Can an Obligation Bridge Germany's PV Capacity Gap? Insights from a Regional Case Study

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ABSTRACT

Reaching Germany's PV expansion goal requires regulatory instruments that promote new investments in PV rooftop installations complementing other environmental measures and enhancing coordination among stakeholders and alongside the building lifecycle. In great regional detail, this paper examines how an obligation tied to new building construction and renovation in the residential and non-residential sectors might further PV expansion and considers its socio-economic implications. The findings suggest that while a PV obligation could significantly advance national energy goals, it would contribute only a fraction of the annual growth in PV capacity needed. The research identifies a positive correlation between the impact of PV obligations for non-residential building construction and regional gross domestic product, indicating a potential distributive effect where less affluent regions lag further behind in sustainable energy production.
In conclusion, a PV obligation could play a key role in future German energy legislation, but broader measures must complement it. Policymakers need to carefully balance the PV obligation's potential for capacity growth with the risk of undermining public acceptance of the energy transition.

1. Introduction

Achieving Germany's ambitious decarbonisation goals institutionalised by the energy transition requires a massive build-out of generation technologies running on renewable energy sources. Solar-based generation technologies, such as ground-mounted and rooftop photovoltaic (PV) systems, are considered essential for decarbonising the German electricity supply alongside offshore and onshore wind. According to the latest targets of German energy policy, total PV capacity needs to increase from around 85 GW installed at the beginning of 2024 to a targeted value of 215 GW by 2030 [16], with rooftop installations significantly contributing to this expansion. Reaching this expansion goal requires a further build-out rate of roughly 1.5 GW per month, higher than the capacity additions observed in the recent past.

Academia has long focused on analysing the potential of rooftop PV systems in Germany and why these potentials are not leveraged in reality. Engineering methods are employed to investigate PV deployment limits. For instance, the authors in [19] evaluate the performance of rooftop PV systems, revealing a south-north yield gradient and noting that over half of the rooftop PV systems underperform relative to generation expectations. Further studies assess the technical potential of rooftop PV systems by processing high-resolution irradiation data specific to German cities, e.g. [11], and by analysing satellite data to estimate PV rooftop potentials, e.g. [15]. Economic studies reveal both the potential and barriers to adoption. For example, the authors in [17] apply a consumer segmentation model, showing high PV saturation in affluent regions with high shares of (semi-) detached houses, particularly in rural areas compared to urban ones. Also, findings from [6] indicate no economic or technical advantages for households from systems larger than 8 kWp, suggesting a feed-in subsidy of 10 ct/kWh to provide sufficient investment incentives and highlighting the role of heat pumps and welfare-enhancing rebound effects in improving economic gains. Furthermore, the research in [5] assesses the impact of municipal building regulations on solar adoption, finding that municipalities with restrictive solar policies have 10.4% less solar PV capacity than those in the control group. In contrast, electricity prices and the achievable self-consumption share drive profitability, with diffusion barriers arising from split incentives, risk, and uncertainty, according to [13]. Summarising these findings, Germany exhibits significant technical and economic PV potentials, yet deployment rates fall short of desired levels.

Given these developments, additional regulatory instruments beyond the measures already implemented in Germany, such as feed-in premia for owners of rooftop installations, are considered necessary to promote new PV installations and enhance coordination in expanding rooftop systems. Specifically, questions arise about how regulatory adjustments would enhance PV deployment and which design efficiently enables the bridging of the PV capacity gap between current expansion rates and those necessary according to political expansion plans in Germany until 2030.

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In environmental regulation policies, market-based instruments can be distinguished from command-and-control instruments [18, 12]. Market-based instruments typically internalise negative externalities by reflecting them in market prices, thereby incentivising adaptations in the market behaviours of relevant stakeholders. As a result, these instruments often feature a higher degree of cost-effectiveness. Examples include environmental taxes and emission trading schemes. In contrast, command-and-control instruments implement compulsory measures, such as standards and obligations, to achieve the desired environmental outcomes. While these instruments typically do not induce innovations due to their generally restricted scope and specific requirements, they may achieve the desired outcomes with a faster response.

Taking into account the necessary investments in PV systems in the coming years and the rapid implementation of PV installations required to achieve the desired build-out targets, this paper aims to investigate the additional contribution that command-and-control instruments, particularly differently designed PV obligation schemes, can make toward achieving Germany's PV expansion goals. Specifically, the paper examines:

(i) The technical potential of PV installations resulting from an installation obligation for building construction,

(ii) The breakdown of results by the residential and non-residential sectors,

(iii) Regional disparities in PV capacity additions with detailed geographic insights,

(iv) The effects of a PV installation obligation for building renovation, and

(v) The effectiveness of obligation schemes from the perspective of additionality.

The remainder of this paper is organized as follows: Section 2 outlines the methodology used to compute projections for the future building stock evolution and details all assumptions regarding the representation of PV capacity in this work. Section 3 discusses the technical potential of different PV obligation schemes in Germany with varying regional detail, considering aspects related to additionality. Section 4 presents the results of the analysis. Finally, Section 5 reveals implications for efficiently designing future PV regulation policies relevant to German policymakers and, more broadly, the energy policy community.

2. Methods and data sources

Computing the PV capacity resulting from regulatory interventions requires forecasting future building activities and PV technology developments together. The following outlines all statistical data on existing PV installations in Germany incorporated in this study. Based on this, reference installations are derived, distinguishing between different building types and classes. It also presents the methodology used to compute projections for new construction activity and all assumptions associated with building renovation. The key assumptions are listed in Table 1.

2.1. PV reference systems

The German PV fleet consists largely of small, decentralised PV installations in the residential sector. To derive a reference system representing future rooftop installations in this sector, this study analyses all PV configurations observed in Germany in the past and projects identified developments to the near future.

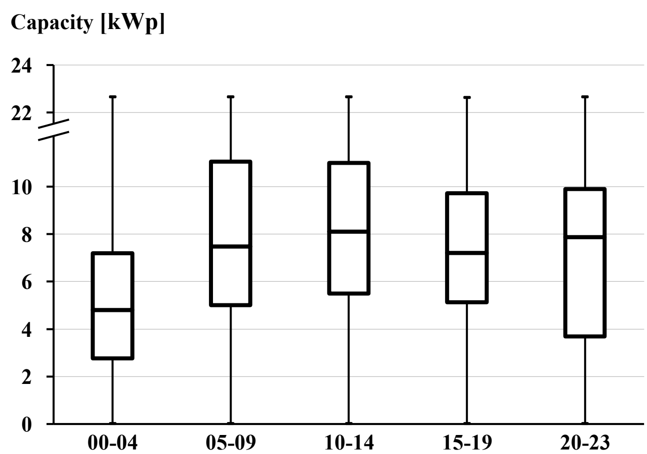


Figure 1: Distribution of observed residential PV capacity additions

The core energy market data register, a database of all German renewable power generating units with mandatory entries verified by grid operators, reports over 3.7 million individual PV units currently installed in Germany, each with detailed configuration information [4]. These installations predominantly feature a name-plate capacity below 11 kWp. A clear trend towards larger systems is observable in the first years, followed by a plateau (see Fig. 1)[1]. While the median PV configuration size for a new rooftop installation was 4.80 kWp during 2000-2004, it reached 7.88 kWp during 2020-2023. Considering these developments, this work assumes a reference PV configuration size of 8 kWp for each future rooftop installation in the residential sector.

The non-residential building sector in Germany is much more heterogeneous than the residential sector. Due to the significant variation in type and size of these buildings, the projection for non-residential new construction activity

[1] Since the core energy market data register contains many flawed entries, the 1.5 IQR rule was used to exclude outliers and create the box plots.

Table 1
Key Assumptions

Parameter	Value
Residential buildings	
Average PV-system size per building	8 kWp
Energetic renovation rate	1.5 %
Non-Residential buildings	
Number of building classes	9
Range of roof area ratios	0.47 - 0.59
Installed capacity per solar panel	0.2 kWp/m^2
Average usable roof area	60 %
Energetic renovation rate	
heated/cooled buildings	1 %
not heated/cooled buildings	0 %

considers usable floor area rather than absolute building numbers to describe future construction activity.

The projections of usable floor areas in the non-residential sector are matched with empirical roof-to-floor area ratios for nine different building classes to derive a reference PV configuration for each class. The roof-to-floor area ratios, sourced from [9], range from 0.47 square meters of roof area per square meter of usable floor area in the case of office buildings to 0.59 for storage buildings and agricultural facilities. Furthermore, it is considered feasible to cover 60% of the roof area with PV modules in the non-residential sector, with an area-specific PV capacity of 0.2 kWp/m^2.

The reference systems can be combined with new construction projections for the residential and non-residential sectors and expected building renovations discussed subsequently to compute the development of future PV installations resulting from specific installation obligation schemes.

2.2. Projections for construction and renovation activity

Data sources for projetions of construction activity in Germany vary in type and granularity. Therefore, two distinct forecasting methods are proposed to compute the development of the building stock in the residential and non-residential sectors over the coming years. See Fig. 2 for the projection results.

The latest housing market forecast from the German Federal Office for Building and Regional Planning (BBSR) [2] is the starting point to estimate the number of future building completions in the residential sector. The forecast estimates the need for new flats in Germany per 10,000 inhabitants until 2030, broken down into two categories: one- and two-family houses vs. multi-family houses. Additionally, it provides the underlying assumptions regarding population growth. As the housing market forecast does not consider the latest changes in population growth expectations for Germany, the projected needs are updated using the latest population development forecast sourced from the German Federal Institute for Building, Urban Affairs, and Spatial Research [3].

Since the present work requires projecting the future number of building completions, not flats, further adjustments are performed. The updated demand for new flats is converted into a projection of future building construction numbers in the residential sector using historical data on the ratio between one- and two-family houses and the average number of flats per multi-family house.

The entire sequence of computation steps and all included data sources are indicated in the appendix (see Fig. 8 and 9). The computation results provide detailed information on building completions until 2030 yearly, distinguishing between single-, two-, and multi-family houses and broken down to the NUTS3 level for Germany.

Projections on expected building activity in the German non-residential sector are very limited compared to the residential sector. Therefore, this work proposes a trend-based method using past building activity records to project future non-residential building completions measured in floor area size. The so-called regional statistics from the Statistical Offices of the Federation and the Federal States include non-residential sector building activity data, differentiated by utilisation type and regional level, and are used in this study to compute the non-residential building projection. Data from the past 15 years is sourced at the level of NUTS3 regions. The projection assumes an average growth rate computed from this sample for each NUTS3 region. A projection of PV capacity installations in the non-residential sector is derived by combining the average growth rate of usable floor area with the area-specific PV reference systems for each non-residential building type (see prior section).

The projection results provide detailed PV capacity development data associated with future building activity in Germany in the non-residential sector until 2030 at the level of each NUTS3 region.

2.3. Building stock and renovation assumptions

In addition to the completion of new buildings in the residential and non-residential sectors, regulators could mandate PV build-out through an obligation tied to building renovation in the existing building stock. The German residential building stock comprises approximately 19.2 million individual buildings, including 12.8 million single-family houses, 3.1 million two-family houses, and 3.2 million multi-family houses [10].

The non-residential sector includes about 2 million buildings, of which 1.2 million are service buildings and 0.7 million are production facilities [10]. The residential

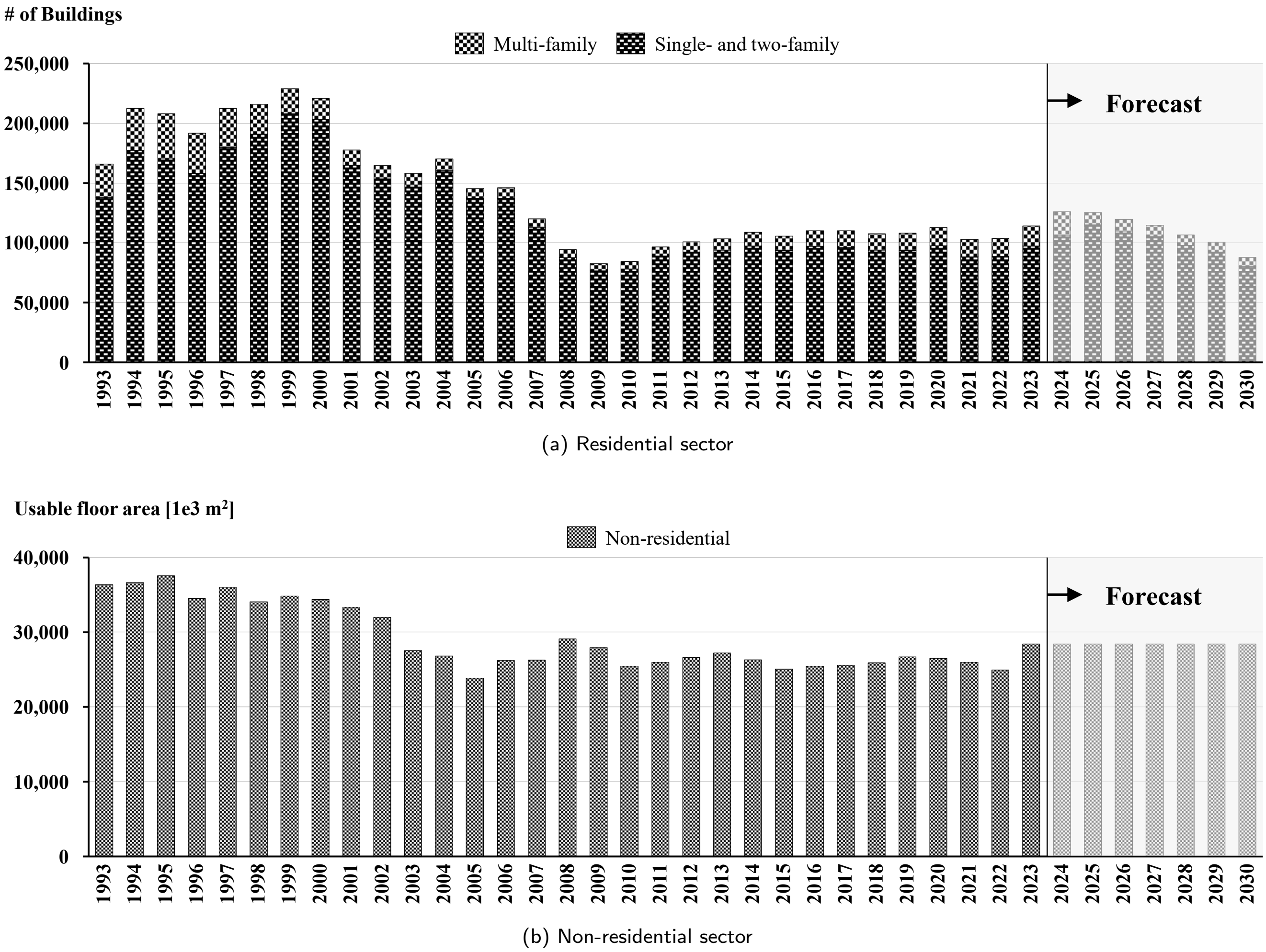


Figure 2: Historical and predicted annual addition of buildings in Germany until 2030

building stock is about ten times larger than the non-residential building stock. Yet, the average sizes of non-residential buildings and their corresponding roof areas are significantly larger.

According to the German Energy Agency, the current renovation rate is stagnant at approximately 1% per year. However, to achieve climate neutrality in the German energy sector by 2045, this rate must increase to 1.9% by 2030 [1]. Therefore, the projection conducted in this work assumes growing renovation rates, with an average value of 1.5% per annum over the next few years.

Renovation rates in the non-residential building sector greatly vary by building type. A clear distinction between heated/cooled buildings (e.g., offices, hotels and restaurants) and buildings without heating/cooling supply (e.g., operational buildings in the agricultural sector) can be made. Buildings in the non-residential sector belonging to the class of non-heated/-cooled buildings are typically rarely renovated and thus not further considered for renovation in this work. Generally, renovation rates observed in the non-residential building sector tend to be lower than in the residential sector due to the shorter lifespan of these buildings; thus, sometimes, they are even rebuilt rather than renovated. For the non-residential sector, renovation rates of 1.0 % per annum are therefore assumed in this study.

3. Results

Implementing a PV obligation impacts the build-out of PV capacity in Germany differently, depending on building types and the design of the obligation. The following section outlines the resulting capacity developments, first aggregated at the national level, before discussing them in greater regional detail.

3.1. Effects of a PV obligation in Germany at a national level

The additional PV capacity induced by the implementation of a PV obligation in both the residential and non-residential sectors for new building completions and building renovation will accumulate to 44.1 GW by 2030. This capacity encompasses 21.5 GW on new buildings and

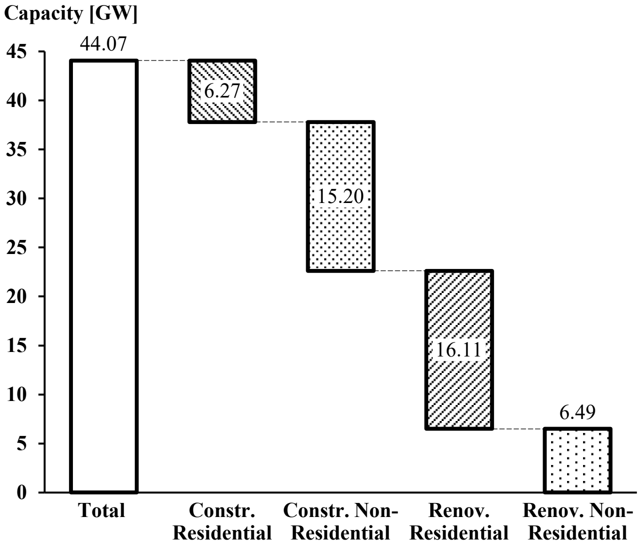


Figure 3: Computed capacity additions resulting from obligation

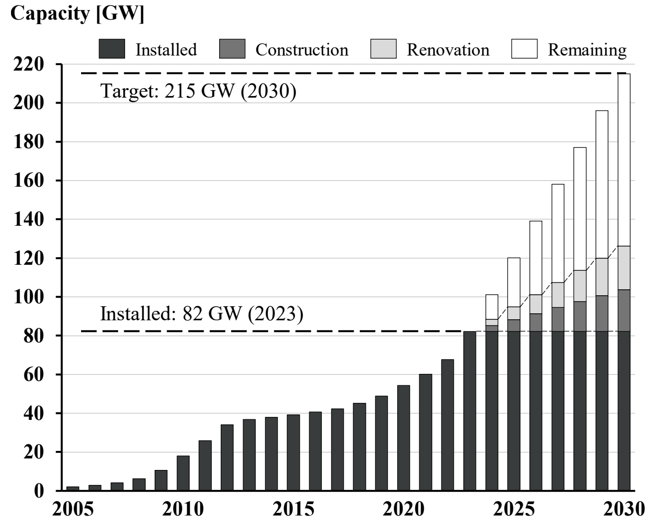


Figure 4: Contribution of a PV obligation to the German 215 GW expansion target by 2030

22.6 GW related to renovation (see Fig. 3).

The potential capacity resulting from an obligation for new buildings splits into 6.3 GW in the residential sector and 15.2 GW in the non-residential sector. Higher construction rates, resulting from shorter building lifespans and larger roof areas, contribute to this distribution with a significantly higher contribution from the non-residential sector

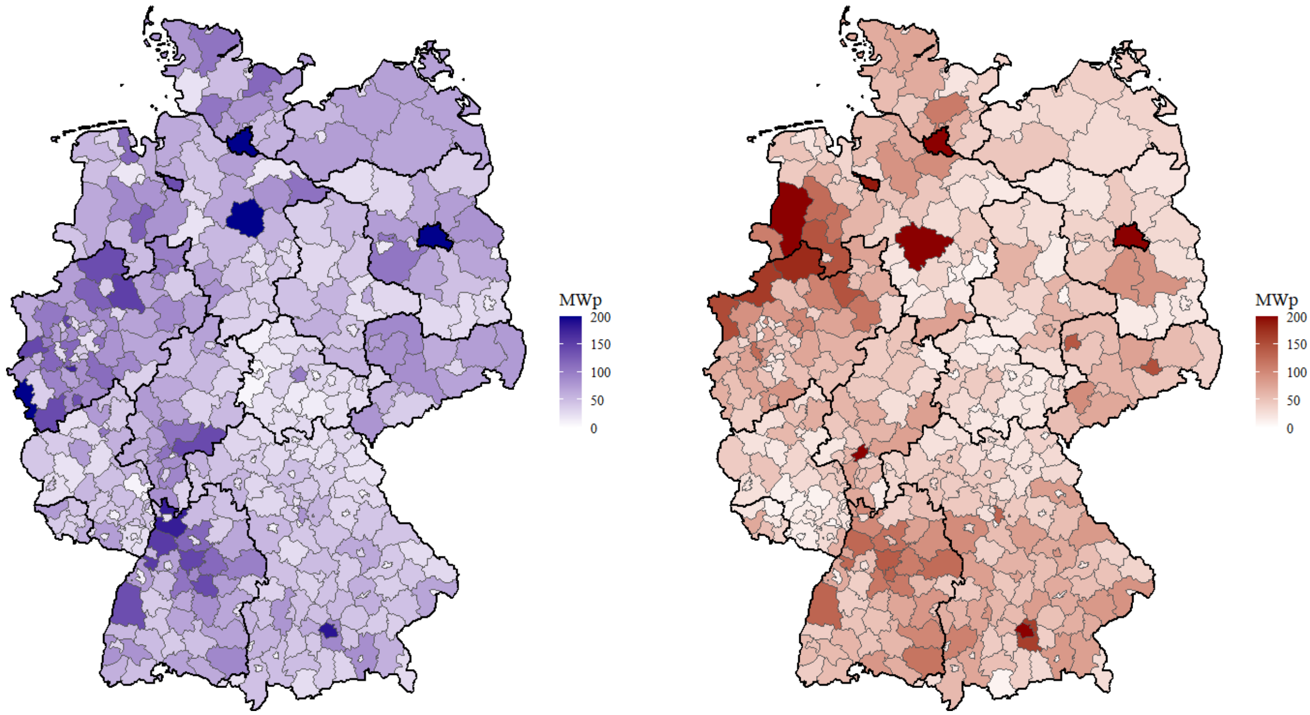
In addition to a PV obligation for new constructions, it is equally important to consider the existing building stock. Legislative trends are shifting towards equating roof renovations with new constructions, generally mandating rooftop PV system installations as a standard procedure. A key consideration in promoting and coordinating the expansion of PV capacity is thus deciding whether to target new constructions, existing buildings, or both.

The total capacity development resulting from an obligation tied to building renovation is 22.6 GW. Unlike the obligation for new building completions, the larger share stems from the residential sector. Renovations in the residential sector account for 16.1 GW, with single-family houses contributing 12.3 GW, whereas renovations in the non-residential sector account for only 6.5 GW.

Comparing the capacity additions in Fig. 3 resulting from an obligation for construction vs. renovation activities provides insights into the potential effectiveness of different PV obligation design options. While an obligation connected with building construction yields significantly more capacity additions in the non-residential sector, an application to building renovation has the most substantial effect in the residential sector.

The total number of yearly building completions is relatively small compared to the existing building stock. Under the 1.5% renovation rate assumed in this work, approximately 290,000 residential buildings will undergo energy-related renovation annually until 2030. This number is nearly twice as high as the average number of new buildings being constructed in the residential sector during one year. Consequently, an obligation on PV installation has a larger effect on resulting capacity additions in the residential sector when applied to building renovation.

The question has yet to be addressed: what is the obligation for PV installation for building construction and renovation that may contribute to the achievement of Germany's expansion targets by 2030, as stated by the German government? Figure 4 displays the total capacity additions resulting from an obligation addressing both building construction and renovation in the residential and non-residential sectors relative to Germany's expansion targets. While the presented capacity figures resulting from an obligation are substantial, their contribution to achieving the 215 GW build-out target, including ground-mounted systems, is limited. Reaching the targeted PV capacity levels will require annual capacity additions of 19 GW. Introducing a comprehensive PV obligation for building construction and renovation in the residential and non-residential sectors could achieve only about 33% of this target. While such an obligation would make a modest but significant contribution, it could be considered a complementary measure alongside other PV support policies to help Germany meet its decarbonisation goals. However, when implementing this policy, additional factors must be considered. The obligation under the German heating law for heat pump installations, which faced significant resistance from homeowners, illustrates that low public acceptance can undermine the effectiveness



(a) Residential sector

(b) Non-residential sector

Figure 5: Cumulative PV capacity increase during 2024-2030 by an obligation combined for building construction and renovation by NUTS3 region

of such measures.

3.2. Effects of a PV obligation in Germany at a detailed regional level

The spatial resolution of the building data at the NUTS3 level used in this study allows for detailed regional analyses, revealing a diverse distribution of PV capacity increases across Germany. Each NUTS3 region encompasses a population ranging from 150,000 to 800,000 inhabitants, with a broad variety of socio-economic and spatial characteristics, e.g. regarding the degree of urbanisation. Figure 5 illustrates the PV capacity increase resulting from the implementation of a PV obligation for new constructions and renovations at the NUTS3 level for both the residential (a) and non-residential (b) sectors. This level of detail enables the identification of regions with the greatest potential for PV development, with the darkest areas indicating the highest potential capacity increases.

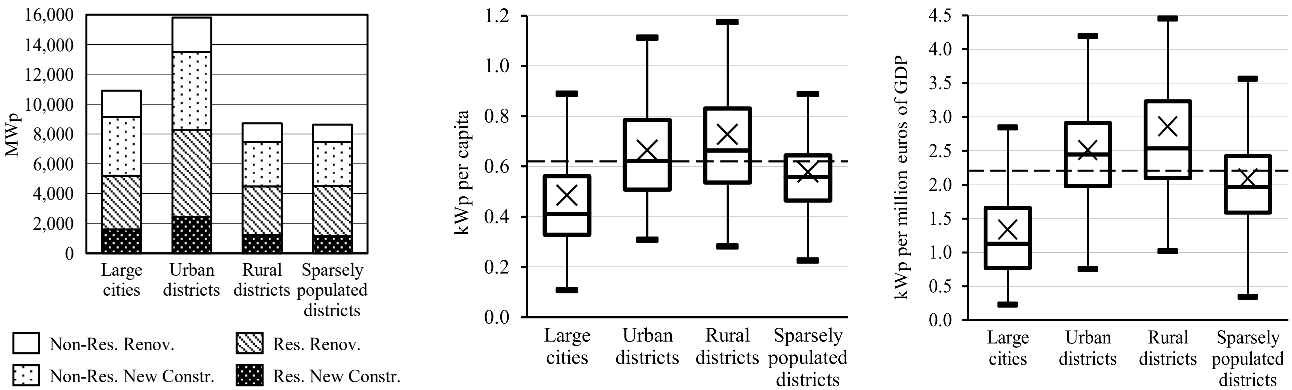
Notably, this illustration does not account for population density; hence, larger NUTS3 regions with similar densities will naturally exhibit more capacity increases in the residential sector.

For residential buildings, significant capacity increases are concentrated in certain urban and suburban areas, notably around Berlin, Hamburg, and parts of North Rhine-Westphalia and Baden-Württemberg. In contrast, capacity growth for non-residential buildings appears more dispersed but is still concentrated in key industrial and commercial regions. The northern and southwestern regions exhibit relatively higher increases in residential building capacity compared to other parts of Germany. In contrast, significant increases in non-residential building capacity are observed in the northwestern and some central regions.

3.3. Effects of a PV obligation in Germany broken down by settlement type

The results discussed in the previous section are corroborated when grouping NUTS3 regions by settlement structure and summing up the related capacity additions. Figure 6 illustrates the capacity increases resulting from building construction and renovation obligations, categorised by the settlement structure of the NUTS3 regions. The figure presents absolute values (a), per capita normalised values (b), and per GDP normalised values (c), distinguishing between large cities, urban districts, rural districts with densification tendencies, and sparsely populated districts.

In absolute terms, the impact of an obligation is predominantly driven by the capacity expansion in urban areas (large cities and urban districts). In contrast, rural areas account for a smaller share (see Figure 6 (a)). Urban regions show the highest increase in PV capacity, totalling 15 GWp. In large cities, the second highest increase of around 11 GWp is observed. Sparsely populated districts have the smallest



(a) Absolute increase (b) Normalised by capita (c) Normalised by GDP

Figure 6: Cumulative PV capacity increase during 2024-2030 by an obligation combined for building construction and renovation by settlement structure

increase, at 7.5 GWp. In all settlement types, capacity growth is predominantly driven by obligations related to renovation in the residential and new construction in the non-residential sector.

Figure 6 (b) reveals an intriguing relationship. When normalising the increases by population within each NUTS3 region, the highest median capacity additions are observed in sparsely populated regions. Despite these regions exhibiting lower total additions, their per capita contribution is more significant. Rural and urban regions follow with slightly lower median values. Large cities exhibit the lowest median addition per capita, suggesting that high population density may reduce the per capita impact. This effect is partly due to the prevalence of single-family homes in less densely populated regions compared to the higher share of multi-family homes in large cities. Additionally, the already high population density in Large Cities limits the potential for new construction.

Relative to economic activity measured by GDP (see figure 6 (c)), rural and sparsely populated regions have similar high median values. However, large Cities exhibit the lowest median increase per GDP.

In summary, a comprehensive obligation has the largest impact in urban regions regarding PV capacity increase in absolute values, with both residential and non-residential sectors contributing. Rural districts contribute most when capacity addition is broken down per capita and GDP, indicating a substantial impact of an obligation in this settlement type despite the lower total effect. Large cities, in contrast, do contribute less substantially.

4. Discussion

The capacity values should be considered in the context of recent developments in PV system installations in Germany. Figure 7 shows the annual net additions in Germany, categorized by system size. Small rooftop PV systems, up to 30 kW, predominantly owned by private households, constitute most of these additions. In contrast, the increase in larger rooftop systems, primarily commercial, is less significant. Ground-mounted PV system expansion mainly involves large installations exceeding 1 MW.

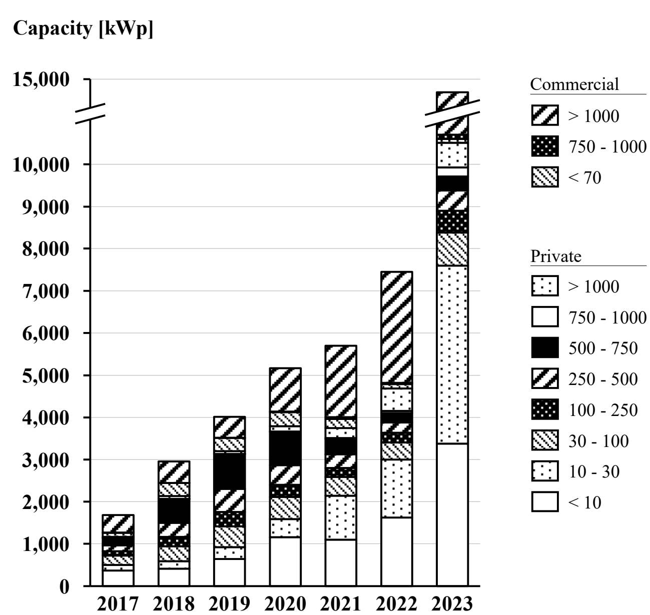


Figure 7: Annual Net Additions by Size Categories

Various forms of a PV obligation have been discussed in politics and recently partially implemented at the state level. This study systematically explores the potential, distinguishing between new construction and renovation and considering both residential and non-residential buildings. Many new buildings are already equipped with PV systems without any mandate, suggesting the additional impact of an obligation might be smaller than the gross impact computed in this study. However, linking the obligation to energy renovations may boost PV installations and enhance energy efficiency through improved insulation. Further, careful implementation is crucial to ensure public acceptance of the energy transition is maintained.

5. Conclusion and policy implications

The installation of PV systems in both the residential and non-residential sectors has accelerated in recent years. However, the expansion targets set by German policymakers remain ambitious, and additional policies may be necessary to meet Germany's decarbonisation goals by 2030.

This study examines the potential impact of a PV obligation on the number of PV system installations. As outlined in the methodology section, we thereby make use of fine-granular data regarding both the existing PV installations and the building stock in Germany. This enables us to assess the implications of such an obligation at the level of different building types as well as at the regional level – with consideration given both to the federal states which are key political stakeholders in the German system and to the impacts along the "urban-rural divide" [7, 8, 14, 20].

While such an obligation is a command-and-control measure that limits individual stakeholder freedom, it could support further expansion if designed appropriately. The findings suggest that a PV obligation could significantly contribute to meeting Germany's 2030 expansion targets, but its viability as a policy tool must be carefully assessed. Currently, PV capacity growth is primarily driven by economic factors, particularly the rising attractiveness of installations due to expected increases in Germany's electricity costs. However, the risk that a PV obligation might negatively affect public acceptance of the energy transition remains underexplored in this study.

When policymakers consider a PV obligation a viable policy measure, they should clearly distinguish between non-residential and residential buildings, as the non-residential sector presents a significantly greater potential. Moreover, firms are typically better equipped to make capital-intensive investments than households. Yet, in many sectors, the required return on investment is higher than for private homeowners.

In the residential sector, the existing building stock has a substantially higher potential for PV expansion through obligations linked to renovation than the new construction segment. Conversely, new constructions offer a larger potential in the non-residential sector. Therefore, a PV obligation for new buildings could be more effective in the non-residential sector. Instead, subsidies or other direct support policies could incentivise the residential sector to manage capital-intensive investments. Such an approach also considers that the additional impact of a new construction obligation in the residential sector will likely be limited due to the high level of recent investments already encouraged by current market signals and policies.

The regional variations in impacts identified in this research indicate that the effect of an obligation is highest in urban areas in terms of absolute PV capacity additions. In contrast, rural areas experience higher per capita PV capacity growth, mainly due to the higher share of residential buildings, especially single-family homes. Nonetheless, enforcing regional PV obligations can be challenging, as this would require regionally differentiated policies, which might raise concerns about potential discrimination.

A future research approach could be to refine the regional level of detail in both construction forecasts and PV availability, enabling analyses at a smaller scale than NUTS3 or even at the building-specific level, complemented by studying the public acceptance of a PV obligation.

The policy implications from this study can be summarized in five key points:

1. Targeted PV Obligation for Non-Residential New Buildings:
   The non-residential sector, particularly new constructions, offers the highest potential for PV system expansion. A targeted obligation in this sector could drive substantial capacity increases, as firms are better equipped for large-scale investments.

2. Financial Incentives for Residential Renovations:
   In the residential sector, the focus should be on incentivizing PV installations during building renovations. Direct support mechanisms such as subsidies or low-interest loans would encourage homeowners to invest in PV systems, particularly given the lower expected returns compared to the non-residential sector.

3. Consideration of Regional Disparities:
   Urban and rural areas display different growth dynamics in PV adoption. Policymakers should account for these variations when designing obligations or incentives, ensuring policies are equitable and addressing concerns about regional disparities in implementation.

4. Potential sources of regional political resistance:
   Federal states with lower wealth and weaker economic dynamics may oppose the introduction of a PV obligation especially for existing buildings. They may fear that such an obligation may put an additional and excessive burden on their citizens.

5. Potential sources of popular unrest:
   Inhabitants in rural areas – which generally have lower

average incomes – may consider an obligation as an additional limitation of their freedom of choice while observing that the current non-mandatory regime already induces considerably higher PV installations (both in absolute terms and on a per capita basis) in rural areas.

CRediT authorship contribution statement

Felix Meurer: Conceptualization, Methodology, Software, Investigation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Marco Sebastian Breder:** Conceptualization, Methodology, Software, Investigation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Michael Bucksteeg:** Supervision, Project administration, Funding acquisition, Writing - Review & Editing. **Hannes Hobbie:** Conceptualization, Methodology, Software, Investigation, Formal analysis, Data Curation, Funding acquisition, Writing - Original Draft, Writing - Review & Editing, Visualization. **Dominik Möst:** Supervision, Project administration, Funding acquisition, Writing - Review & Editing. **Hendrik Scharf:** Conceptualization, Methodology, Software, Investigation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Christoph Weber:** Supervision, Project administration, Funding acquisition, Writing - Review & Editing.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DEEPL, grammarly and ChatGPT in order to check for grammar and spelling. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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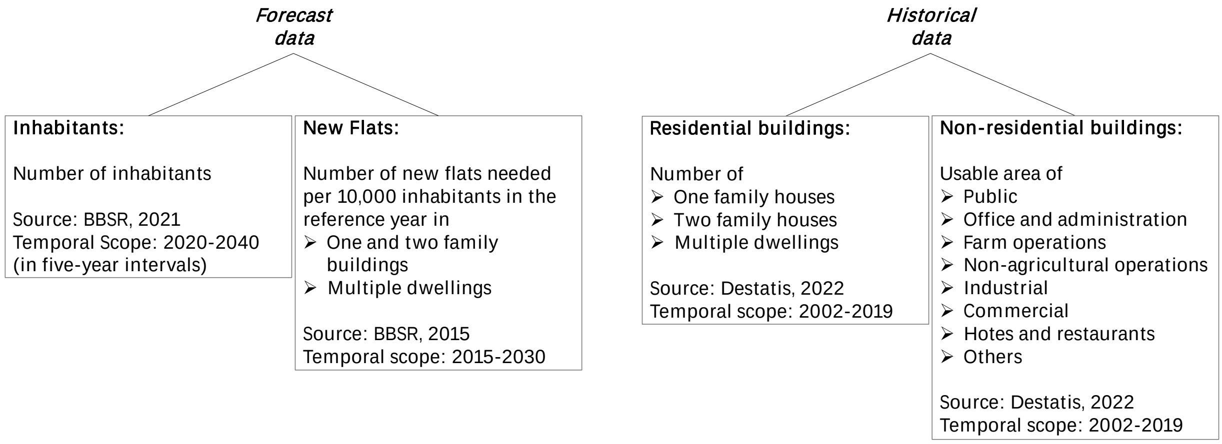

Figure 8: Type, origin and short description of the data used for forecasting the development in construction activities on a municipal level. Own illustration.

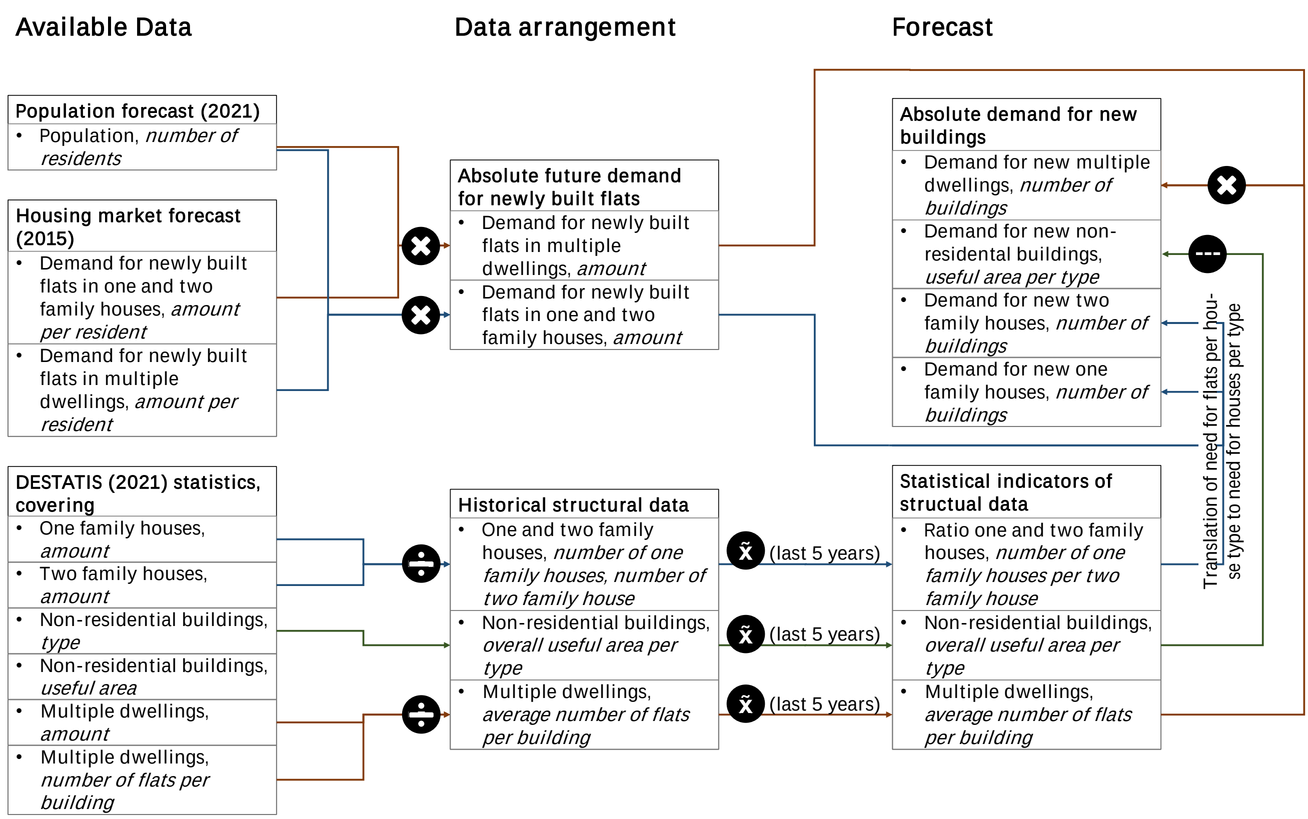

Figure 9: Scheme of the processing of the available data for determining new buildings per building type in the years 2023 to 2030. Own illustration.

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