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Unlocking the untapped potential

How local administrations coordinate decentralized Photovoltaic Systems on Multi-Family House Roofs

Summary: This research paper explores the untapped potential of multi-family house roofs for photovoltaic (PV) installations and the role of local governments in coordinating their utilization. It highlights the significance of decentralized, private power generation and the integration of artificial intelligence (AI) for roof surface identification. The paper emphasizes the need for coordination through local administrations to facilitate the implementation of PV systems on multi-family house roofs. By leveraging AI technology, local governments can efficiently identify suitable rooftops and coordinate among various stakeholders to enable the expansion of decentralized PV systems. The study underscores the importance of collaboration between local governments and their residential companies and citizens. The study also contributes to the Actor Network Theory by incorporating the role of administrations and emphasizing the significance of data sets as components within a network.

Keywords: PV Systems, Multi-Family House Roofs, Public Administration, Structural Hole Theory, Chief Sustainability Officer

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A. Introduction

The reduction of fossil fuel consumption is a pressing concern in many European countries, driven by the imperative to address climate change and promote sustainable development. United Nations Sustainable Development Goal (SDG) 7 emphasizes the need for universal access to "affordable, reliable, sustainable and modern energy for all" (United Nations 2015). Renewable energy sources, such as wind, hydro, and PV systems, are recognized as key technologies in achieving these targets, and their deployment is advancing worldwide (Gielen et al. 2019). Renewable energy technologies, with their lower cost per kWh and reduced CO2 emissions compared to traditional fossil fuels, play a vital role in meeting these goals (Gernaat et al. 2021). To achieve the set targets, the expansion of carbon-neutral energy sources needs to double every 5 to 7 years (Rockström et al. 2017).

The transition from fossil fuels to renewable energy technologies also has the potential to drive transformation in production, distribution, and consumption patterns. The energy transition is not merely about enhancing efficiency in economic and climate protection contexts; it has the power to revolutionize the entire energy market. Consumers can become "prosumers" (a portmanteau of *producers* and *consumers*) through decentralized electricity generation. In many developing countries lacking robust energy infrastructure and grid systems, off-grid solutions, especially those based on PV systems, have emerged as a common means of electricity generation and consumption (Kemausuor et al. 2018). These solutions offer a high degree of energy independence, which has sparked discussions in developed countries like Germany, particularly in the aftermath of the Russian invasion of Ukraine. The Russian war of aggression acted as a catalyst: In response to the war and rising energy and electricity prices, demand for balcony power plants rose in Germany (Der Tagesspiegel 05.07.2023).

Despite having well-established energy infrastructure, Germany has witnessed an increased drive for greater sovereignty from Russian gas imports. To address this concern, a key pillar outlined in the coalition agreement involves incentivizing the utilization of rooftop space for solar energy (SPD & Bündnis 90/Die Grünen & FDP 2021, p. 44). The building sector accounts for 34% of Germany's final energy consumption (BMWK 2021, p. 56). To combat the climate crisis and achieve climate goals equitably, the expansion of renewable energy, especially PV systems in the building sector, is a critical step. Although the deployment of PV systems on private buildings has been heavily promoted nationwide for years, progress remains slow, particularly for multi-family houses in urban areas. While federal and state governments provide the necessary financial resources, the financial incentives alone seem insufficient. In contrast, municipalities can play a decisive role, being closely attuned to the needs of citizens and capable of collaborative engagement with them (Arda et al. 2023).

This study thus aims to explore the research question: *How can municipalities promote the expansion of PV systems on multi-family houses?* The study will address the following sub-questions: *Which stakeholders are crucial for the expansion of PV systems on multi-family houses? How can municipalities coordinate these stakeholders to foster PV expansion?* Employing an actor-network methodological approach, the study will comprehensively analyze the entire network of stakeholders associated with this topic. The Structural Hole Theory will be employed to identify where and what type of further coordination among the identified stakeholders is necessary. Various stakeholders will be interviewed to ascertain their roles and connections within the thematic context. Through these connections to other stakeholders, diverse actors have been identified.

B. Theoretical background and related work

The impact of fossil fuel energy utilization has been extensively researched. There is a scientific consensus that the consequences of climate change on the environment, economy, and our collective coexistence are profound, necessitating urgent action. Decision-makers of municipal energy providers have already acknowledged that the electricity market will undergo transformations. This chapter delves into the current state of the transition towards a more decentralized electricity market, presenting the latest scientific insights. Additionally, it outlines the relevant stakeholders identified thus far, elucidates the economic, legal, and technical frameworks, and describes the theory underpinning this research.

I. PV systems on multi-family houses

The potential of PV systems in Germany remains vastly untapped. According to a study by market research firm EUPD Research, there are approximately 11.7 million single and two-family houses suitable for PV installations in Germany.[3] In this study, multi-family houses are defined as residen-

3 In Germany, the construction type of single- and two-family houses is predominant in residential buildings: at the end of 2018, 83% of residential buildings had only one or two dwellings, with only minor differences between the eastern German states (82%) and the western German states (84%). Even in the city states (Berlin, Bremen and Hamburg),

tial buildings with more than three residential units. Their share of the German housing market has been rising for several years, due in particular to increased construction and financing costs (Schmid 2021). However, with only 1.3 million PV installations on such buildings by the end of 2020, there is an untapped potential of 89% of the considered roof areas (Schwartzman 2021). Another study of Fraunhofer ISE found that less than 10% of the total available roof potential is currently utilized (Wirth 2023). These figures underscore the significant expansion opportunities for PV systems in Germany and its potential contribution to the overall energy generation.

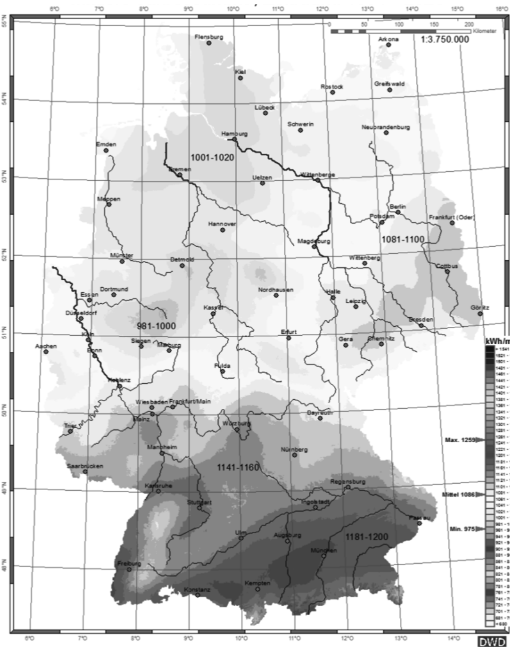
To maximize electricity generation from PV panels, sufficient solar irradiation is crucial. Apart from factors like altitude and average cloud cover at a location, latitude plays a pivotal role in determining the intensity of local solar radiation. In general, PV installations in southern Germany are more efficient than those in the north (see figure 1). Additionally, PV panels should be oriented correctly towards the sun, facing south, and free from obstruction by trees, buildings, or other structures. These various criteria need to be individually assessed for each property. However, residents or property owners are often unaware of most of this data, with some information being stored in public institutions.[4]

In this context, the rooftops of multi-family houses present significant potential for further PV expansion. However, progress in this area has been minimal in recent years, and a large portion of the available spaces remains unutilized. One of the reasons is the resistance of landlords towards PV installations on rental properties, often related to the issue of *split incentive* (Penny 2019). This problem arises because, in standalone PV investments, property owners bear the entire cost and risk, while the primary benefits accrue to the tenants. This situation has been exacerbated in recent years

the figure was 65%, or about two-thirds of all residential buildings (Sascha Krieger et al. 23.06.2021).

4 As the first city in Europe, the city of Osnabrück has established an area-wide solar potential register under the name "Sun-Area" (Martina Klärle et al. 2009) in cooperation with the Osnabrück University of Applied Sciences. This uses laser scanning data for a location analysis and potential calculation for PV and thermal solar systems for buildings in the city of Osnabrück. The latest edition of this web-based platform introduces homeowners to an expanded array of information. In addition to assessing the viability of their rooftop for PV installations, users can now explore the potential for solar thermal systems dedicated to water heating or heating support. Furthermore, the inclusion of a yield calculator provides an avenue for evaluating the economic viability of implementing a personal PV setup. This assessment takes into consideration prevailing investment expenditures, regulatory feed-in tariffs, and the attainable level of self-consumption of generated electricity (Stadt Osnabrück 2023).

Figure 1: Global radiation in Germany (German Meteorological Service 2021)

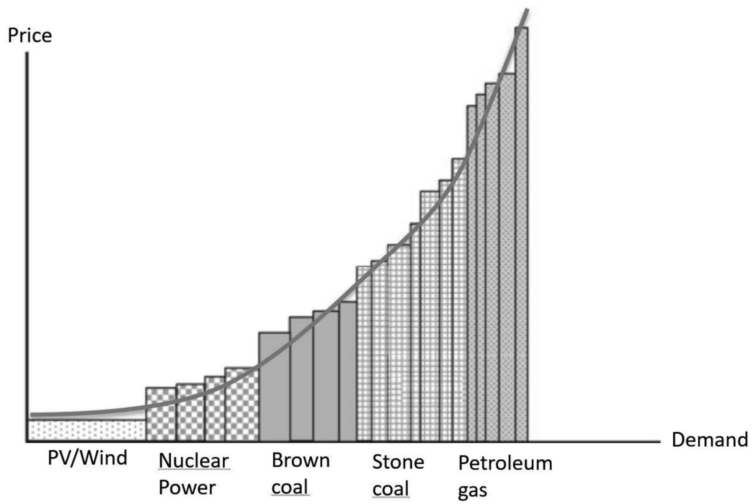


due to declining feed-in tariffs, leading to reduced profitability for PV operators. The financial benefits for tenants could prompt property owners to increase the net cold rent, citing lower ancillary costs. However, the acceptance of such an approach by tenants is currently unknown. Neither the current municipal support nor the economic attractiveness of electricity generation has led to a massive expansion of PV systems. While the idea that a profitable business model leads to more investment in this model seems intuitive, the implementation is more complex and less straightforward.

II. Energy Market Status Quo

The energy sector traditionally lacks a strong consumer-oriented focus, leading consumers to perceive electricity as a commodity that requires no active management on their part (Wang and Hu 2009). Furthermore, most users have limited understanding of the energy sector (Chen et al. 2021) and, according to Wörner et al. (2022), "do not feel the need to develop an understanding of topics such as market logic of supply and demand or abstract measurement units such as kilowatt-hours." However, consumer awareness of this information is crucial to making economically sensible decisions. Electricity prices can be formed based on the Merit-Order Model (s. figure 2), where the price is determined by the cost of the most expensive power plant that is demanded or required for electricity supply (currently gas power plants) (Wawer 2022). Since the infrastructure will continue to rely on gas power plants, it is expected that end consumers may not benefit from an infrastructure predominantly influenced by renewable energies.

Figure 2: Merit Order Principle (Wawer, 2022)



In the emerging decentralized energy market, various stakeholders have achieved success. An exemplar of this trend and a significant constituent of the decentralized energy landscape is the concept of citizen energy co-operatives, highlighted as a positive illustration (Ahlemeyer et al. 2022). According to Ahlemeyer et al. (2022), this cooperative approach necessitates the identification of local key individuals, whose capacities should not be overburdened. Furthermore, it has been observed that political and regulatory/bureaucratic obstacles have frequently hindered the implementation of energy projects within this framework. Following a similar trajectory to the referenced study or as a natural extension thereof, our research delves into the exploration of potential key individuals. In doing so, our study particularly adopt the lens of the public sector, focusing on the pivotal role played by municipalities.

III. Structural Hole Theory

Emerging fields of study are often observed and explored from various perspectives. New technologies, user preferences, or changing environmental factors need to be contextualized within the existing legal framework. Additionally, these aspects are evaluated from political, economic, and organizational viewpoints. The scenario investigated in this paper involves stakeholders from civil society, administration, and the business sector, while considering the legal and technological context. In such open and interdisciplinary fields with a high degree of diversity among the involved actors, the Structural Hole (SH) Theory is particularly applicable (Lin et al. 2022). The SH theory was developed by Burt (1992) for network analysis, focusing on the *who and how* of social structures in networks. The SH theory is used, among other things, to explain managerial performance by examining the advantages and disadvantages of individual positions (Rodan 2010). Other studies employ the SH theory to investigate knowledge transfer in informal networks (Reagans and McEvily 2003) or network dynamics in neighborhoods (Perez and Ting 2022). As a result, the theory is applicable to scenarios that examine a network and the different roles of its actors. The SH theory has become a recognized method in public administration research (Lee and Kim 2010; Reagans and McEvily 2003).

According to Burt (2010), there are typically few connections between groups or communities in networks, resulting in limited communication among them. This lack of connection is referred to as a Structural Hole, which, according to the SH theory, can be occupied by an SH spanner, acting as a broker of information or similar between the groups. Similarly, Lin et al. (2022) describe the absence of connections between actors as SH, which can be filled by other actors (SH spanners) as "bridges or intermediaries between them," better coordinating multiple tasks of diverse communities (Lin et al. 2022, 724). The SH theory thus appears suitable for our hypothesis and study. Through the lens of the SH theory, the existing network will be examined to identify potential SHs and corresponding SH spanners.

C. Research Design

In an Actor-network approach, the observation extends beyond human actors to include technology, infrastructure, and other non-human entities. Each actor plays a distinct role within the network and has connections to at least one other actor. The Actor-network methodology was chosen to investigate the human actors, their roles, and their connections within the network. This study focuses on actors at the municipal level who actively participate as actors in the network. These actors comprise individuals, companies, governmental institutions, digital tools, data, and infrastructure.

I. Case Selection and Description

Examining a network of various actors is particularly successful in a well-defined region. The Osnabrück region was selected due to several advantages, including the author's existing contacts with the municipal energy provider, local government, and property management. Nevertheless, most actors also possess experience or current tasks in this field on a supra-regional level. The federal and state levels were deliberately excluded, even though the topic of PV installations in the private sector and the utilization of multi-family buildings is also discussed at these upper federal levels. However, networks at the municipal level differ significantly from those at the state and federal levels in terms of actor types, tasks, and themes.

Data collection was carried out through various methods involving multiple actors. Interviews were conducted via video calls, phone calls, and face-to-face interactions. Additionally, a moderated exchange between two actors took place through video calls, and several thematically related workshops were held with one actor as part of a project seminar. Each interviewed actor was also asked about other actors they deemed significant in this subject area, enabling the identification of a diverse set of actors and facilitating access to other actors within the network through existing connections. This snowballing approach proves particularly valuable in this context to explore the network comprehensively and avoid overlooking any actors. The initial actors were contacted based on the author's assumption of their role within the network, and further actors were reached out to based on recommendations from previous interviewees.

II. Data Collection and Analysis

The current state of existing connections was first assessed and presented. Primarily, unstructured interviews were conducted with various individuals on the topic. Unstructured interviews were chosen since the author had limited prior knowledge about the specific domains of the actors. The actors were asked about their general views on the subject, and the author followed up with spontaneous queries that arose during the interviews. No interview guide or other standardized instruments were employed because each interview was unique, and no two actors were interviewed in the same manner. All actors were solely questioned about their tasks, needs, and connections to other actors in the subject domain. Subsequently, potential collaborations were mapped, and an actor-network was developed to encompass all connections.

In addition to the interviews, an inductive approach involved a moderated discussion between two actors to test their expressed requirements for another actor. Furthermore, multiple workshops were conducted with one actor to extensively collect their requirements. Specifically, a face-to-face interview (IN-I) was conducted with a property management representative from Osnabrück. This individual professionally manages numerous properties in Lower Saxony, primarily acting as an external property manager for multi-family houses owned by various property owners. The same individual was subsequently brought into a video conference with a startup founder (Startup I) from Lower Saxony, specialized in leasing roof spaces of multi-family houses for the installation of PV systems. Both actors engaged in a discussion moderated by the author (MD-I) on the topic of PV systems on multi-family houses.

An interview on Smart Metering was conducted via video conference with the CEO of a municipal energy provider (IN-II). Several workshops (WS-I) on decentralized power supply were held with Stadtwerke Münster as part of a project seminar. A telephone call (IN-III) was made with the originator of the SoFiE project (Solar Finder Engine; Startup II) from the Münster Hackathon 2021, and publicly available data on the project was gathered. The project had won first place in the previous Hackathon, and the originator is now employed by Stadtwerke Münster for its implementation.

Lastly, a face-to-face interview (IN-IV) was conducted with a municipal executive to discuss the requirements and potential tasks of municipalities in this context.

Table 1. Overview of interviewees

Pseudonym	Position	Affiliation	Type	Topic
IN-I	CEO	Property management	Face-to-face interview	Power dynamics in owner's meeting
MD-I	Managing Director + Founder	Property management + Startup I	Video-Call	Lease of roof spaces
IN-II	CEO	Municipal Energy supplier	Video-Call	Smart Metering
WS-I	Head of Department IoT	Municipal Energy Supplier	Workshops	Tenant electricity
IN-III	Founder	Startup II	Phone Call	Solar Finder Engine
IN-VI	Head of Department Organization & Digitalization	Municipality	Face-to-face interview	Municipal sustainability strategy and organization

D. Findings

The following section presents the results of the qualitative analysis pertaining to the actors and the overall network. The information is derived from the interviews and reflects the self-disclosures of the respective interviewees. A brief description of each actor is provided, along with their classification into the corresponding group. Furthermore, the connections among the different groups are illustrated, and potential Structural Holes (SH) are identified.

I. Group "Multifamily houses"

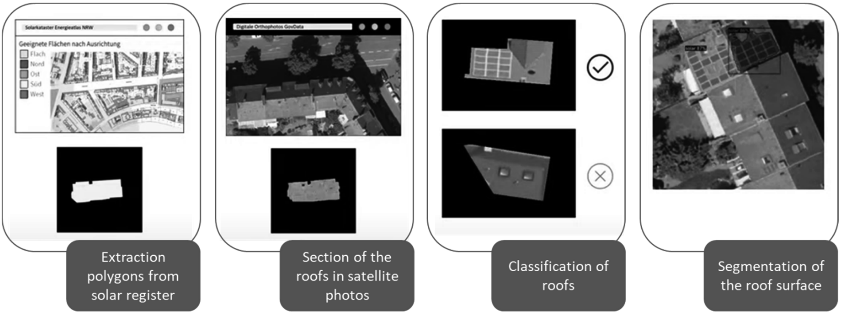
The decision regarding the utilization of rooftop space for PV installations is made by the respective property owners, who may not necessarily be the occupants of the property. In the case of multi-family houses, the property owners are often landlords of one or more apartments within the building. A property can be occupied by either owners or tenants, and in multi-family houses, a mix of both can be present. Frequently, property management companies are engaged to handle tasks such as billing for utilities, administering repairs, and maintaining the property. According to IN-I, this also includes activities like window, heating, and rooftop maintenance, which property management companies routinely mention on their own. However, organizing the installation of a PV system is not a standard responsibility of property management so far and must be explicitly commissioned by the owner's community.

Tenants residing in a multi-family house do not have voting rights within the owner's community, thus lacking direct influence over whether a PV system is installed on the rooftop or not. They can only exert influence through expressing a desire for renewable energy usage, expressing interest in purchasing an electric vehicle and requiring a charging station, or deciding to enter or terminate a tenancy. As such, tenants are the actor group with the least impact on the decision-making process. However, as direct beneficiaries, they could significantly profit if locally generated electricity were provided to them at favorable rates.

Property owners, especially those not residing in the respective properties, stand to benefit less from such installations. A discounted electricity tariff is not of interest to them, and adding lower utility costs to the rent is not appealing. According to the property manager (IN-I), owners do not expect tenants to consider these long-term costs when seeking a rental property. Moreover, the demand, especially in urban areas, is so high that rental properties are unlikely to remain vacant for extended periods. This lack of financial incentives, coupled with the complexity of decision-making processes within usually annual owner's meetings, results in a limited motivation for owners to engage in decentralized power generation. IN-I points out that owners would not only require the financial means for the initial investment but also need a high degree of idealism due to the lack of incentives. In a typical owner's meeting, there is often insufficient time to thoroughly address the complex topic.

The group consisting of property owners, tenants, and the infrastructure related to the respective rooftop spaces typically does not act as individual entities but is organized through property management. This group has connections to the municipal energy provider and private businesses, such as craftsmen, through property management. Thus, gaining access to this group is usually achieved through property management, which has access to all actors within this group. According to IN-I, property management holds a kind of preparatory power by highlighting the possibility of installing a PV system and preparing corresponding decision-making processes for the owner's meeting. However, this is rarely done due to the associated high effort. IN-I suggests that with a more straightforward con-

Figure 3. AI Model of Solar Finder Engine (SoFiE, MünsterHack 2021).



ceptualization, more property management companies would utilize this option.

II. Group "Startup"

The context of PV installations on multi-family houses is still relatively new and evolving. It is not uncommon for startups to emerge in this environment, driving innovation and experimenting with suitable business models. During WS-I, a startup was identified that specializes in AI-based detection of suitable rooftop spaces. Using machine learning, the startup trained an AI that automatically identifies rooftops based on solar exposure and recognizes rooftops already occupied by PV installations. Initially, publicly available data (solar cadastre) was used to extract polygons and generate roof segments from satellite images (Digital Orthophotos GovData). The startup performed manual classification of these segments to train the AI (figure 3). The startup then develops a score that represents the suitability of a rooftop. Publicly available data on roof pitch, which can be found, for example, in the construction office of the municipality, are required for this purpose. Establishing a connection with the municipality would, therefore, be beneficial. With the score, property owners or property management companies could be targeted with information about how suitable their respective properties are.

In the conversation with the CEO of the municipal energy provider (IN-II), another startup was discussed, which focuses on leasing rooftop spaces for PV installations. The business case of this startup involves aggregating suitable rooftops (pitch, size, condition) and subsequently installing

PV systems. The PV system is operated by the startup, and the generated electricity is sold. The above-mentioned model of tenant electricity is used, which is offered to the residents of the property. The remaining electricity is fed into the power grid, and the corresponding compensation is received. According to IN-II, the startup takes over the coordination of all approval and installation matters related to the PV system, relieving property owners of the decision-making process. The lease payment for property owners is an additional source of revenue without any cost.

Access to property management companies or owner communities as potential customers is crucial for this startup. During the moderated interview (MD-I), mutual requirements and needs were elucidated. The power dynamics within the owner's community were not entirely known to the group of startups. Additionally, the startup could add another criterion for assessing rooftop spaces. Rooftops that will require repairs in the coming years cannot be economically fitted with a PV system beforehand. From this, the insight was derived that synergy effects could be utilized, such as reusing the scaffolding for the installation of the PV system during the roof repair or renewal. This collection of mutual requirements is deemed highly important for the respective groups.

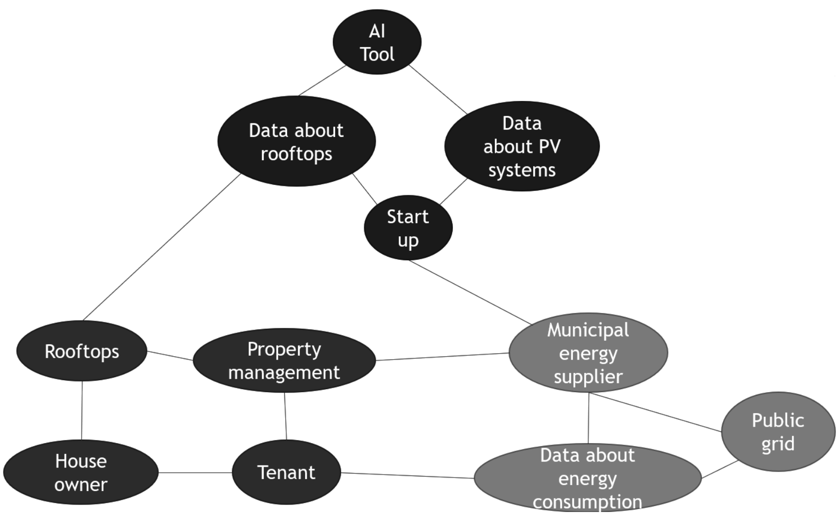
III. Group "Municipal utilities"

Municipal utilities traditionally hold responsibility for electricity generation and distribution within their jurisdictions. They play a significant role in advancing the energy transition locally and have corresponding strategies in place. A critical task of municipal utilities is to balance electricity supply and demand, which must be maintained at a constant frequency of 50 Hertz. The storage capacity for electricity is limited in this context. The prediction of electricity demand for the following day or the next few months is based on historical consumption data, taking into account factors such as weekdays, times of the day, and seasonal variations. According to WS-I, these forecasts have become increasingly challenging due to the decentralization of the electricity market.

Based on these new conditions (decentralized electricity market, more challenging predictions, prosumers), the municipal utilities from WS-I derived the task of establishing a smart grid. Intelligent metering systems are utilized to enable intelligent control of the lower two grid levels (low-voltage and medium-voltage levels). Various sensors are installed to build a so-called Smart Grid. The municipal utility involved in WS-I uses LoRaWAN sensors and gateways for transmitting electricity consumption data from end-consumers. Additionally, visualizing consumption data on an energy data platform for end-consumers has been identified as another task. The data collected from the Smart Grid is processed and made available to end-consumers to provide insights into their electricity consumption or possible electricity production. The municipal utilities are also contemplating offering end-consumers a tenant electricity model or similar models. However, as these efforts are only tangentially related to their core business, the activities in this area are still limited. As a result, connections to end-consumers exist primarily in the context of electricity contracts but not specifically related to the installation of PV systems. The innovative approaches of startups are closely monitored by municipal utilities, and in the case of WS-I, they are even supported through a hackathon.

From the interviews and workshops, several insights were gained regarding the tasks and connections of relevant actors in the context of PV installations on multi-family houses. Missing connections were particularly noted concerning data exchange (roof suitability, roof pitch, smart meter data, and contact persons of property owners). The following section presents an actor-network that corresponds to the current situation developed in this chapter, followed by proposing an extension in the next chapter.

Figure 4: Actor Network with different actor groups



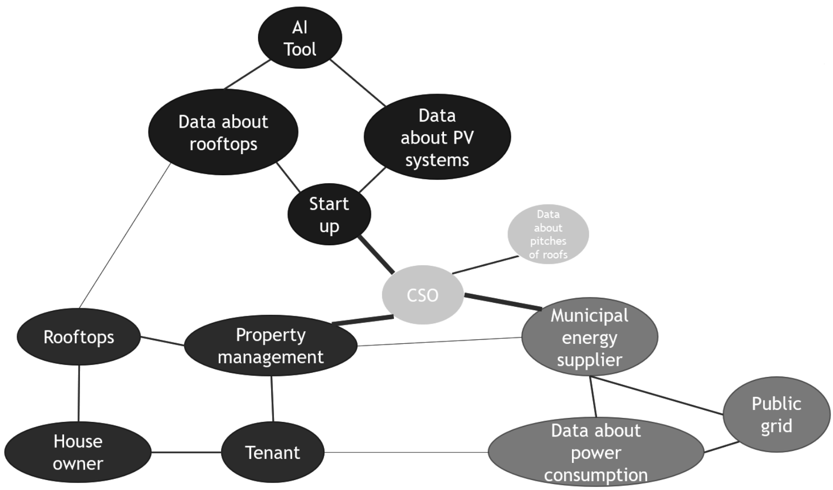
E. Chief Sustainability Officer and Discussion

The developed and depicted network reveals three groups with internal connections and partial connections with other groups. Municipal utilities are linked to both other groups through startups and property management companies. Apart from these connections, there are loose links between individual actors in the network, such as between tenants and data on their electricity consumption. Particularly, the data within each group are of interest to the other groups. For identifying suitable rooftop areas and facilitating decision-making in property owners' meetings, the exchange of all relevant data is crucial.

However, there is currently no cooperation between the different groups. Property management companies do not consider this as their responsibility, and municipal utilities also focus on other core business areas. Although some startups attempt to develop business models involving cooperation, they face various capacity issues related to regulations or influential connections. Additionally, limited personnel in their early stages hinders their ability to contact potential customers extensively. A coordinating entity that gathers and transparently presents the requirements and needs of all stakeholders is lacking. Furthermore, such a coordinating entity could address the inclusion of missing actors, such as in this case, the data on the pitch of the roofs. Most interviewed actors expressed positive views on the prospect of a municipal coordinating body when directly questioned.

This coordinating entity was presented by interviewees either as a position in the local administration, which we call Chief Sustainability Officer (CSO), or as a cooperative platform at the municipal level. The CSO acts as a classic SH spanner, filling a structural "hole" by having access to all groups and collecting their requirements and needs. From this position, cooperation between the groups can be actively organized, no longer relying on informal networks. In this case, the establishment of a CSO in municipal administration could provide a better overview and easier access to official data within the administrative organization. The proposed platform could also serve as a SH spanner, particularly suitable for data exchange. According to the Actor Network Methodology, such a platform is considered an actor, just like natural persons, institutions, infrastructure, data, or software. However, in this specific context, the focus is primarily on stakeholder requirement analysis, coordination tasks, and establishing connections between the actors.

Figure 5: Actor Network with CSO as a SH spanner



F. Implication and Conclusion

The technological components necessary for addressing climate change are already available. However, the progress towards achieving the set goals regarding global warming is alarmingly slow, putting the targets at serious risk. It is evident that the solution to this challenge lies not only in major political arenas or innovative technologies but also in the formation of new networks. This study contributes one of the crucial building blocks, among many, towards tackling climate change through a qualitative analysis. The study presents a possibility to promote the expansion of renewable energy generation, focusing on the building sector and describing how relevant actors in the network can be coordinated to facilitate the installation of PV systems on multi-family houses.

Practical implications arise from depicting this actor network and defining the role of a municipal CSO in this specific context. The actors have been categorized into four groups (property management companies, startups, municipal utilities, and administrations), with some loose connections already existing between individual actors. However, to expedite and streamline the expansion of PV systems on multi-family houses, active coordination among all actors is imperative. Currently, there is no actor fulfilling this coordinating role within the existing network. Such a role could be assumed by a CSO, adding it as another responsibility in their portfolio. Additionally, a municipal CSO can provide crucial public data to the focused network, further justifying the role of a CSO in this context. Moreover, having this coordination activity in public hands is beneficial, as it is rarely financially rewarded, and a municipal CSO operates without a profit motive.

Expanding the role of a CSO prompts consideration of additional responsibilities that can contribute to sustainable development. One potential avenue involves the monitoring of sustainability initiatives, ensuring compliance with sustainability laws, and implementing appropriate educational initiatives as needed (Farri et al. 2023). Furthermore, the inclusion of new stakeholders or the identification and integration of existing ones within the network could enhance its effectiveness. For instance, the group of investors, comprising private investors, national government funding programs, or local banks, could be taken into account. This group could establish suitable funding programs aligned with specific planned activities by the CSO. Although this particular stakeholder group of investors was not mentioned in any of the interviews or workshops, its potential inclusion remains conceivable, providing avenues for future research and practical implementation. The notion of a more comprehensive portfolio for the CSO thus opens up opportunities for broadening their scope of influence and fostering collaboration across an even wider spectrum of actors.

Theoretical contributions lie in describing the interconnections between actors beyond the structural hole spanners and examining the perspective of a non-profit-driven SH spanner. The study demonstrates that various actors can establish connections with one another even in the absence of a SH spanner. While some connections may be relatively loose, they are still present. Certain connections may only be directly known to one actor, particularly concerning data collection, where natural and legal persons, as well as infrastructure, must be considered as actors within the network.

The actor network analysis conducted in this research sheds light on the interconnections and interactions among various stakeholders involved in the deployment of PV systems on multi-family houses. The identified actor network highlights the presence of three distinct groups, each having internal connections and some shared links with other groups. The crucial role played by the CSO as a structural hole spanner is evident in facilitating communication and collaboration among the different groups.

One significant implication of this study is the recognition of the need for enhanced cooperation and data exchange between the identified actor groups. The lack of cooperation and data sharing among these stakeholders hinders the effective implementation of PV systems on multi-family houses.

Establishing a coordinating entity, such as a CSO or a municipal-level cooperation platform, could bridge the existing gaps and promote collaborative efforts among the actors.

The findings also highlight the potential of startups in driving innovation and promoting sustainable solutions in the context of PV systems. However, these startups face capacity constraints, regulatory challenges, and resource limitations. Therefore, supporting these startups and providing them with opportunities to grow and collaborate with other stakeholders can significantly contribute to overcoming barriers in the adoption of PV systems. Furthermore, the importance of data accessibility and transparency cannot be understated. Making relevant data, including roof suitability, roof inclination, and smart meter information, publicly accessible would enable informed decision-making and encourage broader participation from stakeholders. This aspect becomes particularly relevant in the context of a CSO or a cooperation platform, which can facilitate the exchange of critical data among the relevant actors.

In conclusion, this research has provided valuable insights into the actor network involved in the deployment of PV systems on multi-family houses. The actor network analysis has elucidated the interconnected relationships among the identified groups, emphasizing the significance of the CSO as a pivotal figure in bridging communication gaps between stakeholders. The study's implications highlight the need for improved collaboration and data sharing among the various actor groups. Establishing a coordinating entity, such as a CSO or a municipal cooperation platform, presents a promising solution to address existing challenges and foster synergistic efforts. The role of startups in driving innovation and exploring new business models for sustainable energy solutions has been acknowledged. Supporting these startups and removing regulatory hurdles can pave the way for innovative solutions to flourish.

Overall, this research contributes to the understanding of actor interactions and provides a foundation for future studies and initiatives aimed at advancing the adoption of renewable energy solutions in multi-family houses. By recognizing the significance of coordination and data transparency, stakeholders can work together to overcome barriers and accelerate the transition towards a greener and more sustainable future.

The study has some limitations. The study's scope is relatively regional, focusing on the Münsterland and southern part of Niedersachsen. Nevertheless, it is reasonable to assume that other regions in Germany may exhibit similar or at least comparable networks. Nonetheless, some information and data are limited to the German context and may only apply to other countries with different legal, political, and technical conditions to a limited extent. The most significant limitation is the small sample size. To enhance the rigor of the findings, future studies should explore whether actors with similar roles in other regions produce the same results.

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

During the preparation of this work the authors used ChatGPT3.5 in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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