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Concept and Modelling of Participation Opportunity for Large-Scale Renewable Energy Plants

Theresa Liegl[1], Toni Goeller[2], and Simon Schramm[1]

[1] Munich University of Applied Sciences, 80335 Munich, Germany

[2] MINcom Smart Solutions GmbH, 82041 Oberhaching, Germany

Abstract. Citizen participation in the energy transition is desirable for many reasons: it increases acceptance of renewable energies, fulfils the wish to make one's own contribution to the energy transition and generates relevant parts of the necessary capital for the transformation of the energy system. This paper presents a scalable participation concept for the German legal framework which allows citizens to invest in and partially consume electricity from large-scale renewable energy plants at the time of generation. The developed concept provides a method for direct financial involvement via a direct contract with local electricity suppliers and virtual self-consumption by matching demand with PV generation – without the need for property ownership or new subsidies. Different consumer types and participants shares of a large-scale PV plant are modelled and simulated for the years 2019-2021. The financial advantage of citizen participation depends on the type of energy generation plant, yearly (solar) yield, on the remuneration for the surplus energy quantity, on the electricity procurement costs, on the customer's energy consumption, on the amount, and time flexibility and others. This paper shows that all analysed consumer types have the potential to profit from the model every year, although simulations are dependent on variable annual factors and assume the energy supplier's short-term procurement. The approach's scalability and organizational simplicity could expedite the development of local participatory projects and contribute significantly to Germany's energy transition.

Keywords: Citizen Participation, Self-Consumption, Renewable Energy Model, Simulation

1. Introduction and Literature Review

The energy transition is one of the greatest challenges facing our society. The successful implementation requires, among other things, the expansion of decentralized renewable generation systems such as photovoltaic systems (PV) or wind turbines. This also requires the acceptance and investment from the private sector, although there are different ways to involve citizens in the energy transition: political public participation (formal or informal), economic participation and financial participation [1]. Examples of financial participation are so called energy communities. The Clean Energy Package delineates a framework for energy communities derived from two separate European directives. The Internal Electricity Market Directive (EMD) is focused on creating equal competition conditions in the energy market. The Renewable Energy Directive II (RED II) aims to encourage the growth of renewable energy sources [2]. Under RED II, the EU mandates member states to support the expansion of renewable energy, including through renewable energy communities, and to consider them in their support schemes [2]. Furthermore, both directives enable citizens to form energy communities as associations, cooperatives, or similar organizations, allowing for organized collective participation in the energy system. In Germany, energy communities have increasingly become the focus of attention in recent years, however, there is a lack of this comprehensive legal basis that effectively supports the various forms of citizen energy communities. Without such legislative support, many innovative business models remain theoretical and are very difficult to implement in practice [2]. Therefore, the use (self-consumption) of this self-generated renewable electricity in Germany has so far been reserved primarily for property owners. Exceptions are the tenant electricity model and the special regulations for balcony PV systems [2]. The explicit aim here should be that all citizens, regardless of property ownership or residential location, are able to benefit equally from the yield of renewable generation plants (e.g. PV power plants). Due to the urgency of expanding the renewable energy production, this paper explores a simple and scalable concept for the German legal framework of citizen participation, allowing citizens to invest in large-scale renewable energy plants and consume some of the electricity themselves at the time of production. This so-called generation-synchronous energy yield is built on existing frameworks and contractual relationships, is compliant with the applicable legal framework and is easily transferable to other suppliers and regions in Germany.

In general, various approaches for the financial participation of citizens have also already been investigated in research [2]. For example, the EU project NEMoGrid developed and defined innovative business models that promote the penetration of renewable energy into the distribution grid [3]. In Germany, pilot projects have investigated various trading models. The Pebbles project, for example, investigated a blockchain-based energy and flexibility trading model in which all participants act as producers and consumers on the market. Both, the willingness of citizens and the feasibility were demonstrated [4]. However, the system and cannot be implemented within the framework of current legislation. Other possibilities are projects with participation concepts in renewable electricity generation or discounted citizen electricity tariffs, which are already being implemented more frequently [4, 5]. These studies evaluate the economic framework conditions, the need for political support measures as well as the social effects and participation structures that are crucial for the successful implementation and scaling of these business models in Germany. Nevertheless, citizens have the opportunity to participate in the energy market through municipal companies and public utilities [6]. This form of financial participation has a long tradition in Germany and is demonstrated by numerous successful projects in which citizens are involved in energy supply companies as shown by the German Association of Local Public Utilities (VKU) [7]. Such ventures not only contribute to local value creation, but also to the acceptance and successful progress of the energy transition among the population [7]. Other feasible models such as tenant electricity have already been investigated in science and applied primarily in multi-family houses as Braeuer et al. show [8]. Ahlemeyer et al [9] identify success factors for community energy projects in their work and emphasise that low complexity and a high level of professionalism in the business models are crucial for success. The modelling of user-centred systems, as shown by Belmar et al. [10] and Klein et al. [11], assess the feasibility of the implementation of such business models.

For the German feed-in tariff legislation Klein and Deissenroth [12] analyse the investment behaviour for residential PV systems based on a profitability model. The model shows that higher uncertainty, such as volatile electricity prices or shifts in policy incentives, can reduce probability of investment by increasing perceived risk [12]. In contrast to this, Klamka et al. [13] investigate the self-consumption in systems without support mechanisms and with sector coupling. The model explained there provides the savings potential of PV self-consumption after the support period in Germany based on 25 different reference consumers. In addition, the use of different consumer types instead of just the standard load profiles for research purposes is emphasized [13].

Therefore, the following approach describes and models a participation concept that builds on existing electricity supplier contracts and enables self-consumption - regardless of ownership of land or property, subsidies, and cooperative shares. The model uses different consumer types and varying market prices to analyse the financial yield for the participants in this business model. This paper presents the basic idea of the participation concept, the financial model, and the consumer incentives.

2. Business model

In the following a business model is described that can be implemented by energy suppliers under the current legal framework in Germany, mainly based on the German Renewable Energy Sources Act (ger.: Erneuerbare Energie Gesetz, EEG) [14], as described further below. Electricity customers have the opportunity to participate financially in a large, renewable generation plant in the local area by purchasing shares in the plant. The energy supplier is the system owner and sells the PV system shares to the participants. By measuring consumption at the customer's connection to the grid in periods of 15 minutes or less, a self-consumption over grid (here called virtual self-consumption) is calculated from the time-specific energy yield and the customer's electricity consumption. This virtual self-consumption is independent of existing electricity supply contracts of private individuals and thus an opportunity for a community of share owners to achieve partial renewable self-sufficiency.

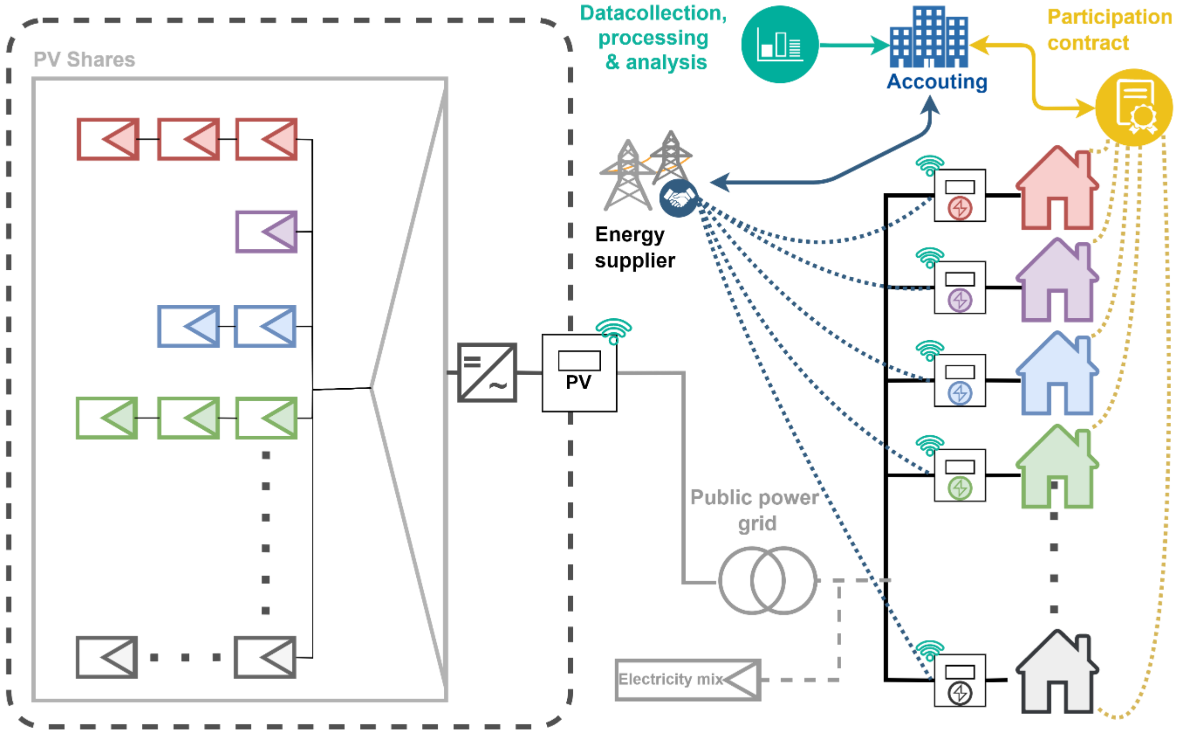

***Figure 1**. Schematic system concept of the generation-synchronized energy yield and relation of the relevant parties involved.*

For the purpose of large-scale generation participation, one or more large-scale renewable generation plants, e.g. a photovoltaic (PV) system (dashed box in Figure 1 left), are divided into different shares of the participants (coloured houses in Figure 1 right). Participants can invest for one-time payment or an annual fee $C_{invest,n}$ depending on the size of their PV system shares. The number and size of the participants' PV shares depends on the respective application. For the participants' share of energy production, the total output power is scaled with the acquired share $P_{PV,n}(t)$. Thereby t is the time in 15-minute intervals and $P_{PV,n}$ is the average power per time unit. The PV system feeds the power output into the public grid. This concept requires metering systems with at least 15-minute readings. In order to be able to determine the virtual self-consumption, the renewable energy generation systems and participants (consumers) are connected to an accounting system via their smart electricity meter.

The accounting system calculates credits or dues according to the participant contract and is operated by or on behalf of the energy supplier. The additional costs incurred as total costs for PV system, marketing fees and margins for the energy supplier are covered by the annual fee $C_{invest,n}$. The virtual self-consumption can be used to offset the participant's electricity demand $P_{demand,n}(t)$ against the proportionate electricity generation of the co-financed PV plant share at the same billing interval.

In order to determine the self-consumption at any time, the power values of the electricity demand and the generation of the respective investor share are required. If the PV power output is greater than $P_{demand,n}(t)$, the entire demand is covered by the PV system investment share and is considered virtual self-consumption $P_{self,n}(t)$. In case that $P_{PV,n}(t)$ is less than the electricity demand, the virtual self-consumption is equal to the plant output share $P_{PV,n}(t)$, see Eq. (1):

$$P_{self,n}(t) = \min(P_{PV,n}(t), P_{demand,n}(t)). \quad (1)$$

The index n describes the dependency of the respective values on the individual participants. If the generated PV power is higher than the electricity demand, the resulting surplus power of the individual participant $P_{surplus,n}(t)$ can be calculated from the difference between generation $P_{PV,n}(t)$ and consumption $P_{self,n}(t)$ (Eq. (2)).

$$P_{surplus,n}(t) = P_{PV,n}(t) - P_{self,n}(t) \quad (2)$$

The electricity is offset against the simultaneous consumption and sold directly in case of surplus. In detail, this means that participants (consumers) directly use the electricity from their share of the renewable generation plant up to their total consumption $P_{demand,n}(t)$. When their share of the PV plant output exceeds their consumption, the difference $P_{surplus,n}(t)$ is balanced at or above market value. This participant-specific calculation is virtual, as the energy supplier sells the output of the PV system on the energy market via so-called direct marketing (ger.: Direktvermarktung) [14], [15]. The direct marketing of electricity is mandatory in Germany for renewable energy systems with an installed capacity of over 100 kW [14]. For systems with an installed capacity of more than 1 MW, which must also directly market their electricity production, the award price in the public tenders (ger.: Ausschreibungswert) determines the minimum guaranteed remuneration of the electricity (ger.: Anzunehmender Wert) [14].

The respective market value minus the marketing fee is paid out as the profit from the surplus - the participants receive income through a profit distribution. This means that the income for participants $I_{total,n}$ is made up of the self-consumption tariff and the surplus tariff, see Eq. (3).

$$I_{total,n} = \sum^{t}(P_{self,n}(t)) \times c_{energy} + \sum^{t}(P_{surplus,n}(t) \times c_{directmarketing}(t)) \quad (3)$$

where

- the sum is over all the measurement periods (t) within a billing period, here one year.
- c_{energy}: price per kWh for energy supply, not counting the German network fees, levies and electricity taxes, since those apply to virtual self-consumption as well as to the remaining energy supplied by the utility. If c_{energy} is not a flat tariff, but a dynamic tariff such as an exchange price, it has to be adapted to $c_{energy}(t)$
- $c_{directmarketing}(t)$: The price achieved for grid feed-in at the respective time, minus a margin for direct market access, see Section 4.3.

The energy supplier covers the remaining electricity demand through the electricity exchange.

The participants have a normal electricity supply contract with the energy supplier. Participants therefore pay a base price and a working price for their whole electricity demand, as it can be seen in section 4.3. In addition to the electricity costs, including c_{energy}, costs for network fees, levies, and electricity taxes c_{tax} and the basic tariff for energy supply $C_{base,n}$ (without additional costs for smart meter), participants pay an annual investment fee $C_{invest,n}$. This covers the energy supplier's annual investment costs, marketing costs, operating costs and a margin. The annual investment costs for the PV plant are calculated using the annuity method. Total annual energy costs for consumers are calculated as follows (Eq. (4)):

$$C_{total,n} = \sum^{t}(P_{demand,n}(t)) \times (c_{energy} + c_{tax}) + C_{base,n} + C_{invest,n}. \tag{4}$$

Based on this, an energy savings can be distributed back to the participants in the form of reduced electricity procurement costs, as shown in Eq. (5).

$$R_{a,n} = \frac{I_{total,n} - C_{total,n}}{C_{invest,n}} \times 100 \tag{5}$$

This financial yield $R_{a,n}$ increases the more electricity the customer uses, synchronized with the generation times of the renewable plant. This means that if your investment is not able to deliver energy at the time of purchase, the electricity will be purchased at the standard rate of the municipal utility (residual electricity purchase).

In order to better assess the effects of different cost structures and framework parameters on the business model, the concept described above is converted into a simulation program.

3. Input Data and Consumer Simulation

The simulation program was developed and implemented in MATLAB [16] and is based on a simulation of one year at a quarter-hour resolution. Values for different years can be imported. The assumptions and input parameters are explained in more detail below. This paper also presents a model for financial yields and the simulation results. The following input data are exemplary for the district of Ebersberg near Munich, Germany.

3.1 Input Data for PV Generation

For the scalable modelling the ground-mounted PV system is provided with standardized output curves. The years (2019 to 2022) are selected because they are as up-to-date and representative data is available. CAMS (Copernicus Atmosphere Monitoring Service) data [17] were adjusted to the location and orientation for irradiation using the open-source PVlib [18], temperature data are used in 10-minute resolution from the DWD [19]. The solar energy yield is calculated by integrating the time resolved output power for each year. Table 1 shows the average radiation and the specific yield for the years 2019 - 2022.

Table 1. *Specific annual yield for PV power plant for 2019-2022.*

Year	2019	2020	2021	2022
Specific annual yield in kWh/kW	1,146	1,172	1,096	1,227

The annual costs for installation and maintenance are calculated using the annuity method [20]. Average values from the literature are used for the investment and operating costs of the generation plants [20], as Table 2 in Section 4.3 shows.

3.2 Consumer Classification

The 74 “representative electrical load profiles for residential buildings in Germany” from HTW Berlin [21] are used as input data for the customer’s time resolved energy consumption. The synthesized load profiles map the characteristic dynamics of household load profiles with pronounced load peaks better than standard load profiles. This data does not contain any metadata, such as household size, etc. Nevertheless, the load profiles can be categorized based on annual electricity demand. For more detailed analysis of the load profiles, please refer to the data documentation [21]. Due to the large differences in the electricity demand of the various households and the uneven distribution of household sizes, two standardized target groups are defined for the model: 2-person and multi-person households. According to the Federal Statistical Office Germany (destatis) [22], these had an average annual electricity demand of 3,188 kWh for 2-person households and 4,937 kWh for a multi-person household in 2019. Therefore, the load profiles no. 16 for two-person households (3,197 kWh) and load profile no. 31 for multi-person households (5,010 kWh) are singled out for detailed calculations, see section 5.3. Commercial consumers are not analysed in this article.

Electromobility is also included in the model. This is based on an annual mileage of 10,000 km and a car energy consumption of 20 kWh/100km. The charging behaviour of the consumers plays an important role in the use of renewable energies and thus for the participation: the time of charging can have a major influence on the virtual self-consumption. Therefore, two charging behaviours are examined for a charging process with 11 kW and simplified charging control: “charging during the day” starting at 11 a.m. and “charging after work” starting at 6 p.m. In both cases, the annual electricity demand for charging the electric cars is 2,278 kWh.

For the integration of sector coupling, the use of a heat pump for multi-family households is simulated on the basis of the above mentioned DWD temperature data [19]. The thermal output is calculated using the heating degree days method. The number of heating degree days is calculated by adding up the differences between the heating limit temperature of 15°C and the average outdoor temperature for all heating days [23]. The annual heat demand is assumed to be 18,000 kWh for a 4-person household. The electricity demand of the heat pump is determined from this using a temperature dependent coefficient of performance (COP) based on the mentioned temperature data [19]. This results in an annual electricity demand for the heat pump of 5,744 kWh.

3.3 Economic Parameters and Electricity Market Data

To calculate the costs and revenues, as shown in section 3, several business input parameters are required for the simulation and are listed in Table 2.

Table 2. *Economic parameters and references for simulation.*

Economic parameter	**Value**	**Reference**
Basic price, net	9.29 €/month	yearly average [24]
Energy price, without VAT and costs for sales	9.68 ct/kWh	[25]
Taxes and network fees	14.6 ct/kWh	[26]
Annual investment fee for participants including margins	100 €/kW per year	own assumption
Installation costs PV	800 €/kW	[18]
Annual operation costs PV plant and direct marketing	15 €/kW per year	based on [18]

The annual electricity costs of the participants are calculated on the basis of the basic price, energy price (+ costs for sales) and taxes and network fees, as shown in Table 2. The investment fee for the participation includes all costs incurred by the energy supplier and billing service provider and could be adjusted for different projects. In addition to the direct marketing fee and margin, the costs for the PV system in particular should be covered.

The calculation of revenue from electricity market sales, as described in Section 3, is based on the monthly market values for PV systems. If the monthly market value is lower than the guaranteed remuneration of the project, the responsible grid operator compensates the difference by means of a so-called "sliding market premium" [14]. The respective monthly market values are used for each simulated year [27]. The supplier perspective is also considered in the model: The energy supplier buys the required electricity at the day-ahead price based on the standard load profiles. The day-ahead electricity price is also imported for the respective year in 15-minute values [28].

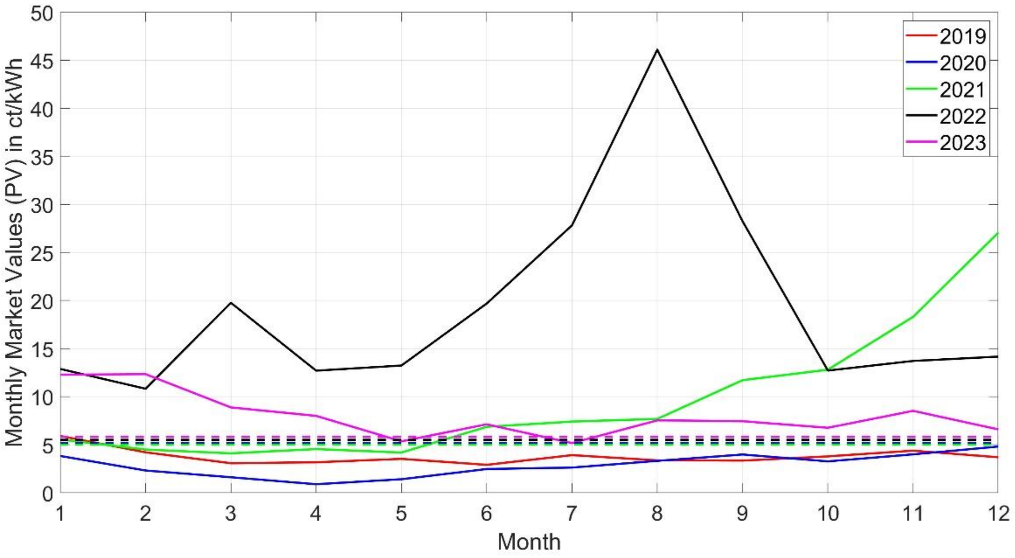

Figure 2. *Straight lines represent monthly market price and dashed lines show the average tender price for PV energy in 2019-2023.*

Figure 2 shows the monthly market values for the years 2019-2023 in colour, as well as the corresponding tender bid values for PV systems (dashed line). The monthly market values in the years 2021-2023 vary greatly due to various influences such as the war in Ukraine. The average tender bid values vary between 5.01 ct/kWh and 5.83 ct/kWh.

4. Simulation Results

The simulation results of the model described are shown and discussed below using 2021 as an example. The simulations and calculations of the key parameters are carried out for the years 2019-2022.

4.1 Analysis of Energy Self-Sufficiency and Self-Consumption Rate

Based on the described model and the input data, self-consumption and self-sufficiency of variable electricity demand and installed capacity of the participants PV share are calculated and presented for the years 2019-2022. The total installed capacity of the PV power plant is the sum of all participant PV shares and is expected to be greater than 1 MWp (see direct marketing [14]). Self-sufficiency is the ratio of annual self-consumption $\sum^t P_{self,n}(t)$ to the participant's total consumption $\sum^t P_{demand,n}(t)$. The 74 annual load profiles are sorted according to annual energy demand in order to calculate the variables as a function of electricity demand and installed capacity of the PV share. This means that the load profiles are retained and vary non-linearly with energy demand. This representation of different load profiles can be seen in the results by means of the flickering curves. Figure 3 shows the self-sufficiency and the self-consumption for all annual load profiles at different participant PV shares in year 2021. The self-sufficiency is between 20 % and 60 % depending on the size of the installed capacity of the PV share. With greater PV share investment, the proportion of self-consumption decreases and local self-sufficiency increases significantly. A high self-consumption rate (greater than 50 %) can only be achieved for consumers with a low PV share and high consumption. These values could improve significantly with (de)centralized storage systems, which has not yet been investigated in this paper.

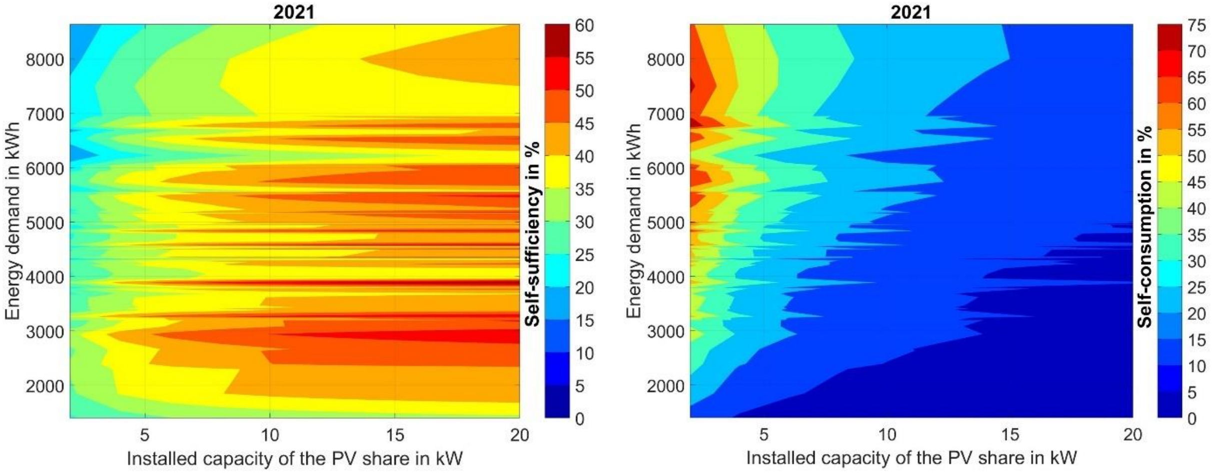

***Figure 3**. Self-sufficiency (left) and self-consumption (right) of different PV share capacities in 2021.*

4.2 Dependence of Financial Yield

In this paper, the customer-side profitability of generation-synchronized consumption is examined on the basis of the return on investment (financial yield, see Eq. (5)). The financial yield is calculated for each year as a function of energy demand (of the various consumer types) and PV share, see section 3. Figure 4 below shows the financial yield again for 2021.

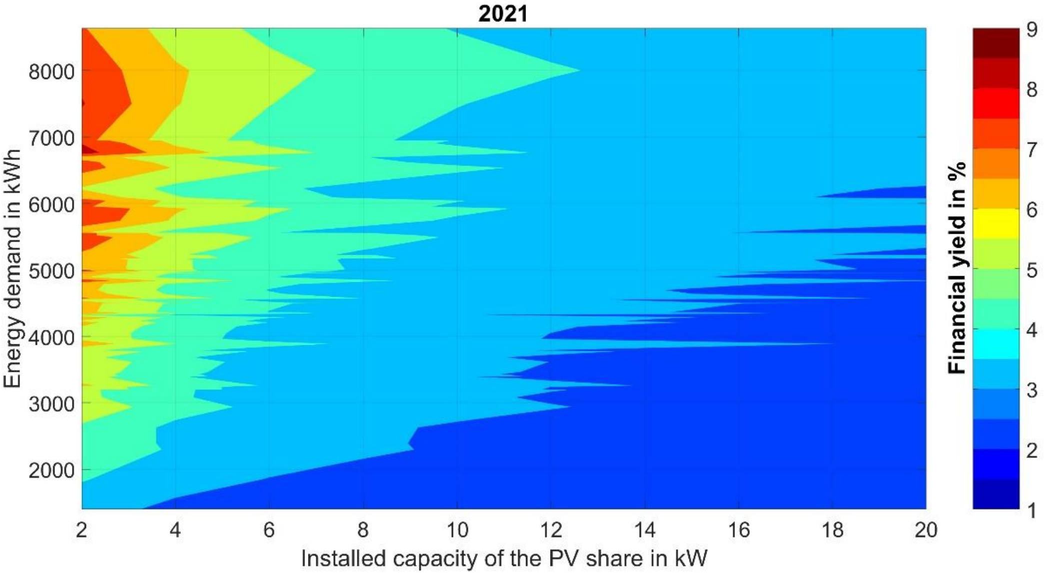

***Figure 4**. Financial yield depending on energy demand and PV share in year 2021.*

In 2021, the financial yield was between 2.3 % and 8.0 %, depending on the consumer and PV share. In this case, there is also no linear relationship between energy demand and yield, as the load peaks of the load profiles vary. Therefore, self-consumption was especially profitable, as the sale of surplus electricity did easily cover the investment due to the high market prices at the end of 2021.

4.3 Consumer Scenarios and Sector Coupling

As shown, the financial yield varies depending on the ratio of electricity demand and capacity of PV share for the basic consumer load profiles. To simulate and analyse specific participants different consumer scenarios are defined in the following. Table 2 shows the reference consumers including sector coupling, as described in section 4.2, and their total annual electricity demand.

Table 3. *Specific consumer scenarios and annual electricity demand.*

Scenario	**Consumer description**	**Annual electricity demand in kWh**
C_{2p}	2-person household basic demand	3,197
C_{4p}	4-person household basic demand	5,010
C_{4emd}	4-person household with EV “charging by day”	7,288
C_{4emn}	4-person household with EV “charging after work”	7,288
C_{4wp}	4-person household with heat pump	10,754

To analyse the financial yield for participants with electric mobility or heat pumps, the consumer scenarios defined in Table 3 are simulated for each year. Figure 5 shows the results for the year 2021.

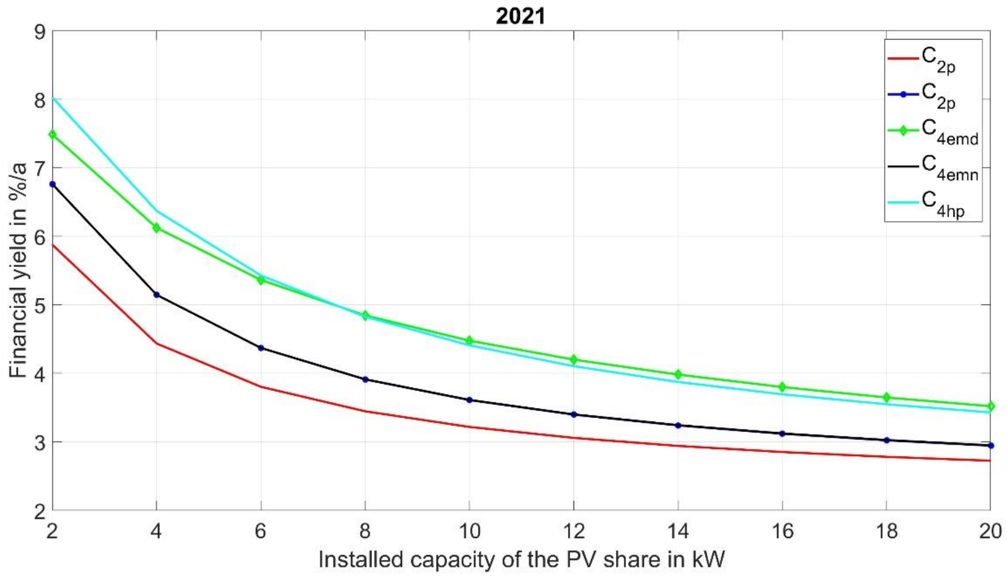

Figure 5*. Financial yield for different consumer types scenarios for year 2021.*

It can be clearly seen that the higher electricity demand of the multi-person household C_{4p} with the same PV share means a higher financial yield compared to the two-person household C_{2p}. For electromobility, the type of charging mode is crucial for the level of financial yield. With evening charging mode C_{4emn}, the financial yield does not change significantly compared to C_{4p} despite higher energy demand and is between 6.8% and 2.9%. The daytime charging mode C_{4emd} significantly improves the financial yield up to 7.5% to 3.5%. Consumers with a heat pump C_{4hp} have a slightly higher financial yield for smaller PV shares and a slightly lower yield at higher shares. This can be explained by the discrepancy between power demand and generation in the electrified heating sector and the lower peak power of the heat pump compared with the wall box used for EV charging.

4.4 Annual Differences

The financial yield depends dramatically on revenue from electricity sales and therefore on the fluctuating market value of PV. In order to better illustrate the annual fluctuation, the financial yield for the years 2019-2022 is shown for the reference consumer multi-person household C_{4p} and a PV share of 6 kW.

Table 4. *Financial yield for different consumer types with 6 kW PV share in 2019 – 2022.*

	2019	2020	2021	2022
C_{4p}	0.44 %	-0.04 %	4.37 %	25.04 %
C_{4emd}	0.78 %	0.24 %	5.36 %	26.44 %
C_{4hp}	0.88 %	0.32 %	5.43 %	28.02 %

The table shows that there are fluctuations of one and a half order of magnitude between 2019 and 2022. In 2022 in particular, high financial yields can be achieved by selling the surplus electricity at high market values. The variation of irradiation and thus the PV yield shown in section 4.1 has significantly less influence on the yield. Consumers with higher consumption (C_{4emd} and C_{4hp}) benefit from the price trends and have a better return on the same investment even in years with lower market values (2019 / 2020) due to self-consumption.

5. Discussion and Conclusion

The participation concept presented here offers all citizens - especially vulnerable households, as they are independent of ownership and income - the opportunity to participate in the generation of renewable energy and thus benefit from synchronized consumption. The results show that this type of financial yield depends above all on the monthly market values and can therefore vary greatly for different types of consumer and different years. In the best year, a return of over 25 % can be expected for a multi-person household, whereas no financial return can be expected in the worst conditions. With rising market prices (2021, 2022), feed-in after direct marketing may well prove profitable and even exceed the benefits of self-consumption. In an average year, the returns for an investment of 6 kW are around 5 %. The dependence of the financial yield on load profiles and sector coupling is also shown in more detail: In the case of electromobility, the type of charging mode (during the day or in the evening) is crucial for self-consumption and therefore for profitability. In summary, there is a profitable way of participating in the PV system for every consumer type in every year examined. Smaller PV shares in particular are more profitable for the private consumers analysed here. This could be different for commercial consumers due to varying load profiles.

However, it should be noted that the simulation results depend heavily on the annually varying input parameters and assume short-term electricity procurement by the supplier. The modelling explained here calculates in 15-minute values and with annually varying irradiation and temperature values. The fluctuation in the load profiles and thus a long-term view of the yield is not considered. On the one hand, the yields may differ slightly for other load peaks and annual energy demands. Margins and levies, on the other hand, have a major influence, which is why an optimal ratio between these parameters still needs to be found here.

A final assessment of the participation concept could only be made by performing and evaluating field tests. In future, the effects of such a participation concept could also be investigated on the part of the energy supplier. The more precise information on consumer behaviour could be used to restructure energy procurement in order to purchase energy on the electricity exchange more accurately. In connection with this, an investigation into dynamic tariffs would be important - on the financial side for consumers and energy suppliers, but also psychologically for consumer behaviour. Nevertheless, an expansion of the business model with this form of participation could protect both the supplier and customers from price increases in the future. In the region, the implementation of the concept therefore contributes to the achievement of regional climate targets and local value creation. The current trend of rising network fees and falling energy prices is challenging. Since the local consumption of produced renewable energy reduces the demand on network expansion in higher voltage levels, policy makers should extend network fee reductions, further increasing the benefits of this model for the network operator, the local utility, and the consumers.

In a larger context, the scalability of the approach and thus replicability ensures simple municipal transferability. As a result, the project development of participation concepts based on extended self-consumption can be accelerated within the framework conditions applicable in Germany and thus represents a valuable contribution to the entire energy system.

Data availability statement

Due to an ongoing project proposal with third parties, additional data that support the findings of this study (code) are available from the corresponding author, T.L., upon reasonable request.

Author contributions

Conceptualization (T.L); Methodology (T.G.; S.S.); Software (S.S); Visualization (T.L); Writing – original draft (T.L.); Writing – review & editing (T.G, S.S, T.L)

Competing interests

The authors declare that they have no competing interests.

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