the final thesis of the Master studies. Hence, there is limited time for conducting the interviews, which also reduces the overall number of interviews held. In addition to this, the outcome of the study heavily depends on the availability and contribution of the interview partners. With the strategy, to interview a high variety of stakeholders of solar energy in Germany, it is to some extent possible to compensate the limited total number of interviews.

2. Background

This section begins with a literature review, pointing out the status quo that the research topic, constraint by the research questions, has in literature.

Furthermore, this chapter provides fundamental background information on which the research questions are based. This includes a generic introduction of energy as well as electricity production and usage, before the focus is put on renewable energies and solar energy in particular. A brief technical foundation of photovoltaics and the different PV systems/PV plants is followed by an overview of the historic development of energy production and consumption in Germany. In this context, the regulatory framework and the characteristics of the energy transition are presented.

2.1. Literature Review

2.1.1. Global Studies

Today, the development of renewable energies supported by governmental policies is a global phenomenon. Muhammed and Tekbiyik-Ersoy (2020) have analysed the relation between certain policy instruments and their effects on renewable energies in three major industrial nations with China, the USA and Brazil. Results show that a higher total amount of policies directly relates to a higher installed capacity of renewable energies. The same conclusion was also drawn for the number of corresponding patents. Two specific categories of energy policies were identified to have the most significant positive impacts, which are policy support and regulatory instruments. Whereas policy support measures ensure strategic planning and encourage the industry, regulatory instruments "comprise of auditing, codes and standards, monitoring, obligation schemes, and other mandatory requirements" (Muhammed and Tekbiyik-Ersoy, 2020, p. 12) aimed at an expansion of renewable energies. Additionally, economic instruments, especially feed-in tariffs (FIT), are important to incentivize investments.

A critique at RE targets is stated in the study by Rosenberg, Lind and Espegren (2013). The authors argue that targets are often planned and calculated without analysing the variable of energy consumption. But in reality, the impacts of an increasing or decreasing energy demand have a huge impact on goal achievements. They also argue that because of the characteristics of renewable energies, a higher share in the energy mix can usually be achieved with a decreasing demand, whereas higher energy demand would probably mean a higher total installed capacity of RE, but the share would be less. Due to these findings, the authors emphasise the importance of focusing on efficient energy consumption in addition to expanding the energy production capacity (Rosenberg, Lind and Espegren, 2013).

With their analysis of different nations, Muhammed and Tekbiyik-Ersoy (2020) point out that results cannot be generalized among countries. On the other hand, they also conclude that the policies in China are of particular interest for countries that plan to expand their solar energy capacities. A study conducted by Ye, Rodrigues and Lin (2017) evaluates the impressive development of PV in China by analysing Chinese energy policies, with particular focus on FIT. After introducing new FIT regulations, China has managed to install 77 GW of PV capacity in a spell of five years. Furthermore, China has become a key player in the PV market, exporting a huge amount of PV technology components globally. FIT are nowadays a common policy instrument worldwide, but China has two particularities that distinguish their regulations. To support an appropriate spatial development of PV and avoid over-production in certain areas, China has introduced different FIT for different regions. Secondly, FIT rates are frequently updated in accordance with market- and price developments, so that return rates can be kept stable. Despite the conclusion that FIT policies have had successful impacts on the PV development in China, especially for increasing installed capacities, the authors also conclude that they pose high interferences in the free market (Ye, Rodrigues and Lin, 2017).

2.1.2. Studies focusing on Germany

For Germany specifically, several previous studies have analysed their energy policies, the PV market and expected future developments. In a study carried out by Moore and Gustafson (2018), the achievements regarding installed capacity of RE are mentioned, but Germany's energy policy is criticized to only focus on increasing the share of renewable energies. The authors point out the lack of attention towards economic efficiency, market prices and energy security related aspects. The critique is similar to the above-mentioned arguments stated in the policy analysis on Norway (Rosenberg, Lind and Espegren, 2013). Furthermore, the authors have identified a lack of regulations on existing infrastructure and emphasise potential risks concerning grid stability, if different RE sources are further expanded. In their opinion, "a sound energy policy should strike an even balance between sustainability, energy security, and economic efficiency" (Moore and Gustafson, 2018, p. 2). In addition, the ecologic motivation of the policies is questioned, as Germany has missed its carbon dioxide (CO_2) emission targets. With increasing regulations, however, Germany will have more urgency to reach these targets, which could move the focus more on efficient energy consumption. This in turn could pose to be a limiting factor for reaching the capacity additions for RE and PV in particular. On a positive note, the overwhelming public acceptance of the energy transition in Germany is emphasised. At the same time, the government should be cautious to maintain this level, as future issues such as drastic price increases could potentially limit the public support (Moore and Gustafson, 2018).

Throughout literature, there are numerous studies about the PV market in Germany. Wirth (2023) has collected a wide range of facts in a publication. The importance of the energy technology is pointed out, stating that PV is already a significant contributor in the electricity mix, reaching a share of 10% in 2022. Especially the dropped system prices are stated as a driver, emphasizing the fact that large-scale PV systems can produce the cheapest electricity among all energy technologies. Besides, market mechanisms alone are not enough to reach further addition plans and governmental support measures, mostly within the EEG, are crucial for future development. On that behalf, declining FIT in recent years are seen critically. This development, related to the so-called degression rule, is also pointed out by Henning et al. (2021) in a similar study. Furthermore, regulatory aspects such as time-consuming approval processes, guaranteed long-term electricity purchase prices and specific support for integrated PV systems need to be tackled. These systems are expected to have a large contribution in coming years, as they allow PV to be built in already used areas, which is said to reduce land-use conflicts elsewhere. Especially a further expansion of traditional ground-mounted systems is seen critical, as they are in direct conflict with agriculture and nature protection. However, such systems could also have positive ecological impacts, if carried out projects engage in renaturation of the area (Wirth, 2023).

In contrast, an analysis by Henning et al. (2021) points out the importance of roof-top PV systems for Germany. By 2021, 70% of the installed PV capacity was contributed by roof-top systems, amounting to approximately 40 GW. The highest share falls to small residential systems up to 10 kWp. Regarding the development until 2030, they see the possibility of installing 140 GW of PV on roof tops. On the other hand, uncertainties regarding future economic feasibility and bureaucratic requirements are mentioned as limiting factors. On top of that, tendering and restrictions for self-usage of electricity could also lead to hesitations among investors.

The German government has recently published a new strategic plan for PV development in Germany. In this study, they claim that a variety of measures have been implemented and further ones will follow in the coming years to make sure the targets are reached. As an overall share, they aim for 30% PV in the electricity mix (BMWK, 2023). Similar to Wirth (2023), large-scale systems are reckoned as important contributors going forward, because of the lower relative costs. However, the governmental publication argues for a high share of classic ground-mounted systems. Other system types such as Agri-PV, Floating PV and PV on parking lots are also mentioned to have increased importance and new specific regulations are planned for these. Roof-top PV systems are said to be important especially because of the possibility to consume the energy directly. It is also argued, that public acceptance can be further increased by financial incentives and the enhancement of community participation models (BMWK, 2023).

2.2. What is energy?

During the 18th century, scientists began using the term energy to describe "diverse phenomena as the transfer of heat, the motion of bodies, the operation of machinery and the flow of electricity" (Everett, 2012, p. 1). In science, energy is now described as "the capacity to do work" (Demirel, 2016, p. 13). To understand this concept, it is important to be aware that energy is present in various forms. The potential energy contained in a system can be accessed through energy conversions, in which the work releases the energy from the system in a specific form. As a result, usable energy such as motion, light, heat or electricity becomes accessible. Energy is measured in different units, depending on its form, but the most prominent unit used as a basis is Joule (J). With regards to electricity, the unit of kilowatt hours (kWh) is used, with one Watt equal to one J/s (Demirel, 2016).

In the early stages, energy was used in simple processes and applications, especially through burning material such as firewood to generate heat and facilitate cooking. The industrial revolution during the 19th century accelerated the energy demand and, through the introduction of machinery like steam engines, transformed the way that energy was used. Besides firewood, coal and later also oil became much more prominent energy sources used for burning processes. In the 20th century, the energy demand continued to rise drastically, closely linked to rises in population and economic growth. On the downside, burning fossil fuels causes emissions, through which different gases are set free that can cause severe environmental damage. The most notable issue is that atmospheric gases, such as CO_2, accelerate climate warming, which results in numerous negative consequences for the earth's ecosystems (Everett, 2012). Today, approximately 80% of the world's energy supply is received from fossil fuels (Ritchie, Roser and Rosado, 2022). But because of the environmental harm caused, their ending availability and energy security concerns, the share of these energy resources in the global energy mix should decrease and they are to be replaced by sustainable alternatives, so-called renewable energy sources (Everett, 2012).

2.3. What is renewable energy?

As the term "renewable" suggests, renewable energy (RE) can be extracted from natural resources, that can reproduce itself infinitely. Besides the unlimited availability, RE also causes much less emissions compared to traditional fossil fuel energy (United Nations, 2022). As a matter of fact, almost all the RE sources are referred back to the sun's energy, with geothermal heat being the exception. Because the sun's radiation on the earth is unevenly distributed, climatic- and weather patterns occur and wind and water flows are the consequence. Furthermore, sun light also enables plants to grow, inevitable for biomass production. These types of renewable energies are referred to as indirect solar energy usage. They always require more than one conversion of the energy. In contrast, solar energy can also be used directly, requiring only one energy conversion. In general, this is done with two main technologies which are solar thermal systems that use the sun light to produce heat, and photovoltaics, through which electricity can be generated (Bhatnagar, 2021).

2.4. Photovoltaics

2.4.1. Technical background and functionality

The energy technology photovoltaics (PV) converts sun light into electricity. This is possible through so-called solar cells, which are combined to larger units, the solar modules, as visible in figure 2 below. The modules in turn can also be connected to larger systems, depending on the targeted maximum capacity of the power plant (Energy.gov, no date).

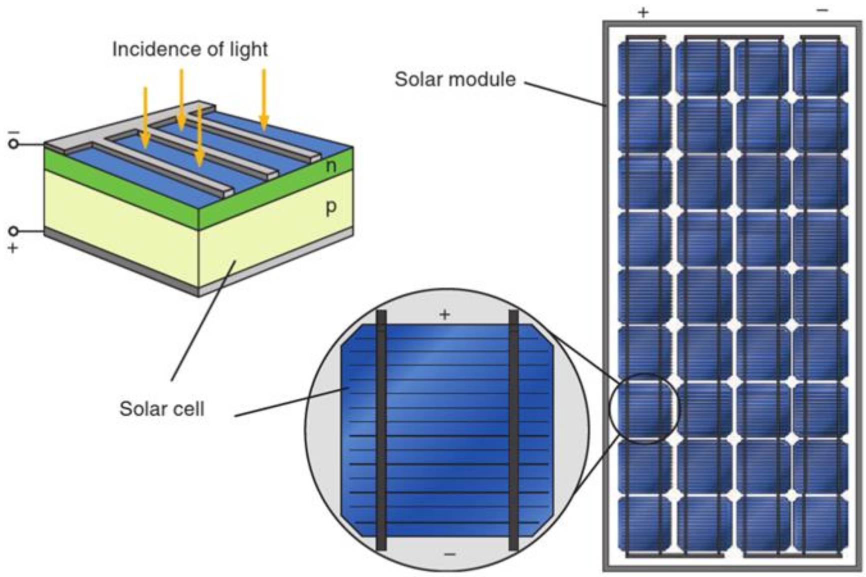


Fig. 2. Illustration of solar cells (Mertens, 2014, p.13)

Within the solar cells, physical procedures occur that are similar to a photodiode. As the sun light hits the cell, a movement of electrons from one side to the other is caused. In parallel, electron holes, which have the capacity to transport electrons, move to the opposite side. Simply speaking, an electric current establishes within the cell. This current is then derived through electric contacts on both sides (electric minus- and plus poles) of the cell. It should be noted, that this movement of electrons carries on infinitely, as long as sun light penetrates the cell (Mertens, 2014).

The power that a PV system provides is measured in the unit Watts (W). Depending on the size of the system, the larger units Kilowatts (kW), Megawatts (MW) and Gigawatts (GW) are used. With regards to the power output, the efficiency number of PV plays a key role. Presently, PV systems reach efficiencies of around 20%, meaning that this share of the energy input (sunlight) can be converted into electricity output. Furthermore, the output of a PV system is highly dependent on current outside conditions, such as sun radiation, weather and temperature. For calculations, ideal outside conditions are assumed and the power value is then called Watt Peak (Wp) (Mertens, 2014).

To illustrate such a calculation of potential power output, the following example is presented. An assumed roof-top PV plant is built in Germany on a size of 40 square meters and with modules having an efficiency of 20%. The potential capacity of this solar PV system would be as follows:

$$1000\,\frac{W}{m^2}\;x\;40\;m^2 x\;0{,}2\;=8000\;Wp=8\;kWp$$

2.4.2. Different solar PV power plants

In general, solar PV plants always use a certain number of solar modules, that consist of a certain number of solar cells. What differs greatly between various PV plants is how, where and how many of these modules are applied. PV can be used as stand-alone systems in local settings without connection to the grid, to directly use the generated electricity. Relevant to this research task, however, are larger systems that are connected to the electricity grid (Weller *et al.*, 2010). Hence, the different grid-connected PV power plants that exist today are presented at this stage. The two most common ones are roof-top PV systems and ground-mounted PV systems. Additionally, so-called integrated PV systems are presented, as they have been becoming more prominent recently. The key argumentation basis for such systems are land-use conflicts and additional benefits in form of synergies. As a matter of fact, integrated systems aim to install PV in areas that are already sealed or used for economic purposes (Wirth *et al.*, 2021).

A brief overview of the different PV systems that are in scope for this research project, is given in the following chapters below.

2.4.2.1. Roof-top PV

Roof-top PV plants are the most common PV systems in Germany, amounting to around 70% of all installed PV plants (Wirth et al., 2021). A majority of these systems have installed capacities between 10 and 30 kWp, typical sizes for private households. In the past few years, larger roof-top systems have increased in number. They have been installed on commercial buildings and can have sizes of 500 kWp and more. In the past, roof-top PV systems in Germany have been heavily subsidized through feed-in tariffs, as installation costs were more expensive. Nowadays, the subsidies have been reduced significantly, as the PV systems have become much more affordable and the electricity market price has increased. Therefore, it is more common to directly use the produced electricity from the individual roof-top system, instead of feeding into the grid (Held *et al.*, 2019).

2.4.2.2. Ground-mounted PV

Ground-mounted PV systems typically have a greater installed capacity than roof-top PV systems, as they are built on expansive areas in the countryside. Usually, quit fields that have been used for economic, agricultural or even military purposes before, are taken into consideration for ground-mounted PV systems. As PV can be mounted flexibly within these spaces, it has the advantage to optimize the direction and angles of the modules to maximize the electricity output. In some cases, PV systems that track the sun light during a day and therefore change its direction are used as well (Solarenergie.de, no date). Hindering factors for such systems are land-use conflicts, environmental protection areas and acceptancy problems from local residents. Due to necessary preparatory procedures such as feasibility studies or approval processes, ground-mounted systems usually take quite long to be readily installed (Wirth *et al.*, 2021).

2.4.2.3. Agriculture PV (Agri-PV)

The technology of Agri-PV combines land usage for agricultural purposes with electricity generation through photovoltaics. The basic concept is that existing fields are covered with PV modules at a certain construction height and density, depending on the growth conditions that the cultures need. Due to these different heights in which the PV modules are installed, Agri-PV is divided into category 1 systems, that have high mounting structures and category 2 systems with much lower constructions, closer to the surface. Studies have found out that covering the fields with PV has positive effects on some of the cultures, as heavy precipitation and direct sun light are shielded. Depending on the complexity of the constructions, Agri-PV systems have significantly higher installation costs than ground-mounted PV systems (Wirth *et al.*, 2021).

2.4.2.4. Floating PV

This technology uses swimming substructures to enable PV modules to float at the surface of waters. In Germany, it is applicable especially at former open pit mines or other artificially created lakes. Due to the fact that the PV modules at the surface of the water reflect incoming sun light, overheating of waters can be prevented. On the other hand, negative impacts on these ecosystems have to be considered and especially the shore areas of the waters cannot be used, which limits the availability of space for PV (Wirth *et al.*, 2021).

2.4.2.5. Building-integrated PV (BIPV)

As PV modules are available in different forms and colours nowadays, it is possible to directly integrate these modules in buildings, for example as elements in facades. By doing so, additional areas of properties can be used for electricity generation and because no extra construction systems are needed, less material than in roof-top PV systems is needed. However, the planning processes, architectural constraints and potentially complex module structures can increase costs for such applications (Wirth *et al.*, 2021).

2.4.2.6. Road-integrated PV (RIPV)

Potential integration of PV systems into road infrastructure is possible through noise barriers, canopies or with PV as the actual driving- or walking surface. The main advantage is, that already sealed surfaces are used, so no additional land-use conflicts occur. Another advantage is that overshadowing the driving surface can potentially increase its lifecycle time. However, high construction costs, especially for canopies over roads, as well as safety standard that have to be met, must be considered as drawbacks (Wirth *et al.*, 2021).

2.4.2.7. Urban PV

Urban PV describes all PV systems that are installed in urban areas within already sealed surfaces. Examples are PV systems above parking areas or garages for cars or bikes. In some of these application areas, the shade provided can be a positive effect, especially in summer when urban areas heat up drastically. Because already sealed surfaces are being used, no land has to be sacrificed that provides natural habitat for species or can be used for other purposes. The relative costs to conventional systems depend on the costs of the specific constructions (Wirth *et al.*, 2021).

2.5. Solar PV in Germany

2.5.1. The energy transition

Already in the 1970's, protests against nuclear energy in Germany have triggered political attention for changes in the country's energy system. In the 1990s, different federal laws were initiated that introduced mandatory payments for renewably produced electricity, as part of the bid to increase feed-ins from renewable energy sources. The breakthrough certainly was the adoption of the Renewable Energy Sources Act (EEG) in the year 2000. This law, which since has been updated many times, targets "reducing CO_2 emissions, increasing power production from renewable sources, and promoting energy efficiency" (Moore and Gustafson, 2018, p. 1). Its main instruments are feed-in tariffs and priority regulations for electricity produced by RE sources. The latest update has become valid from January 1st 2023 and its regulations concerning PV will be discussed in chapter 2.5.3. With the governmental regulations included in the EEG, Germany has been able to significantly increase its share of renewable energies, a value that was only 6% in 2000 (Moore and Gustafson, 2018). In 2022, the share of renewably produced electricity has reached a value of 44%. Photovoltaics contributes with a total share of around 10%, with only wind power having a higher share with 22% (Agentur für Erneuerbare Energien, 2023). Overall, Germany aims to increase the share of renewable energies to 80% by 2030, with photovoltaics having a key role in achieving this target (BMWK, 2023).

Besides the focus on increasing the installed capacity of RE, improving the energy efficiency has become another major target. Especially the achievement should be reached, that energy consumption does not grow in parallel to GDP growth anymore. In that context, Germany has invested heavily in energy efficiency improvement measures. Even though the overall energy consumption has remained fairly constant since 2000 and GDP has increased significantly, this can only be described partly as a success. This is because the majority of the improvements have been made within private households, but the energy intensive sectors industry and transportations have remained more or less the same (Moore and Gustafson, 2018).

The energy transition has also come with several problems, especially for the power grid. The nature of RE to be dependent on outside conditions and the fact that they are very distributed location-wise, are challenges for grid management. This also explains why Germany still has its second highest share of primary energy production resulting from coal and is also dependent on electricity imports from neighbouring countries. The high share of coal furthermore is a limiting factor why Germany has not been reaching its emission targets (Moore and Gustafson, 2018).

2.5.2. The Up's-and Down's of the German PV market

The development of the PV market in Germany has faced significant fluctuations since the EEG first became valid. Figure 3 below shows the annual installed capacity in Gigawatts. In 2022, a value of 7,2 GW has been reached, continuing the steep upward trend since 2018. The columns for the years 2023 until 2030 show the governmental targets, which see the annual installed capacity triple over the next four years and then stabilize at 22 GW per year. Despite the positive recent development and the promising outlook for PV, the graphic also shows a significant collapse of the PV market between 2013 and 2017. As a matter of fact, between 2010 and 2012 the capacity additions were already on a higher level than last year (BMWK, 2023).

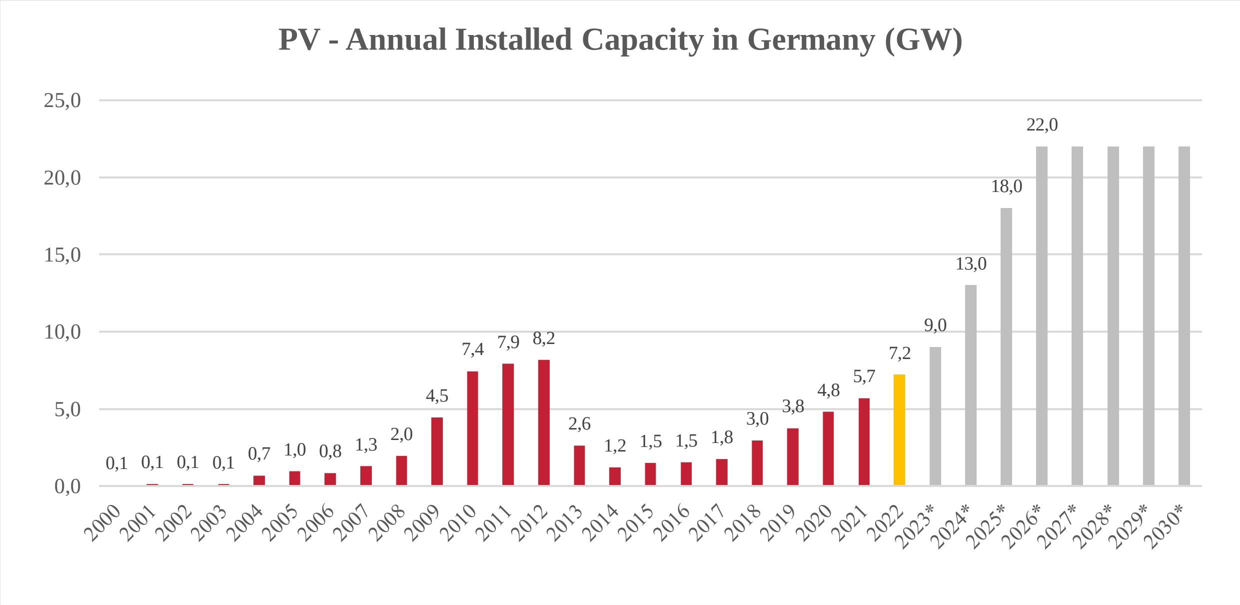


Fig. 3. Annual installed PV capacity (Own illustration based on Quaschning, 2023 and BMWK, 2023)

The reason behind was an EEG update in 2012 which included monthly reductions of PV-related subsidies and grants. This was initiated by the government, as PV system costs had decreased at that time and the government felt that less support for the market was needed. However, it quickly became evident that the decreases in system prices could not match the drastic decreases in subsidies, which lowered the attractiveness of PV for consumers. As a result, the market collapsed by 55% in 2013 and the annual installed capacity remained constant on a low level until 2017 (BSW Solar, 2014).

The upward trend in the market since 2018, especially accelerating in the past two years, is down to several reasons. On the one hand, system costs have continued to decrease greatly, as a matter of fact by 75% in the past 12 years. Furthermore, feed-in tariffs have decreased as well. This has made it less attractive for end consumers to feed-in the electricity produced into the grid, but with rising energy prices, solar PV has become more and more attractive especially for private users, because the energy can be used directly (Wirth *et al.*, 2021).

Another driving factor was the governmental election in fall 2021. The new government with contribution of the green party, agreed to develop the PV market in Germany with high urgency and changed the targets for the share of renewable energy in the electricity mix to 80% until 2030 and committed to reaching climate neutrality until 2045. In addition, the government has made several adaptations to the EEG, with a large reform of the act having been published in January 2023 (Enkhardt, 2021).

The PV-related regulations of this new EEG version are discussed in chapter 2.5.3.

2.5.3. The latest EEG and its regulations for PV

The latest version of the EEG, which became valid as of 1st January 2023, is seen as the biggest amendment of the act in years. It is aligned to the targets from the Paris Agreement to limit climate warming to 1,5°C and therefore has the overarching target of increasing the share of renewable energies in Germanys electricity mix to 80% already by 2030. This should be achieved especially through an acceleration of the installed capacity of solar PV and wind energy (Die Bundesregierung, 2022).

Already previous to releasing the new EEG, feed-in tariffs for solar PV system have been increased for the first time in many years. Furthermore, the EEG includes less bureaucratic hurdles, especially regarding grid connection. Before, it was the usual practice that a net operator had to be present for the connection. This is now no longer the case for small systems up to 30 kWp and should speed up the installation process. If PV systems cannot be installed on the roof, the EEG now also subsidizes PV systems in gardens. Another measure is that the so-called EEG levy was cancelled. This had to be paid by electricity consumers before in order to support the development of renewable energies. Because of the cancellation of this levy, the government hopes to encourage electrification for private and commercial players, which should reduce emissions (BMWK, 2022).

For small private systems there are additional new regulations. The 70% rule is not valid anymore, that had limited feed-in before, so now it is possible for producers to feed-in 100% of their produced electricity. Secondly, the EEG allows the operation of two different PV systems on one roof, offering the possibility to have one system for own usage and one to feed into the grid. The EEG also features tax improvements, as the earnings from grid feed-ins and also the self-used electricity now require no value-added tax anymore. Additionally, no value-added tax needs to be paid for delivery and installation of PV systems up until 30 kWp, instead of 10 kWp which was the boundary before (Solarwatt, 2023).

There are several changes for larger systems, too. Public tendering, which had been carried out for ground-mounted PV systems already, is now also possible for areas appropriate for integrated PV systems such as Agri-PV or Floating PV. In addition, there are general improvements regarding public tendering, which in the past has often been a hindering factor for PV installations. Commercial roof-top systems that can be financed by market bonuses do not need to take part in tenders anymore. There are also no tenders necessary anymore if a PV system between 300 and 750 kWp is built for private usage. Finally, tendering omits if the PV project is carried out by public energy agencies. Furthermore, privileged areas besides roads and tracks have been increased from 200 meters to 500 meters, providing additional possible areas for PV systems (Solarwatt, 2023).

2.5.4. PV electricity costs

There are several concepts to calculate the financial performance of a power plant for electricity generation. One of the most prominent ones is the concept of Levelized Cost of Electricity (LCOE). With the formula that can be seen below, it is possible to calculate the price of generated electricity over time, in relation to the initial investment costs, annual operating costs (including maintenance and fuel) and the estimated lifetime of the power plant. The final result is given in a currency value per kWh, usually in Euro cents per kWh (Ragheb, 2017).

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

I_0 = Investment costs

A_t = Annual total costs in year t

$M_{t,el}$ = Generated energy in the specific year in kWh

I = Interests

n = Economic lifetime in years

t = Year of usage

A study published by Fraunhofer in 2021 applied the LCOE concept and compared different conventional and renewable energy technologies in Germany with each other.

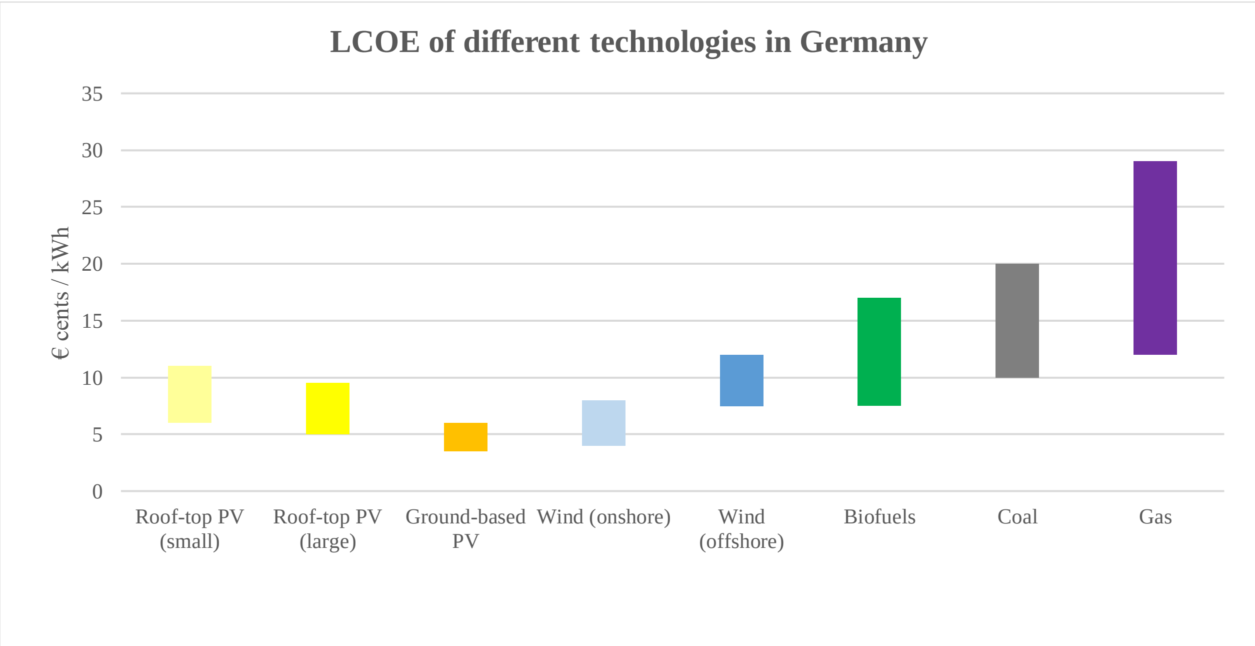


Fig. 4. LCOE of different energy technologies in Germany (Own illustration based on Kost et al., 2021)

The outcome, which can be viewed in figure 4, showed that large scale PV power plants are today the cheapest from of electricity generation, with LCOE ranging between 3,5-6 cents/kWh. Smaller scale roof-top PV systems reach values from 6-11 cents/kWh. The LCOE for wind power range from 4-8 cents/kWh for onshore plants, but are with 7,5-12 cents/kWh significantly higher for offshore wind power. The in Germany traditionally important conventional energy generation technologies coal and gas have much higher LCOE. Coal reaches values from 10-20 cents/kWh and gas even between 11-29 cents/kWh. However, what has to be kept in mind is that LCOE always assumes that power plants are newly built from today. Of course, existing power plants could be more efficient from a financial perspective, so the opportunity cost of shutting down an old power plant and replacing it with a newly built one have to be considered. On the other hand, this study also shows that renewable energy technologies can now compete in economic terms with conventional technologies (Kost *et al.*, 2021).

2.5.5. PV environmental compatibility

In general, solar PV as a renewable energy source with zero carbon emissions in the energy generation has a comparably high environmental compatibility. Furthermore, natural resources are not used up within the electricity generation processes, which give the technology a clear advantage over conventional fossil fuel technologies (Tsoutsos, Frantzeskakib and Gekas, 2005).

On the other hand, there are some negative impacts for the environment as well. With the space needed for large ground-mounted systems, existing eco-systems in these areas can be negatively influenced. Furthermore, a potential loss of chemicals from the components of the solar panels could pollute soils and water in close proximity of the power plants. Another aspect is the visual distraction from the solar modules and how this changes the landscape. Besides the environmental impact of the actual solar PV plants, the impacts related to production and transportation of PV components should also be considered. These cause carbon emissions through burning conventional fuels and use-up a high amount of energy in general. Especially because of the global supply chains, high distances need to be covered through transportation. Negative environmental impacts can also occur from the mining processes, necessary to get the raw materials for the different components of a solar PV plant. These excavation procedures come with significant interventions into local landscapes. Furthermore, depending on the conduction of these processes, chemical pollution is a risk, too. Finally, towards the end of the product lifecycles, waste is another issue. Hence, it is important to introduce waste management systems and component recycling, especially to reduce mining processes in the future (Tsoutsos, Frantzeskakib and Gekas, 2005).

3. Methodology

3.1. Research problem and motivation for research

As presented in the literature review, the past development of photovoltaics is covered to a great extent in previous studies. There is also a lot of research available on energy policies, both for renewable energies in general and photovoltaics in particular. Case studies across the globe have shown the effectiveness of such governmental support measures and the possibility to significantly scale-up renewable energies. At the same time, short-comings are also pointed out.

For Germany, the targets and the approach for future development regarding PV is transparent. Traditionally, the most important PV systems are small-scale residential roof-top PV systems and large-scale ground-mounted systems. In addition, more recently, new concepts such as Agri-PV, Floating PV and Road-integrated PV have emerged, which are summarized with the category of integrated PV (Wirth *et al.*, 2021).

To the authors' best knowledge, there is no holistic analysis evaluating the feasibility of the capacity addition targets by the German government and the contribution of different PV systems towards these targets. For adequate strategic planning, both from politics and industry, it is important to know the opportunities and problematics from these different system types in Germany.

In this study, both the policies and the market constraints are evaluated, in order to come to a conclusion of the reachability of the capacity addition targets. Furthermore, the different above-mentioned PV systems are analysed based on economic and ecological criteria. With the results, the relative importance of the individual system types within the total capacity addition plans until 2030 can be stated. Additionally, potential actions can be pointed out that further support different system types.

3.2. Data collection procedures

To address the research problem, data is collected through the qualitative methods of semi-structured interviews and literature analysis.

The core empirical data generation of this research project is realised through semi-structured interviews, conducted with stakeholders of the solar energy branch. Semi-structured interviews offer the participants the flexibility to express their opinions and thoughts in detail and at the same time give the researcher the possibility to somewhat steer the communication with a previously prepared interview guide (Galletta and Cross, 2013). The use of pre-defined questions, focusing on the main research tasks included in the research question, enable access to the thoughts and view-points of different stakeholders, which are important for the generation of theory. Applying mostly open-ended questions also makes sense for this research, because it enables gathering the individual opinions and experiences of the stakeholders to a high extent. That is especially important, as the main part of this research is a future outlook and thoughts are often in conceptual or visionary state. Because of these reasons, applying the data collection method of semi-structured interviews is a great fit for this research project.

How exactly the interviews were prepared and conducted is documented in chapter 3.2.1. Furthermore, the applied interview guide is included in Appendix A.

To support the data generated from the interviews, literature analysis is carried out. On the one hand, this methodology is applied to provide a profound knowledge foundation of the energy transition in Germany, including corresponding governmental regulations, and the key characteristics of renewable energies in general and photovoltaics in particular. All this information is vital both for the researcher to construct the research design and for the readers to obtain all necessary background knowledge. To summarize, literature analysis in this context is the basis for “advancing knowledge and facilitating theory development” (Snyder, 2019, p. 333) which will follow later in the research process. The outcomes of this part of the research are presented in the Background chapter.

On the other hand, literature analysis is also used to evaluate characteristics of the different PV systems types, to complement the data collected from the stakeholder interviews and to address the research questions. Economic and ecological aspects of these system types are the main focus points. More information about this part of the methodology is available in chapter 3.2.2.

3.2.1. Conducting the semi-structured interviews

Before the actual conduction of the interviews, a number of preparatory measures were undertaken. At first, potential interview partners had to be defined. For the following search, organizations and individuals had to fulfil some criteria, which qualify them as potential interview partners. These criteria can be viewed in table 1 below.

Table 1. Criteria for interview partners (own illustration)

Criteria #	Criteria for interview partners
Criterion 1	Active stakeholder of solar energy in Germany (organizational)
Criterion 2	Several years of experience within photovoltaics (individual)
Criterion 3	Employed in a role with visionary/developmental view (individual)
Criterion 4	Awareness of market and regulatory framework in Germany (individual)

The second step was to create a list with the different key stakeholders of solar energy in Germany. This list did not include any specific organizational or personal names at first, instead it was aimed at defining categories for the stakeholders. The categories include experts from different academic, political and industrial institutions.

In table 2 below, the stakeholder categories and the number of interview enquiries made per category are listed.

Table 2. Stakeholder categorization (own illustration)

Stakeholder category	Number of enquiries
Academic institution	2
Energy Provider	8
Industry – Manufacturing	10
Industry – Trade	11
Industry – Installation and Maintenance	3
Politics – Federal	1
Politics – Regional	3
Services and Consulting	2

Subsequently, the potential interview participants from the different stakeholder categories were contacted. The approach was to contact persons directly per mail, providing a summary about the research project and the framework of the interview. Overall, an interview acceptance rate of 28% was reached.

Another important preparation was the creation of an interview protocol, also referred to as interview guide. As explained before, a guide with pre-defined questions is used in semi-structured interviews. However, it has to be constructed and used carefully in order to achieve as much objective primary data from the interview partners as possible. Reciprocity and reflexivity are two crucial factors to consider during the interviewing process, which are further elaborated on in chapter 3.2.4. One further consideration was about which language to use for the interviews. As this research project was conducted in English and potential interview partners would have likely spoken English fluently, it was first considered to do the interviews in English. However, there would have also been a risk that the quality and the quantity of the collected data could have decreased and the set-up of having an interview conducted between two native German speakers seemed more secure.

For the interviews in this study, it was decided to use Microsoft Power Point as a program for the interview guide, because interviews were carried out in online meetings using Microsoft Teams and Power Point offers the possibility to share some graphical information. The Power Point presentation was constructed in a way, that it guides the researcher and the participant through the different sections of the interview, including graphics that should be used as a starting point of discussions. At the same time, it was paid close attention, that the graphics displayed and questions asked do not influence the opinions and the answers of the participants in an unintended way. Therefore, only widely available data which can be assumed as common knowledge within the solar energy branch was used. Additionally, it was emphasised within the interviews that the information provided represent actual facts. All the slides and questions from the interview guide can be found in the Appendix in section A.

The interview guide was generally structured in three segments, increasing the specificity and theory-orientation gradually during the interview (Galletta and Cross, 2013).

The opening-segment includes an introduction of the purpose of the research as well as an expression of gratitude towards the participant. Furthermore, it has to be ensured that the participant has signed a consent form and that the recording and transcription of the interview is agreed on. When the actual interview begins, the questions within this segment are fairly open, but with clear relation towards the research question. By doing so, a comfortable environment is created in the interview, as the participant can narrate from his/her experience. It also provides the opportunity for the researcher to take the time for notes and focus on details, that can be further probed later in the interview (Galletta and Cross, 2013). In the case of this research project, open questions regarding the general state of photovoltaics in Germany and personal takes on the past- and anticipated future development were asked.

Within the middle segment of the interviews, the style of questioning changes towards more specific questions, increasing the theoretical depth. For this, a set of specific questions is prepared in the interview guide that the researcher follows. It is also key for the researcher to actively probe for meaning by engaging with the interviewee. Also, it should be paid attention to narratives already derived in the opening segment and it is the responsibility of the researcher to bridge to these thoughts, draw connections and probe for meanings. This segment is key for theory generation in order to identify answers to the research questions (Galletta and Cross, 2013). Therefore, the questioning in this segment within the present research project focused on the following main aspects of the research questions: the capacity addition targets and the legal framework of the German government, different PV power plants and the future photovoltaics mix as well as ecologic and economic benefits and drawbacks of the different PV plants.

Finally, the concluding segment does not address any questions on completely new topics. Instead, the researcher and the participant look back to earlier narratives and pursue the targets of further meaning-making and identifying theoretical connections. The researcher has to make sure that theories can be derived from existing narratives and should use questions accordingly. If this process is nearing the end, the participant can be asked to add any further comments, signalling the termination of the interview. As the interview fades out, the valuable contribution of the interviewee should be highlighted (Galletta and Cross, 2013). For this research task, a few questions with possible theoretical connections were already incorporated in the interview guide. However, it depended highly on the actual narratives of the previous segments of the individual interview, what questions were actually asked in the concluding segment.

As the interviews were recorded (audio and video) and the transcribing function of Microsoft Teams was used, the entire interview data had been available for the researcher afterwards. Subsequent to the conduction of the interviews, the automatically generated transcripts were reviewed for correctness with the audio recording. In the following, the transcripts were reworked to a simplified, cleaned-up and anonymised version that was then used in the data analysis section which is further elaborated on in chapter 3.3.

3.2.2. Literature analysis to support interviews

As stated in chapter 3.1, literature currently lacks information regarding the contribution of different PV system types in the capacity addition plans.

Traditionally, literature analyses are often conducted to analyse and compare existing theory, extensively looking through a complete set of literature. On the other hand, "literature reviews can also be useful if the aim is to engage in theory development" (Snyder, 2019, p. 334). In such cases, systematic literature analysis is not the right approach and instead so-called integrative literature review can be applied. With the advancement of knowledge as a target in mind, this approach aims to analyse meanings and perspectives from different publications. Compared to systematic reviews, it is not required to analyse a complete set of literature, e.g. all articles available in a certain time span. Instead, integrative literature reviewing comes with more creative researching procedures, to find the most appropriate publications with high connection to the underlying research question (Snyder, 2019).

Based on these theoretical guidelines provided by Snyder (2019), literature analysis as a qualitative method was used in this study to complement the data from the stakeholder interviews, contributing with quantitative and qualitative information regarding the key criteria of the different PV plants. Especially concerning the more traditional PV systems such as roof-top- and ground-mounted PV, literature offers a wide range of information that could be used for comparisons between the different PV systems. Additionally, studies on anticipated future development of PV could be applied as well as comparative studies from different countries.

At first, some inclusion criteria for potential publications were defined. They had to be either in English or German language and with a publication date in 2018 or newer. Furthermore, only publications that are peer-reviewed and scientific were taken into consideration. Lastly, publications had to match certain keywords, which are: Roof-top PV, Ground-mounted PV, BIPV, Agri-PV, RIPV, Floating PV, LCOE, potential, challenges, chances (all connected to PV). After the initial search, the publications were roughly evaluated regarding their fit to the research project by reading through the abstracts. The articles left over were then taken into further consideration for contributing to theory development.

3.2.3. Data analysis with Grounded Theory Methodology (GTM)

The empirical interview data was analysed applying the Grounded Theory Methodology (GTM). This method is generally used for theory development and, as the name suggests, aims to do so by deriving theory that is grounded in data. GTM consists of four key components which are “constant comparison, theoretical sensitivity, theoretical sampling, and theoretical saturation” (Oktay, 2012, p. 16). Constant comparison denotes the core functionality of Grounded Theory. The aim during the theory generation process is to constantly compare data with each other and derive concepts in the process. Theoretical sensitivity is described as an attribute the researcher should have. It includes analytic thinking in order to become aware of research strands available in literature. Additionally, it is influenced by personal experience and individual characteristics. As the focus of GTM is to generate theory, sampling should not be done in a systematic manner prior to the data collection. “The aim instead is a sample that allows thorough exploration of the relevant concepts” (Oktay, 2012, p. 7), and this can change during the data collection process. Finally, theoretical saturation means, that a point is reached where newly collected data does not provide any new attributes towards theory generation of a specific category. Data collection can then be terminated (Oktay, 2012).

GTM in practice is characterised by its iterative approach. This means that in the first steps of the data collection, theory is derived inductively. However, as the data collection continues, so does the data analysis. As a result, previously defined theoretical concepts are re-evaluated with newly collected data, resulting in deductive theory testing. This multi-stage process continues as long as the saturation point is not yet reached (Oktay, 2012).

Theory development within GTM is realised through coding data and identifying categories and concepts from the codes. More concretely this means that the collected data should be examined for frequently occurring themes and patterns. When these correspondences and similarities are identified they can then be grouped together and be given a title, which then represents the specific code. Further along the analysis process, more and more codes will be formed and the abstraction level increases. This will then enable the researcher to define categories, also referred to as concepts, that consist of several codes and form a group of generated theory (Bryant and Charmaz, 2007).

Overall, GTM is regarded as a great fit for this study, because real-world situations could be examined through interviewing the solar branch stakeholders and the collected data could be used to generate new theory. Furthermore, the iterative character of GTM strongly supported the inductive theory generation process and helped to build-up theory already in parallel to the data collection from the interviews.

Concretely in this research project, the procedural approach of coding, developed by Strauss and Corbin, was used to rearrange the collected data and integrate it into categories, before ultimately new theory was developed. As part of the coding, the following three steps were applied: Open coding, axial coding and selective coding. In the first step, data was examined, broken down and rough categories were formulated. Secondly, relations between the categories were searched and sub-categorisation was applied to refine the data. Selective coding was actually carried out in parallel to axial coding which helped to generate the final core categories by validating the relationships of the categories with a high level of abstraction (Belgrave and Seide, 2019). A condensed overview of the outcomes from the coding procedures can be viewed in the Appendix, section B.

3.2.4. Comments on limitations, reciprocity and reflexivity

The research was limited due to time constraints. Therefore, only a certain number of interviews could be conducted and the developed theory could only be tested to a small degree. As mitigation, the variety of stakeholders interviewed was targeted to be as high as possible and criteria were chosen, that were possible to evaluate within the time constraints.

Furthermore, the role of the researcher had to be acknowledged during the research. With personal theoretical knowledge and work experience in the solar industry of the researcher, there was existing bias regarding the research field. Due to that reason, it was paid close attention during the creation of the interview guide, that personal opinions were not part of the sections and questions. This data collection approach with applying semi-structured interviews also posed some challenges. To maintain the objectivity as high as possible in the research and to make theory development transparent, all interviews were transcribed electronically and transcripts were worked with closely in the data analysis of the research.

During the actual interviews, it was crucial to acknowledge the terms reciprocity and reflexivity. Often, the researcher is described as an instrument, emphasising the active role he or she has in the generation of theory. Regarding reciprocity, it is the researcher's responsibility to guide the flow and direction of the interview and the unfolding theories. As a result, depending on the involvement of the researcher during the conversations, the outcome can highly differ or is highly influenced by the researcher's actions. On the other hand, this is important as well, because the researcher always seeks to answer the research question of the research project and therefore has to guide the interview participant to a certain extent in order to focus on the main topic areas, connected to the research questions. Of course, through the conduction of several interviews, past experiences help to improve the interviewing skills. Within the process of coding the data from the transcripts, engagement of the interviewer is analysed as well. This process is called reflexivity and should be included in the outcome of the research (Galletta and Cross, 2013).

Overall, the interview protocol as an instrument to guide the researcher worked well. The most important topics were touched with the same or very similar questions across the different interviews that were held. Despite, a few anomalies were identified in the transcripts, where the researcher actively influenced the conversation in an unintended way. In general, the open- and middle-segment of the interviews were not much of a problem, as the number of follow-up questions was less. In contrast, in the closing-segment, active probing for meaning often led to a higher involvement of the researcher. In some of the interviews, this led to open discussions, and the personal opinions of the researcher obviously became a part of the data, too. Whereas these impacts can be expected from studies like this, it is still important to consider them as part of the results. For the coding, some of the data impacted by high involvement of the researcher was evaluated critically and was left out in a few cases, in which the connection to the personal opinion of the researcher was too high. At the same time, it could also be detected that the previous knowledge of the researcher actually helped in the data collection procedures, especially the interviews. Specific follow-up questions on different narratives were only possible because of this previous knowledge. Furthermore, the flow of the interview could be ensured at almost all times, for example by summarising already mentioned aspects or by bridging the conversation to another topic. With more and more interviews conducted, it also became noticeable, that already collected information from previous interviews was tested with the current interview partners, even though this information was not originally included in the interview guide.

4. Results

The questioning in the interviews and the previously defined research questions provided a structuring format for the results of the data collection. The application of coding as a part of the grounded theory methodology (see chapter 3) enabled the creation of theoretical knowledge for the different sections of this structure that provide answers to the research questions.

To summarize, solar PV is regarded as the cheapest and most environmentally compatible energy technology and is expected to be the main contributor in the energy transition in Germany in the coming years. The ambitious governmental targets, political measures and the enormous demand will lead to significant growth. In principle, the governmental target to install 215 GW until 2030 is reachable, but there remains serious doubt whether this value is realistic. The main challenges to overcome are lacking installation capacities and bureaucratic hurdles. The 2030 PV mix will likely consist mostly of ground-mounted and roof-top PV systems, with the share of large-scale systems rising to make use of scale effects, however integrated PV systems can make an increasing contribution if appropriately supported. The chapters below elaborate further on these theories.

4.1. Recent dynamics in the PV branch

4.1.1. Overall market development

The development of solar PV in Germany can be summarized as being dynamic, strong and positive. Interviewed stakeholders see several drivers that have caused this rebound, because despite a previous boom between 2009 and 2012, the market had collapsed, and it was not before 2018 that it began to grow again. One of the main drivers originates from PV technology itself. As prices have decreased significantly, PV is now often the cheapest form of electricity generation. This has generated more interest from consumers and enabled new business cases and investment opportunities. Additionally, the dependency on governmental support measures is not as high as it used to be in the past. Despite the financial attractiveness, potentially rising interest rates remain a concern, that could potentially eliminate economic benefits and slow-down market growth.

Another driver is from the political side. Since the new German government was formed in 2022, renewable energies in general and PV in particular have been in great focus. The EEG and corresponding support measures have been reworked and new ambitious targets were formulated to underline the governmental plans to increase PV capacity drastically.

A further driver has been the energy crisis in the past couple of years, with rising electricity prices and energy import concerns due to political tensions. With that, the desire to reduce import dependencies and price uncertainties has increased among consumers and the government. Therefore, market demand is extremely high, as more and more private and commercial consumers consider using PV for their own electricity demand.

To summarize, these drivers have made PV the energy technology with the highest public acceptance. In consequence, PV is expected to be the fastest growing energy technology in Germany in the coming years, significantly increasing its share in the electricity mix. PV growth is expected to be even faster than growth of wind power, although wind is said to be the second major contributor going forward. The main advantages of PV in comparison to wind power are shorter installation times and higher public acceptance.

4.1.2. Impacts of the EEG amendment

The EEG remains an important instrument for PV development and the 2023 amendment will further support the capacity installations and underlines the governmental ambitions, however there are still adaptations necessary, especially to improve conditions for landlord-to-tenant electricity and integrated PV concepts.

The newest version of the EEG has mainly been taken positively across the PV market. Especially the governmental ambition to quickly and significantly increase the installed capacity of PV that becomes clear with the annual installed capacity plans, has been very well received by stakeholders. Furthermore, some of the concrete measures are expected to make a significant impact. For example, the elimination of tendering for medium-scale PV systems is of great importance for the market segment Commercial and Industrial (C&I), where a lot of potential systems will be below the limit of 750 kWp. Without tendering, the planning phase of a potential PV system can be shortened and the uncertainty with regards to the overall investment is reduced, as fixed feed-in tariffs can be calculated with. Another frequently mentioned point is concerned with additional privileged areas adjacent to rail tracks and motorways. Before, the areas with a proximity of 200 metres were privileged for PV systems, but now the increase to 500 metres has offered the potential for more and larger systems. Further key improvements seem to be specifically addressed at installation firms and private customers, strengthening the segment of residential PV systems. For a majority of newly built private roof-top PV systems, no grid operator has to be present anymore when the system is connected, as the limit has been increased to 30 kWp. This should avoid the case that the PV systems are completely built but operation has to be postponed because of the limited availability of grid operating agents. The elimination of value added tax for private consumers with regards to purchasing PV systems and using the own produced electricity is seen as another motivational aspect for consumers and positively influences the demand in the residential roof-top PV segment.

Besides the praise for the EEG's ambition and its various improved regulations, there remain critics and suggestions for enhancements. It appears to be consented, that the current regulatory basis will not be sufficient to reach the total installation target of 215 GW until 2030. It is also questioned whether this value is actually enough, as the energy demand is expected to rise significantly due to further electrification, for example with e-Mobility and electrified heat pumps. A repeated critique of the EEG regulations is concerned with the unattractiveness for landlords to install a PV system on a leased-out property. There are still complicated and bureaucratical obligations for the landlord to account for the electricity consumption of the tenants and the associated earnings. Stakeholders regard this landlord-to-tenant electricity as a very important segment with great potential as there are still many areas available and electricity can be consumed directly by various parties living in the property. Another factor that could hinder the capacity addition targets is the lack of EEG support measures for large-scale systems, even though these are growingly realized today through Purchase Power Agreements. PPAs are contracts between an energy producer and an energy buyer, which can either be a corporation or a grid operator. These contracts usually have durations of five years or more and secure a certain electricity price, however there are also flexible contracts in which the price is related to current market prices (Next, 2023). The financing model of PPAs reduces the influence of the EEG and increases the dependencies on market development only. There is also the risk that large-scale systems are built outside of Germany, where the regulations are more beneficial.

4.2. Feasibility of the capacity addition targets

It is expected that the PV market will grow significantly until 2030. The question remains though, how large the growth will actually be and if the capacity addition plans by the German government can be reached. As stated earlier, the EEG foresees total capacity additions of 215 GW until 2030, ramping up the annual installed capacity from 7 GW in 2022 to 22 GW in 2026 and then keeping this pace of installations until 2030.

The majority of the stakeholders are of the opinion that these targets will not be reached even though theoretically it would be possible. Interestingly, there have been some interview partners that do not think that the targets in the next few years can be reached because the market cannot grow so quickly, whereas others reckon this ramp-up phase is indeed realistic, but they are sceptical about the feasibility of managing the total amount of 22 GW per year. But despite the anticipation of missing out on the targets, they are not said to be completely unrealistic and a high share of the overall planned capacity could probably be reached. Surely, future regulatory measures, for example through amendments of the EEG, could improve the situation. An interesting fact is, that there is a consent that from the demand side, these targets could definitely be reached. There are even some arguments that the demand for 22 GW is already present today. So, the challenges really lie on the supply side. Table 3 below lists the most frequently mentioned challenges and their criticality of reaching the installation targets. The criticality is assessed from both the likelihood and the magnitude of the impact, as expressed by the interview partners.

Table 3. Major challenges to reach the governmental target of 215 GW installed capacity (Own illustration)

Challenge	Stakeholder mentions	Criticality
Installation capacities	73%	High
Bureaucratic hurdles	64%	High
Financing	27%	Medium
Import dependencies/Supply Chain	27%	High
Local acceptance	18%	Low
Material scarcity	18%	Medium

The most critical challenge standing in the way of the targets are lacking installation capacities. From all interviewees, 73% mentioned this challenge. As the annual installations should triple, the amount of installation companies and ultimately skilled workers should increase at a similar rate. However, this is seen as highly challenging. One reason is that installation companies are growing much more cautious, because they do not want to risk a situation like in 2013 again, where the market suddenly collapsed and many people had to be released or businesses shut down. The other factor is the sheer lack of skilled workers. Technicians and electricians are scarce in general and there is high competition between different industrial sectors to secure the capacities. Within Germany, there are nowhere near enough graduates to saturate the demand. Therefore, the dependence on skilled workers from abroad is high. To some extent, the demand can be fulfilled with people from abroad. However, immigration is a critical societal topic in Germany and the potential is therefore limited and unpredictable. The most critical resource are electricians required to connect the plant once completely mounted. Potentially, parts of the shortage could be compensated by workers from other parts of the energy sector, in particular from nuclear energy and coal-fired energy. To what extent this would actually be a relief is doubtable, because the overall amount of people is not too high and qualifications and skills might not always be sufficient.

Secondly, bureaucratic hurdles represent hindering factors for reaching the targets. Especially approval processes for large scale systems, landlord-to-tenant electricity and missing regulations for integrated PV solutions are mentioned. At the same time, progress with the latest EEG amendment is recognizable which is why stakeholders are hopeful, that further hurdles can be eliminated in the coming years.

The challenge of financing is on the one hand related to increasing interest rates. This imposes the risks, that some investments for PV systems become less attractive or even not financially viable. This challenge should be monitored closely by the responsible governmental ministries, as prompt adaptions of regulations and support measures might be necessary to react to interests' development in order to ensure installation growth rates.

27% of the interviewed stakeholders mention possible supply chain issues, especially related to the high dependence on Chinese imports. Obviously, the financial competitiveness of PV could to a high extent be ensured only because of the decreased prices which are possible because of lower production costs. But potential political decisions and conflicts could potentially lead to supply chain issues and then there would be no plan B, as there are hardly any production capacities in Germany and the rest of the EU today. Therefore, it is highly emphasised by some stakeholders to aim building up such capacities again. As a matter of fact, in the previous PV boom around 2010, there were many manufacturers in Germany, which was referred to in the interviews.

Local acceptance is generally seen as a less critical factor and is only mentioned by 18% of interviewees. Actually, PV is argued to be the most accepted energy technology, even among renewable energy sources. In comparison to wind energy and biomass, it does not influence the environment and the landscape as much and can be integrated much better in existing areas. However, it is still possible that there are local counterparts, especially concerning large ground-mounted systems. The less area becomes available, the more this could turn out to be an issue.

Material scarcity is named as a challenge by 18% of the stakeholders, but is mostly seen as an issue that will be resolved within the next year as the post-COVID supply chain problematics fade away. On the other hand, material availability is also connected to the import dependencies and could therefore potentially become an issue again in the future. Therefore, the overall criticality is medium, as it is not a likely scenario in the coming years, but if it occurs then it would cause significant damage to the market.

4.3. The role of Integrated PV

Overall, stakeholders regard integrated PV as a niche, at least until 2030. However, with regards to the annual capacity addition target of 22 GW, integrated PV will have to play a part and potentially contribute with 1-3 GW annually in the coming years. Interestingly, integrated PV is mostly not regarded as necessary from the perspective of the availability of areas, which has been one of the main arguments for this PV system type. But the majority of the interviewees see no shortage in spaces, as they mention the still enormous potential on roof-tops in both the residential- and the C&I segment. Besides roof surfaces, the potential for ground-mounted systems is also still high and expected to become higher as more areas will be authorised for PV systems, such as the privileged areas adjacent to rail tracks and motorways. On the other hand, integrated PV can provide synergies and attractive business cases for property owners. As a matter of fact, the interest for such concepts has highly increased already, especially among industrial players and investors.

A summary of the main positive and negative aspects derived from the stakeholder interviews is provided in table 4 below.

Table 4. Comparison of positive and negative aspects of integrated PV (Own illustration, values for potential based on Wirth et al., 2021)

Integrated PV system type		Potential	Main positive aspects	Main negative aspects
	**Agri-PV**	1.700 GW	▪ High area potential ▪ Synergies with agriculture, e.g. prevent extreme weather occurrences ▪ Category 2 for lower growing cultures more cost efficient	▪ Category 1 has high installation costs ▪ Business cases and knowledge not present for farmers
	**Building-integrated PV (BIPV)**	440 GW	▪ Electricity can be consumed directly and at lower costs ▪ Less seasonal fluctuations than roof-top systems	▪ Less electricity output than roof-top PV ▪ Special, non-standardised modules necessary ▪ Approval procedures
	**Floating PV**	44 GW	▪ Relatively low LCOE ▪ Electricity can be used directly, if lake still used by industry ▪ Reduce overheating of water	▪ Low area potential ▪ Interest conflicts for lake usage
	**Road-integrated PV (RIPV)**	303 GW	▪ Synergies with e-Mobility possible ▪ Noise protection barriers have a double use if PV modules are applied	▪ Installation costs ▪ Security concerns (accidents, fires etc.)
	**Urban PV**	59 GW	▪ PV is built on sealed surfaces ▪ Direct electricity usage, e.g. on parking lots (synergies with e-Mobility)	▪ Low area potential ▪ Missing business cases

The value in the column potential is taken out of the study from Wirth et al. (2021) and was presented to stakeholders during the interviews. The reason behind that was to find out, if it is perceived that the PV mix in Germany will align with the area potential in the long-term future, especially because reduced area conflicts are often a main argument for integrated PV solutions. The potential for roof-top PV and ground-mounted PV as non-integrated systems was given at 26% and 6% respectively in this study. At least until 2030, integrated PV will not make a major contribution in the overall installations of PV, therefore the raw area potential will have only little influence on the overall PV mix.

Out of the different integrated PV systems, Agri-PV seems to be the concept that is regarded as the most promising and influential one in coming years. Pilot projects have shown that competitive LCOE can be reached for the so-called Agri-PV category 2. Extreme weather occurrences such as heavy rainfall, hail or intense sun radiation are weakened by PV modules and therefore positive effects for crops and other cultures are possible. And even though the overall yield is likely to be lower with PV than without it, this does not necessarily mean lower income for the operating farmer.

Instead, operating a PV plant is an additional revenue stream and even reduces the entrepreneurial risk. On the other hand, Agri-PV still comes with high investment costs and LCOE are higher than for traditional ground-mounted systems, especially related to superstructures necessary for category 1 Agri-PV systems. This reduces the attractiveness for different investors and limits the potential contribution for the overall capacity installations in Germany. Potential improvements could be achieved, if new regulations specifically for Agri-PV are integrated in the EEG. Especially separate feed-in tariffs could make a difference to account for lower outputs and higher installation costs and therefore increase the economic attractiveness of such systems. Furthermore, the development of new system constructions could make Agri-PV more effective and less expensive. A suggestion is to create systems in which PV modules are based on wire ropes instead of concreted pillars. This would have the advantages that less construction material is necessary and also that less fixed points of the mounting-structures disturb the agricultural land. Another access point is to increase awareness among stakeholders, especially land-owners and farmers. Obviously, Agri-PV is a completely new possibility of land-use for these stakeholders and knowledge is very limited. If advantages, synergies and business cases are more present to these stakeholders, the demand can be expected to increase. Of course, reaching financially attractive return rates is the baseline.

BIPV also comes with a high potential and without space conflicts, as facades on buildings are typically not used for other purposes. It provides a possibility to significantly increase the energy output that properties have, if roof-top PV is combined with additional PV systems on facades. Another advantage is that such PV plants are not as sensitive to the current position of the sun, which results in less seasonal fluctuations. Furthermore, if they are built on the east and west flank of a building, these systems can use the sun's daily radiation as long as possible. Own the downside, the overall electricity output will always be lower than for roof-top- and ground-mounted PV systems, as modules are not positioned in ideal angles and directions to the sun. The application of the actual modules is another issue. In most cases, standardised modules will not be applicable for facades due to safety reasons or design and architectural constraints. This means that specific modules and mounting systems need to be developed and as of today, hardly any module manufacturer has such products in their portfolio. Besides developing and introducing such products to the market, approval procedures for these modules should also be taken into account and postpone the market-readiness of BIPV. The higher costs and reduced efficiencies lead to the fact that such systems are usually not worthy investments as of today, at least with the current support measures from the EEG. Specific feed-in tariffs for BIPV systems could be a game changer for this technology, similar to Agri-PV.

Floating PV is regarded as the integrated PV solution that has the highest market-readiness already. As a matter of fact, there are several plants installed in Germany today (gh, 2022). LCOE are similar to ground-mounted systems and make this PV system type financially attractive. If Floating PV is applied to lakes at which there is still industrial activity such as sediment excavation, the electricity can be used directly on site. An ecological advantage is said to be related to the cover the PV modules provide for the water surface. Many lakes have the problem in hot summer periods, that the water overheats and the ecosystem collapses. If the PV modules provide shade and reflect more sunlight, overheating could be limited. Despite these positive economic and ecologic aspects, the potential for Floating PV in Germany is limited, as there are not many appropriate water areas available. Furthermore, new regulations within the water resources act (German: "Wasserhaushaltsgesetz") have limited the availability even more. With the recent amendment, PV systems on waters must have a minimum distance of 40 metres to the shore and cannot occupy more than 15% of the overall surface area of the water (Bundesamt für Justiz, 2023). This regulation has caused frustration among the PV market stakeholders, as already planned projects had to be paused and the potential for new projects has been limited highly. Even if it appears likely, that these regulations will be loosened again in the future, the core problem of limited availability and also usage conflicts will remain for Floating PV.

RIPV is overall regarded as the least influential PV system type among stakeholders. The main concerns are high installation costs because of large superstructures and corresponding mounting systems as well as safety issues related to accidents. Maintenance would also be complicated and connected with higher costs. Additionally, this is still a conceptional idea and hardly any first-hand data could be collected from pilot projects yet. Besides covering the roads with PV however, it could also be possible to apply PV in noise protection barriers. This is regarded as a more promising alternative, because there are no safety issues and costs would be much lower. If such barriers have to be built anyways, applying PV modules instead of other usually applied materials is not seen to have a significant impact on the costs, especially not if the added value of generated electricity is taken into account. The possibility of capturing the sunlight from two sides could prove to be another advantage of such installations. Finally, RIPV in general could possibly become more important in the future, as synergies with electro mobility (e-Mobility) exist. Produced electricity could be used directly to feed recharging facilities for vehicle batteries.

Urban PV is aimed to have no land-use conflicts, as already sealed surfaces that have no other purpose than the one, they already have, are used. The most potential for such systems is seen with regards to parking areas, which are covered by PV. This again would lead to synergies with charging facilities for e-Mobility. Furthermore, shade that is created by such systems is beneficial in summers when cities tend to heat up a lot. For other applications however, most stakeholders do not see a real business case currently which makes the potential limited. It is emphasised that rather all possible roof surfaces are targeted at first.

4.4. Contribution of different PV systems for 2030 PV mix

As the section on integrated PV suggests (chapter 4.3), these PV systems are expected to have a fairly low contribution within the overall capacity addition plans of 215 GW until 2030. Despite their potential regarding available area, synergies with for example agriculture and e-Mobility and new business cases, their importance will only be secondary.

In a study conducted by Wirth et al. (2021), the area potential for different PV systems was evaluated. Based on these findings, the PV mix in Germany would consist to two thirds of integrated PV and only one third of ground-mounted and roof-top systems. Interview partners were asked, whether they believe that the PV mix will align with this area potential in the long-term future, so even beyond 2030. As visible in figure 5 below, this is predominantly not expected to be the case, as roof-top- and ground-mounted systems will continue to be the main contributors. However, the results also indicate that almost half of the interview partners believe that integrated PV will increase in importance, contributing a decent share in the overall mix. Nonetheless, a small share (18%) of the interview partners reckons, that the PV mix will indeed align with the area potential in the future.

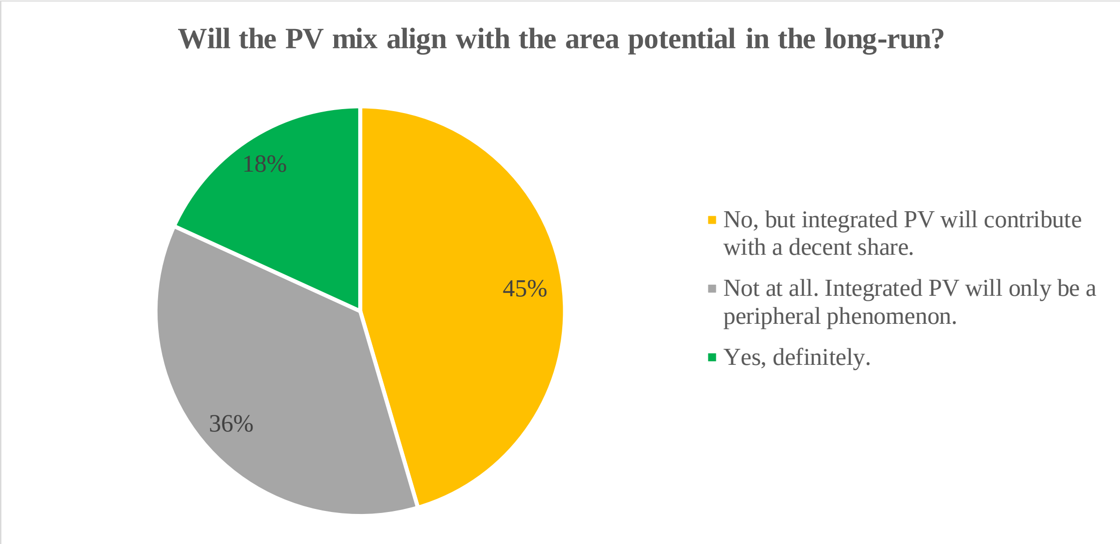


Fig. 5. Stakeholder opinions on whether the long-term PV mix will align with the area potential for different PV systems (Own illustration)

Based on the assessment of interviewed stakeholders, the two system types of ground-mounted systems and roof-top systems will approximately have an equal share in the installations until 2030. There are several reasons for this, which are listed below.

Large-scale ground-mounted PV systems have the cheapest LCOE today, not only within different PV systems but compared to all energy technologies. For this reason, these plants are attractive for investors and even though the EEG provides relatively little support measures, the growing business model of PPAs is likely to ensure significant growth. These large-scale systems will be very important to reach the addition targets, as scale effects apply and shortages of installers are mitigated. Certainly, a high amount of PV can be installed faster with less but individually larger plants than with a high amount of small-scale PV plants. The German government has already answered to the discussion regarding available areas, by increasing privileged adjacent areas of rail tracks and roads that will help to build more PV plants. It is also expected, that more spaces such as idle agricultural fields or former waste disposal sites are released for PV purposes in the near future.

One often publicly discussed down-side of ground-mounted systems is that they, unlike basically all other PV systems, are not using already sealed surfaces, and therefore negatively influence landscapes and even have harming effects on eco-systems. For the majority of the stakeholders interviewed, this issue is not confirmed. Of course, it depends on the specific environment that is there prior to the construction of a PV system. But for example, it would not happen, that a plant is approved to be built in an environmentally protected area, but rather already heavily used areas for industrial or economic purposes are taken into consideration. As a matter of fact, some stakeholders argue that the construction of a PV plant could actually lead to positive environmental impacts. Once built, the area of a ground-mounted PV system is hardly touched by humans, allowing biodiversity to develop. In comparison to monocultural crop fields, the biodiversity could therefore be significantly higher. Furthermore, project operators increasingly introduce their own rules to make such plants more environmentally-compatible, for example by leaving space for wild flowers and bees or by having sheep graze on the area instead of using lawn-mowers.

An example is the initiative “Gute Planung” by the federal association for renewable energy economy. Within this certificate (fig. 6), the association along with several players involved in planning, constructing and operating ground-mounted PV systems, assures to fulfil certain environmental requirements for PV plants.

Fig. 6. Certificate "Gute Planung" as a best practice approach for ground-mounted systems (bne, 2023)

Precisely, it is structured in five core areas. Within section A, obligations towards local communities are contained. Section B includes regulations and obligations towards farmers and part C comes with certain requirements regarding the integration in the landscape. Furthermore, section D touches upon obligations to conduct measures for biodiversity improvements and lastly in part E, regulations on planning, realization, operating and technical requirements are elaborated on (bne, 2023).

For roof-top PV systems, there are also numerous reasons on why their importance will continue to be high. The residential segment that includes the classic small-scale PV systems on private houses with installed capacities of typically 10-30 kWp, is anticipated to continuously have strong growth. Rising electricity prices, decreased system costs, charging of electric vehicles and the desire to have an independent electricity supply are all driving factors. Besides private houses, rented properties also still have a high potential and with possible adaptions in the EEG regarding landlord-to-tenant-electricity, this segment could become dynamic very quickly. The largest impact however concerning roof-top PV systems is expected to come from the C&I segment. Currently, this segment is still weak, only contributing approximately one Gigawatt to the installed capacity in 2022. The reasons behind this are seen in EEG regulations and corporate investment strategies. The EEG had prescribed tendering for PV systems of this scale, which made the planning process complicated. Secondly, amortization times have been a hindering factor for more installation. It has often not been perceived as an attractive investment for commercial organizations to finance a PV plant, as periods of roughly 10 years to reach a return on investment are simply too long. However, change is anticipated now for this segment. With the new EEG regulations, tendering is now no longer required for the majority of PV plants built in the C&I market. Additionally, the attractiveness has increased as well, but more from a consumption perspective, reason being the rising electricity prices and the general uncertainty on the energy market. Therefore, consuming the self-produced electricity to fixed prices is of increasing importance for the C&I sector. Another driver for the increased demand from this sector is sustainability. Organizations are pushed either by governmental regulations or customer expectancies to increase the sustainability of their operations. Producing carbon-free electricity with PV systems on owned properties will be an important aspect in this context.

5. Discussion

It becomes obvious from the results, that there is a positive outlook for the PV market in Germany and significant growth can be expected in the coming years.

Despite the anticipated growth, it seems unlikely, that the capacity addition plans will be reached to full extent. The market already has experienced massive growth in recent years to reach an annual installed capacity value of 7,2 GW in 2022. The plan to triple this number until 2026 appears to be too ambitious, particularly with the present challenges that are still in the way.

For most of the stated challenges it will depend on how quick those can be solved with appropriate measures. From a policy perspective, it appears that the government is aware of that urgency and it can be expected that further adaptions of the EEG through amendments will be released in the near future. The PV strategy document, which was published very recently by the corresponding ministry already addresses a number of the main challenges, such as landlord-to-tenant electricity and specific regulations for IPV (BMWK, 2023). On the other hand, it also appears that the EEG does not have the primary control of PV development in Germany anymore. One reason is the economic attractiveness of the technology, due to decreased system prices, which enables investments detached from subsidies. This becomes obvious with the fact that a large share of new large-scale PV systems is realized outside of the EEG regulations and with PPAs instead. Furthermore, it is seemingly out of the EEG's scope to address the most significant challenge, which are lacking installation capacities in form of skilled workers. However, as a high number of additional workers needs to be established, governmental actions at other flanks could prove to be important. For this, there should be three access points. At first, controlled and well-managed immigration must be ensured to hire skilled workers from abroad. Secondly, educational measures need to be undertaken in order to build up a higher number of skilled workers within Germany. Finally, the corresponding jobs for PV assembling and electric engineering must be made more attractive. These are definitely actions with time pressure, as it can be expected that it will take several years until effects become visible.

A critical aspect going forward is how to proceed with integrated PV. From the results, one could argue that this should not be prioritised, as those systems are only expected to make minor contributions within the installation plans for the near future. Opposed to that, the high area potential, the fact that no new areas need to be touched, synergies that could be realized and attractive investment opportunities are strong arguments to emphasis the development of IPV more. In addition, a more long-term perspective on PV development would be another argument for IPV. With the electricity demand expected to rise significantly due to decarbonisation and electrification, one can expect that PV will be expanded further beyond 2030. Considering the expected installations up until then, free areas and also roof-tops could eventually become scarce. Against this backdrop, it is important to lay the basis for a higher share of IPV as early as possible. For the practice this means that awareness needs to be created and appropriate support measures defined, so that the market can develop and incorporate products and solutions for IPV with higher pace. It has already been concluded within the recent PV strategy from the government, that IPV systems, especially Agri-PV and PV on parking lots, require specific policies (BMWK, 2023). This aspect has also been stated by Wirth et al. (2021) and Wirth (2023) in previous publications. In the results of this study, IPV has divided opinions. Despite, approximately two thirds of the interviewees believe that IPV will become more important in the near future and contribute to the PV mix with significant shares. The argument that separate measures for those systems are needed has also been frequently stated by interview partners. One specific suggestion that appeared several times is the introduction of specific FIT for different system types. As a matter of fact, this would bring back the EEG's control for PV development to some extent.

With regards to previous studies in the research area, a number of similarities and overlaps as well as some differences and conflicts between the results have been identified.

Rosenberg, Lind and Espegren (2013) argue, that targets for energy production capacities are often inaccurate, because they do not consider the development of energy demand and consumption patterns. Moore and Gustafson (2018) confirm this viewpoint by concluding that the focus in Germany's energy transition predominantly lays on increasing the production capacities. A similar strand was mentioned by some of the interviewees in this study. There are arguments, that electricity demand is expected to rise significantly until 2030, even values of up to 30% are regarded as possible. Drivers for this are seen especially in the electrification of processes, that are carried out for decarbonisation in order to reach emission targets. Electric vehicles and electric heating systems are among the most popular applications. These arguments show that the capacity addition plans must be closely assessed with different developments of future energy demand and according measures need to be undertaken. If the electricity demand will rise as much as 30%, the capacity addition plans of 215 GW until 2030 will likely not be enough to satisfy the demand. On the other hand, there is the option to look at the consumption side and target efficiency improvements.

Stakeholders agree, that PV alongside wind power will be the main contributor in the electricity mix in Germany. It is acknowledged, that PV alone is not enough, but the combination with wind power will enable a good balance in the electricity production. A minor share can then be contributed by biomass, water and geothermal electricity in the long-term future. Moore and Gustafson (2018) outlined, that a major risk concerning future PV expansion is losing public acceptance. This however could not be confirmed with the results from this study. Only 18% of the interview partners have mentioned this as a challenge and many arguments go in the opposite direction, as PV is seen as the energy source with the highest public acceptance. Several reasons for this also were identified. The low LCOE make PV an attractive investment for a variety of stakeholders. Furthermore, the simplicity and accessibility of the technology make it available for the majority of people. Thirdly, PV is regarded to have less environmental impacts than other renewable energy sources as it does not require interferences in landscapes to such a high magnitude.

Regarding the different PV system types, there is an agreement that large-scale system will become more important and therefore significant growth is expected for this segment. This is also in line with the remarks made in the PV strategy by the German government, in which ground-mounted systems and C&I roof-top systems are said to be of particular importance within the installation plans (BMWK, 2023). Besides this accordance, opinions on the contribution of different PV system types vary widely. Whereas BMWK (2023) anticipates an even contribution of ground-mounted- and roof-top systems, Henning *et al.* (2021) sees a dominant share of roof-top systems and Wirth (2023) argues that ground-mounted systems should be the exception and instead areas like fields, lakes and sealed surfaces in urban areas should be used for integrated PV solutions. A similar pattern is identifiable in the results from the semi-structured interviews. Ground-mounted systems are generally a point of conflict. There are some arguments, that regard this system type as crucial for the planned capacity additions, due to cheap LCOE, a great scalability and the simplicity of construction. On the other hand, land-use conflicts are mentioned from counterparts. They argue that a significant increase of ground-mounted systems would take away important areas with rich soils that should rather be used for agricultural purposes or as nature reservoirs. Further conflict on this system type is present regarding the financing structures. Whereas some critics regarding the EEG are presented, other arguments state that these systems are not dependent on the EEG anyways, because PPAs on the market have been more profitable for a number of years already. As stated earlier though, this should be regarded as a risk for the achievement of the capacity addition plans, as the government has only little leverage or steering opportunity for this type of systems.

As mentioned, the contribution of IPV systems is also a conflict point. Whereas Wirth *et al.* (2021) and some stakeholders argue that there is no way around IPV because of scarce areas and land-use conflicts, others do not agree with this argument at all and state that roof-top PV and available areas for ground-mounted PV will be good enough to reach the installation targets. They rather see IPV as an add-on, which can be used if investments are attractive. Opinions also vary on the importance of different IPV system types. The only agreement appears to be that RIPV is not feasible in the near future due to costly mounting structures and safety concerns. Though, if one looks at IPV from the perspective of creating synergies, RIPV has one of the obvious synergies with e-Mobility, producing electricity where it could be used directly by vehicles. On those grounds, integration possibilities should be further pursued. Instead of a direct integration in roads, noise-barriers adjacent of roads could be a better area of application. Agri-PV has a high area potential due to the magnitude of agriculturally used areas in Germany and potentially yields attractive synergies, as cultures are protected from extreme weather and additional revenue streams can be generated by farmers. For these reasons, it is seen as the most promising IPV solutions among interview partners from this study, generally agreeing with Wirth *et al.* (2021). However, it is not expected that Agri-PV will become the most applied PV system type in Germany by any means. Besides Agri-PV, BIPV is regarded to have great potential. When appropriate system solutions are found and regulations are adapted for this system type, PV systems on facades could experience rapid growth. They provide an attractive business case for property owners, as they have a more constant electricity production than roof-top systems and could therefore be used in combination. By doing so, the overall electricity output from buildings can also be scaled-up.

To generalize the finding, it can be stated that there is currently no agreement among PV stakeholders, which system types should contribute to which extent. At the moment, this might not be as critical, because PV is targeted to be expanded so heavily, that it does not matter as much, where the systems are being built. However, looking into the future, this could pose problems. If areas become scarce, investments for individual PV system types become less attractive or if unbalances in the electricity production occur, an unsystematic installation strategy might be regretted. It has to be considered that measures to develop and support individual system types take time and have to be planned well in advance. Therefore, more research should be carried out to identify a future PV mix in Germany. This can be based on the results of this study, where advantages and disadvantages of the different system types as well as potential measures are pointed out.

6. Conclusion

This study provides a thorough assessment of the installation plans by the German government for PV. Through analysing existing literature and conducting semi-structured interviews with important stakeholders of PV in Germany, the development of PV until 2030 can be estimated with higher confidence. In addition, the results of the study are applicable for policymakers as well as industrial players for strategic decision-making. It should be noted though, that this study was constrained by a tight time frame and the availability of interview partners, so therefore deeper analyses will need to be conducted in the future to refine the results. Comments on potential future studies are made in chapter 6.1.

Even though the anticipated installed capacity of 215 GW until 2030 could theoretically be reached, especially because of the high demand due to different drivers, some major challenges will likely hinder that target. Limiting factors often mentioned in previous studies include public acceptance issues and material shortages due to supply chain problematics. As the analysis of the interviews shows, these two factors will likely not be as critical anymore going forward. With that result, regulations and bureaucratic processes as well as lacking installation capacities remain as the two major challenges derived from this study and with regards to previous publications.

Certain regulations regarding planning and approval stretch the implementation time of ground-mounted systems, slowing-down the capacity expansion. Landlord-to-tenant electricity on rented properties could become a major contributor as electricity can be used directly by residents and the area potential is great, but complex regulations regarding the usage and accounting of the electricity often scare away potential investors. These can be regarded as two important access points for policy makers. Improved regulations concerning those PV system applications could have a high impact for capacity additions and therefore contribute significantly towards reaching the targets.

As the annual installed capacity is aimed to be tripled in a few years, a much higher number of skilled workers is also required. However, there is already a scarcity of electricians and assemblers on the market, which raises the question how this work force should be build up in order to fulfil the demand. It seems unlikely that the German market itself will be able to solve this issue. One possibility could be to hire a larger number of skilled workers from abroad, for which the right legal constraints would have to be put in place. Besides, there is no getting-around educating people in Germany. For this, the corresponding jobs and apprenticeships need to be made more attractive.

The variety of PV systems has increased and will likely become more diverse in the future. Until 2030 however, the main contribution to installed capacities will come from the established roof-top- and ground-mounted systems. This can mainly be reasoned due to low LCOE, investment attractiveness, energy independency requirements and awareness for these system types and the business cases from customers. The share of ground-mounted systems will increase, because plants are usually large and therefore have a much higher output than roof-top systems. However, the previously weak C&I segment for roof-top systems is also expected to make a much more significant contribution within the capacity additions in the coming years.

Integrated PV systems divide opinions both in existing literature and among interview partners of this study. Because the available areas within the segments ground-mounted PV and roof-top PV are more than enough to reach the installation targets, there are some arguments that integrated PV is not needed. On the other hand, there are arguments against a significant expansion of large-scale ground-mounted systems, as they take away areas that could for example be used for agricultural purposes or renaturation projects. Overall, with regards to the installation targets until 2030, the predominant result is that integrated PV will not be a major contributor. At the same time, it appears realistic that integrated PV systems will increase in importance and contribute with a small share, i.e. a few GW annually, to the capacity additions. Apart from the additional areas that can be targeted, synergies within agriculture and with e-Mobility as well as investment attractiveness are expected to be the main drivers. Opinions also differ regarding which integrated PV systems are more important than others. The two most promising system types seem to be Agri-PV and BIPV. Floating PV is economically attractive, but is limited due to a lack of appropriate waters.

However, in order to increase the amount of integrated PV systems, LCOE must decrease, awareness must be generated and policy measures established that can compensate the economic disadvantages that these systems still have compared to traditional systems. A specific measure could be to introduce separate FIT for the different integrated PV system types.

6.1. Possible future work

The first suggestion for future work is to extend the study with regards to the interview partners and include other more indirect stakeholders of PV as well. This would include for example energy investors, farmers, architects and private consumers. Results could be used particularly to develop a better understanding of the application possibilities for integrated PV, their feasibility and appropriate support measures.

As land-use conflicts are an often-stated argument against a significant expansion of ground-mounted PV, studies should be carried out in this direction. For this, analyses of available areas and anticipated future area demand for agriculture are necessary to conclude whether Agri-PV is required from a perspective of combined area usage. Another connection point in this context would be to consider the ecological impact of ground-mounted systems in comparison with Agri-PV and also in comparison to the previous state that different areas used for ground-mounted systems have.

Furthermore, it appears to be important to have quantified data to compare the performance of different PV system types. On that behalf, case studies on different integrated PV systems could be conducted, comparing values such as energy output and LCOE. Additionally, one could even go a step further and aim to quantify non-economic factors such as emissions saved, biodiversity impact or aesthetics. With these kinds of results, a ranking model could be created, comparing the different PV systems in a transparent way and which can be used to accurately project an optimal long-term PV mix based on all relevant economic and ecological criteria.

With one of the risks being the dependency on imports from outside of the EU, analyses for PV development focusing on the realisation of capacity additions with a certain number of components manufactured within the EU could be a reasonable research area. Special attention should be put on the cost-competitiveness based on LCOE regarding the different origins of components.

If the focus is not solely put on PV but on the total energy mix, energy system modelling could be applied to develop different scenarios for the energy mix in Germany and potentially challenge the capacity addition targets for PV. In such scenarios, different estimates for the uncertain future energy demand should also be taken into consideration and corresponding implications would need to be pointed out.

7. Acknowledgement

I would like to use this opportunity to express my gratitude to several people. Without your exceptional support and contribution, I could not have realized the thesis in the way I have.

At first, my thanks go out to all my interview partners, which I cannot call by name here unfortunately. Thanks a lot, that you took the time to conduct the interviews with me and have provided valuable and fascinating knowledge. Because of your contribution, I could collect a lot of useful data on the one hand and had some really enjoyable conversations on the other hand as well.

Secondly, I am thankful to have received great guidance during the different stages of my thesis. Thank you, Maryna, that you helped me structure and focus my research, asked critical questions, provided methodological and practical knowledge and gave me the freedom to develop my research. I am glad that you took the time to supervise my thesis. Furthermore, I want to thank Daniel, who was my subject reviewer. Your feedback was highly useful and surely increased the quality of my writing.

Furthermore, I would like to thank my colleagues at *BayWa r.e.* who supported me during the thesis writing process, answered questions from my side and helped me gain more insight branch knowledge.

As this thesis is the final task of my Master studies, I want to use this opportunity to thank all the people I met during these two years and who made this an instructive and exciting time. Thanks to all the professors and staff from *Uppsala Universitet* and *Sveriges Lantbruks Universitet* for hosting and carrying out the programme in Sustainable Development. As well, thanks to all my study colleagues and friends for the interesting discussions and groupworks, but especially that you made this whole time an unforgettable and enjoyable experience.

Finally, I would like to thank my parents and my whole family, who have been exceptionally supportive. Without you, I could have never come this far and I am thankful for the opportunities that you have made possible for me. A special thanks that, besides the support you gave me, you have always showed high interest in the things I do and tell. This is not something that can be taken for granted and I highly appreciate that.

Felix Rüsseler

Hamburg, June 2023

8. References

Agentur für Erneuerbare Energien (2023) *Grafik-Dossier%3A+Der+Strommix+in+Deutschland+2018-2022*. Available at: https://www.unendlich-viel-energie.de/mediathek/grafiken/grafik-dossier-strommix-2015-2022 (Accessed: 30 March 2023).

Belgrave, L.L. and Seide, K. (2019) 'Coding for Grounded Theory', in *The SAGE Handbook of Current Developments in Grounded Theory*. SAGE Publications Ltd. Available at: https://dx.doi.org/10.4135/9781526436061 (Accessed: 3 February 2023).

Bhatnagar, K. (2021) 'The 6 Indirect Forms Of Solar Energy: Explained | Solar Funda', 31 May. Available at: https://solarfunda.com/indirect-forms-of-solar-energy/ (Accessed: 6 December 2022).

BMWK (2022) *Neuer Schwung für erneuerbare Energien*. Available at: https://www.bmwk.de/Redaktion/DE/Schlaglichter-der-Wirtschaftspolitik/2022/10/05-neuer-schwung-fuer-erneuerbare-energien.html (Accessed: 18 February 2023).

BMWK (2023) 'Photovoltaik-Strategie'. Bundesministerium für Wirtschaft und Klimaschutz (BMWK. Available at: https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/photovoltaik-stategie-2023.pdf?__blob=publicationFile&v=6 (Accessed: 30 March 2023).

bne (2023) *Gute Planung PV, bne - Bundesverband Neue Energiewirtschaft e.V.* Available at: https://www.bne-online.de/de/verband/gute-planung-pv/ (Accessed: 24 May 2023).

Bryant, A. and Charmaz, K. (2007) *The SAGE Handbook of Grounded Theory*. London, UNITED KINGDOM: SAGE Publications, Limited. Available at: http://ebookcentral.proquest.com/lib/uu/detail.action?docID=1138448 (Accessed: 4 February 2023).

BSW Solar (2014) 'Solarstrom-Zubau 2013 mehr als halbiert | Bundesverband Solarwirtschaft', 9 January. Available at: https://www.solarwirtschaft.de/2014/01/09/solarstrom-zubau-2013-mehr-als-halbiert-2/ (Accessed: 30 March 2023).

Bundesamt für Justiz (2023) *Gesetz zur Ordnung des Wasserhaushalts 1) 2) (Wasserhaushaltsgesetz - WHG) § 36 Anlagen in, an, über und unter oberirdischen Gewässern*, *Bundesministerium der Justiz*. Available at: https://www.gesetze-im-internet.de/whg_2009/__36.html (Accessed: 24 April 2023).

Bundesnetzagentur (2023) *Bundesnetzagentur - Presse - Bundesnetzagentur veröffentlicht Daten zum Strommarkt 2022*. Available at: https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2023/20230104_smard.html (Accessed: 18 February 2023).

Demirel, Y. (2016) *Energy*. 2nd edn. Switzerland: Springer Cham (Green Energy and Technology, 1865–3529). Available at: https://doi-org.ezproxy.its.uu.se/10.1007/978-3-319-29650-0.

Die Bundesregierung (2022) *Ausbau erneuerbarer Energien | Bundesregierung*, *Die Bundesregierung informiert | Startseite*. Available at: https://www.bundesregierung.de/breg-de/themen/klimaschutz/novellierung-des-eeg-gesetzes-2023972 (Accessed: 12 December 2022).

Energy.gov (no date) *How Does Solar Work?*, *Energy.gov*. Available at: https://www.energy.gov/eere/solar/how-does-solar-work (Accessed: 6 December 2022).

Enkhardt, S. (2021) *Ampel-Koalition will Photovoltaik-Ausbau auf 200 Gigawatt bis 2030*, *pv magazine Deutschland*. Available at: https://www.pv-magazine.de/2021/11/24/ampel-koalition-will-photovoltaik-ausbau-auf-200-gigawatt-bis-2030/ (Accessed: 30 March 2023).

Everett, B. (2012) *Energy Systems and Sustainability : Power for a Sustainable Future.* 2nd edn. Oxford: Oxford University Press.

Galletta, A. and Cross, W.E. (2013) *Mastering the Semi-Structured Interview and Beyond: From Research Design to Analysis and Publication*. New York, UNITED STATES: New York University Press. Available at: http://ebookcentral.proquest.com/lib/uu/detail.action?docID=1187368 (Accessed: 2 February 2023).

gh, A. (2022) *Deutschlands derzeit größte Floating-PV-Anlage*, *SOLARIFY*. Available at: https://www.solarify.eu/2022/02/11/634-deutschlands-derzeit-groesste-floating-pv-anlage/ (Accessed: 5 May 2023).

Gründinger, W. (2017) 'Introduction: What Drives the Energiewende?', in W. Gründinger (ed.) *Drivers of Energy Transition: How Interest Groups Influenced Energy Politics in Germany*. Wiesbaden: Springer Fachmedien (Energiepolitik und Klimaschutz. Energy Policy and Climate Protection), pp. 11–40. Available at: https://doi.org/10.1007/978-3-658-17691-4_1.

Held, A. *et al.* (2019) 'Zukünftige Finanzierung von PV-Anlagen unter 750 kW – Bedarf, Anforderungen, Kosten, Szenarien und Förderung'. BMWK. Available at: https://www.bmwk.de/Redaktion/DE/Publikationen/Studien/zukuenftige-finanzierung-von-pv-anlagen-unter750kw.pdf?__blob=publicationFile&v=6 (Accessed: 30 March 2023).

Henning, Dr.B. *et al.* (2021) 'Markthemmnisse für den beschleunigten Ausbau von Photovoltaik-Dachanlagen'. Photovoltaik Forum Service GmbH and Kanzlei von Bredow Valentin Herz. Available at: https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Klima/Klima-Allianz-Analyse-zu-Photovoltaik-Dachanlagen.pdf (Accessed: 5 May 2023).

IRENA (2022) 'RENEWABLE POWER GENERATION COSTS IN 2021'. International Renewable Energy Agency. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf?rev=34c22a4b244d434da0accde7de7c73d8 (Accessed: 16 March 2023).

Kost, C. *et al.* (2021) 'STROMGESTEHUNGSKOSTEN ERNEUERBARE ENERGIEN'. FRAUNHOFER-INSTITUT FÜR SOLARE ENERGIESYSTEME ISE. Available at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/DE2021_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf (Accessed: 19 November 2022).

Mertens, K. (2014) *Photovoltaics: Fundamentals, Technology and Practice*. Newark, UNITED STATES: John Wiley & Sons, Incorporated. Available at: http://ebookcentral.proquest.com/lib/uu/detail.action?docID=7103965 (Accessed: 12 December 2022).

Moore, J. and Gustafson, T. (2018) 'WHERE TO NOW? Germany Rethinks its Energy Transition', *German Politics and Society*, 36(3), pp. 1–23. Available at: https://doi.org/10.3167/gps.2018.360301.

Morris, C. and Jungjohann, A. (2016) *Energy Democracy*. Cham: Springer International Publishing. Available at: https://doi.org/10.1007/978-3-319-31891-2.

Muhammed, G. and Tekbiyik-Ersoy, N. (2020) 'Development of Renewable Energy in China, USA, and Brazil: A Comparative Study on Renewable Energy Policies', *Sustainability*, 12(21), p. 9136. Available at: https://doi.org/10.3390/su12219136.

Next (2023) *Power Purchase Agreement (PPA): Was ist das?*, *Next Kraftwerke GmbH*. Available at: https://www.next-kraftwerke.de/wissen/power-purchase-agreement-ppa (Accessed: 5 May 2023).

Oktay, J.S. (2012) ‘Introduction to Grounded Theory and Its Potential for Social Work’, in J.S. Oktay (ed.) *Grounded Theory*. Oxford University Press, p. 0. Available at: https://doi.org/10.1093/acprof:oso/9780199753697.003.0001.

Ragheb, M. (2017) ‘Chapter 25 - Economics of Wind Power Generation’, in T.M. Letcher (ed.) *Wind Energy Engineering*. Academic Press, pp. 537–555. Available at: https://doi.org/10.1016/B978-0-12-809451-8.00025-4.

Ritchie, H., Roser, M. and Rosado, P. (2022) ‘Energy’, *Our World in Data* [Preprint]. Available at: https://ourworldindata.org/energy-mix (Accessed: 5 January 2023).

Rosenberg, E., Lind, A. and Espegren, K.A. (2013) ‘The impact of future energy demand on renewable energy production – Case of Norway’, *Energy*, 61, pp. 419–431. Available at: https://doi.org/10.1016/j.energy.2013.08.044.

Snyder, H. (2019) ‘Literature review as a research methodology: An overview and guidelines’, *Journal of Business Research*, 104, pp. 333–339. Available at: https://doi.org/10.1016/j.jbusres.2019.07.039.

Solarenergie.de (no date) *Freiflächen-Photovoltaik: gewerblicher und privater Nutzen*, *Solarenergie: Informationen zu Photovoltaik und mehr*. Available at: https://solarenergie.de/photovoltaikanlage/arten-von-pv-anlagen/photovoltaik-freiflaechenanlagen (Accessed: 27 March 2023).

Solarwatt (2023) *EEG-Novelle 2023: Änderungen bei Photovoltaikanlagen*, *Solarwatt | Photovoltaikanbieter für Module und Speicher*. Available at: https://www.solarwatt.de/ratgeber/eeg-novelle-2023 (Accessed: 30 March 2023).

S&P Global (2020) *What is Energy Transition?* Available at: https://www.spglobal.com/en/research-insights/articles/what-is-energy-transition (Accessed: 18 February 2023).

Tsoutsos, T., Frantzeskakib, N. and Gekas, V. (2005) ‘Environmental impacts from the solar energy technologies’, *Elsevier*, 33, pp. 289–296.

United Nations (2022) *What is renewable energy?*, *United Nations*. United Nations. Available at: https://www.un.org/en/climatechange/what-is-renewable-energy (Accessed: 6 December 2022).

United Nations (2023) *Goal 7 | Department of Economic and Social Affairs*, *Department of Economic and Social Affairs - Sustainable Development*. Available at: https://sdgs.un.org/goals/goal7 (Accessed: 16 February 2023).

Weller, B. *et al.* (2010) *Detail Practice: Photovoltaics: Technology, Architecture, Installation*. Basel/Berlin/Boston, SWITZERLAND: Walter de Gruyter GmbH. Available at: http://ebookcentral.proquest.com/lib/uu/detail.action?docID=1075522 (Accessed: 27 March 2023).

Wirth, Dr.H. (2023) ‘Aktuelle Fakten zur Photovoltaik in Deutschland’. FRAUNHOFER-INSTITUT FÜR SOLARE ENERGIESYSTEME ISE. Available at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/aktuelle-fakten-zur-photovoltaik-in-deutschland.pdf (Accessed: 5 May 2023).

Wirth, H. *et al.* (2021) ‘Solaroffensive für Deutschland’. Greenpeace. Available at: https://www.greenpeace.de/publikationen/20210806-greenpeace-kurzstudie-solaroffensive.pdf (Accessed: 13 February 2023).

World Economic Forum (2023) *Why we need to rethink energy security in the transition to net-zero*, *World Economic Forum*. Available at: https://www.weforum.org/agenda/2023/01/davos23-rethink-energy-security-transition-net-zero/ (Accessed: 16 March 2023).

Ye, L.-C., Rodrigues, J.F.D. and Lin, H.X. (2017) ‘Analysis of feed-in tariff policies for solar photovoltaic in China 2011–2016’, *Applied Energy*, 203, pp. 496–505. Available at: https://doi.org/10.1016/j.apenergy.2017.06.037.

Appendix A – Interview Guide

Slide 1/10

No questions on this slide.

Slide 2/10

Fragen im Opening Segment:

1. Was ist ihr persönlicher Bezug zur Solarenergie?
2. Wie sehen Sie die Entwicklung der Solarenergie in Deutschland in den letzten Jahren?
3. Welche Rolle spielt die Photovoltaik ihrer Meinung nach in der Energiewende in Deutschland?

Questions Opening Segment (translated):

1. What is your personal connection to solar energy?
2. How do you see the development of solar energy and in particular photovoltaics in Germany in recent years?
3. What role do you think photovoltaics plays in the energy transition in Germany?

Slide 3/10

Fragen im Opening Segment:

4. Was ist ihre Meinung zum neuen EEG in Bezug auf die Solarenergie bzw. Photovoltaik?

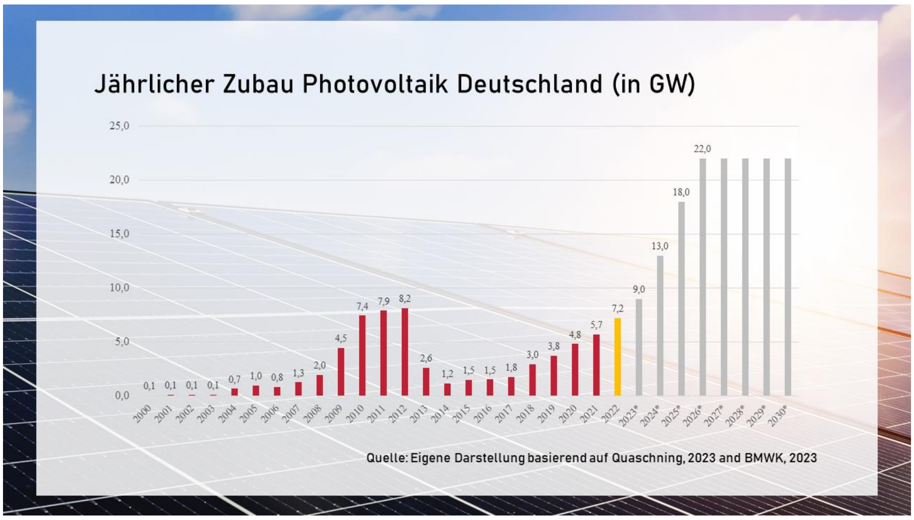
Questions Opening Segment (translated):

4. What is your personal take on the new EEG law (2023) with regards to photovoltaics?

References

Verbraucherzentrale (2023). EEG 2023: Das hat sich für Photovoltaik-Anlagen geändert. Verbraucherzentrale.de. Available from: https://www.verbraucherzentrale.de/wissen/energie/erneuerbare-energien/eeg-2023-dashat-sich-fuer-photovoltaikanlagen-geaendert-75401[Accessed 21.04.2023]

Slide 4/10



Fragen im Middle Segment:

1. Halten Sie die von der Bundesregierung vorgestellten Ausbauziele für die Photovoltaik für realistisch?

2. Was sind für Sie die größten Herausforderungen die es zu bewältigen gilt, um die Ausbauziele zu erreichen?

Questions Middle Segment (translated):

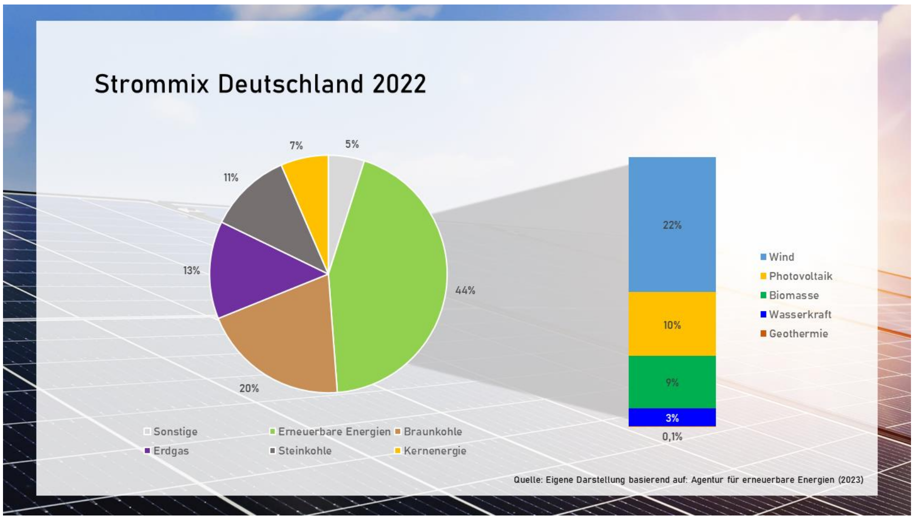
1. Do you regard the capacity addition targets for photovoltaics by the German government as realistic?
2. What do you think are the biggest challenges to overcome in order to reach these targets?

References

Quaschning, V. (2023) *Installierte Photovoltaikleistung in Deutschland seit 1990*, *Volker Quaschning - Erneuerbare Energien und Klimaschutz*. Available at: https://www.volker-quaschning.de/datserv/pv-deu/index.php (Accessed: 30 March 2023).

BMWK (2023) 'Photovoltaik-Strategie'. Bundesministerium für Wirtschaft und Klimaschutz (BMWK. Available at: https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/photovoltaik-stategie-2023.pdf?__blob=publicationFile&v=6 (Accessed: 30 March 2023).

Slide 5/10



Fragen im Middle Segment:

3. Welchen Anteil wird die Solarenergie ihrer Meinung nach langfristig im Energiemix von Deutschland einnehmen?

Questions Middle Segment (translated):

3. From your perspective, which will be the long-term share of photovoltaics in the German energy mix? Please give reasons!

References

Own illustration based on Agentur für Erneuerbare Energien (2023). Grafik-Dossier%3A+Der+Strommix+in+Deutschland+2018-2022. Agentur für Erneuerbare Energien. Available from: https://www.unendlich-vielenergie.de/mediathek/grafiken/grafik-dossier-strommix-2015-2022 [Accessed 30.03.2023]

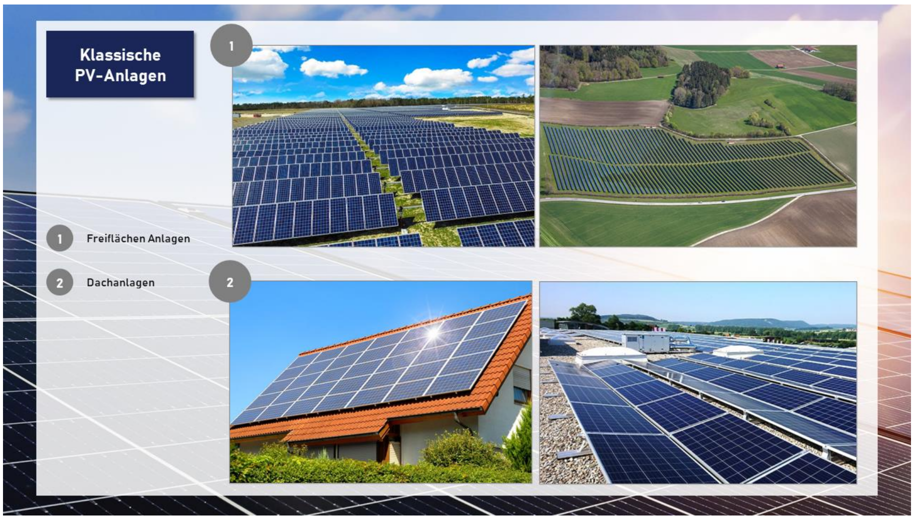
Slide 6/10

No questions on this slide.

References

Solarenergie.de (2022). Nachgeführte PV-Anlagen: Funktionsweise, Vor- und Nachteile. Solarenergie: Informationen zu Photovoltaik und mehr. Available from: https://solarenergie.de/photovoltaikanlage/arten-von-pv-anlagen/nachgefuehrte-pvanlagen [Accessed 21.04.2023]

Slide 7/10



No questions on this slide.

References

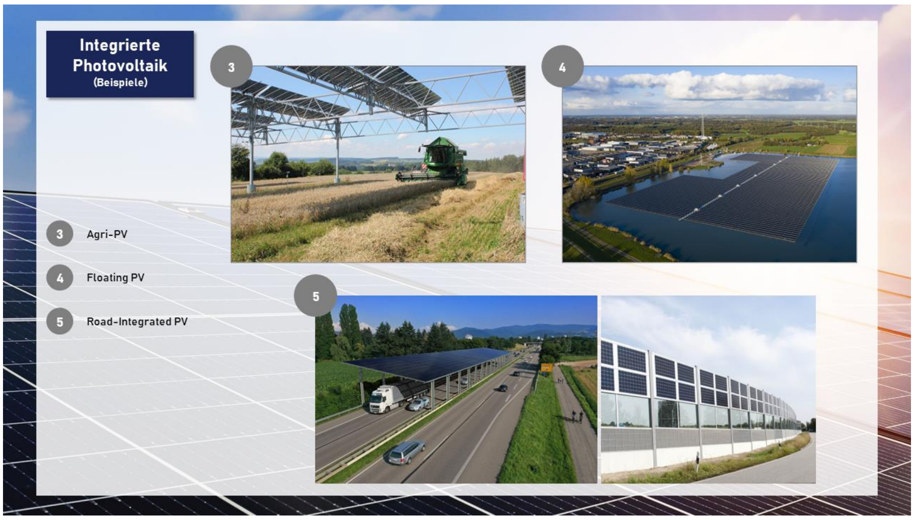
Stauffer, N. (2020). Researchers find benefits of solar photovoltaics outweigh costs. MIT News | Massachusetts Institute of Technology. Available from: https://news.mit.edu/2020/researchers-find-solar-photovoltaics-benefits-outweigh-costs-0623 [Accessed 21.04.2023]

Schürer, J. (2022). Lohnen sich Photovoltaik-Freiflächenanlagen für Landwirte?. Agrarheute. Available from: https://www.agrarheute.com/management/betriebsfuehrung/lohnen-photovoltaikfreiflaechenanlagen-fuer-landwirte-593350 [Accessed 21.04.2023]

North Africa Post (2019). Ghana: 12 MW Rooftop Solar PV to be constructed. The North Africa Post. Available from: https://northafricapost.com/28211-ghana-12-mw-rooftopsolar-pv-to-be-constructed.html [Accessed 21.04.2023]

Sonnenwende2020 (2019). Gutes Geschäft: Solarstrom vom Industrie- und Gewerbedach. Sonnenwende 2020. Available from: https://sonnenwende2020.de/blog/8-blog/33-solarstrom-industrie-gewerbedach.html [Accessed 21.04.2023]

Slide 8/10



Fragen im Middle Segment:

4. Die Bundesregierung hat angekündigt zusätzliche Flächen für neue PV-Konzepte wie Agri-PV, Floating PV oder RIPV freizugeben. Welche Bedeutung messen Sie dieser sogenannten „integrierten PV" in der Erreichung der Ausbauziele bei?
5. Wie schätzen Sie diese Konzepte in Bezug auf deren Installationskosten und Betriebskosten ein?
6. Wie würden Sie die technische Reife dieser Technologien beurteilen?

Questions Middle Segment (translated):

4. The German government wants to provide more spaces for new PV concepts such as Agri-PV, Floating PV or RIPV. How important do you think these „integrated PV plants" are to reach the capacity addition targets?
5. How performant are these concepts in installation costs and operating costs compared to traditional PV systems?
6. How would you rate the technological maturity of these concepts?

References

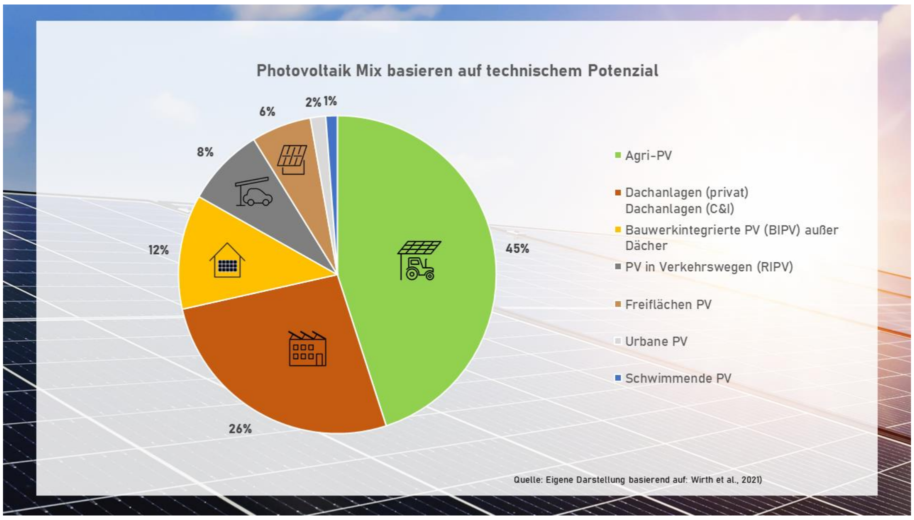
Fraunhofer ISE (no date). Agri-Photovoltaik: Chance für Landwirtschaft und Energiewende. Agri-PV. Available from: https://agri-pv.org/de/ [Accessed 21.04.2023]

HIS (no date). Schwimmende Photovoltaik-Anlagen: kein Problem!. HIS Renewables GmbH. Available from: https://www.his-solar.com/blog/floatingpvholland [Accessed 21.04.2023]

Fraunhofer ISE (no date). Photovoltaik in Verkehrswegen. Fraunhofer ISE. Available from: https://www.ise.fraunhofer.de/de/leitthemen/integriertephotovoltaik/verkehrswege-photovoltaik-ripv.html [Accessed 21.04.2023]

Fraunhofer ISE (no date). Photovoltaik in Verkehrswegen. Fraunhofer ISE. Available from: https://www.ise.fraunhofer.de/de/leitthemen/integriertephotovoltaik/verkehrswege-photovoltaik-ripv.html [Accessed 21.04.2023]

Slide 9/10



Fragen im Middle Segment:

7. Basierend auf dem technisch realisierbaren Potenzial sähe der Photovoltaik-Mix in Deutschland wie folgt aus. Wie schätzen Sie den tatsächlichen Mix 2030 ein?
8. Wie begründen Sie den jeweiligen Anteil im PV-Mix?

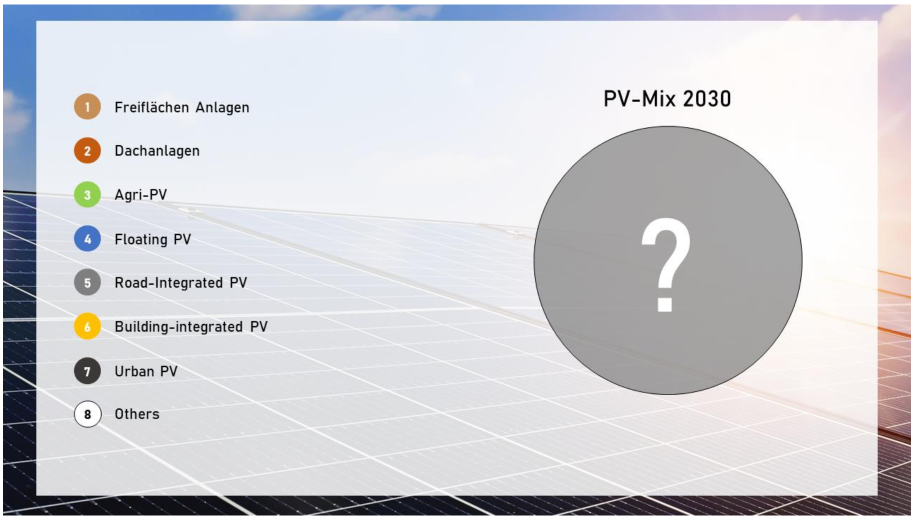
Questions Middle Segment (translated):

7. Based on the technical potential, the PV mix in Germany would look as follows. How would you estimate the actual mix in 2030?
8. What are your reasons for the specific shares in the mix?

References

Wirth, H. *et al.* (2021) ‘Solaroffensive für Deutschland’. Greenpeace. Available at: https://www.greenpeace.de/publikationen/20210806-greenpeace-kurzstudie-solaroffensive.pdf (Accessed: 13 February 2023).

Slide 10/10



Fragen im Middle Segment:

9. Wie beurteilen Sie die Auswirkungen der verschiedenen PV-Anlagen auf die Biodiversität?
10. Denken Sie, PV wird sich langfristig als günstigste Alternative zur Stromgewinnung etablieren?

Questions Middle Segment (translated):

9. How would you assess the biodiversity impact of the different PV plants?
10. Do you think, PV will establish itself as the cheapest technology for electricity generation on a long-term basis?

Fragen im Concluding Segment:

It must be noted, that questions in this segment varied highly between the interviews, based on the trajectory the narrative of the interview had taken in the previous segments.

1. Hat die Photovoltaik Vorteile gegenüber anderen erneuerbaren Energien, da sie in bestehende versiegelte Flächen integriert werden kann?
2. Kann man festhalten, dass integrierte PV-Anlagen in den kommenden Jahren eine deutlich größere Rolle in den Ausbauplänen spielen werden?
3. Aufgrund Faktoren wie des techn. Potenzials und positiven Auswirkungen für die Kulturen scheint Agri-PV viele Vorteile zu haben. Wird diese Technologie langfristig die am meisten verbreitetste PV-Anlagenart sein?
4. Haben Sie noch weitere Anmerkungen?

Questions Concluding Segment (translated):

It must be noted, that questions in this segment varied highly between the interviews, based on the trajectory the narrative of the interview had taken in the previous segments.

1. Does PV have a comparative advantage to other renewable energy technologies because it can be integrated in the environment without land-use conflicts?
2. Can it be said that integrated PV will become a much bigger contributor to PV capacity additions in the coming years?
3. Will Agri-PV, because of its various benefits become the most important and widely used PV power plant?
4. Do you have any more additions or comments?

Appendix B – Coding Documentation

First step: Open Coding

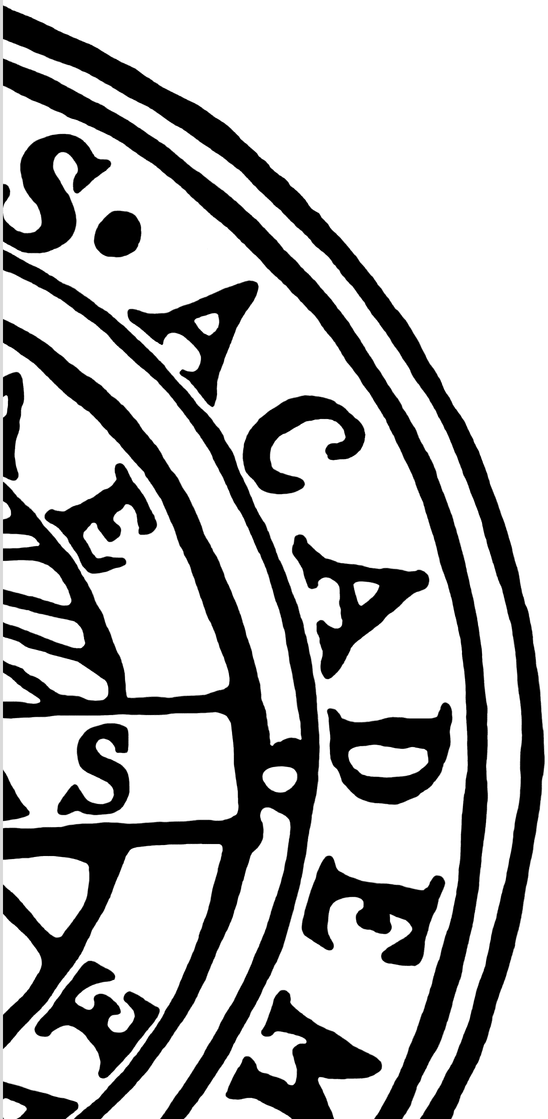
Category	Code #	Code	Components of the code
PV development	OC 1	Germany could be much further already in PV development	▪ Massive boom already 2010-2012 ▪ Regulations/policies destroyed the market ▪ Same annual installation in 2022 as 2010
	OC 2	Market has recently shown strong rebound and dynamic	▪ 2013-2017 poor, since then massive growth ▪ New government in 2021 ▪ New and updated policies/EEG ▪ Ukraine war and energy independence as drivers
	OC 3	Acceptance of PV higher than ever	▪ Everyone wants to do it ▪ Investment to make money ▪ Use own electricity, be independent ▪ Sustainable, clean energy
	OC 4	Cheap energy technology which has enabled various business cases	▪ System prices have dropped significantly ▪ Own usage or selling to grid possible
	OC 5	PV will play the central role for the energy transition in the coming years	▪ Quickest installation ▪ Cheapest technology ▪ Highest acceptance ▪ Great potential
	OC 6	PV and wind power will become the two major contributors in Germanys energy mix, PV reaching 30% in 2030	▪ PV growth will be faster than wind ▪ But only PV is not enough ▪ Wind has advantage of more hours of production ▪ The two can reach 60-90% in the long run
	OC 7	High interest rates could be a risk for capacity additions as investments become less attractive	▪ Rising interest can decrease demand ▪ Tax reductions etc. can be compensated
EEG and installation targets	OC 8	Political direction and new EEG is a positive development, but we need more to reach the targets of 215 GW	▪ Ambition of the government positive ▪ Key improvements, less bureaucracy ▪ Not so positive/important for large-scale systems
	OC 9	2030 Targets could be realistic, especially because the market is there, but there remain challenges	▪ Regarding demand we could already build 20 GW per year ▪ Questionable whether market/industry/regulations can adapt so quickly

Category	Code #	Code	Components of the code
EEG and installation targets	OC 10	A lack of installation capacities appears to be the main obstacle, with other challenges seemingly not so critical	▪ Almost everyone mentioned lack of installers and are uncertain where people should come from ▪ Too much immigration might be a risk ▪ Material availability not a major concern
	OC 11	Landlord-to-tenant electricity still a big issue	▪ Too complicated to operate the system under current regulations ▪ Investments are therefore usually not carried out
	OC 12	Dependence on China is still a risk, building up production capacity in Germany and EU should be the target	▪ Large dependency for components from China ▪ Political crises could shut down the market ▪ Sustainability in the supply chain
Integrated PV (IPV)	OC 13	Traditional roof-top systems (RTS) and ground-mounted systems (GMS) will remain the major contributors in the coming years	▪ Best LCOEs ▪ Profitable investments ▪ Functioning policy constraints
	OC 14	In order to reach 22 GW annual installed capacity, integrated PV will have to play a supporting role	▪ Areas could become scarce in the future ▪ Synergies can be used
	OC 15	IPV is not necessarily needed from the perspective of available area	▪ Small share of roof-tops with PV so far ▪ Additional areas for ground-mounted systems will be released
	OC 16	For IPV to work, costs have to decrease, regulations need to be adapted and new support measures created	▪ Often complex mounting structures ▪ Lower energy output, but the same feed-in tariffs make investment unattractive ▪ Too little knowledge and awareness of potential customers like farmers
	OC 17	In general, more large-scale systems should be installed to reach the 22 GW annual targets	▪ More effective usage of installers and electricians ▪ Lower number of systems needed ▪ Scale effects
Environ-mental impacts	OC 18	PV is seen as a highly ecologically-compatible energy technology	▪ Sealed surfaces are used ▪ Ground-mounted systems can increase biodiversity ▪ No noise and movement
	OC 19	PV can be integrated into existing sealed surfaces like roof-tops or parking lots	▪ No new natural areas need to be taken away for PV

	OC 20	PV has ecological advantages over wind power and biomass	▪ Optical obstruction not as high ▪ No noise and movement ▪ Biodiversity can be higher for a ground-mounted system compared to a biomass production crop field
	OC 21	Ground-mounted systems can create higher biodiversity	▪ Depends what the area was before ▪ Compared to agriculture better, no monoculture, not as frequent human impact, higher energy output ▪ Regulations to actively support biodiversity in GBS
	OC 22	Higher emphasise should be put on value creation- and supply chains in order to improve the sustainability of the life cycle of PV	▪ Not only focus on carbon-free production of electricity ▪ Life cycle analyses
Contribution of different system types	OC 23	Integrated PV will not make a major contribution until 2030	▪ LCOE comparably bad ▪ Regulations and policies ▪ Awareness ▪ Business Cases ▪ Products and services
	OC 24	The main contributors to the PV mix will be roof-top systems (especially medium C&I scale) and ground-mounted systems	▪ "Running system" ▪ Still high area potential ▪ Energy independency as driver
	OC 25	Opinions on whether GMS or RTS will be the most important differ highly between stakeholders	▪ GMS: scalability, LCOE ▪ RTS: Shorter implementation times, no lack of areas
	OC 26	IPV will be growing because it has various advantages, and 22 GW cannot be done alone with RTS and GMS	▪ Synergies, no new areas are taken, new business cases e.g. Agri-PV ▪ Synergy with e-Mobility and applying PV in urban areas like parking lots
	OC 27	Agri-PV and BIPV seem to be the most promising technologies whereas RIPV and Floating PV will not be major contributors in Germany	▪ Agri-PV huge area potential ▪ BIPV as well and as addition to RTS ▪ Floating PV not enough space available in Germany ▪ RIPV comes with security concerns and high costs

Second step: Axial Coding

Code #	Code	Open codes
AC 1	Market development, decreasing prices and political attention has made PV the fastest growing energy technology in Germany and will be the most important contributor in the energy transition until 2030	1-6
AC 2	The EEG remains an important instrument for PV development and the 2023 amendment will further support the capacity installations and underlines the governmental ambitions, however there are still adaptations necessary, especially to improve conditions for landlord-to-tenant electricity and integrated PV concepts	8-11
AC 3	The demand is easily there to reach the capacity addition targets, but the main challenge is the lack of enough installation capacities	9, 10
AC 4	The biggest contributors will be roof-top and ground-mounted PV systems, especially large-scale ones, with integrated PV systems growing and contributing with smaller shares to reach the 22 GW per year target	13, 17, 23-26
AC 5	Integrated PV, especially Agri-PV and BIPV, can be important, not necessarily regarding space availability, but because of synergies. However, for their share to increase, costs need to decrease and new support measures must be defined	14-16, 23, 26, 27
AC 6	PV is an environmentally-compatible energy technology and has advantages over other renewable energy technologies like wind power and biomass, as it can be better integrated in landscapes and positive biodiversity impacts are possible. The value creation process though is criticised and should be focused on regarding sustainability improvements	12, 18-22


S·ACADEM