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Assessing the Role of Electricity Sharing in Meeting the Prerequisites for Receiving Renewable Support in Latvia

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Abstract: Active customers play a critical role in the successful implementation of support schemes, paving the way for the emergence of an energy community. This analysis explores the cooperation among active customers and the implications for developing energy communities. Furthermore, the motivations for consumers becoming active customers in the context of Latvia are illuminated, while also exploring the broader context of navigating the complex regulatory landscape to promote self-consumption. In contrast to prior studies, which often focus on individual or homogenous group participation, this analysis uniquely examines collaborative frameworks that incorporate varied customer categories and profiles. This approach not only underscores the role of tailored regulatory structures in fostering self-consumption, but also presents practical policy insights for incentivizing community-based energy models. The findings reveal that individual participation of active customers in support schemes only achieves the minimal self-consumption threshold in 47% of cases. In contrast, membership in an energy community significantly increases this rate, reaching 84%. These encouraging results underscore the importance of promoting energy community membership among active customers, which subsequently demonstrates substantial potential when promoted across diverse load profile categories. Additionally, the integration of photovoltaic and wind turbine technologies consistently improves self-consumption values.

Keywords: active customer; energy community; self-consumption; support scheme; incentive; net billing system; renewables; load profile; self-sufficiency; modelling

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1. Introduction

In pursuit of sustainable energy integration in an urban environment and achieving a zero-emission economy [1,2], European Union member states have prioritised the establishment of energy communities (EComs), which serve as a fundamental first step for the development of positive energy districts [3] by fostering localised electricity generation, consumption and sharing. Moreover, EComs can facilitate the seamless integration of positive energy districts into urban environments without the need for complex smart grid technological infrastructure, such as automation and distributed control management systems. Notably, the European Union supports such energy initiatives through several key directives and initiatives:

- Renewable Energy Directive: Defines the need for support schemes for local-level energy generation from renewables, increases electricity SC by active customers and determines electricity sharing within EComs as the backbone of increasing renewable energy availability at a local level [4].

- Energy Efficiency Directive: Mandates the necessity to increase overall energy efficiency in buildings, reduces fossil-fuel-supplied energy consumption and increases the share of renewables in final consumption (including energy generation from renewables and the circumstance of sharing it with end users) [5].
- European Green Deal: Creates a set of policy initiatives to ensure zero net greenhouse gas emissions by 2050 and motivates economic growth by the use of renewables, including local energy generation and energy-sharing initiatives (as mentioned in the Renewable Energy Directive) [6].

However, the introduction of EComs faces several challenges, such as determining what would motivate consumers to become active customers (also referred to as prosumers), what kinds of support schemes or financial incentives could be incorporated to facilitate this transition, and whether it would be both feasible and beneficial for the active customers involved [7]. These challenges are particularly pronounced in urban areas, as the proportion of the European Union population living in cities has been steadily increasing, driven by both internal migration and international immigration [8]. Moreover, the standards set by the Strategic Energy Technology Plan [9] have yet to be achieved—if they are even achievable at all—due to technological limitations and complexities associated with residential areas containing multi-family dwellings. Given these challenges, it becomes essential to explore how different European Union member states, such as Latvia, navigate the complex regulatory landscape to promote SC and encourage consumers to become active customers, particularly when there is still considerable debate over the most beneficial legal frameworks and support mechanisms needed to foster these efforts [10].

The research that served as the basis for this article has been conducted within the framework of the Driving Urban Transition Partnership project "Positive Energy Districts Driven by Citizens" (PERSIST) [11], which aims to evaluate existing schemes directly or indirectly supporting investments at the consumer level into assets that contribute to long-term changes in electricity production or consumption. The self-consumption (SC) value is crucial for evaluating support schemes because it directly affects the economic viability and effectiveness of renewable energy investments. By understanding the potential for on-site energy generation and consumption, policymakers can design incentives that maximise financial benefits for individuals, encourage energy independence, and promote sustainable practices.

There is some scholarly agreement regarding the SC strategy being one of the most feasible and short-term pathways toward sustainability [12,13]. However, there is neither a unanimous consensus nor a universal legal framework to regulate SC or support the efforts of active customers, whether individual or commercial. As a result, experiences across European countries vary significantly due to the differing regulations implemented to encourage consumers to become active customers and the mechanisms used to oversee these activities and ensure legal certainty.

For example, Germany has been a frontrunner in providing financial incentives through its Renewable Energy Sources Act or EEG (German: Erneuerbare-Energien-Gesetz) [14], a central piece of legislation designed to promote renewable energy sources and ensure the country's energy transition, known as the Energiewende. Households that use electricity generated by their photovoltaic systems and feed excess electricity into the grid are eligible for feed-in tariffs [15], which are fixed payments according to EEG regulations. For small rooftop systems with SC that started operation in January 2024, the feed-in tariff can be up to 8.2 cents per kWh for 20 years, depending on the size of the system. Moreover, there are no specific requirements for SC to be eligible for these payments. However, for smaller rooftop photovoltaic systems, different proportions of SC and feed-in tariffs are accounted for, including full feed-in cases or landlord-to-tenant arrangements, which may include additional compensations [15].

Spain implemented feed-in tariffs in the early 2000s, which significantly increased the occurrence of photovoltaic and wind turbine installations [16]. Recent regulations have introduced specific considerations regarding SC and the associated government benefits. These regulations focus on two main models: full SC and partial SC. In the full SC model, there is no specific percentage of SC required to receive benefits. Instead, the electricity consumed directly by the household or business reduces their electricity bills [17]. In the partial SC model, any surplus electricity generated and fed into the grid is compensated by the Spanish government. This compensation is based on market prices and provides a payment for the excess electricity supplied to the grid [17]. Moreover, to access these benefits and ensure proper grid integration, solar photovoltaic installations must comply with registration and technical standards [18].

A similar pattern is observed in the Netherlands, where households and businesses can consume all the electricity they generate (which, therefore, makes it a full SC model), reducing their electricity bills proportionally. There is no specific requirement for a minimum percentage of SC to receive benefits under the current policies. Regarding partial SC, excess electricity that is not consumed can be fed into the grid under the net metering system (until 2031) or compensated at a reduced rate in the future as the scheme is phased out [19]. Thus, maximising SC will become increasingly advantageous as net metering benefits are reduced.

Shifting to the country study of the analysis, Latvia's approach to promoting SC among active customers is structured around several support mechanisms under the Electricity Market Law [20]: a net metering system, a net billing system, electricity trading and electricity sharing within EComs.

The net metering system, partially discontinued in 2024, allows households with up to 11.1 kW of renewable energy generation capacity to transfer excess electricity back to the grid, converting it into virtual credits to offset household electricity costs. This system will remain available to existing users until 2029 [20]. The net billing system, which replaced the net metering system for active customers, permits households, small- to medium-sized enterprises and public buildings to offset electricity consumption across multiple load profiles [21]. Excess electricity is converted into non-taxable value credits, with eligibility for state aid [22] requiring an SC ratio of at least 80% and a capacity of not more than 999.99 kW [21]. Electricity trading is less favoured due to additional taxes [23] and fees [24], making it a less attractive option for active customers.

Upcoming regulation [25] for EComs, expected by the end of 2024, will allow electricity sharing within communities, potentially enhancing the overall SC, and EComs must achieve an SC rate of 80% with a total capacity limit of 15 MW.

It means that Latvia's regulatory framework encourages maximising SC through the net billing system and EComs, while options for feeding excess electricity back into the grid remain limited. Moreover, taking into account the peculiar SC level determined by Latvia's legislation against the background of regulations in other EU countries, coupled with the lack of experience of Latvia's end users and active customers in ECom creation due to ongoing adoption of ECom regulation [25], there is a knowledge gap regarding how and if EComs in Latvia can help the country reach an 80% SC level. In this context, considering the regulations and requirements of Latvia's legislation, several key questions emerge:

1. Is active customer participation in an ECom a guaranteed condition for meeting the 80% SC rate required for renewable support?
2. Which ECom configurations and consumer groups in the coalition can raise an ECom's SC rate to meet the legislative requirements?

The primary goal of this study is to explore how Latvia's legal and policy frameworks affect the SC rates of active customers and to identify strategies for increasing SC rates to meet legislative objectives through participation in EComs. This understanding will help identify gaps in information and facilitate improvements in the development of EComs.

The novelty of this work lies in addressing the problem of the reduced rate of SC of active customers, with a specific focus on the creation of ECom configurations, considering the combination of different load profile categories.

This analysis is set against the broader EU context, where countries strive to achieve sustainability and zero-emission goals by maximising renewable energy sources. The challenges in motivating consumers to become active and aligning legal frameworks with these objectives are particularly significant in urban areas, where the complexities of multi-family dwellings pose additional obstacles [26]. Investigating the mechanisms through which different ECom configurations can enhance SC rate is essential for advancing the climate neutrality objectives. By optimising SC, it is possible to significantly increase the proportion of renewable energy sources in final energy consumption. This transition not only supports the reduction of greenhouse gas emissions, but also mitigates dependence on centralised energy generation systems, which are primarily reliant on fossil fuels. Such strategies are vital for fostering energy resilience, promoting sustainable practices, and aligning with global climate commitments.

The Section 2 introduces the methods and models of the research: collection of the historical data of load profiles; division of electricity load profiles, taking into account net billing system application and type of load profile; modelling and calculation of photovoltaic and wind turbine generation; the methods of generating photovoltaic and wind turbine energy; formulation of operational scenarios to evaluate the SC rate for various cases (active customer, ECom, photovoltaic or wind turbine installation); estimation of the percentage values of SC rate. The Section 3 presents the SC rate results of an individual consumer versus EComs, as well as considering load profile categories. The discussion and conclusions are summarised in the Sections 4 and 5.

2. Methodology and Models

The development of a SC model necessitates a comprehensive approach that encompasses several critical steps. Initially, it is important to analyse specific load profiles to understand the energy usage patterns and the diversity of consumers. This model is complemented by determining appropriate photovoltaic (PV) sizing and generation capabilities as well as wind turbine (WT) generation data. Additionally, it is necessary to make the underlying assumptions that will determine the structure of the mode. The next step consists of the development of a structured algorithm, which is critical to accurately model and optimise SC scenarios. This multifaceted methodology aims to assess adherence to the requirements of renewable support schemes.

Additionally, the self-sufficiency rates (SSR) of active customers are calculated and analysed in this study. SSR [27] plays a crucial role in promoting environmental sustainability and aids in assessing the readiness of active customers to engage in EComs.

2.1. Electricity Load Profiles

To assess how different electricity consumption patterns within an ECom can enhance the overall active customers' SC, it is essential to first define and outline the specific load profiles that are to be used in the modelling process.

One hundred annual hourly electricity consumption data sets (load profiles) of Latvia were analysed in the modelling process (see Appendix A). These data were collected from two primary sources: smart meter readings collected by the distribution system operator "Sadales Tīkls" [28] and individual measurements conducted by Riga Technical University researchers and data analysts.

In this pool of load profiles, it was important to consider the specific characteristics of cities and the diversity of consumers to facilitate a wider range of conclusions after modelling their mutual electricity sharing operations and scenarios. It is necessary to note that the analysis is based on modelled data, as the hundred active customers in the study do not have real installations of RES. Instead, we calculated the rated power of PV and WT systems based on their real energy consumption patterns. This modelling approach allows us to assess the potential performance of these systems under different scenarios.

Therefore, the selected load profiles were categorised into four primary categories:

1. Residential: Encompasses electricity consumption of households and living areas, including dwelling houses, apartment buildings, and dormitories.
2. Industrial: Includes consumers with high, stable electricity consumption involved in production activities, urban infrastructure services and the use of heavy-duty equipment. This category encompasses factories, a fire station, a barn and a pump station.
3. Commercial: This category includes medium and variable electricity load profiles involved in service provision, business and care services (a bank, a hospital, hotels, offices, a parking lot, shops, supermarkets and a swimming pool).
4. Education: Consumers with variable electricity consumption and capacity engaged in educational, research and innovation activities. Profiles in this category include kindergartens, secondary schools, a college, university faculties, a library, a laboratory, and an auditorium.

Moreover, each profile is further assigned to one of five annual consumption levels and three power generation types as defined by Latvia's legislation [21]. According to the solar installation capacity calculations outlined in Section 2.2, which are based on annual consumption, each participating consumer is categorised either as a microgenerator or a power plant and further classified into one subgroup based on capacity thresholds (11.1 kW, 49.9 kW, 999.9 kW). Subsequently, the capacity of solar installations is modified to align with the group classification. For example, if the initial PV system power for a residential load profile is 12 kW, then after the classification process described above, it should be adjusted to 11.1 kW accordingly to Latvia's legislation. Thus, the PV-rated power for each load profile is adjusted and used for subsequent calculations, as detailed in Section 2.3.

The distribution of these load profiles across the aforementioned groups and subcategories is visualised in Figure 1.

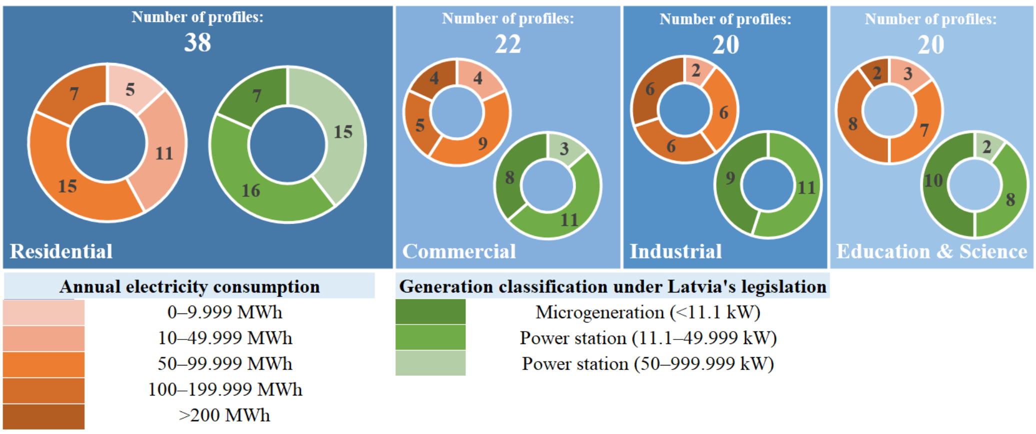


Figure 1. Distribution of consumer profile groups.

To comprehensively evaluate the SC rate (SCR) of active customers and EComs across different configurations and scenarios, it is essential to establish a clear understanding of the interplay between electricity consumption and generation patterns. Furthermore, incorporating comprehensive data sets encompassing a variety of renewable energy sources (RES), such as PV and wind power systems, is crucial for accurately modelling electricity generation outputs based on installed capacities.

Consequently, the following sections will present and analyse the distribution of electricity generation sources, along with corresponding generation data.

2.2. Photovoltaic and Wind Turbine Generation Model

2.2.1. Photovoltaic Potential and Generation

The greatest potential for SC for active customers lies in utilising PV systems. The methods for calculating PV generation vary from straightforward empirical models to advanced simulation software. Effectively using these methods allows stakeholders to make knowledgeable choices, increase energy production, improve system efficiency, and aid the shift towards a sustainable, renewable energy future. Calculating PV generation by using real PV data plays a fundamental role in accurately assessing the performance and efficiency of solar energy systems in practical applications. This empirical approach to PV generation helps to validate the accuracy of simulation models and facilitates informed decision-making in system sizing, component selection, and performance optimisation. Real PV data provide valuable insights into the actual performance of solar panels under varying environmental conditions, such as solar irradiance levels, temperature fluctuations, shading effects, and system losses.

This article presents a methodology for calculating the total PV generation for a specific load profile. This calculation involves multiplying the determined installed capacity (P_{PV}) of the PV installations (kW) (see Section 2.2.2.) by the PV specific generation, W^t_{PV}, (kWh/kW), which was derived from the analysis of actual PV systems in Latvia. The resultant total energy generation ($W^t_{res,PV}$) can be expressed as follows:

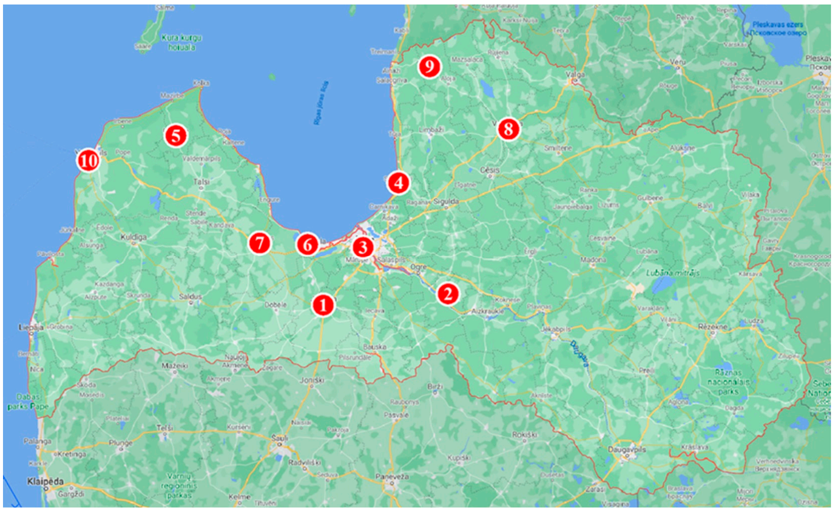
$$W^t_{res,PV} = P_{PV} \cdot W^t_{PV} \tag{1}$$

In order to analyse Latvia's PV generation level, the SolarEdge Monitoring Platform [29] was selected as the source of information. SolarEdge is a world-class manufacturer of inverters and power optimisers with its own monitoring platform that continuously monitors more than 1.5 million solar plants worldwide. This platform has public information on more than 29 thousand solar plants worldwide. Specifically, for Latvia, there is information on 26 solar energy production plants. Ten solar energy production facilities were selected, whose locations are evenly distributed throughout the country as indicated in Figure 2a, considering the total capacity of various installed PV units and the available information on the production of solar panels throughout the observation period. The data set includes hourly solar generation from 1 January 2022 to 31 March 2024. The list of selected facilities and their installed capacities can be seen in Table 1, and the location of the facilities is presented in Figure 2a (the number in a red circle in the figure corresponds to the facility's number in the Table 1).

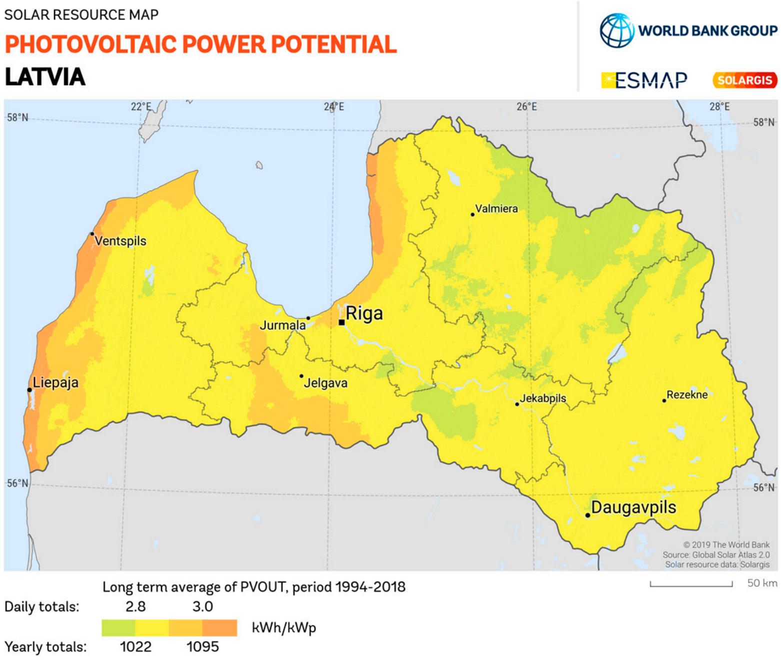
Table 1. List of selected objects in Latvia.

No.	1	2	3	4	5	6	7	8	9	10
Name of facility	Jelgava	Lielvarde	RTU	Saulkrasti	Solenergo Dundaga	Solenergo Kauguri	Solenergo Tukums	Solenergo Valmiera	Staicele	Ventspils VNT
Installed capacity (kW)	5.88	3.43	3.3	6.37	6.6	11.09	9.6	7	3.92	105

Aside from details on the particular facilities, Table 1 also demonstrates how the selected PV installations cover all three categories of generators, starting with small microgenerators of a few kW that one might see on roof of a family house, up to power stations exceeding 50 kW that may be found in a dedicated solar power plant or an industrial area.



(a)



(b)

Figure 2. (**a**) Locations of selected facilities in Latvia. (**b**) Latvia's PV power potential (PVOUT) (reprinted with permission from Ref. [30]. 2023, Global Solar Atlas).

The solar resource map (Figure 2b) represents the average yearly totals of electricity production from a 1kW-peak-grid-connected solar PV power plant. The PV system configuration consists of ground-based, free-standing structures with crystalline-silicon PV modules mounted at a fixed position with optimum tilt to maximise energy yield. The use of high efficiency inverters is assumed. In the simulation, losses due to dirt and soiling was estimated to be 3.5% [31]. According to the solar energy potential map of Latvia [30], it can be seen that most facilities are located in areas where the amount of annual solar potential is 1095 kWh/pkW, which is the highest value in the territory of Latvia.

For ease of data interpretation and informed decision-making based on relative values, the specific value method was used. All ten facilities were reduced to a capacity of 1 kW. By employing the method of average values, the vector of the average monthly PV generation values was computed and is presented in Figure 3. This chart shows how seasonal PV output is in Latvia, which can result in differences in the SCRs obtained in this study and those calculated for a sunnier climate, e.g., in central or southern Europe. The data obtained will be further used for the SC model, which is considered in Section 2.3.

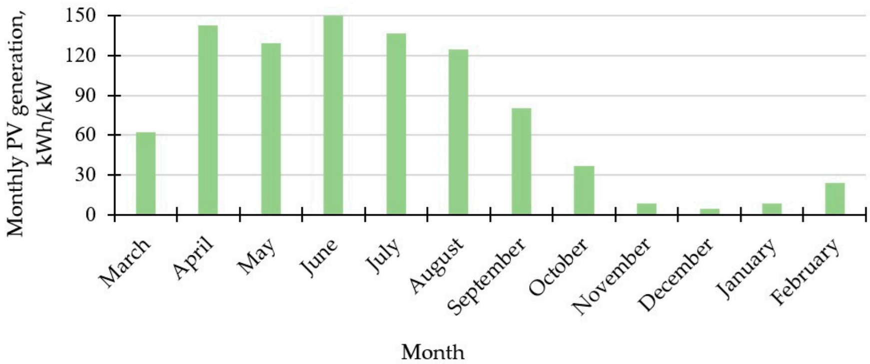


Figure 3. Average per-unit PV generation (1 March–28 February).

After understanding the PV generation, the next step involves calculating the PV power for each active customer in order to assess their SCR accurately.

2.2.2. Photovoltaic Power Calculation

Selection of appropriate methods for PV power system sizing is vital for creating efficient solar energy systems in EComs. Numerous methods and tools have emerged to aid in calculating and choosing PV capacity [32].

The decision-making process regarding the right PV power system involves consideration of factors such as installation space, budget limits, desired efficiency, and local regulations. Techniques like energy balance calculations, load profile analysis, and economic assessments help determine the optimal size and setup of the PV power system to meet energy needs efficiently. Two techniques of PV sizing (kW) are selected, which are based on the following:

1. Average daily energy consumption by the consumer and average daily number of hours of peak solar activity in the country [33].

Average peak sun hours ($H_{PV,av}$, h) vary greatly depending on the consumer's location and local climate. To determine a user's average daily energy consumption ($E_{day,av}$, kWh), it is necessary to obtain 12 months of kWh usage data for comprehensive yearly analysis. The next step is to calculate the average monthly energy consumption of the consumer and, after that, to determine the daily consumption:

$$P_{PV} = \frac{E_{day,av}}{H_{PV,av}} \cdot k_{ef} \quad (2)$$

where k_{ef} is the efficiency of the PV (for further calculations, it is considered to be 23% (the mean value from report data [34])). The average peak sun hour number in Latvia is 5 h [35].

2. The annual energy consumption by the consumer and the annual solar potential of the country. The PV sizing can be formulated by Equation (3):

$$P_{PV} = \frac{E_{year}}{A_{PV,poten}} \quad (3)$$

where E_{year} is the total annual energy use by a consumer in kWh; $A_{PV,poten}$ is the annual solar energy potential per kW of panels in kWh/kW (for further calculations, 1095 kWh/pkW is considered).

Once the two parameters are determined, the resulting energy generation ($W^{t}_{res,PV}$) must be calculated using Equation (1).

2.2.3. Modelling of Wind Turbine Generation

The next promising option for SC is the use of WTs, which can generate electricity all year round, unlike PV systems. At the moment, there is a shortage of wind turbines in Latvia's market [36]. After conducting market research, four types of turbines available on the market were selected: a 5 kW horizontal turbine (GREEN AH-5kW) and 3 kW, 4 kW, and 5 kW vertical turbines (VH turbines). Considering the average wind speed in Latvia at a height of 10 m, horizontal turbines are more efficient because they can generate more electricity at lower wind speeds (reaching maximum power at around 8–10 m/s, compared with 12–14 m/s for vertical turbines) [37]. Their levels of noise transgress the allowed limit in urban areas. In contrast, vertical turbines are more suitable for cities due to their significantly quieter mode of operation. Another critical factor for installation is finding a suitable location. While vertical turbines are more compact, finding an appropriate installation site can still be challenging, especially if it is impossible to mount WTs on rooftops.

To calculate the potential amount of electricity that each of the four selected turbines could generate, data from the Riga meteorological station regarding the average wind speed for each hour in 2022 were used [38]. Using the technical data of the turbines—specifically, the approximation of power curves based on wind speed—an estimation was made on how much electricity each turbine could generate per hour in the year 2022. For the approximation of the output power curve, a 5th-degree polynomial was selected (Figures 4 and 5). The choice of polynomial degree was determined by an algorithm aimed at representing the WT output power curve with the highest accuracy, allowing a maximum degree of 5. In spite of the fact that, in practice, the degree of the polynomial for WT output generation is rarely chosen to be greater than 3, we decided to use a 5th-degree polynomial.

Using a 5th-degree polynomial or a 3rd-degree one does not significantly impact the results of the paper, as the generation model provides only an approximate value for potential generation. Additionally, factors such as variations in WT types, locations, and installation heights introduce even greater deviations from the modelled results in practice—factors that we did not take into account in order to simplify the model.

Scenario variety for different groups of active customers and varying self-generation capacity is very important for result representation and analysis of SCR and SSR. As a result, the next step is to model different scenarios for active customers with varying self-generation capacities from WT and PV.

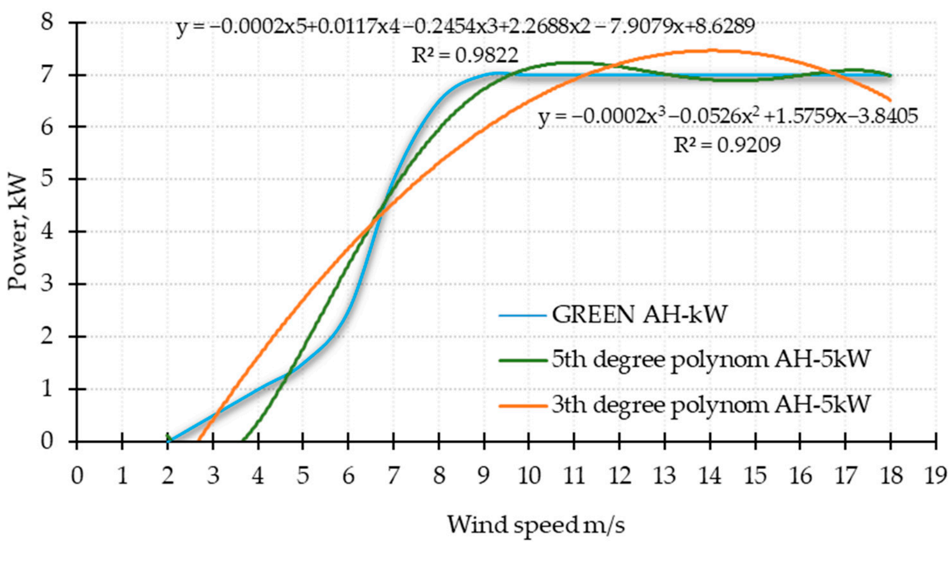


Figure 4. Approximation for horizontal wind turbine GREEN AH-5kW.

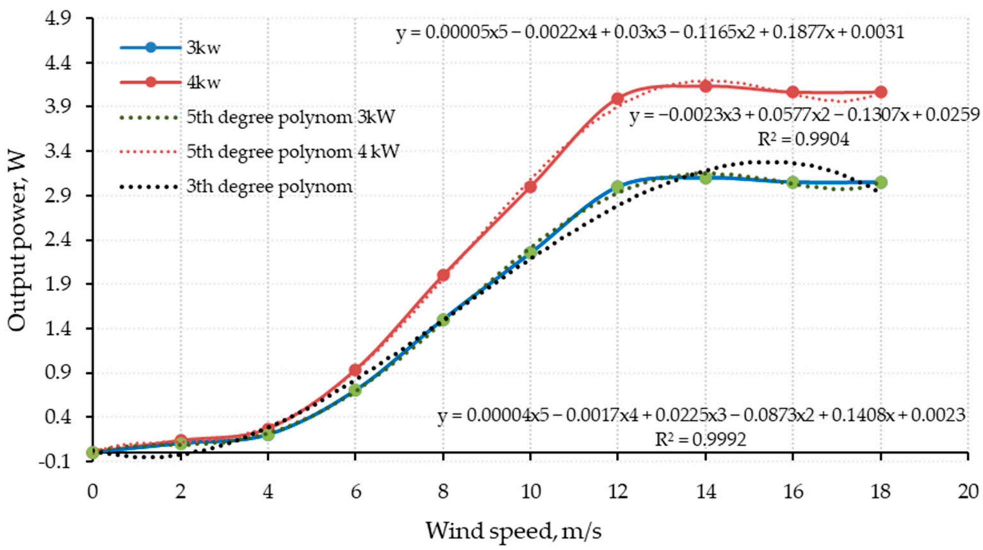


Figure 5. Approximation for vertical WTs VH-3kW and VH-4kW.

2.3. Self-Consumption Ratio and Self-Sufficiency Rate Model

The creation of an SCR and SSR model is crucial for analysing the ability of active customers to meet the defined conditions of the RES support scheme and their willingness to become part of the ECom. By focusing on self-consumption, active customers can identify patterns in consumption behaviour and assess the optimal capacity and efficiency of RES technology.

The following equations define SCR and SSR [39]:

$$SCR = \frac{W_{SC}}{W_{gen}} \cdot 100\% \tag{4}$$

$$SSR = \frac{W_{gen}}{P_{cons}} \cdot 100\% \tag{5}$$

where W_{SC} is directly consumed PV energy by the active customer in kWh, W_{gen} is generated RES energy in kWh, and P_{cons} is the energy consumption of the active customer in kWh.

In this study, 59 scenarios were selected for 100 load profiles (see Appendix B). Specifically, these scenarios include a scenario when only one active customer has PV installations (1PV), and also include EComs scenarios: two active customers have PV installations (2PV), three active customers have PV installations (3PV), four active customers have PV installations (4PV), one active customer has PV installations and one active customer has a WT (1PV&1WT), etc., up to scenarios with 3 active customers with PV and 2 active customers with WT (3PV&2WT). It is important to note that three different types of WTs are used in the scenarios: a 3 kW vertical WT, a 4 kW vertical WT, and a 5 kW horizontal WT (types of WTs available on the Latvia's market) [36]. Since two methods for calculating the installed PV power are presented in this paper, this results in a total of 56 scenarios involving PV technology. Also, the 57th–59th scenarios should be singled out and are presented, involving only one active customer with 3 kW, 4 kW and 5kW WTs. For each scenario, all possible combinations of the 100 available load profiles were explored using a brute-force approach.

The structural diagram of the algorithm for evaluating the SCR for one active customer and EComs is provided in Figure 6. It has to be noted that for one active customer, the process "*k*" is ignored, which is responsible for creating combinations of EComs.

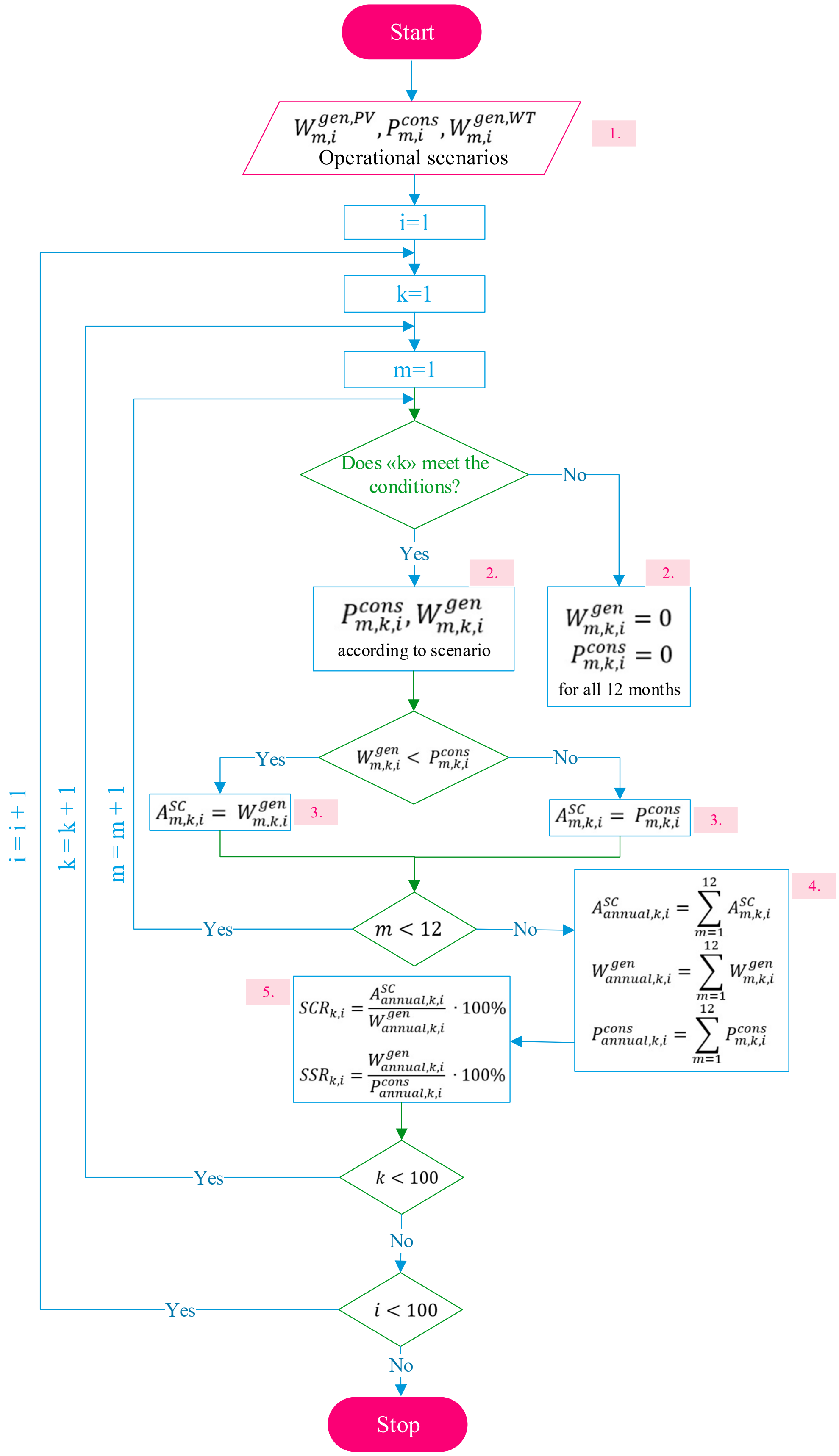


Figure 6. The structure of the algorithm for assessing the SCR and the SSR.

The algorithm uses the monthly (m) measurements of energy consumption $P_{m,i}^{cons}$, energy generation by the PV, $W_{m,i}^{gen,PV}$, and WT system, $W_{m,i}^{gen,WT}$, and the selected operational scenario (Block 1, Figure 6). In order to make the structural diagram in Figure 6 more concise, the conditions for "k" checked according to the number of active customers (i) are specified separately:

$$2\ active\ users : if\ k = i\ ,\ \ W_{m,i}^{gen} = 0\ AND\ P_{m,i}^{cons} = 0 \tag{6}$$

$$3\ active\ users : \left\{ if\ k = i\ \rightarrow\ W_{m,i}^{gen} = 0\ AND \right. \\ P_{m,i}^{cons} = 0\ if\ i = 100\ AND\ k = 99\ \rightarrow\ W_{m,i}^{gen} = 0\ AND\ P_{m,i}^{cons} = 0 \tag{7}$$

$$4\ active\ users : \left\{ if\ k = i\ \rightarrow\ W_{m,i}^{gen} = 0\ AND\ P_{m,i}^{cons} = 0 \right. \\ if\ i = 98\ AND\ k = 99\ \rightarrow\ W_{m,i}^{gen} = 0\ AND\ P_{m,i}^{cons} = 0\ if\ k = 99\ OR \\ k = 100\ \rightarrow\ W_{m,i}^{gen} = 0\ AND\ P_{m,i}^{cons} = 0 \tag{8}$$

$$5\ active\ users : \left\{ if\ k = i\ \rightarrow\ W_{m,i}^{gen} = 0\ AND\ P_{m,i}^{cons} = 0 \right. \\ if\ i = 97\ AND\ k = 98\ \rightarrow\ W_{m,i}^{gen} = 0\ AND\ P_{m,i}^{cons} = 0\ if\ k = 98\ OR \\ k = 99\ OR\ k = 100\ \rightarrow\ W_{m,i}^{gen} = 0\ AND\ P_{m,i}^{cons} = 0 \tag{9}$$

For each combination of active customers, the monthly energy consumption by the i-th and k-th active customer, $P_{m,k,i}^{cons}$ and energy generation by the WT or the PV system for the i-th and k-th active customer, $W_{m,k,i}^{gen}$, are calculated (Block 2, Figure 6). If the consumption amount exceeds generation during a given month, the value of the monthly SC by the ECom of the i-th and k-th active customer, $A_{m,k,i}^{SC}$, is equal to $W_{m,k,i}^{gen}$; and if not, then to $P_{m,k,i}^{cons}$ (Block 3, Figure 6). The SC value is calculated for each month. After all 12 months of the net billing system period have been calculated, the annual SC, $A_{annual,k,i}^{SC}$, energy generation, $W_{annual,k,i}^{gen}$, and energy consumption, $P_{annual,k,i}^{cons}$, by the ECom of the i-th and k-th active customer are estimated (Block 4, Figure 6). After that, the SC rate, $SCR_{k,i}$, and the self-sufficiency rate, $SSR_{k,i}$, for the ECom of the i-th and k-th active customer are defined (Block 5, Figure 6).

The above-presented algorithm is implemented in the MATLAB R2020b (9.9.0.1467703) environment.

Also, some limitations were introduced for this model. Firstly, the net billing system period was maintained according to valid legislation; i.e., from 1 March until the last day of February [20]. Secondly, the number of WTs was limited due to load profile sizes and installation possibilities. Finally, EComs involving only WT owners were not considered due to the high SCR results from an individual active customer.

3. Results

3.1. An Individual Active Customer

In order to evaluate the positive impact of EComs on the efficiency of renewable energy use, one can start by considering the performance of an individual active customer for use as a baseline. The results obtained for the 100 active customers described in Section 2.1, using the methodology presented in Sections 2.2 and 2.3, when they individually generate and consume power only from PV panels, are presented in Figure 7. It should be noted right from the beginning that results in Figure 7 only include results for the second method of PV sizing for a more compatible comparison with an individual WT-powered active customer, for which a similar method for sizing is used. Afterwards, when comparing the individual active customer and EComs, results obtained by both methods are used. N_{PROP} in Figures 7 and 8 represents the number of load profiles or active customers with the corresponding values of SCR and SSR.

The SCRs shown in Figure 7a indicate that for individual, PV-powered active customers, the selected installed capacity (rated power) is relatively high compared to the demand because in more than half of the cases, the 80% SCR requirement for PV support is not met. This is also corroborated by the high SSRs in Figure 7b. As can be seen in the second histogram, most values are above 50%, with a large portion of load profiles reaching the 80–100% range. In contrast to SSRs, the SCR values are also less concentrated. When looking more into the details of these results, it can be seen that the rated power of PV installations is often close to the limits imposed by the support scheme. For comparison, the same metrics are presented in Figure 8 for individual active customers with only WTs installed.

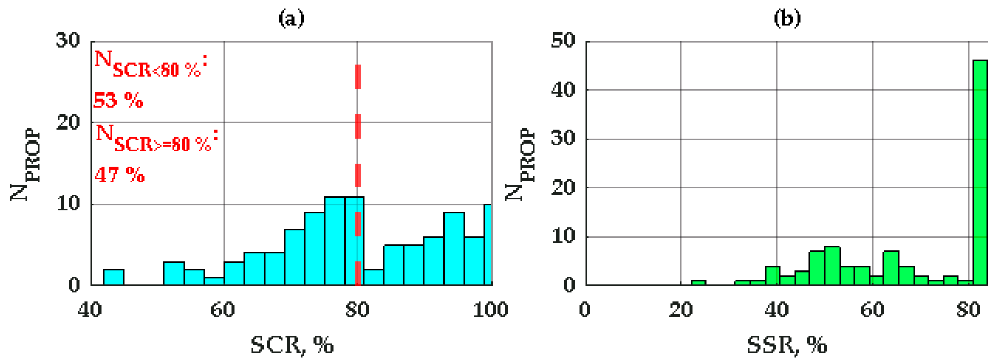


Figure 7. Histograms of: (**a**) SCRs with $N_{SCR<80\%}$ and $N_{SCR\geq80\%}$ indicating the percentage of individual active customers that would not reach the 80% SCR requirement and ones that would reach it, and (**b**) SSRs for individual active customers with only PV panels installed.

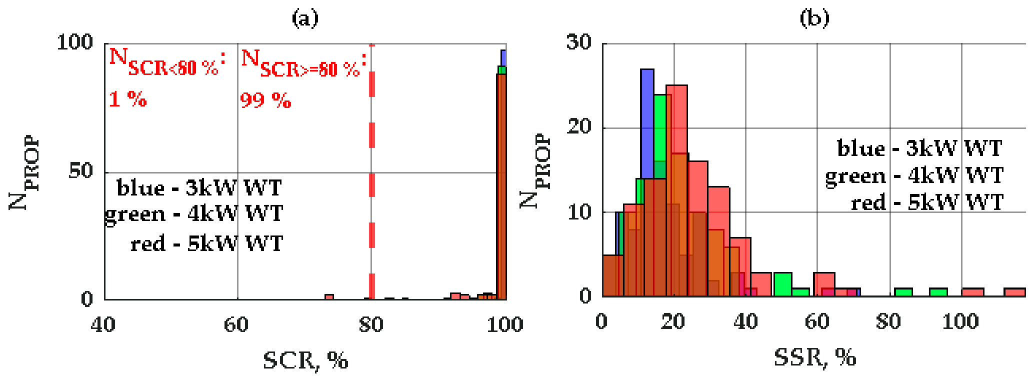


Figure 8. Histograms of (**a**) SCRs, with $N_{SCR<80\%}$ and $N_{SCR\geq80\%}$ indicating the percentage of individual active customers that would not reach the 80% SCR requirement and ones that would reach it, (**b**) SSRs for an individual active customer with only WTs installed.

The results for individual, WT-powered active customers presented in Figure 8 show practically an inverse situation, where installed capacity is relatively low compared to the demand. This is evident from Figure 8a, where approximately 99% of the cases reached the 80% SCR requirement, with most being in the 90–100% range for all turbine types (indicated using different colours). On the other hand, the SSRs provided in Figure 8b are below 50% for most load profiles. When analysing the specific cases, it could be observed that the selected number of WTs often resulted in a rated power significantly below even the limits of the support scheme with the defined installation space limitation being the most significant reason.

Furthermore, it can be observed that the higher the installed capacity of the WTs used, the higher the SSRs in Figure 8b, because the net rated power obtained is higher in this situation, even if the maximum number of turbines with a higher rated power is lower.

3.2. Energy Communities

3.2.1. Overall Results

Next, renewable power use can also be evaluated for various scenarios of EComs. The SCRs and SSRs for all the scenarios of EComs considered are presented in Figure 9, where bars represent the mean values for all scenarios, including the results obtained using both methods for sizing PV installations and all three WT types considered; error bars (black segments) demonstrate the minimum and maximum values. Numbers adjacent to "PV" and "WT" refer to the number of active customers with the particular renewable sources installed constituting an ECom in each scenario, except for 1PV and 1WT, which represent individual active customers.

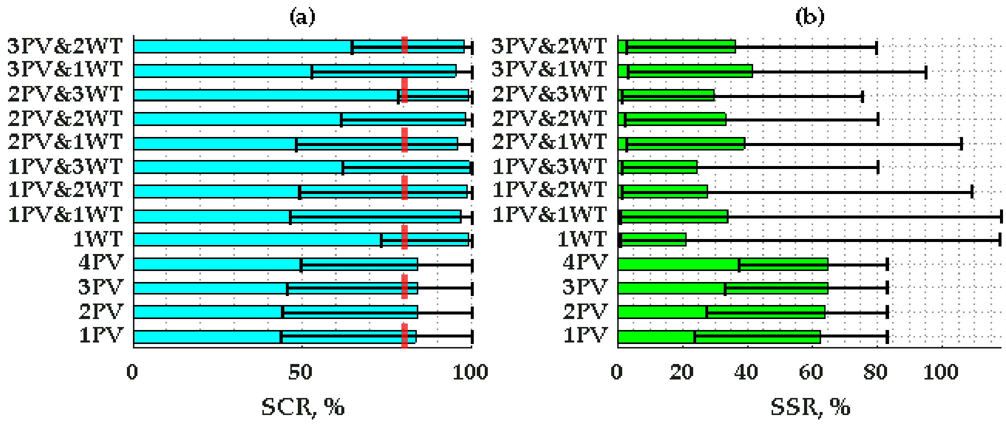


Figure 9. Obtained (**a**) SCRs (red dashed line is minimal 80% SCR requirement) and (**b**) SSRs for different scenarios of EComs and individual active customers.

One observation that can be made from Figure 9a is that the overall individual PV-powered active customer as well as EComs consisting of only this type of active customer have SCRs lower than an individual WT-powered active customer or EComs including WT-powered active customers. This is evident by both the minimum and mean SCR values, which are 43.6–49.5% and approximately 84%, respectively, for PV power use only, and 46.2–78.4% and 95.5–99.6%, respectively, if WT-powered active customers are involved. Furthermore, only between 63.5% and 68.1% of scenarios involving only PV-powered active customers reach the 80% SCR requirement, in contrast to 94–99.9% if at least one WT-powered active customer is included, as shown in Figure 10. This result can be explained first by the comparatively low installed capacity of WTs in relation to demand, as mentioned in Section 3.1 and shown in the SSR chart in Figure 9b, and second by different generation profiles, which foster more efficient power consumption by various cooperating active customers. When EComs include WTs, it can be observed that for a fixed number of PV-powered active customers, the SCR increases along with an increase in the number of included WT-powered active customers. This is most evident in the minimum SCR values in Figure 9a, and the number of scenarios reaching the 80% SCR threshold in Figure 10. An increase in the number of PV-powered active customers in EComs with a fixed number of WT-powered active customers results in a noticeable increase in minimum SCR values, yet at same time, there is a minuscule drop in the mean SCRs, as can be observed in Figure 9a. If only PV power is used, addition of more PV-powered active customers results in an increase in minimum SCRs; in terms of the number of scenarios achieving the 80% value, as shown in Figure 10, there is a 4% increase after transitioning from an individual active customer to an ECom made of two PV-powered customers, after which this sub-scenario proportion oscillates at around 68% while the mean SCR stagnates around the 84% value. Overall, the number of PV-powered active customers involved increases the total amount of power produced but does not guarantee a significant rise in SCRs, especially in mean terms. While compared with an individual PV-powered active customer, EComs with PV only seem to offer limited improvement in the efficiency of energy self-consumption; a change to mixed RES EComs seems to boost SCRs dramatically as shown in Figure 9a. On the other hand, for an individual WT-powered active customer, SCRs are already high as discussed before, but they are overtaken by the ECom scenario "2PV&3WT" as to all SCR measures and by the scenario "1PV&3WT" as to the mean SCR as well as the proportion of scenarios that reach the 80% SCR requirement. Thus, it can be seen that cooperation with other active customers enabled by EComs fosters more effective consumption of power produced by the EComs compared to individual PV-powered active customers and, to a lesser extent, also compared to individual WT-powered ones.

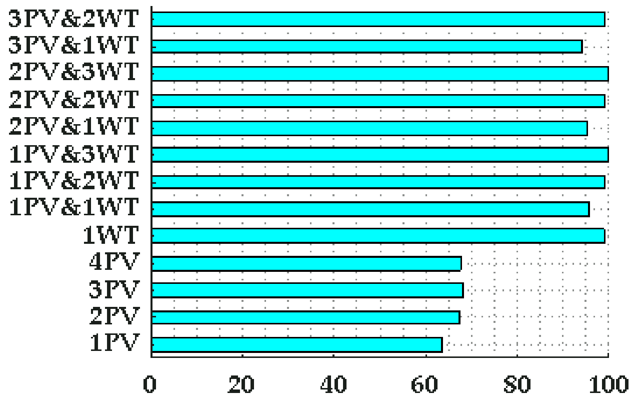


Figure 10. Proportion of sub-scenarios reaching the 80% SCR requirement for different scenarios of EComs and individual active customers.

As could have been expected, the SSR values in Figure 9b present an almost diametrically opposite picture with the active customer and EComs using solely PV power characterised by the highest minimum and mean SSRs, which are 23.4–37.3% and 62.7–65%, respectively. This is in stark contrast to the WT-powered active customers and EComs including them with minimum SSR values of 0.7–2.9% and mean SSR values of 21.2–41.8%. Thus, PV-powered EComs are more attractive from a self-sufficiency point of view at the expense of limited SCRs that fail to meet the 80% requirement approximately 1/3 of the time, as shown in Figure 10. Furthermore, for the PV-powered individual active customers and EComs, the minimum SSRs rise from 23.4% to 37.3% and the mean SSRs from 62.7% to 65% with an increasing number of involved active customers. Considering the simultaneous slight growth in SCRs, the increase in the number of PV-powered active customers in such EComs improves the energy performance overall, especially after changing from an individual active customer to an ECom, as indicated in Figure 11. While SSR is below 100%, the closer an ECom scenario is to the right upper corner of this figure, the better its overall energy performance, because movement towards it represents both higher renewable energy generation relative to the net demand and more efficient consumption of this energy. For a WT-powered active customer joining another active customer to form a mixed RES ECom, there is a noticeable improvement in mean and minimum SSRs, with a slight trade-off (reduction) in SCRs in the case of joining EComs including one or two WT-powered active customers, as shown in Figures 9–11. One seemingly paradoxical result in terms of SSRs is that according to Figure 9b, the maximum values for a WT-powered active customer and EComs including this type of customer not only exceed the ones for several ECom scenarios solely powered by PV panels, but they also exceed the 100% SSR mark for an individual active customer and ECom scenarios "1PV&1WT", "1PV&2WT", and "2PV&1WT", which indicates that there are at least some ECom setups that may constitute a positive energy district. After a more detailed review of the results, it was found that in these sub-scenarios, the net power demand was below the amount of energy production of an individual WT installed by one or two WT-powered active customers.

An overview of renewable power use and generation for all ECom scenarios with separate mean SCR and SSR values for each WT type (highlighted using same colours as in Figure 8) is presented in Figure 11. This figure demonstrates the trade-off between these two metrics for various cases, meaning a potential reduction of one to increase the other one. This can be considered in the case of a change in WT type used and/or a change between scenarios. In this plot, it can be observed that the larger the fixed number of WT-powered active customers is, the better the trade-off ratio of SSR improvement to SCR deterioration is for various numbers of PV-powered active customers. The mean values of these ratios for all WT types are 3.3, 8.7 and 50 for EComs, including one, two and three WT-powered active customers, respectively. Meanwhile, for EComs with a fixed number of PV-powered active customers, changes in the number of WT-powered ones are characterised by the mean trade-off ratios of 3.6, 2.8 and 2.1 for EComs including one, two and three PV-powered customers, respectively. Thus, having a higher stable number of WT-powered customers and integrating more PV-powered ones afterwards appear to be a more attractive approach for ECom development from a renewable-energy-efficiency point of view than the other way around. Figure 11 also shows that an individual WT-powered active customer can achieve overall improvement in renewable power use by becoming part of an ECom in scenarios "1PV&3WT" or "2PV&3WT". In mean terms for all WT types, these ECom scenarios provide 0.2% and 0.1% improvement in SCRs, as well as 3.4% and 8.4% growth in SSRs, respectively. It can also be pointed out that in contrast to the PV-powered active customer, this improvement is achieved by a change to mixed-source EComs.

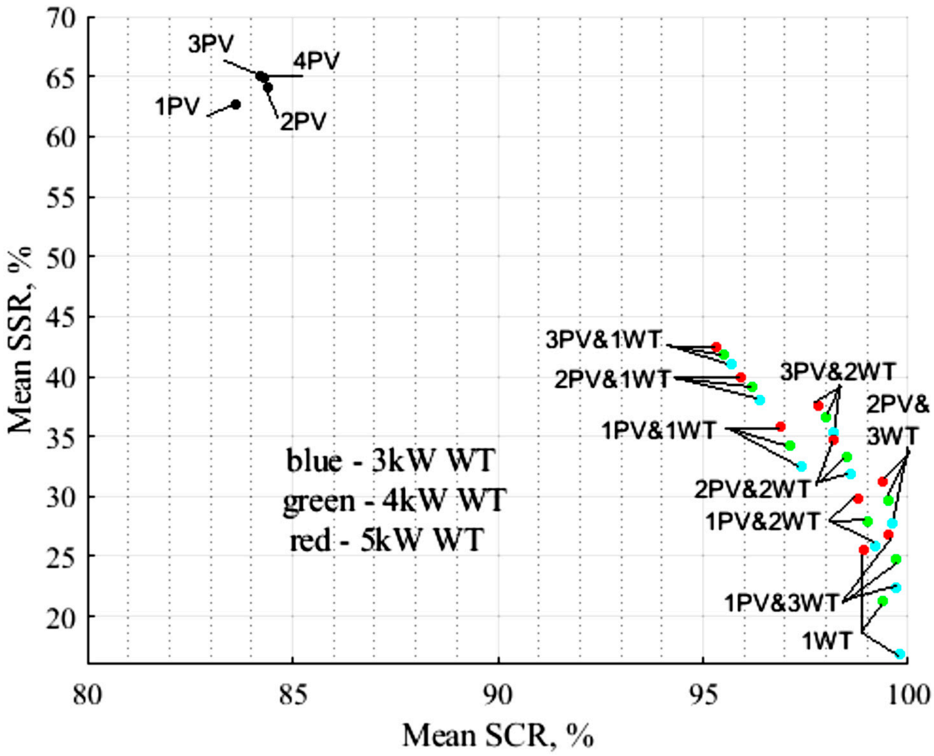


Figure 11. Mean SCRs and SSRs for different scenarios of EComs and individual active customers with distinct types of WTs.

When comparing the results for different WT types in Figure 11, it can be observed that the use of more powerful WT types resulted in higher SSRs, as observed also for an individual WT-powered active customer in Section 3.1 with an evident trade-off in SCRs. However, the SSR-to-SCR trade-off ratios obtainable from detailed results show that for most ECom types, the trade-off becomes less efficient (meaning that less SSR is gained for the same reduction in SCR) when changing from 4 kW to 5 kW turbines in comparison to the replacement of 3 kW turbines with 4 kW ones. The mean values of these ratios for all ECom scenarios are 7.6 and 9.7 for these two changes in WT rated power, respectively. In regard to ECom scenarios “1PV&2WT”, “1PV&3WT” and “2PV&3WT”, they can be mentioned as achieving better exchange ratios—when increasing the rated power of the WTs used—than individual WT-powered active customers and various ECom scenarios that include such customers.

It should be mentioned that ultimately, the optimal combination of active customers would depend on the importance associated with these two important metrics or other criteria, if required, and they could change based on assumptions, the situation or location analysed, and control and energy storage technologies considered, yet this is beyond the scope of this study.

3.2.2. Load Profile Categories

Let us analyse the outcomes of mean SCR and SSR values with regard to load profile categories individually to gain a comprehensive understanding of their interdependencies. Figure 12 compares SCR (in blue) and SSR (in green) across four sectors: Commercial, Education, Industrial, and Residential.

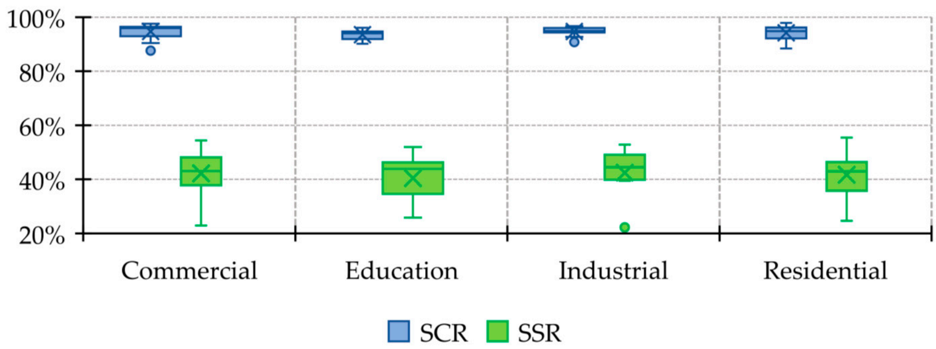


Figure 12. Mean SCR and SCR values for each load profile category.

The average SCR value is the same across all sectors (ranging from 94% to 95%), proving the effectiveness of creating an ECom. At the same time, this indicates that the considered sectors with renewable energy systems and their combination, such as PV and WT, are adept at utilising the electricity among active customers, leading to minimal export of excess energy to the grid. The mean value of the SSR values varies slightly from sector to sector, ranging from 40% to 42%. The range of SSR values extends from about 23% to 55%. More detailed information about each load profile category for each scenario can be observed in Figure 13.

Upon analysing the graphs, it is observed that the distribution trend of the results in the “2PV”, “3PV” and “4PV” scenarios deviates from other scenarios. The SSR range for PV coalition ranges from 48% to 72%, whereas in coalitions PV+WT systems, it ranges from 3% to 68%. The variation is due to the limited number of WTs that can be installed within each consumption category. Furthermore, in these three PV scenarios, combinations exist where the minimum SCR level of 80% is not met (mostly in the “Education” and “Residential” categories). This occurs because the solar generation schedule remains largely unchanged. For instance, households with similar electricity consumption and energy usage patterns may not always experience an increase in SCR when combined into EComs.

In scenarios utilising a combination of PV and WT, a similar trend is observed: at lower SSR values, there appears to be a higher SCR. The “1PV&3WT” scenario exhibits the highest average SCR indicators, ranging from 97% to 100% for all load profile categories. Relatively, the SSR indicator does not exceed more than 40%. A lower SCR applies to the “3PV&1WT” scenario and is equal to 80% (the maximum SSR equals 69%). The variability is due to the unpredictable nature of wind generation, which can compensate for the electricity demand of active customers during periods without PV panel generation.

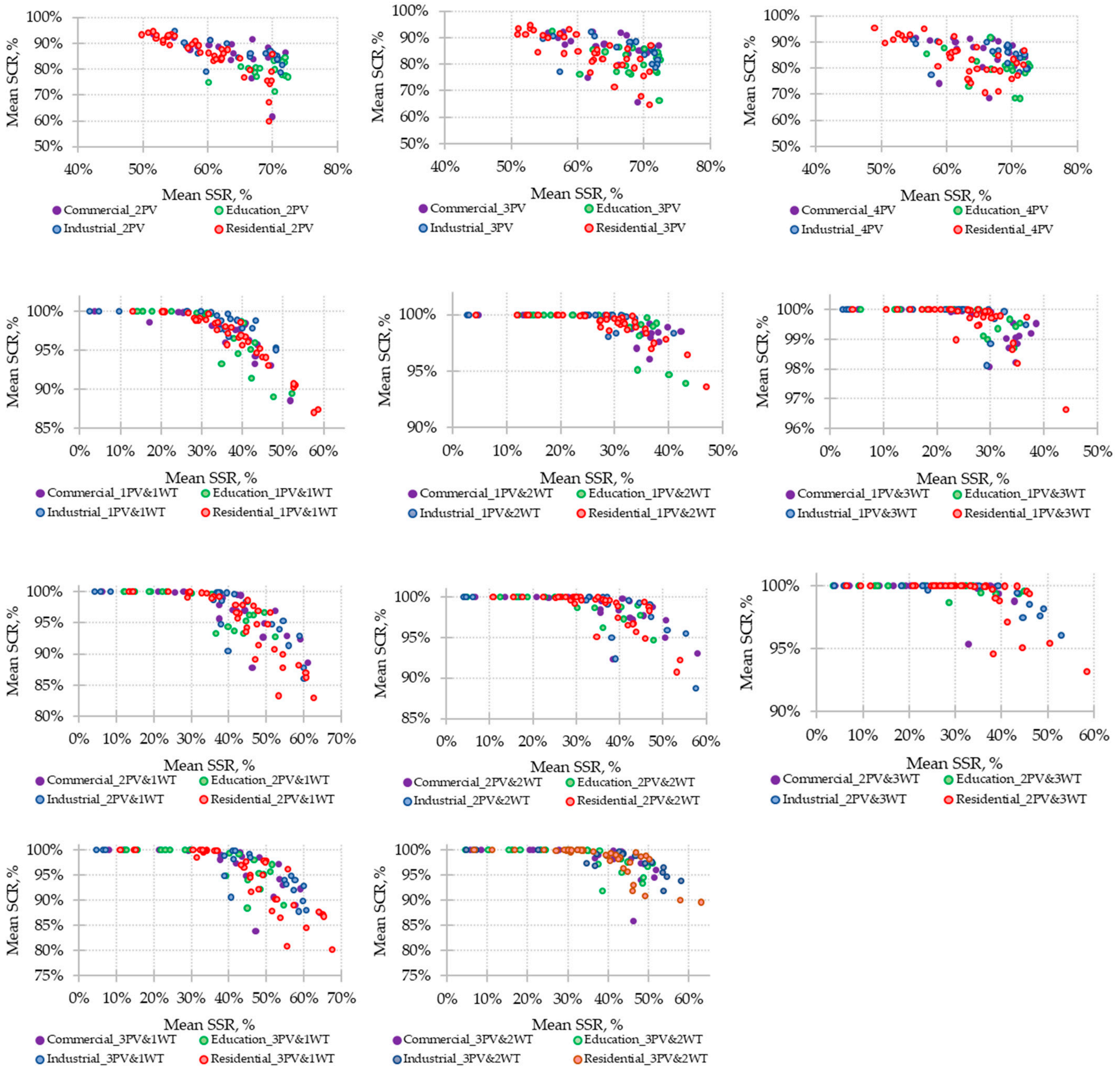


Figure 13. Dependence of SCR value on SSR for each category under various ECom configurations.

The analysis of ECom formations across various load profiles reveals significant challenges in achieving adequate SCR values. Specifically, as was concluded above, in scenarios such as "2PV", "3PV", and "4PV", as well as in select cases of "2PV&1WT" and "3PV&1WT", the SCR values consistently fall below the minimally required 80% threshold. In addition, the following was found out:

1. Among the 20 industrial load profiles examined, 15 profiles displayed insufficient joint SCR values. Notably, combinations of industrial profiles with educational (e.g., kindergartens, secondary schools), commercial (e.g., swimming pools, administrative buildings), and other industrial profiles (e.g., frying stations, barns, pumping stations) demonstrated significant incompatibilities. Furthermore, EComs with residential profiles (e.g., private houses, dwelling buildings) proved particularly ineffective, with half of the combinations involving 38 residential profiles failing to achieve the 80% SCR threshold.

2. In the analysis of 20 educational profiles, 16 exhibited inadequate joint SCR values. Educational institutions such as kindergartens, libraries, university laboratories, and secondary schools struggled to meet the minimum SCR threshold when paired with residential profiles (21 out of 38) and certain commercial profiles (e.g., swimming pools, administrative buildings, various stations). This suggests that educational institutions may struggle to align their energy demands with profiles that exhibit either high or highly variable energy needs. Additionally, reduced SCR values were noted among similar educational profiles, particularly among secondary schools and combinations of kindergartens with secondary schools, as well as among libraries and kindergartens. This indicates that rare cases even within joint energy profiles may lack the variability or load complementarity needed to optimize SCR values.
3. A significant proportion (63%) of the residential profiles assessed also demonstrated insufficient SCR values when forming EComs with other categories or within the same group.
4. The analysis identified several commercial profiles, specifically, swimming pools, hotels, shops, and supermarkets, as particularly problematic. In approximately half of the cases, these profiles failed to meet the designated SCR threshold when combined with residential profiles (15 out of 38). Similar deficiencies were observed in EComs with other commercial profiles (e.g., administrative facilities), educational profiles (e.g., universities and schools), and industrial profiles (e.g., fire stations and pumping stations).

Upon examining the data, the authors believe that the failure to achieve the minimum SCR value can be attributed to the following factors:

- The PV generation schedules across various profiles exhibit a similar temporal pattern, failing to adequately address energy demand during critical periods such as mornings and evenings.
- The disparity in PV generation capacities from profile to profile is substantial, with some profiles generating energy hundreds of times more or less than others, leading to inefficiencies in energy distribution and consumption.

These results highlight the need for improved alignment of energy production and consumption patterns to improve the SCR of different load profiles by introducing different RES technologies.

3.2.3. Specific Examples from Load Profile Categories

In this section, each type of load profile category will be considered, which fails to meet the minimum threshold value (80%) for SC. These examples will show how the creation of an ECom with the same and other load profiles affects the SCR value. Figure 14 displays a bar graph of the mean SCR across the four categories. The numbers on the left indicate the number of the load profile from the whole list where 100 profiles are analysed.

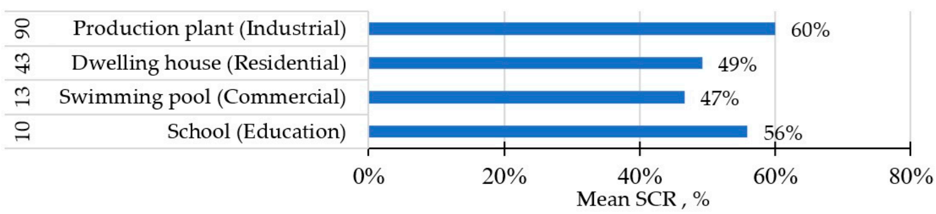


Figure 14. SCR value of selected load profiles of the Industrial, Residential, Education and Commercial categories under consideration.

Load profile No. 13, with the lowest SCR value, was chosen to illustrate how participation in an ECom could allow this rate to exceed the 80% threshold.

Figure 15 depicts that, across all the load profile categories, the average SCR for a PV ECom does not exceed the minimum threshold. It is clear from the data that when commercial load profiles are included, there are some outliers approaching 80%, although these instances are rare. However, in cases where both PV and WTs are combined, the SCR consistently surpasses the minimum requirement. These results suggest that integrating a mix of renewable energy technologies increases the SCR value. Additionally, the findings indicate that an active customer can form a coalition across different load profile categories.

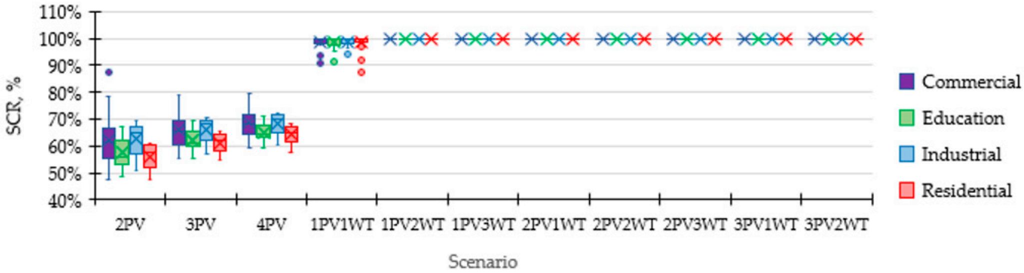


Figure 15. SCR value according to scenario and load profile category (No. 13).

As previously indicated, there is a notable correlation between the SCR value and the SSR value. This relationship is also reflected in Figure 16.

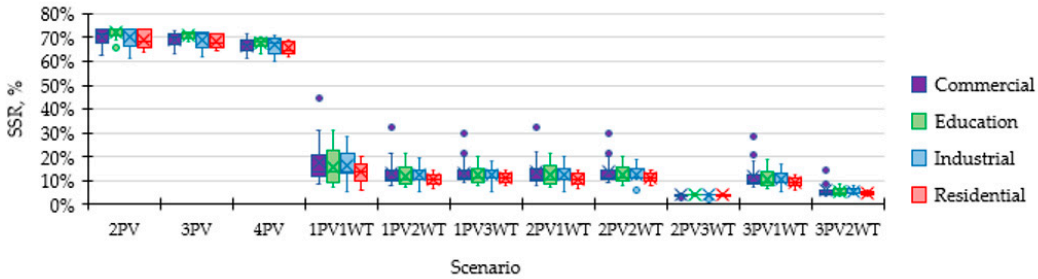


Figure 16. SSR value according to scenario and load profile category (No. 13).

Figures 17–20 present graphs depicting the mean SCR values across different scenarios for the specified four load profile categories: No. 13, No. 43, No. 10 and No. 90.

For load profile No. 13 out of the 54 scenarios depicted in Figure 17, the SCR value consistently improved from 50% to 100% for one method of the PV rated power (see Section 2.2.2), and from 44% to 100% for another method. It is worth noting that the SCR value surpassed the 80% threshold in 48 cases, which can be deemed a positive result.

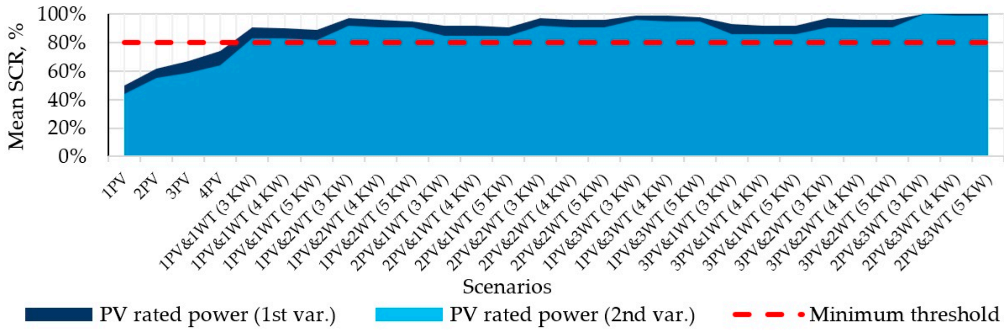


Figure 17. Mean SCR value according to scenario (No. 13).

In the case of the 43rd load profile (Figure 18), the SCR value surpassed the 80% limit in 45 scenarios: using the first method for calculating PV power (dark blue), the SCR exceeded the minimum threshold in 24 scenarios; in the second case (light blue), it exceeded the minimum threshold in 21 scenarios. The highest values are achieved in the "1PV3WT" and "2PV3WT" scenarios.

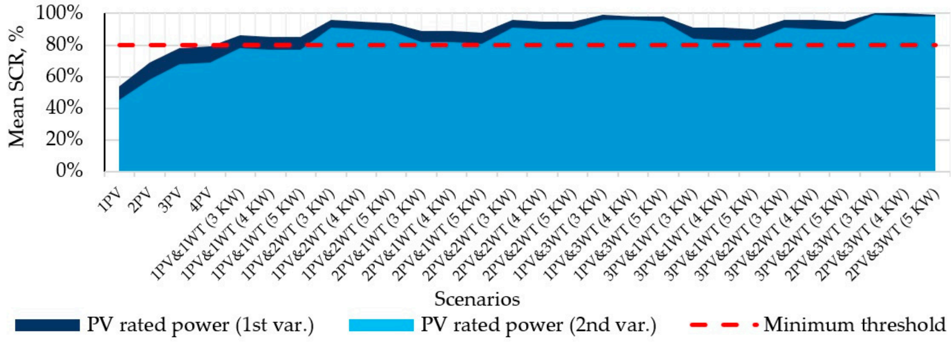


Figure 18. Mean SCR value according to scenario (No. 43).

In the case of the 10th load profile (Figure 19), the initial SCR value was 56% (see Figure 14). Through participation in EComs, an active customer can increase the SCR to between 61% and 100%, depending on the scenario. A total of 49 scenarios (out of 54) were successful in improving SCR.

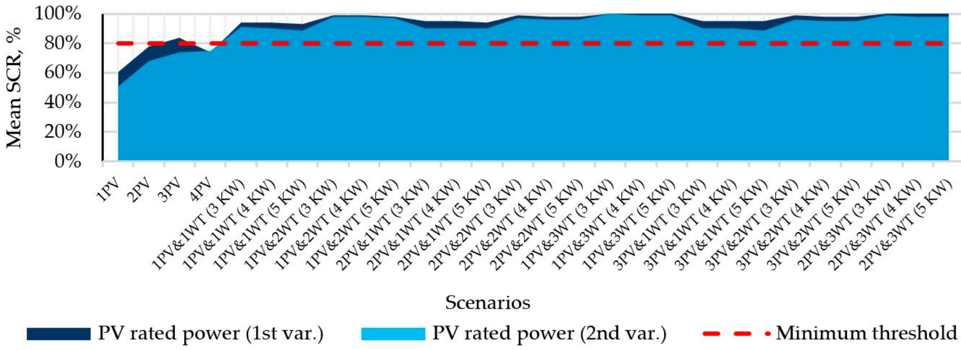


Figure 19. Mean SCR value according to scenario (No. 10).

For load profile No. 90 (Figure 20), the SCR value consistently increased from 60% to 100% across both methods of PV-rated power calculation. Notably, the SCR value exceeded the 80% threshold in 49 scenarios.

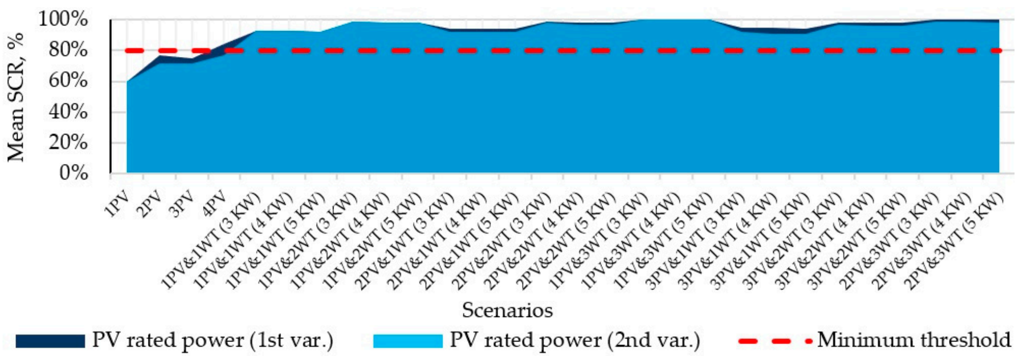


Figure 20. Mean SCR value according to scenario (No. 90).

Load profiles No. 10, 13, 43 and 90 showed improvements in their SCR metrics across multiple scenarios, highlighting the benefits of ECom creation.

These findings underscore the necessity for active customers among diverse load profiles to join in EComs, taking into consideration the use of RES technology diversity such as PV and WT for achieving legislative SCR requirements.

4. Discussions

Numerous scientific studies have investigated opportunities and challenges related to support schemes for individual active customers and EComs. The design of these support schemes is dependent on the economic potential of each country. This study focuses on Latvia and examines its regulatory framework for promoting SC among active customers through its net billing system and EComs. At the moment, regulation in Latvia for EComs or active customers who act jointly is only being drafted. Therefore, this study provides possible scenarios for the creation of EComs, analysing their impact on the overcoming of regulatory barriers. This assumption will not only provide an overview of the benefits to all the stakeholders involved, but also promote a more economically efficient energy transition.

The study focused on SCR and SSR as key indicators for assessing the effectiveness of Latvia's support programme for RES. ECom scenarios combining PV and WT systems, such as "1PV&3WT," show a consistently high SCR (97–100%), even though the SSR remains moderate. This arrangement demonstrates that mixed-source EComs are better suited to meet the SCR threshold, especially when individual PV installations struggle to align generation with demand. Mixed load profiles (e.g., combining residential with educational or commercial) can utilize energy more effectively by balancing the demand variability between profiles.

In the future, several directions for future research on the subject of this paper are possible, e.g., technical aspects like sufficiency and potential need for strengthening of distribution grids in case of a wide proliferation of RES and localised power sharing among members of different types of EComs. Another option to be considered separately or in conjunction with the first one is the potential impact of energy storage and different control approaches on the self-consumption rate and/or potential overloading of distribution grids, which could improve the overall sustainability of power supply. This analysis can also be expanded geographically considering other countries, which entails potential differences in climate, energy supply options, and regulatory norms. Furthermore, the potential of government policy changes must be considered, such as an implementation of the upcoming ECom regulations in Latvia or redefinition of renewable support schemes to accommodate them, in order to foster adoption of renewable energy sources and participation in EComs. Moreover, it is essential to balance both SCR and SSR, striving for scenarios where SC is optimized alongside high self-sufficiency to minimize dependency on external energy sources. Achieving this balance is crucial for ensuring the long-term sustainability and resilience of energy communities. The authors intend to explore this balance further in future work, focusing on strategies and technologies that can simultaneously enhance both SCR and SSR. This will include investigating the integration of energy storage systems, demand-side management, and additional renewable energy sources to optimize the performance of energy communities and reduce external energy reliance.

5. Conclusions

The findings indicate that for individual PV-powered active customers, the generated electric energy often exceeds the actual demand. Specifically, in more than 50% of the cases examined, the 80% SCR requirement necessary for PV support was not achieved. These results indicate that PV generation and demand is often not coordinated well. In order to overcome the associated risk of losing government support, these PV-powered active customers will either have to adapt timing of their electricity use or adopt battery storages, or join an ECom to share excess power. In contrast, individual WT-powered active customers are characterised by significantly lower installed power due to space limitations; however, as a result, they are better able to achieve high SCRs for mixed-source ECom scenarios. At the same time, in some cases involving WT-powered customers with a low net power demand for an ECom, it appears that it is possible to achieve a net positive generation level, which is one of the requirements for development of a positive energy district. Both individual PV- and WT-powered customers can achieve simultaneous SCR and SSR improvement by changing to at least some form of an ECom. In case of a PV-powered active customer, these are PV-only ECom scenarios, and for WT-powered customers, these are a mixed-source ECom with 3 WT-powered customers. However, for other ECom scenarios, this evolution would involve a trade-off between SSRs and SCRs. In this regard, having a higher fixed number of WT-powered customers in an ECom followed by an introduction of more PV-powered ones overall seem to achieve more efficient improvements compared to having a larger set number of PV-powered customers and introducing more and more WT-powered ones. An increase in the rated power of the WTs used generally increases SSRs, yet on the other hand, the obtained results indicate that the trade-off with the SCRs becomes less efficient as change to turbines of greater and greater power takes place.

SCR and SSR for various load profile categories (Commercial, Education, Industrial, and Residential) were analysed as well. The analysis reveals that the average SCR (about 95%) is consistent across all sectors, underscoring the effectiveness of establishing EComs. In contrast, SSR shows a lower average value (40%–42%). Notably, the distribution trends for the ECom scenarios "2PV", "3PV", and "4PV" diverge from those of other ECom scenarios, with SSR values spanning from 48% to 72%, and lower ranges in coalitions involving WT systems, from 3% to 68%. This variation is attributed to the limited number of WTs that can be installed within each load profile category. Importantly, some coalitions, particularly in the "Education" and "Residential" categories, often fail to meet the minimum SCR threshold of 80%. For ECom scenarios that combine PV and WT, a consistent trend emerges; i.e., lower SSR values correlate with higher SCR values, indicating greater grid dependence. The ECom scenario "1PV&3WT" demonstrates the highest average SCR, while the SSR remains below 40%. Conversely, the ECom scenario "3PV&1WT" exhibits lower SCR values. This variability is primarily due to the unpredictable nature of wind generation, which can meet electricity demand during periods of low solar output, highlighting the importance of integrating diverse renewable energy sources to optimise self-consumption and enhance the overall efficiency of energy systems.

For detailed analysis, four load profiles from each primary group were chosen. The analysis shows that the mean SCR across four load profile categories is below the 80% threshold when operating as individual active customers. Load profile 13 illustrates how joining an ECom can boost SCR above this level. Load profiles 10, 43 and 90 similarly exhibited SCR enhancements, reinforcing the positive impact of ECom participation on sustainability outcomes. These findings underscore that combining PV and WT technologies consistently enhances SCR values and the potential for an active customer to create an ECom across various load profiles categories.

In summary, EComs with mixed load profiles and RES sources provide a path for Latvia's energy transition to PED, optimizing self-consumption, promoting sustainability, and enhancing economic efficiency.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

No. Load Profile	Category of Load Profile	Annual Electricity Consumption, kWh	PV Rated Power, kW (by 1st Method)	PV Rated Power, kW (by 2nd Method)	WT Power, kW (3 kW)	WT Power, kW (4 kW)	WT Power, kW (5 kW)
1	private house	9057.53	6.29	8.27	3	4	5
2	private house	15,560.84	10.81	11.10	3	4	5
3	shop	82,755.59	50.00	50.00	9	12	15
4	production plant	100,856.32	50.00	50.00	9	12	15
5	hotel	93,185.16	50.00	50.00	9	12	15
6	private house	18,735.40	11.10	11.10	3	4	5
7	private house	26,223.10	11.10	11.10	3	4	5
8	kindergarten	20,259.06	11.10	11.10	3	4	5
9	bank	102,269.90	50.00	50.00	9	12	15
10	secondary school	53,112.28	36.88	48.50	9	12	15
11	university	25,504.70	11.10	11.10	3	4	5
12	university	113,451.92	78.79	103.61	30	36	40
13	swimming pool	180,131.21	125.09	164.50	30	36	40
14	university	68,014.58	47.23	50.00	9	12	15
15	dormitory	29,703.83	11.10	11.10	3	4	5
16	production plant	405,947.42	281.91	370.73	30	36	40
17	production plant	261,680.87	181.72	238.98	30	36	40
18	production plant	346,911.31	240.91	316.81	30	36	40
19	dormitory	148,519.13	103.14	135.63	30	36	40
20	university	68,627.51	47.66	50.00	9	12	15
21	university	65,038.94	45.17	50.00	9	12	15
22	admin. building	25,504.70	11.10	11.10	3	4	5
23	supermarket	1,289,343.52	895.38	999.00	30	36	40
24	RTU library	128,565.63	89.28	117.41	30	36	40
25	university	128,565.63	89.28	117.41	30	36	40
26	admin. building	82,268.60	50.00	50.00	9	12	15

No. Load Profile	Category of Load Profile	Annual Electricity Consumption, kWh	PV Rated Power, kW (by 1st Method)	PV Rated Power, kW (by 2nd Method)	WT Power, kW (3 kW)	WT Power, kW (4 kW)	WT Power, kW (5 kW)
27	laboratory of university	216,796.47	150.55	197.99	30	36	40
28	admin. building	12,947.41	8.99	11.10	3	4	5
29	admin. building	123,402.89	85.70	112.70	30	12	15
30	shop	131,532.08	91.34	120.12	30	36	40
31	private house	91,600.57	50.00	50.00	9	12	15
32	private house	90,160.17	50.00	50.00	9	12	15
33	private house	137,725.69	95.64	125.78	30	36	40
34	private house	88,729.28	50.00	50.00	9	12	15
35	private house	90,601.35	50.00	50.00	9	12	15
36	dwelling house	79,491.11	50.00	50.00	9	12	15
37	dwelling house	93,634.99	50.00	50.00	9	12	15
38	dwelling house	96,654.15	50.00	50.00	9	12	15
39	dwelling house	127,573.67	88.59	116.51	30	36	40
40	dwelling house	59,138.25	41.07	50.00	9	12	15
41	dwelling house	93,645.05	50.00	50.00	9	12	15
42	dwelling house	116,571.48	80.95	106.46	30	36	40
43	dwelling house	132,520.18	92.03	121.02	30	36	40
44	dwelling house	80,704.65	50.00	50.00	9	12	15
45	dwelling house	81,990.53	50.00	50.00	9	12	15
46	dwelling house	150,446.32	104.48	137.39	30	36	40
47	dwelling house	8744.35	6.07	7.99	3	4	5
48	dwelling house	4799.00	3.33	4.38	3	4	5
49	dwelling house	46,822.53	32.52	42.76	9	12	5
50	secondary school	192,711.20	133.83	175.99	3	4	5

No. Load Profile	Category of Load Profile	Annual Electricity Consumption, kWh	PV Rated Power, kW (by 1st Method)	PV Rated Power, kW (by 2nd Method)	WT Power, kW (3 kW)	WT Power, kW (4 kW)	WT Power, kW (5 kW)
51	college	189,196.47	131.39	172.78	30	36	40
52	fire station	38,478.87	26.72	35.14	9	12	15
53	secondary school	308,337.92	214.12	281.59	30	36	40
54	private house	28,059.38	11.10	11.10	3	4	5
55	pump station	69,861.70	48.52	50.00	9	12	15
56	supermarket	286,581.85	199.02	261.72	30	36	40
57	production plant	255,735.11	177.59	233.55	30	36	40
58	shop	143,299.40	99.51	130.87	30	36	40
59	production plant	188,442.31	130.86	172.09	30	36	40
60	production plant	76,803.27	50.00	50.00	9	12	15
61	dwelling house	161,086.54	111.87	147.11	30	36	40
62	production plant	110,347.13	76.63	100.77	30	36	40
63	production plant	214,109.97	148.69	195.53	30	36	40
64	production plant	153,158.10	106.36	139.87	30	36	40
65	production plant	108,757.58	50.00	50.00	9	12	15
66	hospital	690,644.93	479.61	630.73	30	36	40
67	hotel	129,829.20	90.16	118.57	30	36	40
68	office	43,181.12	11.10	11.10	3	4	5
69	dwelling house	61,021.15	42.38	50.00	9	12	15
70	secondary school	49,469.88	34.35	45.18	9	12	15
71	car garage	78,161.60	50.00	50.00	9	12	15
72	barn	38,490.91	26.73	35.15	9	12	15
73	private house	71,797.49	49.86	50.00	3	4	5
74	production plant	58,642.00	40.72	50.00	9	12	15
75	production plant	86,139.00	50.00	50.00	9	12	15
76	production plant	257,812.33	179.04	235.45	30	36	40

No. Load Profile	Category of Load Profile	Annual Electricity Consumption, kWh	PV Rated Power, kW (by 1st Method)	PV Rated Power, kW (by 2nd Method)	WT Power, kW (3 kW)	WT Power, kW (4 kW)	WT Power, kW (5 kW)
77	secondary school	180,252.40	125.18	164.61	30	36	40
78	shop	72,141.64	50.00	50.00	9	12	15
79	hotel	306,009.31	212.51	279.46	30	36	40
80	private house	17,814.31	11.10	11.10	3	4	5
81	production plant	102,210.07	50.00	50.00	9	12	15
82	office	92,859.58	50.00	50.00	9	12	15
83	private house	9181.17	6.38	8.38	3	4	5
84	office	53,426.82	37.10	48.79	9	12	15
85	secondary school	119,796.28	83.19	109.40	30	36	40
86	shop	55,852.24	38.79	50.00	9	12	15
87	dwelling house	70,464.20	48.93	50.00	9	12	15
88	secondary school	72,751.35	50.00	50.00	9	12	15
89	shop	47,345.97	32.88	43.24	9	12	15
90	office	88,428.49	50.00	50.00	9	12	15
91	shop	90,754.37	50.00	50.00	9	12	15
92	private house	16,442.58	11.10	11.10	3	4	5
93	production plant	93,603.83	50.00	50.00	9	12	15
94	private house	26,905.30	11.10	11.10	3	4	5
95	private house	67,916.52	47.16	50.00	9	12	15
96	private house	23,578.81	11.10	11.10	3	4	5
97	production plant	67,390.16	46.80	50.00	9	12	15
98	private house	5427.21	3.77	4.96	3	4	5
99	production plant	70,464.20	48.93	50.00	9	12	15
100	private house	19,894.69	11.10	11.10	3	4	5

Appendix B

Scenario No.	Description	Marking
1, 2	One active customer who installed PV. PV rated power is calculated by 1st and 2nd method.	1PV
3, 4, 5	One active customer who installed WT. WT rated power is 3 kW, 4 kW and 5 kW	1WT
6, 7	ECom of two active customers who installed PV. PV rated power is calculated by 1st and 2nd method.	2PV
8, 9	ECom of three active customers who installed PV. PV rated power is calculated by 1st and 2nd method.	3PV

Scenario No.	Description	Marking
10, 11	ECom of four active customers who installed PV. PV rated power is calculated by 1st and 2nd method.	4PV
12, 13, 14, 15, 16, 17	ECom of two active customers: one installed PV, the second installed WT. PV rated power is calculated by 1st and 2nd method. WT rated power is: 3 kW, 4 kW and 5 kW. Combinations: 1. PV (1st method) + WT (3 kW); 2. PV (1st method) + WT (4 kW); 3. PV (1st method) + WT (5 kW); 4. PV (2nd method) + WT (3 kW); 5. PV (2nd method) + WT (4 kW); 6. PV (2nd method) + WT (5 kW)	1PV&1WT (3 kW) 1PV&1WT (4 kW) 1PV&1WT (5 kW) 1PV&1WT (3 kW) 1PV&1WT (4 kW) 1PV&1WT (5 kW)
18, 19, 20, 21, 22, 23	ECom of three active customers: one installed PV, two customers installed WT. PV rated power is calculated by 1st and 2nd method. WT rated power is: 3 kW, 4 kW and 5 kW. Combinations: 1. PV (1st method) + WT (3 kW) + WT (3 kW); 2. PV (1st method) + WT (4 kW) + WT (4 kW); 3. PV (1st method) + WT (5 kW) + WT (5 kW); 4. PV (2nd method) + WT (3 kW) + WT (3 kW); 5. PV (2nd method) + WT (4 kW) + WT (4 kW); 6. PV (2nd method) + WT (5 kW) + WT (5 kW);	1PV&2WT (3 kW) 1PV&2WT (4 kW) 1PV&2WT (5 kW) 1PV&2WT (3 kW) 1PV&2WT (4 kW) 1PV&2WT (5 kW)
24, 25, 26, 27, 28, 29	ECom of three active customers: two installed PV, one customer installed WT. PV rated power is calculated by 1st and 2nd method. WT rated power is: 3 kW, 4 kW and 5 kW. Combinations: 1. PV (1st method) + PV (1st method) + WT (3 kW) 2. PV (1st method) + PV (1st method) + WT (4 kW) 3. PV (1st method) + PV (1st method) + WT (5 kW) 4. PV (2nd method) + PV (2nd method) + WT (3 kW) 5. PV (2nd method) + PV (2nd method) + WT (4 kW) 6. PV (2nd method) + PV (2nd method) + WT (5 kW)	2PV&1WT (3 kW) 2PV&1WT (4 kW) 2PV&1WT (5 kW) 2PV&1WT (3 kW) 2PV&1WT (4 kW) 2PV&1WT (5 kW)
30, 31, 32, 33, 34, 35	ECom of four active customers: two customers installed PV, two customers installed WT. PV rated power is calculated by 1st and 2nd method. WT rated power is: 3 kW, 4 kW and 5 kW. Combinations: 1. PV (1st method) + PV (1st method) + WT (3 kW) +WT (3 kW) 2. PV (1st method) + PV (1st method) + WT (4 kW) + WT (4 kW) 3. PV (1st method) + PV (1st method) + WT (5 kW) + WT (5 kW) 4. PV (2nd method) + PV (2nd method) + WT (3 kW) + WT (3 kW) 5. PV (2nd method) + PV (2nd method) + WT (4 kW) + WT (4 kW) 6. PV (2nd method) + PV (2nd method) + WT (5 kW) + WT (5 kW)	2PV&2WT (3 kW) 2PV&2WT (4 kW) 2PV&2WT (5 kW) 2PV&2WT (3 kW) 2PV&2WT (4 kW) 2PV&2WT (5 kW)
36, 37, 38, 39, 40, 41	ECom of four active customers: three customers installed PV, one customer installed WT. PV rated power is calculated by 1st and 2nd method. WT rated power is: 3 kW, 4 kW and 5 kW. Combinations: 1. PV (1st method) + PV (1st method) + PV (1st method) + WT (3 kW) 2. PV (1st method) + PV (1st method) + PV (1st method) + WT (4 kW) 3. PV (1st method) + PV (1st method) + PV (1st method) + WT (5 kW) 4. PV (2nd method) + PV (2nd method) + PV (1st method) + WT (3 kW) 5. PV (2nd method) + PV (2nd method) + PV (1st method) + WT (4 kW) 6. PV (2nd method) + PV (2nd method) + PV (1st method) + WT (5 kW)	3PV&1WT (3 kW) 3PV&1WT (4 kW) 3PV&1WT (5 kW) 3PV&1WT (3 kW) 3PV&1WT (4 kW) 3PV&1WT (5 kW)

Scenario No.	Description	Marking
42, 43, 44, 45, 46, 47	ECom of four active customers: three customers installed PV, two customers installed WT. PV rated power is calculated by 1st and 2nd method. WT rated power is: 3 kW, 4 kW and 5 kW. Combinations: 1. PV (1st method) + PV (1st method) + PV (1st method) + WT (3 kW) + WT (3 kW) 2. PV (1st method) + PV (1st method) + PV (1st method) + WT (4 kW) + WT (4 kW) 3. PV (1st method) + PV (1st method) + PV (1st method) + WT (5 kW) + WT (5 kW) 4. PV (2nd method) + PV (2nd method) + PV (2nd method) + WT (3 kW) + WT (3 kW) 5. PV (2nd method) + PV (2nd method) + PV (2nd method) + WT (4 kW) + WT (4 kW) 6. PV (2nd method) + PV (2nd method) + PV (2nd method) + WT (5 kW) + WT (5 kW)	3PV&2WT (3 kW) 3PV&2WT (4 kW) 3PV&2WT (5 kW) 3PV&2WT (3 kW) 3PV&2WT (4 kW) 3PV&2WT (5 kW)
48, 49, 50, 51, 52, 53	ECom of four active customers: one customer installed PV, three customers installed WT. PV rated power is calculated by 1st and 2nd method. WT rated power is: 3 kW, 4 kW and 5 kW. Combinations: 1. PV (1st method) + WT (3 kW) + WT (3 kW) + WT (3 kW) 2. PV (1st method) + WT (4 kW) + WT (4 kW) + WT (4 kW) 3. PV (1st method) + WT (5 kW) + WT (5 kW) + WT (5 kW) 4. PV (2nd method) + WT (3 kW) + WT (3 kW) + WT (3 kW) 5. PV (2nd method) + WT (4 kW) + WT (4 kW) + WT (4 kW) 6. PV (2nd method) + WT (5 kW) + WT (5 kW) + WT (5 kW)	1PV&3WT (3 kW) 1PV&3WT (4 kW) 1PV&3WT (5 kW) 1PV&3WT (3 kW) 1PV&3WT (4 kW) 1PV&3WT (5 kW)
54, 55, 56, 57, 58, 59	ECom of four active customers: two customers installed PV, three customers installed WT. PV rated power is calculated by 1st and 2nd method. WT rated power is: 3 kW, 4 kW and 5 kW. Combinations: 1. PV (1st method) + PV (1st method) + WT (3 kW) + WT (3 kW) + WT (3 kW) 2. PV (1st method) + PV (1st method) + WT (4 kW) + WT (4 kW) + WT (4 kW) 3. PV (1st method) + PV (1st method) + WT (5 kW) + WT (5 kW) + WT (5 kW) 4. PV (2nd method) + PV (2nd method) + WT (3 kW) + WT (3 kW) + WT (3 kW) 5. PV (2nd method) + PV (2nd method) + WT (4 kW) + WT (4 kW) + WT (4 kW) 6. PV (2nd method) + PV (2nd method) + WT (5 kW) + WT (5 kW) + WT (5 kW)	2PV&3WT (3 kW) 2PV&3WT (4 kW) 2PV&3WT (5 kW) 2PV&3WT (3 kW) 2PV&3WT (4 kW) 2PV&3WT (5 kW)

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