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Exploring sharing coefficients in energy communities: A simulation-based study

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A B S T R A C T

With rising energy prices, it is becoming increasingly attractive for households to form an energy community (EC) and become an active member of the energy system. Therefore, the choice of the right sharing coefficient, which defines how the produced energy is shared, is important for the expected profits. The aim of this paper is to analyse and compare two existing sharing coefficients with two new sharing coefficients. Therefore, we define two EC setups, one with only residential members and one with residential and commercial members, and investigate the impact of the sharing coefficients by using a data driven simulation model. For the analysis, we use a Monte Carlo approach in combination with load profiles of EC members simulated via time series models to account for random variation in electricity demand. The applied methodology gives additional insights on the profitability and the distribution of savings. The analysis shows that sharing coefficients that benefit small consumers are essential to incentivise private members to form an EC with commercial members. It is shown that when such an EC is formed, higher savings, a higher degree of self-sufficiency and a more efficient use of the produced electricity can be achieved.

1. Introduction and state of the art

Climate change and the political endeavour to combat it, or at least to avoid the more serious damage, have been the incubator for countless new regulations and technological innovations in recent years. One outcome of these efforts was a comprehensive update on the European energy policy framework which presents new ways to reach the Paris Agreement and to create new possibilities for the energy supply. This framework, the Clean Energy for all Europeans Package, contains two legislative acts, the renewable energy directive (REDII [1]) and the electricity market directive (EMD [2]), that provides new opportunities for households to share and sell energy, to actively participate in the energy market and to form so-called energy communities (ECs). In general, ECs are a collective and citizen-driven organisation form of households and small and medium-sized enterprises that generate, consume and sell their own produced electricity. With these communities not only the share of renewable energy sources in the system might increase but households can become more independent from the energy market. At the moment, EU countries translate the Clean Energy for all Europeans Package into national law and set guidelines for formation and inclusion of energy communities in the energy system. The importance of these types of technological and political innovations became visible when energy prices started to rise in summer 2022. Throughout Europe, energy became more and more expensive as a result of the war in the Ukraine and Europe's dependence on fossil fuels. This extreme event proves how important it is to implement concepts like ECs that can provide renewable and affordable energy for all and contribute to climate neutrality.

According to Frieden et al. [3] some member states already made major progress towards the implementation of collective self-consumption (CSC) and renewable energy communities (RECs). For example, in Spain and France it is possible to use the public grid for CSCs since 2020 and Greece already passed a corresponding law for RECs in 2018. Other member states like Germany or the Netherlands did not make the same progress towards implementation of the Clean Energy package. The following paragraph will present the different regulatory frameworks for ECs of Austria, Croatia, Greece, Portugal, Slovenia and Spain who were part of the Horizon project COMPILE[1]

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[1] https://www.compile-project.eu.

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that financed the work on this paper. Particular attention is paid to issues related to and affecting the sharing methods within ECs, which this paper is about.

In Austria energy sharing is already enshrined in law as it has been possible to share energy in a multi-apartment building since 2017. The "Kleine Ökostromnovelle"[2] [4] has been introduced permitting several residents at the same location to generate and consume electricity. As part of the Austrian "Erneuerbaren-Ausbau-Gesetzespaket"[3] [5], the previous setting was extended, introducing two forms of energy communities; local renewable energy communities (REC) and citizen energy communities (CEC) as foreseen in the Clean Energy Package. Currently, energy communities in Austria can choose between a dynamic and a static sharing coefficient. When using a static coefficient, every consumer gets a fixed pre-arranged share (based on, e.g., yearly demand, investment, same amount for each consumer) of the produced electricity. If a consumer cannot use the attributed share of energy, it is fed into the grid and cannot be used by the rest of the community. With a dynamic sharing coefficient, the actual demand at a given time step determines the share of energy one receives. This ensures that the maximum energy is used within the community. Currently, most energy communities choose the dynamic sharing coefficient as it increases the self-consumption rate and therefore leads to higher savings [6]. In some cases it is not possible to choose the dynamic approach due to technical reasons. In Croatia, there is currently no final legal framework for energy communities. However, it is discussed that in the future only the grid fee and the value added tax will have to be paid. Members of the energy community have to be behind the same medium voltage (MV) or low voltage (LV) transformer [7]. In Greece, it is possible to share energy through a virtual net metering scheme. This scheme is a bill crediting system and it refers to the net metering of solar energy that is not directly used, but instead fed into the grid. The resulting net metering credits are shared among community members [7]. In 2022, as part of the Decree Law Nr. 15/2022 [8], the regulatory framework for collective self-consumption and energy communities in Portugal was updated. Energy can be exchanged in the proximity of 2 km or behind the same LV substation. Moreover, a local grid tariff for exchanged energy applies. The sharing coefficient can either be static or dynamic. In Slovenia, energy communities are allowed to exchange energy behind the LV transformer paying normal grid fees [7]. The Spanish legislation permits collective self-consumption in a radius of 500 m. In this area, no grid fees are applied. This, on the one hand sets a favourable framework for energy sharing but on the other hand limits the participating parties. The sharing coefficient was changed by the government from a static monthly to an hourly variable coefficient in 2021. However, actual implementation of the variable coefficient is still limited [9].

A key aspect when talking about ECs is the sharing rules that define how the energy is distributed within the community. These sharing rules can have a significant impact on the profitability as well as on the efficiency of an energy community. As stated above, most countries that already incorporated sharing mechanisms in national law use the static or dynamic approach. Nevertheless, these are not the only two possible sharing mechanisms that can be applied. In general, any sharing coefficient can be used to share energy in an energy community. The only obstacle is that the sharing coefficient could be too complex and cause problems when billing the grid operator. By now, the impact of already applied or applicable sharing coefficients is an under-researched topic in scientific literature. Correspondingly, little information about their impact on the profitability on the individual members and energy community set-ups is available.

In the scientific literature, energy sharing and trading has been evaluated for several years and so many different aspects of the topic have been analysed. According to Fina et al. [10], literature on local energy sharing can be classified into three categories. These are game theoretic, agent-based, and system-analysis-based approaches. In addition, there are also studies that investigate trading preferences and decision-making strategies (i.e. Hahnel et al. [11]) or the drivers of joining an energy community (i.e. Kalkbrenner and Roosen [12]). Moreover, literature addressing energy communities and energy sharing often focus on the perfect sizing, technical setup and business models of energy communities (i.e. Braeuer et al. [13], Reis et al.[14], Weckesser et al. [15]).

Articles about the economics and technical setup of energy communities often focus on the optimal cost and energy allocation, which are mainly investigated by using optimisation and game-theoretic approaches. Two examples of optimisation approaches are Jing et al. [16], who proposed a study that focuses on the optimal resource allocation and load scheduling and De Villena et al. [17] who analysed ex-post cost distribution keys that minimize the overall community costs. In contrast, Fleischhacker et al. [18] used two game-theoretic models to investigate the effects of energy sharing in apartment buildings and Hupez et al. [19] proposed two cost distribution approaches based on Nash equilibria and the Shapely value. Another frequently analysed topic is the optimal profit sharing within an energy community or fair peer-to-peer trading concepts. One example is Minuto and Lanzini [20], who analyse profit sharing in a "Virtual-Net-Metering" scheme by using an internal token currency for the members. In contrast, Long et al. [21] analyses fair peer-to-peer energy trading by analysing the three market paradigms bill sharing, mid-market-rate and an auction-based-pricing strategy. However, the focus is on the pricing at which the energy is sold and not how energy can be shared. In general, when discussing sharing mechanisms or energy trading, the scientific literature focuses on the optimal price allocation or complex optimisation schemes rather than on technically feasible or applicable real-world sharing concepts. One exception that investigates the profitability of ECs as well as the best ways to reflect reality is Fina et al. [22], who analysed the differences between simulating profits and estimating them. They applied a simulation model that uses the static and dynamic distribution key and household and PV load profiles. Nevertheless, this study did not investigate the influence of sharing mechanisms, but whether a simulation or an estimation is better suited for predicting profits.

As the impact of sharing methods on the members of an energy community is an under-researched topic, we decided to contribute to this topic. Overall, the paper makes two major contributions to the energy sharing literature. First, we take a closer look at applicable sharing methods and how they impact the self-sufficiency ratio and profitability of the members of the EC. Second, we use a Monte Carlo approach in combination with time series modelling which has advantages over frequently used methods on the topic of energy sharing. The applied method simulates the distribution of savings of the EC members and accounts for random variation when simulating load profiles, which lead to overall more realistic results.

The rest of the paper proceeds as follows. Section 2 presents the available data and the simulation setup. In this section, we describe the Monte Carlo setup, the applied profitability measures and the methodology to simulate load profiles of the community members. In Section 3, the results of the two different scenarios and their sharing coefficients will be presented. Finally, our conclusions are presented in Section 4.

2. Methodology

The goal of this analysis is to propose a realistic picture of the impacts of sharing coefficients on the financial benefit of energy commu-

[2] A Federal Act amending the Green Electricity Act 2012 (ÖSG 2012), the Electricity Industry and Organisation Act 2010 (ElWOG 2010), the Gas Industry Act 2011 (GWG 2011) and the Energy Control Act (E-ControlG), reenacting the CHP Points Act (KPG), and the Federal Act, regulating the technology compensation for biogas plants (Biogas Technology Compensation Act 2017 - BTAG 2017) and the Federal Act providing additional funds from special funds administered by E-Control Austria are enacted.

[3] In force since 28.07.2021.

nity members. Therefore, we decided to follow Fina et al. [22] and use a simulation approach but, in contrast to her work, we define two fixed energy community setups and four different, but still feasible, sharing coefficients (see Table 1).

The applied Monte Carlo approach simulates the distribution of savings for different member types in an energy community over a time horizon of 25 years. Overall, this time horizon will be simulated 1,000 times. We use real household load profiles collected over the time horizon of one year from a pilot site of a Horizon 2020 project. In addition, we decided to simulate load profiles of the community members based on appropriate statistical models to account for random variation and potential risks that may arise from the choice of the applied sharing coefficient. To simulate the load profiles, we use a time series approach that models an individual load profile in each simulation step. Overall, the resulting Monte Carlo approach has two major advantages. First, the outcome of the simulation shows the whole distribution of potential savings and not just point estimates. Second, by simulating load profiles for each simulation step, uncertainty regarding demand is taken into account. In contrast to other scientific articles, we do not analyse the optimal cost or energy allocation to optimize the outcome for the community members, but we show how the sharing coefficients influence the profitability without ex-post optimisation schemes. The analysed sharing coefficients are the (known) static and dynamic approaches and two new ones: A hybrid version of them (which we call “hybrid”) and a new sharing coefficient that distributes electricity stepwise depending on the smallest demand (“even”). In the following section we will describe the available data, the structure of the simulation model, the applied sharing coefficients and economic indicators as well as the statistical model which is applied to generate the load profiles.

2.1. Data

For the analysis, load profiles of real households, a small church and a library that were part of the Horizon 2020 project COMPILE[4] were used. Most of the available data are about the electricity demand of one year in hourly resolution in a Spanish pilot area in the province of Alicante. Overall, more than 50 load profiles of households, small companies and municipality buildings were collected between January 2021 and December 2021. The only load profile that is not located in Spain is the library, which was part of a Croatian pilot area in the project. For the library data are available from August 2021 to August 2022. All load profile have 8,759 entries. For the analysis, we chose six household profiles with heterogeneous shapes and an electricity demand between 2,500 and 6,700 kWh/year (see Figs. B.1 to B.3). There were two reasons for choosing the load profiles of only six households. First, not all member profiles were suitable for this analysis. A considerable number of the profiles had incomplete or inaccurate records or were too similar. As we wanted different household profiles, we chose profiles with different peak times and yearly consumption levels. Second, we wanted to keep the exemplary energy community intentionally small in order to keep the scenarios clear and easy to understand. For further applications the energy community can be easily scaled up to analyse larger or different types of energy communities. The chosen households were divided equally into three groups: low consumption households, medium consumption households and high consumption households. In addition to the residential members we used one commercial building (library) with a yearly consumption of around 52,000 kWh and a municipality building (church) with a yearly consumption of around 1,400 kWh. More information about the community members can be found in the appendix.

The used photovoltaic (PV) production data were not taken from the pilot site, as in this demo the used PV is a large scale PV power plant with the capacity to serve over 14,000 consumers. Therefore, we

[4] https://www.compile-project.eu.

Table 1
Overview on the analysed scenarios.

Scenario 1		Number	SC
	Residential members	6	4
	Commercial members	0	4
Scenario 2			
	Residential members	6	4
	Commercial members	2	4

used data from the online application of PV GIS, which has been developed at the European Commission Joint Research Centre and provides information about solar radiation and PV system performance for any location in Europe and Africa as well as a large part of Asia and America [23]. This enabled us to use PV production data that are suitable for the analysed small energy community setup. We used PV profiles for a 20 and 50 kWp PV plant located in Spain.

To model the household load profiles we do not only use the load profiles itself but also dummy variables of the month, day and hour and outdoor temperature data. According to Weron [24], weather and temperature data are two of the best predictors to estimate electricity demand. As all residential members are located in the area of the Spanish pilot project weather data of the closest available Spanish city were used. The data were downloaded from the website of the weather monitoring station of Murcia (Spain) [25].[5]

2.2. Simulation framework

Due to data availability the simulated energy community is located in Spain in the province of Alicante. In general, the simulation could be applied to any other country or region if the needed load profiles and PV production data are available. The fictitious energy community has one large scale PV plant either on top of a public building or freestanding; therefore no direct self-consumption is assumed. The reason is that when each member owns an individual PV plant and only the excess electricity is shared in the community, the impacts of the sharing coefficients become very small as the main benefit is generated by the direct consumption of the own PV electricity. In addition, as further studies already show that one of the main drivers of the profitability of PV investment in the self-sufficiency rate (SSR) (i.e. Bertsch et al. [26]), we decided to use this setup where the savings are not mainly driven by a high direct consumption of solar electricity. Therefore, the differences in the individual savings represent the impact of the applied sharing coefficient on the financial benefits that each member can expect.

2.2.1. Energy community simulation

We simulate an energy community over the lifetime of the PV panel (25 years) and analyse the expected yearly and cumulative savings of the members. Fig. 1 describes the overall scheme of the simulation model. In the first step, the PV production and the community demand is generated. After that the model simulates the energy community and computes the values of the chosen economic indicators for four different sharing coefficients. The indicators will be described in Section 2.2.3. In general, two different energy community setups will be analysed. First, the impact of different sharing coefficients (SC) on an energy community where only residential members participate is analysed. In this setup we use a 20 kWp PV system and distribute the produced electricity across six households. The second set-up is a mixed energy community were residential and commercial members are included. In this case the PV panel has a size of 50 kWp and the produced electricity is distributed across six households, one municipality building

[5] Note: These weather data were only applied to model the demand of the households.

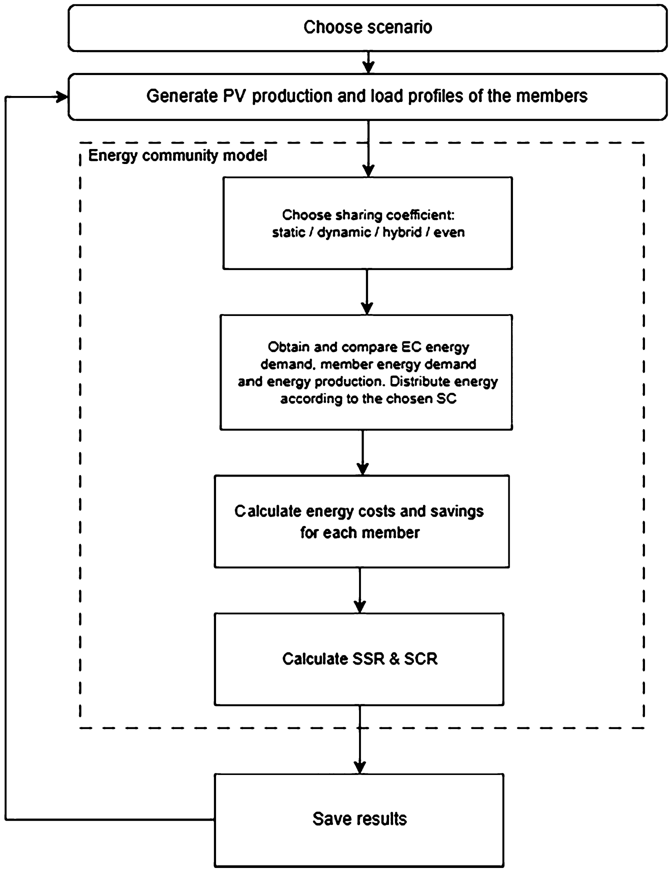


Fig. 1. Representation of one run of the simulation model which represents one year in the energy community.

(a small church) and one commercial member (a library). This second setup describes an energy community where the produced electricity can be consumed more efficiently as the mix of members is more diverse.[6]

Table 2 gives an overview of applied electricity prices and investment information of the simulated energy community. In the simulation model, five different prices are used: (i) the normal grid tariff depending on the hour in which the electricity is needed (P_{Grid}), (ii) the price a member receives when selling electricity to the grid (P_{FI}), (iii) the price a member pays when receiving electricity directly from the PV (P_{EC}), (iv) the price a member receives when selling electricity to the community (P_{Sold}), and (v) the price a member pays when buying electricity from other members (P_{Buy}). The applied price corresponds to the Spanish electricity prices in summer 2022 and the one applied in Deliverable 7.1 of the COMPILE project [7]. In addition, we assume investment costs of 800 EUR/kWp and that over the lifetime of the PV the electricity production decreases by 1% per year. However, the model assumes constant prices and constant electricity demand of the members. A detailed description of the simulation model and its corresponding equations can be found in the appendix.

[6] We decided to use this PV size for 2 reasons. First, we assumed a 5 kWp PV system for a household with around 5,000 kWh electricity demand per year. As three out of six households have an electricity demand lower than 5,000 kWh/year, a PV size of 20 kWp seemed plausible. For the mixed setup, we orientated is on the system size in the pilot area in Croatia. Second, after several test runs until 30 and 60 kWp we saw that a larger PV size did not impact the EC outcome (SCR and SSR) as a larger PV size leads to a higher degree of electricity that is fed into the grid. Nevertheless, a different PV size could be applied as well.

Table 2
Information on the chosen prices and photovoltaic parameters.

Prices I	Hours	in EUR/kWh
Electricity from the grid (P_{Grid})	Hours [10-13], [18-21]	0.3526
	Hour [8-9], [14-17], [22-0]	0.2787
	Hour [1-7], [weekend]	0.2364
Electricity to the grid (P_{FI})	Hours [10-13], [18-21]	0.10
	Hour [8-9], [14-17], [22-0]	0.08
	Hour [1-7], [weekend]	0.07
Electricity from PV (P_{EC})		0
Electricity sold in the EC (P_{Sold})	$P_{FI} + ((P_{Grid} - P_{FI})/2)$	
Electricity bought in the EC (P_{Buy})	$P_{Grid} - ((P_{Grid} - P_{FI})/2)$	
Photovoltaic Parameters		
Installed capacity		20 or 50 kWp
Azimuth angles		1°
Slope		35°
System losses		14%
Investment PV production (IC)		800 EUR/kWp
Yearly deprivation of the PV		1%

Example: P_{Sold} at 10 a.m. is $0.10 + ((0.3526 - 0.10)/2) = 0.2213$ and $P_{Buy} = 0.3526 - ((0.3526 - 0.10)/2) = 0.2213$. As no grid tariffs or other fees in the Spanish setup are charged $P_{Sold} = P_{Buy}$.

2.2.2. *Sharing coefficients*

In the following, the four different sharing coefficients that define how the produced Electricity is distributed among members are described. The description leaves out some details on the precise computation of the sharing rule, which can be found in the appendix.

Static

In this setup the static sharing coefficient is fixed and changes only once a year. The parameter depends on the yearly electricity consumption of the member and is defined as:

$$\delta_{n,Static} = \frac{D_n}{D_{EC}} \tag{1}$$

where D_n describes the yearly electricity demand of household n and D_{EC} the yearly overall electricity demand of the energy community. For example, if the household has a yearly electricity demand of 3,500 kWh and the electricity demand of the community is 35,000 kWh $\delta_{n,Static}$ is 10%. Therefore, the member gets 10% of the production at each point in time. If the amount is larger than the needed electricity amount the excess electricity is sold to the grid. If the amount is lower than the needed electricity the remaining electricity is bought from the grid.

Dynamic

The dynamic sharing coefficient is similar to the static one but changes in each time step (hourly). The parameter depends on the electricity consumption at point in time t:

$$\delta_{n,Dynamic} = \frac{D_n(t)}{D_{EC}(t)} \tag{2}$$

This implies that $\delta_{n,Dynamic}$ changes every hour as the available data are on hourly basis. In practice, the sharing coefficient would change every 15 minutes which would correspond to the smart meter resolution.

Hybrid

The hybrid sharing coefficient is a combination of the static and dynamic sharing coefficient. First, each member gets an amount of electricity dependent on a fixed parameter, which depends on the investment costs of the member where each member has investment costs depending on their yearly electricity demand. This means that the member with the highest demand has the highest investment costs and consequently receives the largest fixed amount.[7] In a second step, the electricity that is not needed can be sold to other members who still need electricity. Therefore, the fixed parameter $\delta_{n,Hybrid}$ has the following form:

$$\delta_{n,Hybrid} = \frac{Investment_n}{\sum_{i=1}^{N} Investment_i} \tag{3}$$

where the investment costs of each member depend on the share of their yearly consumption relative to the demand of the whole community. This means the height of the investment for each member is defined as follows:

$$Investment_n = \frac{D_n}{D_{EC}} \cdot (kWp \cdot 800). \tag{4}$$

In comparison to the static sharing coefficient, each member that has electricity left can sell the excess electricity to other members. Furthermore, the fixed component in the hybrid approach is constant over the whole lifetime of the PV system. To assure that not only one member owning a large share of the PV sells their electricity to the remaining members and the other members with excess electricity have to sell their electricity to the grid, the amount of electricity sold depends on the ratio between the excess and needed electricity. The same logic is applied when the excess electricity is not sufficient to satisfy the demand, assuring that not only one member gets the cheaper electricity from the community and the remaining members have to buy from the grid. Precise details on how this is achieved can be found in the appendix.

Even

The last sharing coefficient differs from the previous ones as it is not really a parameter that divides the produced electricity. In this setup the members receive electricity depending on their electricity demand in kWh and the process has several iterations until the electricity demands of all members are satisfied or the entire produced electricity is distributed. This means that in the first step each member gets the same amount of electricity which is the smallest demand at time t ($min(D_n(t))$) or the entire production divided by the number of members N ($\frac{S_{EC}(t)}{N}$). The electricity amount a member gets depends on the produced electricity. If

$$\frac{S_{EC}(t)}{N} \cdot N > min(D_n(t)) \cdot N \tag{5}$$

applies all members get electricity equal to the smallest demand of the energy community ($min(D_n(t))$). In contrast, if

$$\frac{S_{EC}(t)}{N} \cdot N < min(D_n(t)) \cdot N \tag{6}$$

applies, there is not enough electricity to give all members the amount $min(D_n(t))$ and as a result the production is divided by N ($\frac{S_{EC}(t)}{N}$). After that, the algorithm checks if all members are served or if the entire production is distributed. If not, the next round starts where the new minimum demand is defined and the remaining electricity is distributed.[8] This process is repeated until no member needs any more electricity or until the entire production is distributed. In the case where all members are served and there is still electricity left, the excess electricity is sold to the grid. These revenues are equally distributed across all members at the end of the billing period. Overall, the even sharing coefficient is the one that clearly benefits members with a small electricity demand.

[7] In principle, the fixed parameter may follow any rule and must not necessarily be dependent on investment costs.

[8] More details regarding the sharing algorithm can be found in the appendix.

2.2.3. Economic/profitability indicators

Yearly savings

The most important indicator is the yearly savings of each member. Therefore, we compare the total costs of the reference scenario and the energy community scenario (more details can be found in the appendix). The yearly savings (S_n) assume the following form:

$$S_n = B_n^{Ref} - B_n \tag{7}$$

where B_n is the yearly bill of member n and B_n^{Ref} is the yearly bill of the reference scenario. The reference scenario represents the situation where the member is not part of an energy community and has to buy their entire electricity demand from the grid. B_n and B_n^{Ref} are defined as

$$B_n = \sum_{t=1}^{T} C_n(t) \cdot P_{EC}(t) + CE_{n,Buy}(t) + GE_{n,Buy}(t) + CE_{n,Sell}(t) + GE_{n,Sell}(t) \tag{8}$$

$$B_n^{Ref} = \sum_{t=1}^{T} D_n(t) \cdot P_{Grid}(t) \tag{9}$$

where $C_n(t)$ is the electricity directly consumed from the PV, P_{EC} is the applied price for the electricity, $CE_{n,Buy}(t)$ and $CE_{n,sell}(t)$ are the costs and revenues of buying or selling in the community and $GE_{n,Buy}(t)$ and $GE_{n,Sell}(t)$ are the costs and revenues from buying or selling from/to the grid. In addition, D_n is the total electricity demand of households n and P_{Grid} is the price charged when buying electricity from the grid.

Savings per kWh

This indicator compares the savings of all members relative to their electricity demand, or to be more precise to the amount of electricity the member is entitled to. It is defined as follows:

$$S_{n,kWh} = \frac{S_n}{E_{con} + E_{sold}} \tag{10}$$

where E_{con} represents the amount of electricity that is consumed and E_{sold} the amount of electricity that is sold to the grid. Overall, the exact definition of E_{con} and E_{sold} varies depending on the applied sharing coefficients (see appendix).

Payback period

The payback period of the investment has the following form:

$$PBP = \frac{Investment_n}{\bar{S}_n} \tag{11}$$

where again $Investment_n$ are the investment costs of the members and $\bar{S}_n$ are the average yearly savings of member n.

Self-sufficiency and self-consumption rates

The next two important indicators are the self-sufficiency (SSR) and self-consumption (SCR) rates which describe how much of the electricity demand is provided by the produced electricity and how much of the produced electricity is consumed. SSR and SCR are defined as follows:

$$SSR = \frac{C_{EC}}{D_{EC}} \tag{12}$$

$$SCR = \frac{C_{EC}}{S_{EC}}. \tag{13}$$

In this analysis, C_{EC} describes the yearly total amount of electricity that is consumed by the members of the community, S_{EC} is the yearly total amount of electricity that the PV panel produced and D_{EC} is the yearly total electricity demand of the community. In addition to the SSR and SCR of the entire community, we calculate the SSR of each member to show how much of their electricity demand can be satisfied when a sharing coefficient is applied. The individual SSR is calculated by using the following equation

$$SSR_n = \frac{C_{n,total}}{D_n}, \quad (14)$$

where $C_{n,total}$ is the total amount of electricity member n receives from the EC and D_n is the total electricity demand of households n.

Value-at-risk

For potential members of an energy community the most important information that helps to decide if the household should join an energy community is the expected revenues/savings $E(S_n)$. Another aspect that is crucial for evaluating an investment is the expected losses or worst case scenarios that might arise. The Value-at-Risk (VaR) is a well-know risk measure in financial economics defined as an appropriate quantile in the tail of the distribution of a profit-loss function of an investment [27]. It is the expected profit/loss, usually with a probability of 5%. This logic can also be applied in the context of energy communities and by considering the whole distribution of savings, which are the crucial quantity to pay off the investment costs and to generate profits. For this analysis we use the Monte Carlo approach commonly used to compute the VaR, which is a parametric technique that provides a forward-looking approach to estimate the risk [28]. It is the most suitable approach in our case because the results of the simulation model represent the necessary profile-loss function and the VaR can be computed as a byproduct of our simulation.

2.3. Load profile simulation

In general, various possible methods to model or forecast electricity demand exist ([29], [30], [31]). According to Alfares and Nazeeruddin [29] there are nine frequently used methodologies: multiple regression, exponential smoothing, iterative reweighted least-squares, adaptive load forecasting, stochastic time series, ARMAX models based on genetic algorithms, fuzzy logic, neural networks and expert systems. Another possibility might be to use hierarchical clustering to identify representative operating days or demand behaviour when a large number of load profiles are available [32]. For this analysis, we decided to use a time series approach to simulate the household profiles by following Weron [24].

Usually, electricity demand shows fluctuations dependent on the season, day and time. For example, in summer more electricity is needed for cooling in Mediterranean areas and less is needed during night when nearly everyone is asleep [24]. In addition, the electricity production depends on the seasons and the weather as well. Especially renewable energy sources like photovoltaic cells show significant fluctuations in electricity production. One drawback of this analysis is that only data for a single year was available to estimate the model forming the basis for our simulated load profiles. If several years of data were available, the seasonality in consumption patterns could be modelled more precisely.

To model and forecast load profiles and electricity demand ARIMA and seasonal ARIMA models are a frequently used approach ([33]2, [34], [24]). The following section describes our modelling approaches used to generate representative load profiles and a reasonable PV production.

2.3.1. Residential members - the statistical model

To model the load profiles of the residential members a conditional mean and conditional variance model were used. The conditional mean is modelled with a linear model of the load profiles of the households and a SARIMA model that captures the dynamics of the residuals. The conditional variance is modelled with a standard GARCH(1,1) model [35].

The **modelling approach** can be summarized in three steps:

1. Estimate a linear model with dummy variables for the month, day and hour and hourly temperature data including interaction terms. The model has the following form

$$log(load_t) = \beta_0 + \sum_{i=1}^{23} \beta_i \cdot H_{it} + \sum_{k=1}^{6} \beta_{23+k} \cdot D_{kt} + \sum_{j=1}^{11} \beta_{29+j} \cdot M_{jt} + \beta_{41} \cdot Temp_t + \sum_{j=1}^{11} \beta_{41+j} \cdot Temp_t \cdot M_{jt} + \sum_{k=1}^{6} \sum_{i=1}^{23} \beta_{52+23\cdot(k-1)+i} \cdot H_{it} \cdot D_{kt} + e_t \quad (15)$$

where H_{it} is a dummy variable for the hours 1 to 23, D_{kt} is a dummy variable for the days of the week, M_{jt} is a dummy variable for the months and $Temp_t$ is the outdoor temperature at time t. The autocorrelation function of the residuals (see Fig. 2 - upper left) indicate that the model does not capture the entire seasonality and that the residuals (e_t) still show a seasonal behaviour. Therefore, a SARIMA model was applied to model the residuals (e_t) and capture the remaining seasonality.
2. Model the residuals e_t with a SARIMA Model.

$$e_t = \sum_{j=1}^{p} \phi_j e_{t-j} + \sum_{j=1}^{q} \theta_j \epsilon_{t-j} + \sum_{j=1}^{P} \Phi_j e_{t-s\cdot j} + \sum_{j=1}^{Q} \Theta_j \epsilon_{t-s\cdot j} + \epsilon_t \quad (16)$$

Fig. 2 in the upper right shows two important details. First, the remaining autocorrelation in the residuals of the SARIMA model (ϵ_t) is very weak although still statistically significant and, second, the distribution of residuals appears to be characterized by left-skewness and excess kurtosis. Visual inspection of the residuals and the autocorrelation function of their squares (not reported) suggests non-constant variance. Therefore we applied an ARCH LM test which indicates the presence of conditional heteroscedasticity. Thus, the last step is to model the conditional variance of ϵ_t using a GARCH(1,1) model.
3. The GARCH(1,1) model is defined as

$$\epsilon_t = \sigma_t u_t, \quad (17)$$

where the conditional variance evolves as

$$\sigma_t^2 = \omega + \alpha \epsilon_{t-1}^2 + \beta \sigma_{t-1}^2 \quad (18)$$

and u_t is assumed to follow the skewed t-distribution by Hansen [36] with to have a flexible model capturing the skewness and kurtosis of the innovations via its parameters λ and v. The lower right of Fig. 2 shows the estimated conditional variance $\hat{\sigma}_t^2$ To model ϵ_t, the conditional variance of the GARCH model (σ_t, see - lower right) and a random variable u_t are used.

The **simulation procedure** for the loads has the following 4 steps, where a “tilde” denotes a simulated variable corresponding to the respective one of the models above and a “hat” denotes an estimated parameter:

1. Randomly draw $\tilde{u}_t$ from skewed t-distribution with the estimated parameters $\hat{\lambda}$ and $\hat{v}$.
2. Scale the simulated $\tilde{u}_t$ by the estimated conditional variance $\hat{\sigma}_t$ of the GARCH model to obtain

$$\tilde{\epsilon}_t = \tilde{u}_t \cdot \hat{\sigma}_t. \quad (19)$$

3. Simulate $\tilde{e}_t$ by using the estimated parameters of the SARIMA model ($\hat{\phi}, \hat{\Phi}, \hat{\theta}$ and $\hat{\Theta}$), the simulated residuals $\tilde{\epsilon}_t$ from step 2 (the first 48 values of the original data are used as initial observations).

$$\tilde{e}_t = \sum_{j=1}^{p} \hat{\phi}_j \tilde{e}_{t-j} + \sum_{j=1}^{q} \hat{\theta}_j \tilde{\epsilon}_{t-j} + \sum_{j=1}^{P} \hat{\Phi}_j \tilde{e}_{t-s\cdot j} + \sum_{j=1}^{Q} \hat{\Theta}_j \tilde{\epsilon}_{t-s\cdot j} + \tilde{\epsilon}_t. \quad (20)$$

4. Add the deterministic part using the fitted values from regression (15) to get your simulated load profile:

$$\widetilde{load}_t = exp(\widehat{log(load)}_t + \tilde{e}_t). \quad (21)$$

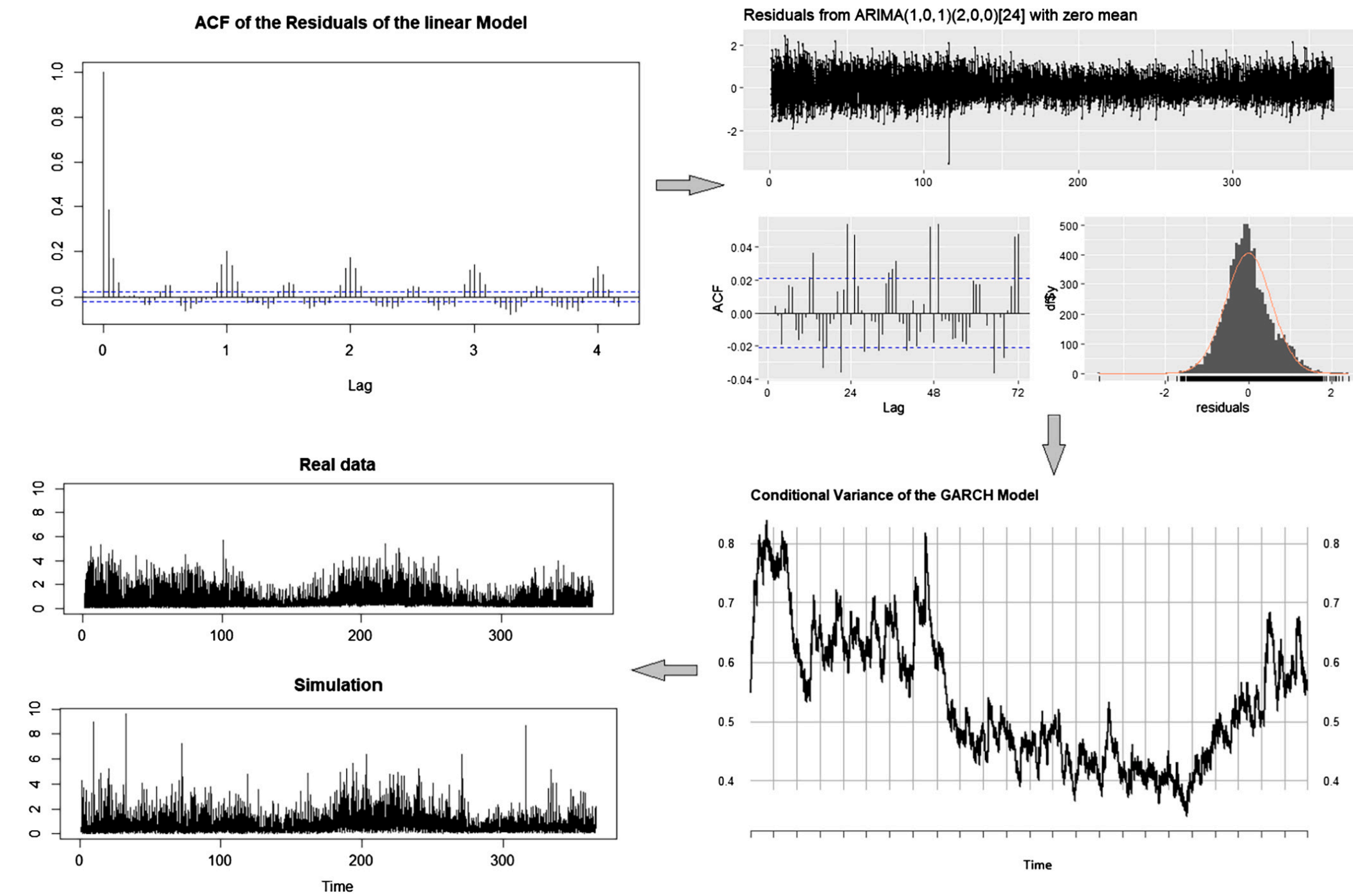


Fig. 2. Load profile simulation ($n = 8,759$) - example.

Table 3
Chosen models to simulate the load profiles for the residential members.

Household	R^2 lin. Mod.	SARIMA	GARCH
Household 1	0.42	(2,0,0)×(2,0,0) [24]	(1,1)
Household 2	0.47	(2,0,0)×(2,0,0) [24]	(1,1)
Household 3	0.57	(0,0,2)×(2,0,0) [24]	(1,1)
Household 4	0.77	(4,0,0)×(2,0,0) [24]	(1,1)
Household 5	0.45	(1,0,1)×(2,0,0) [24]	(1,1)
Household 6	0.20	(1,0,0)×(2,0,0) [24]	(1,1)

Table 3 gives an overview about the applied models for each of the six households for the load profile simulation. In addition, the lower left panel of Fig. 2 shows an example of a simulated trajectory of the load compared to the observed data. The resulting distribution of the yearly electricity demand of the six households can be seen in Fig. 3, which gives a good indication of the variation in yearly electricity consumption of the community members.[9]

2.3.2. Commercial members and PV panel

The load profiles of the library and the church had some missing values and therefore imputation methods had to be applied to fill the gaps. Unfortunately, the time series approach that we used for residential members was not able to adequately model the variation of these variables. This was also true for the PV production as a PV profile has a special shape where sometimes points are constantly 0 because no electricity can be produced, i.e., during night, the morning and the evening. Therefore, to simulate the load profiles of the commercial members and the PV production a different approach is applied. The chosen method is a resampling/bootstrap approach, which assures that, especially for the PV production, no production occurs when there is not enough sunlight available. With this method, the values are drawn from the original data during the corresponding month, day of the week, and hour of the day. This assures a realistic shape of the PV profile and the commercial load profiles and still provides sufficient variation in the production and the demand load simulation. Figs. 4 and 5 show what the simulated yearly PV production and electricity demand of the commercial member looks like.

3. Results

The following section will present the results of the two analysed scenarios on community and on member levels. The section is divided in three parts. First, the results scenarios 1 and 2 will be presented on community and member level with a focus on the average savings, savings per consumed kWh as well as the self-sufficiency (SSR) and self-consumption (SCR) rates. After that, we present the impact of the sharing coefficients and the community setup on the overall profitability and the payback periods (PBP). Here, we present the cumulative savings over the lifetime of the PV panel of each member and which impact the sharing coefficients and investment schemes have on the payback period.

3.1. Scenario 1 - residential members only

Community level

The left graph in Fig. 6 shows the amount of produced electricity that is consumed by the community members as well as the excess electricity that is sold to the grid. Overall, the Figure shows that there is no

[9] For reasons of space the detailed estimation results of each load profile will not be provided in this paper but are available upon request.

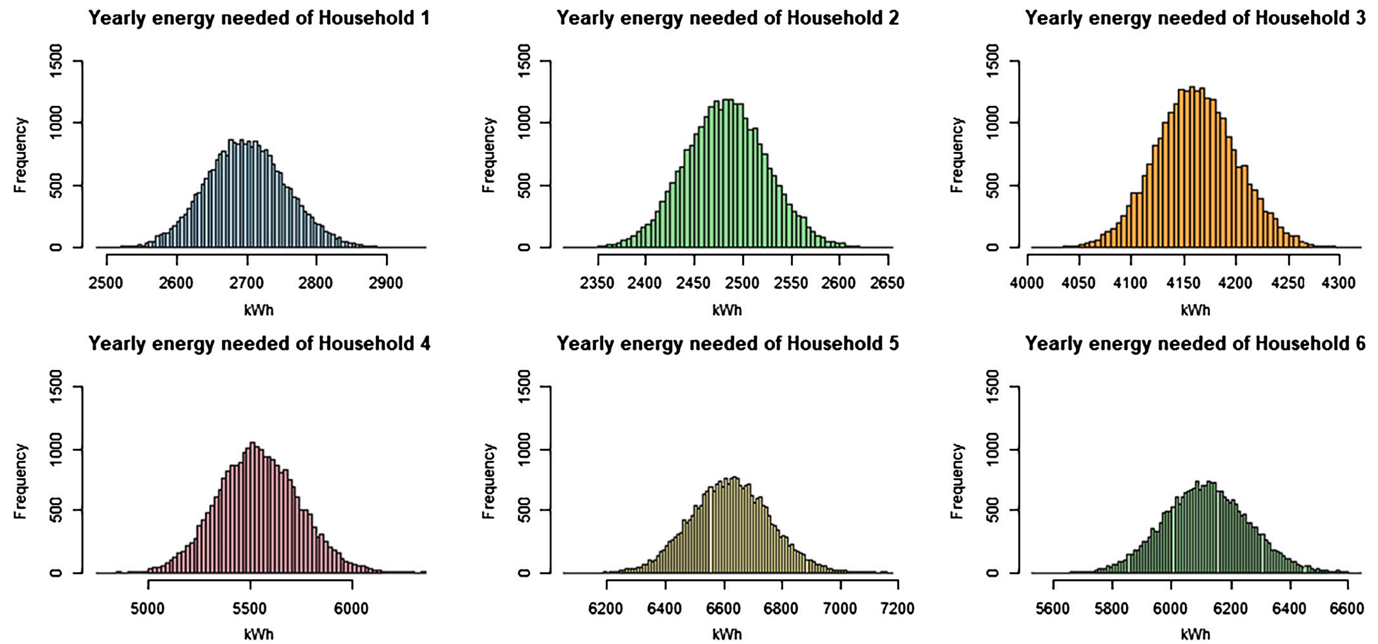


Fig. 3. Simulated yearly electricity demand of all residential members.

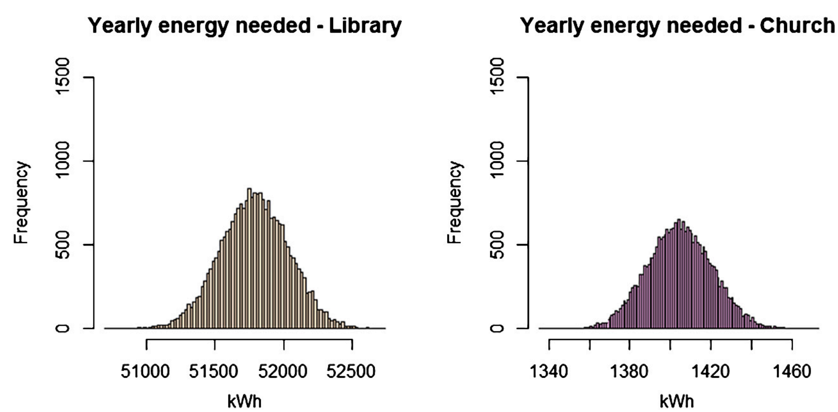


Fig. 4. Simulated yearly electricity demand of the commercial members.

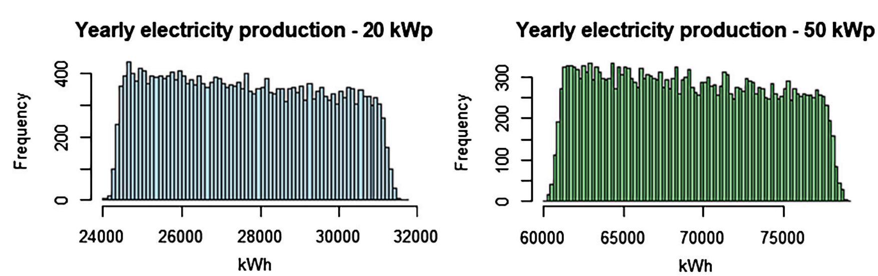


Fig. 5. Simulated yearly electricity production of the PV panels including the yearly deprivation of 1%.

significant difference between the dynamic, hybrid and even sharing coefficients. The only sharing parameter that differs from the others is the static sharing parameter where less electricity is consumed within the community and more electricity is sold to the grid. This result is also reflected in the self-sufficiency (SSR) rate of the community which is presented in the right graph of Fig. 6.[10] The SSR and SCR show similar results for the dynamic, hybrid and even sharing coefficients. The SSR for the static sharing coefficient is 3% points lower than for the other sharing coefficients while the SCR for the static sharing coefficient is more or less the same as for the other sharing coefficients. Overall, the results show that the sharing coefficient has almost no influence on the profitability of the community as a whole.

Member level

First, we analyse the average savings of each household over all simulation runs. Fig. 7 shows that for households 1 and 2 (low electricity demand) the even sharing coefficient provides the highest absolute savings. In contrast, the even sharing coefficient is the worst for household

[10] The SSR describes how PV production can cover the electricity needs and the SCR describes how much of the PV electricity is used.

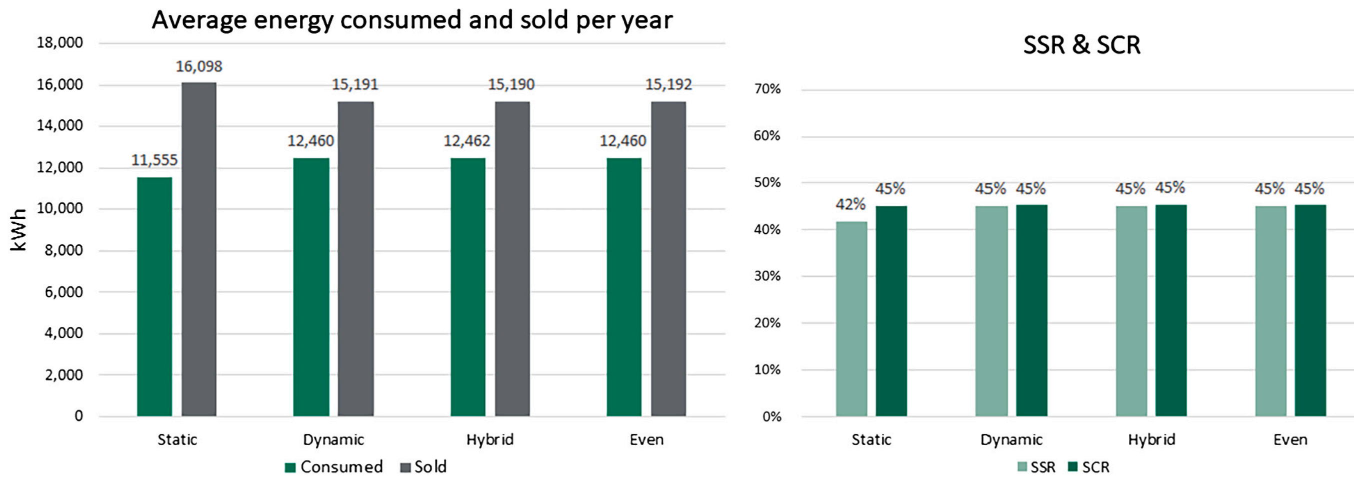


Fig. 6. Results on community level - Scenario 1. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

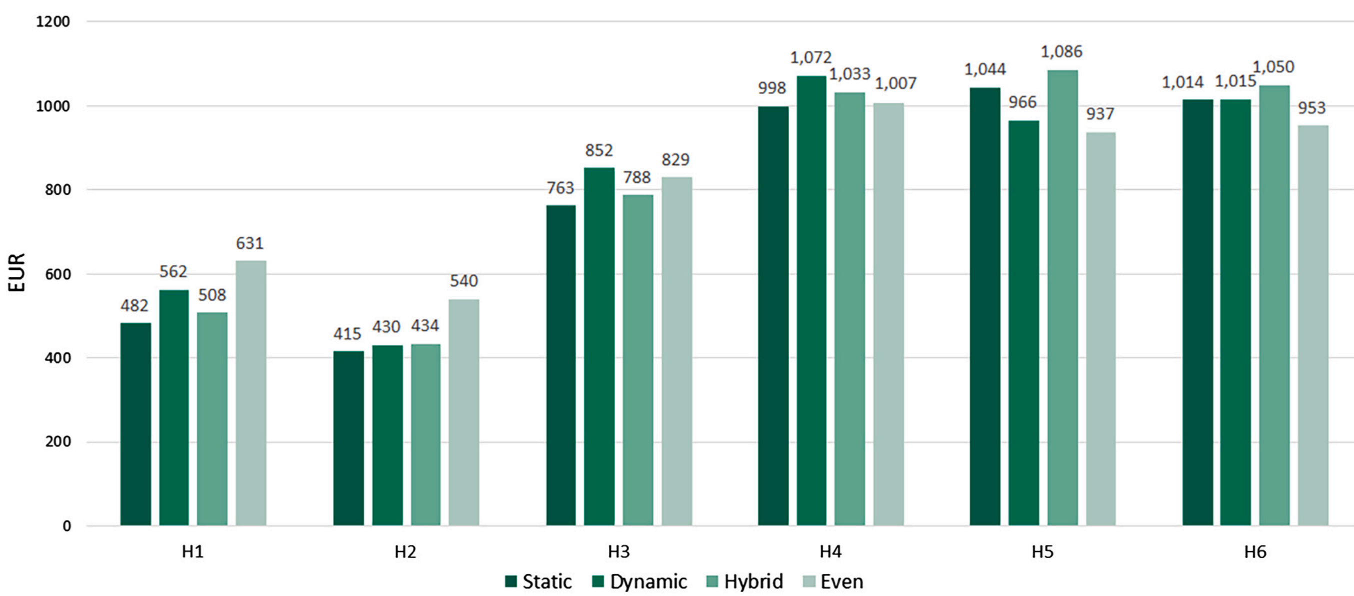


Fig. 7. Average yearly savings of each member in scenario 1.

5 and 6 (high electricity demand). The hybrid sharing coefficient has a better performance for households with high electricity demand while it is rather mixed for the other household types. Overall, the static sharing coefficient has the worst performance for the small and medium household types.

Next, the range of the yearly savings of all members and for all sharing coefficients in Fig. 8 is discussed.[11] It shows that there is more or less variation in the savings depending on the members and the sharing coefficients. For example, household 4 has the largest variance while household 2 has the smallest one. When comparing the sharing coefficients, it can be seen that when applying the hybrid sharing coefficient, the savings have the smallest variation and when applying the static and dynamic sharing coefficient, especially households 4 to 6 have larger variance. In addition, over all simulations household 2 always has the smallest minimum value (364.23 EUR/year) while household 5 has the highest minimum value for the sharing coefficients static and hybrid. For the static and hybrid sharing coefficients household 6 has the highest minimum value. The same is true for the maximum values. Overall, the median value for all households is very close to the average savings in Fig. 8. Finally, we discuss the differences in SSR and savings per kWh in Table 4. Scenario 1 shows that the even sharing coefficient provides the highest SSR for low to medium demand households (household 1 to 3). Contrary to that, high demand households have a better SSR when the dynamic sharing coefficient is applied. The savings per consumed are the highest when using the hybrid sharing coefficient for households 1 to 4. Households 5 and 6 have better results when the dynamic and even sharing coefficients are applied.

Table 4
Self-sufficiency rate (SSR) and savings per consumed kWh of the residential members in scenario 1.

SSR	H1	H2	H3	H4	H5	H6
Static	44.4%	40.5%	47.3%	46.3%	35.8%	40.1%
Dynamic	49.7%	43.2%	49.4%	50.2%	38.9%	43.1%
Hybrid	49.9%	43.5%	49.6%	50.1%	38.5%	43.1%
Even	51.5%	45.4%	50.1%	49.9%	37.9%	42.4%
Savings per consumed kWh (in EUR)						
	H1	H2	H3	H4	H5	H6
Static	0.179	0.167	0.184	0.180	0.158	0.166
Dynamic	0.178	0.171	0.174	0.179	0.184	0.176
Hybrid	0.186	0.177	0.192	0.183	0.165	0.173
Even	0.161	0.148	0.180	0.191	0.186	0.186

[11] More details can be found in the appendix in Table B.1.

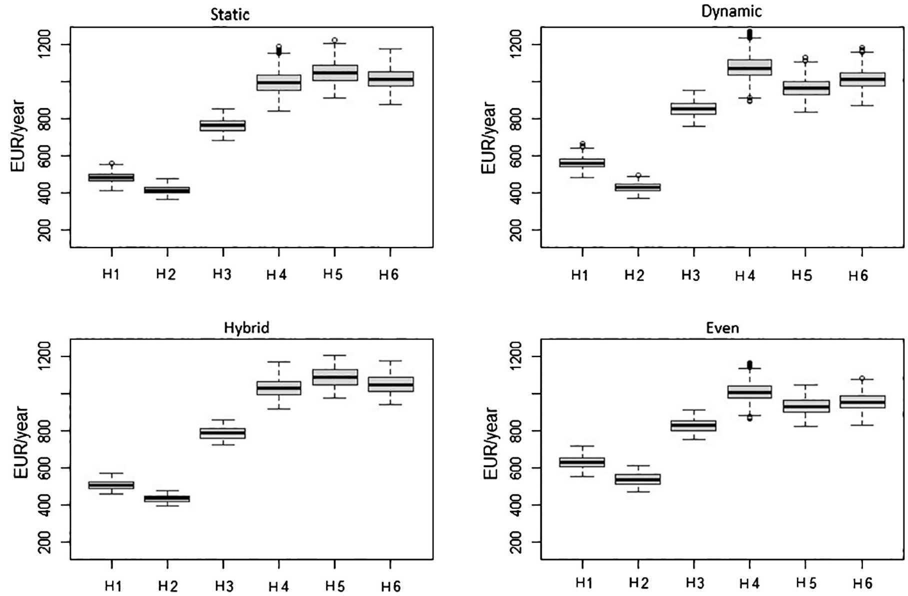


Fig. 8. Savings of the residential members in scenario 1.

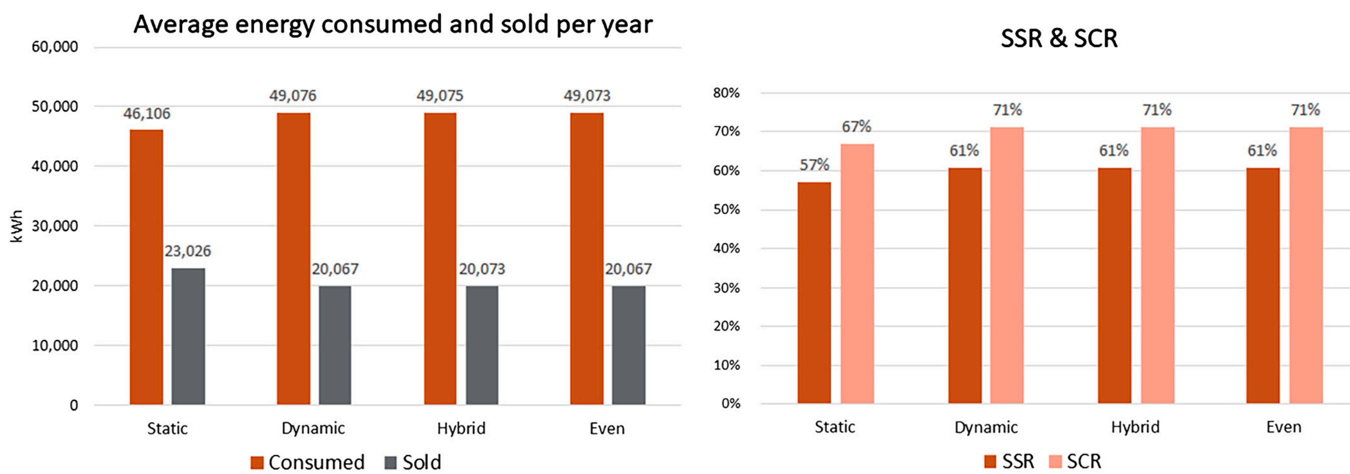


Fig. 9. Yearly results on community level in scenario 2.

3.2. Scenario 2 - residential and commercial members

Community level

In scenario 2, the number of members as well as the PV capacity are increased from six to eight members and from 20 kWp to 50 kWp, respectively. The main difference on the community level to scenario 1 is that in this setup more of the PV electricity is consumed by the community and less electricity is sold to the grid. This derives from the fact that the library and the church need electricity during the day when the highest amount is produced while households usually need more electricity in the evening. The right graph in Fig. 9 shows that now the SSR and SCR is much higher than in scenario 1. The SSR increased from around 43% to 59% and the SCR increased from 45% to around 69%. However, the differences between the sharing coefficients are the same as in scenario 1. This means that on the community level, the dynamic, hybrid and even sharing coefficients are rather similar while the static sharing coefficient is worse than the other sharing coefficients.

Member level

When analysing the savings on the member level some considerable differences to scenario 1 can be seen. First, the average savings for all residential members in Fig. 10 are lower for the static, dynamic and hybrid sharing coefficients. In contrast, for the even sharing coefficient, the average savings are higher than in scenario 1. The results of the church are similar to the results of the households while the results of the library differ as the even sharing coefficient provides the lowest average savings. Second, for the households 2 to 6 and the church the static sharing coefficient generates more savings than the dynamic sharing coefficient. The library generates the highest savings when the dynamic sharing coefficient is applied.

Figs. 11 and 12 take a closer look on savings of each member.[12] As in scenario 1, household 2 has the smallest savings of all residential members while households 5 and 6 have the highest savings. In contrast, the small church has very low savings with a large variance between 174 and 505 EUR/year while the library has savings between 9,939 and 12,947 EUR/year. For the residential members the even sharing coefficient is the one that generates the highest median yearly average savings. In addition, when the hybrid sharing coefficient is applied the savings of the residential members have the smallest variance while the

[12] More details can be found in the appendix in Table B.2.

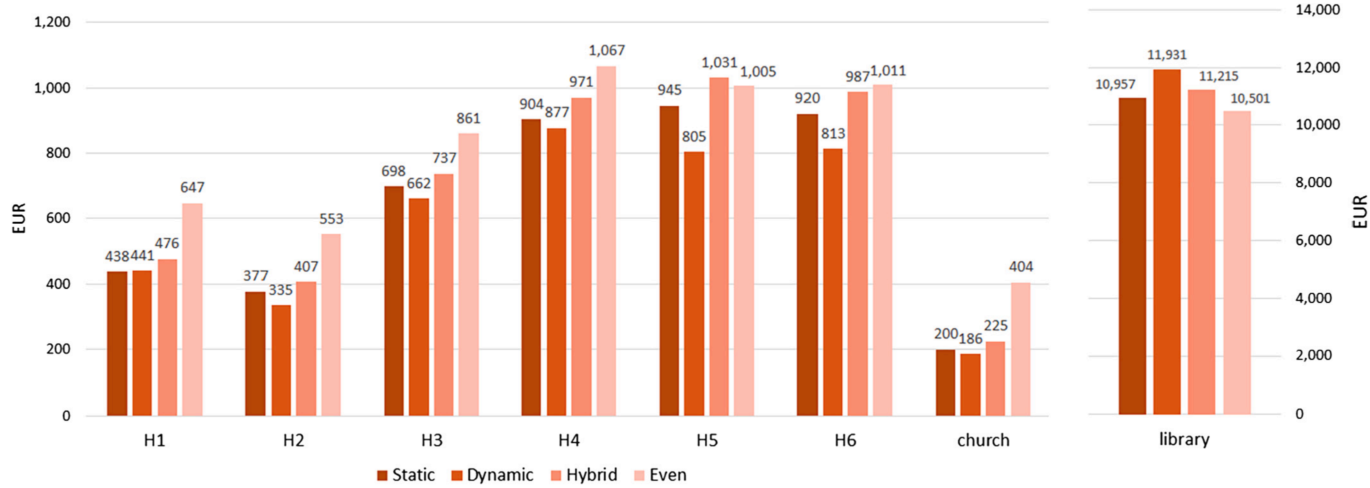


Fig. 10. Average yearly savings of each member in scenario 2.

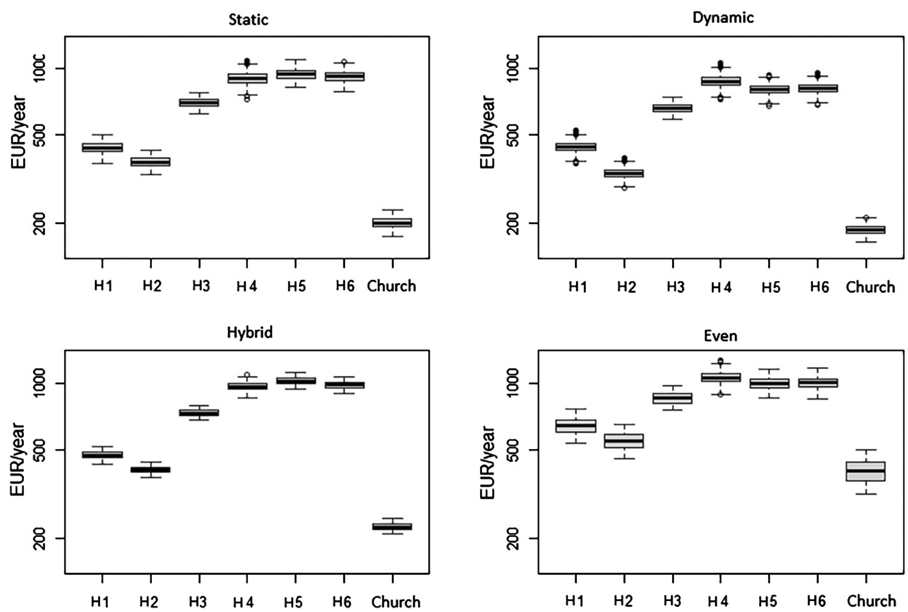


Fig. 11. Savings of the residential members and the small church in scenario 2.

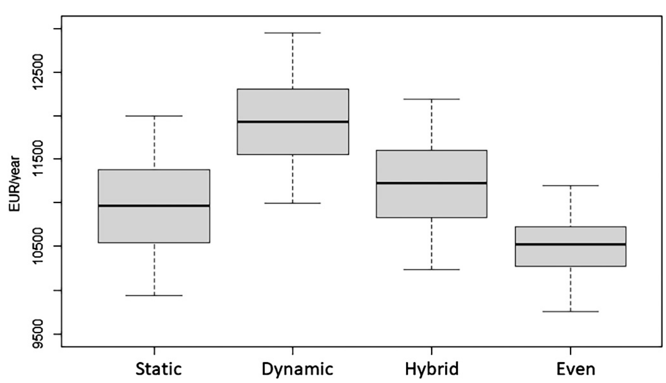


Fig. 12. Savings of the library in scenario 2.

variance is the highest when the even sharing coefficient is applied. As mentioned before, the library has the lowest savings with the even sharing coefficient but Fig. 12 also shows that the savings have the smallest variance in this case.

In contrast to scenario 1, the choice of the most beneficial sharing coefficients for the residential members is much clearer. All households have the highest SSR when the even sharing coefficient is applied (see Table 5). In addition, for the small church the even sharing coefficient is also the best choice while for the library it is the dynamic or hybrid sharing coefficient. When analysing the savings per kWh the dynamic sharing coefficient is the best choice for the church and all residential members while the library would prefer the even sharing coefficient.

3.3. Profitability

First, we analyse the 5% quantiles of the cumulative savings over the 25 year lifetime of the PV plant for each member and sharing coefficients (see Table 6). These quantiles are the 5% Value-at-Risk to be interpreted that with a probability of 95% the savings will not be lower than the presented values. When looking at the 5% quantiles of scenario 1, the results show that each of the three consumption types would prefer a different sharing coefficient. While household 1 would prefer the even sharing coefficient, households 3 and 4 favour the dynamic sharing coefficient and households 5 and 6 the hybrid sharing coefficient. In scenario 2, the residential members of the energy community have

Table 5
Self-sufficiency rate (SSR) and savings per consumed kWh of the residential members in scenario 2.

SSR	H1	H2	H3	H4	H5	H6	Library	Church
Static	42.5%	39.0%	45.7%	44.2%	34.4%	38.5%	66.7%	33.7%
Dynamic	47.6%	41.0%	46.9%	48.6%	37.7%	41.3%	70.6%	39.5%
Hybrid	48.2%	41.8%	48.0%	48.9%	37.7%	41.7%	70.4%	38.9%
Even	53.8%	47.6%	52.9%	53.6%	41.7%	45.9%	67.7%	46.3%
Savings per consumed kWh - in EUR								
	H1	H2	H3	H4	H5	H6	Library	Church
Static	0.190	0.178	0.197	0.191	0.167	0.176	0.248	0.167
Dynamic	0.228	0.219	0.224	0.224	0.227	0.221	0.236	0.224
Hybrid	0.216	0.209	0.222	0.213	0.198	0.204	0.245	0.203
Even	0.165	0.151	0.184	0.196	0.192	0.191	0.28	0.129

Table 6
Value at risk - 5% quantile of the cumulative savings of each member for scenarios 1 and 2.

	Scenario 1	Scenario 2		Scenario 1	Scenario 2
Static	5%-Lvl	5%-Lvl	Dynamic	5%-Lvl	5%-Lvl
H1	11,964.26	10,879.04	H1	13,921.01	10,905.30
H2	10,312.65	9,376.56	H2	10,674.25	8,314.37
H3	19,011.80	17,395.50	H3	21,212.45	16,453.55
H4	24,602.45	22,341.37	H4	26,567.55	21,648.99
H5	25,997.96	23,497.36	H5	23,985.58	19,953.63
H6	25,170.94	22,837.61	H6	25,057.63	20,119.05
Lib.	-	273,326.16	Lib.	-	297,654.38
Ch.	-	4,981.006	Ch.	-	4,622.60
Hybrid	5%-Lvl	5%-Lvl	Even	5%-Lvl	5%-Lvl
H1	12,641.19	11,862.63	H1	15,671.06	16070.72
H2	10,818.31	10,148.32	H2	13,439.24	13,761.39
H3	19,639.97	18,374.74	H3	20,672.32	21,445.28
H4	25,629.50	24,145.52	H4	24,978.06	26,415.41
H5	27,081.30	25,698.89	H5	23,192.79	24,985.73
H6	26,124.27	24,575.35	H6	23,694.57	25,086.27
Lib.	-	279,817.84	Lib.	-	261,920.79
Ch.	-	5,614.16	Ch.	-	10,068.88

Table 7
Investment costs and O&M costs of each member depending on the investment scheme.

Scenario and investment		H1	H2	H3	H4	H5	H6	Library	Church
1	Same investment in EUR	3,867	3,867	3,867	3,867	3,867	3,867	-	-
	Demand-based in EUR	2,267	2,085	3,495	4,653	5,563	5,138	-	-
2	Same investment in EUR	7,250	7,250	7,250	7,250	7,250	7,250	7,250	7,250
	Demand-based in EUR	1,937	1,782	2,987	3,974	4,754	4,390	37,168	1,008
	Library (30 kWp)	2,158	1,984	3,326	4,426	5,294	4,889	34,800	1,123

the best results when the even sharing coefficient is applied. This sharing coefficient does not only provide the highest average savings and SSR but also the highest cumulative revenues at the 5% level. The only exception is household 5 where the hybrid sharing coefficient has the most profitable worst case scenario. In contrast to scenario 1 where the dynamic sharing coefficient provides good results for some members, the dynamic sharing coefficient is the least preferred sharing coefficient in scenario 2. The library has the best results when the dynamic sharing coefficient is applied.

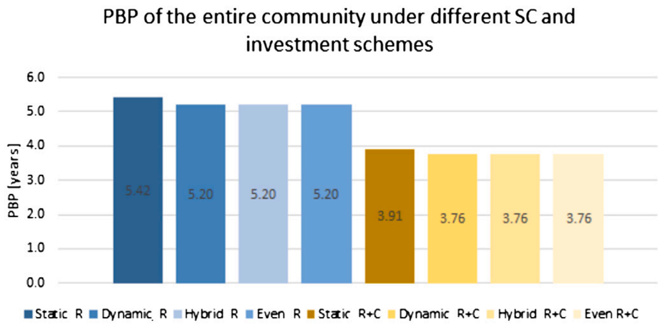
Next, in order to calculate the profitability of the individual entities, different investment schemes were considered (see Table 7). In the first scheme (same investment), everybody invests the same amount in the PV system. In the second scheme (demand-based), the investment is based on yearly demand, meaning that entities with a higher demand invest more. In scenario 2, a third scheme (library 30 kWp) is used, assuming that the 30 kWp PV belongs to the library while the others invest in the 20 kWp according to the demand-based investment scheme. In addition, we assume that over the analysed time horizon one inverter replacement is necessary, the EC has operations and maintenance costs (O&M costs) of 2% of CAPEX per year and that the members have to pay a membership fee of 5 EUR/month[13] (see Table 8).

Table 8
Assumption to additional costs of an energy community.

	Costs	Source
Inverter replacement costs	360 EUR/kW	[37]
O&M costs/year	2% of CAPEX	[38]
EC membership fee	5 EUR/month	DECIDE Workshop Stakeholder Group: renewable energy communities

On the community level, the results for the payback period (PBP) do not vary widely (Fig. 13). In both scenarios, the static sharing coefficient entails the longest PBP while all other sharing coefficients come with

[13] The chosen value for the membership fee is an average value based on discussion at the DECIDE Workshop Stakeholder Group: renewable energy communities which took place on 26.04.2022.



Note: In this figure R = residential members only which stands for scenario 1 and R+C = residential and commercial members which stands for scenario 2

Fig. 13. Payback period (PBP) on community level.

the same PBP, per scenario respectively. This is due to the fact that with a static sharing coefficient not all theoretically possible electricity is exchanged. For all other sharing coefficients, the maximum is reached and only the distribution between the households varies. In general, scenario 2 comes with a slightly shorter PBP as a higher share of the produced electricity is consumed in the energy community. Overall, the investment in the PV is very profitable regardless of the sharing coefficient.

Fig. 14 presents the payback period for scenario 1 for all sharing coefficients and for the two investment schemes on member level. While it can be seen that irrespective of the sharing coefficient all households will regain their investment in a maximum of fourteen years (recall that the assumed lifetime of the system is 25 years), it is also visible that the sharing coefficient and the investment scheme impact the PBP of the individual households. Households with higher yearly consumption have a shorter PBP for the same investment scheme, while the PBP in the demand-based investment scheme is less divergent. This is reasonable as the savings depend on the yearly consumption, and therefore, if the investment is also based on the yearly consumption of a household, differences in the PBP are minimized. It should also be highlighted that the even sharing coefficient impacts the results the most, as it reduces the PBP for households with a smaller yearly consumption in the same investment scheme and increases the PBP for households with a larger yearly consumption in the demand-based scenario, as the even sharing coefficient in general profits smaller consumers and ensures an incentive for smaller households to participate in the energy community.

In scenario 2, three different investment schemes are considered (same investment, demand-based, library 30 kWp (Fig. 15). In contrast to scenario 1, the same investment scheme proposes a case where three entities (household 1, household 2 and the church[14]) are not able to regain the investment of the PV during the lifetime of the system. While household 1 and 2 have at least a PBP below 25 years (16.4 and 20.8 years) when the even sharing coefficient is applied, the church is always unable to get their investment back. The reason is that the yearly fixed costs of the EC for the church are (almost) higher than the savings per year. In general, while low electricity demand members have to invest the same share as all other members, the savings are limited due to the small overall yearly consumption. However, this investment scheme does not seem suitable for an energy community with significantly different yearly consumption of its members. In the other two investment schemes, the PBP is more similar, with the even sharing coefficient having the shortest PBP for all households except for household 5 and the library, but even for those two entities, the PBP is still below seven years. In addition, with the demand-based and library 30 kWp investment scheme the church would also have an incentive to participate as now, the investment becomes profitable. While the church has the highest PBP of all members when static, dynamic or hybrid sharing coefficients are applied, the PBP is similar to the other members when even sharing coefficient is applied. It can therefore be argued that only when applying this sharing coefficient, households or small electricity consumption entities would approve for the library to join the energy community. Based on the Value-at-Risk analysis, the impact of the payback period was assessed. To do so, the savings for the 5% quantile were used for the calculation of the PBP and compared to the PBP based on the average savings. The results show a maximum increase of one year in the PBP for both scenarios under all different sharing coefficients. Therefore, profitability is not significantly impacted. The corresponding tables of the yearly savings at the 5% quantile can be found in the appendix (Tables B.3 to B.8).

[14] We excluded the church from the figure on the same investment scheme as this situation is not economically feasible.

4. Discussion

The aim of this study was to simulate the impact of different sharing coefficients on the financial benefits of energy community members. At the moment, only two types of sharing coefficients are applied to ECs and CSC schemes in Europe. Therefore, we wanted to have a closer look at these sharing coefficients (static and dynamic) as well as on two new sharing coefficients (hybrid and even) and analyse them in two different ECs setups. The results show that an EC with residential and commercial members has overall better results in terms of electricity usage and electricity savings, but members with low electricity demand do not have an incentive to join a mixed EC as long as only the static and dynamic sharing coefficients are available.

When analysing the savings over the lifetime of the PV system, each member type (low, medium, high demand consumer) in a residential only EC prefers a different sharing coefficient. Overall, the largest differences in total savings when comparing sharing coefficients in the residential only setup range from 1,965 to 3,707 EUR over the lifetime of the system. Which means that when the static sharing coefficient instead of the even one is applied, household 1 receives 3.707 EUR less total savings within 25 years. When residential and commercial members form an EC, the even sharing coefficient is the best choice for the residential members as well as the church. For the library, the even sharing coefficient is the least preferred sharing coefficient, but nevertheless joining an EC is very beneficial for the library.

Analysing the PBP reveals some clear results. First, the PBP of the EC in a mixed setup is always lower than in a residential only setup, although the investment costs are more than twice as high. Second, an investment scheme where all members pay the same amount is only reasonable if the electricity demand of the members as well as the savings are similar. Otherwise, the investment scheme disadvantages low demand members. When combining residential and commercial members, this effect becomes even stronger. Without a demand-based investment scheme, the members with the lowest demand may not get their investment costs back during the lifetime of the PV system.

Compared to other studies, this analysis focuses on energy sharing rather than on pricing energy within an energy community. Furthermore, a new method was applied that considers random variation when simulating load profiles, which overall enriches the analysis. The results reveal that the choice of the applied sharing coefficient can have a significant impact on the profitability of an energy community and may impact the formation of different EC setups. These findings contribute to current debates on sharing possibilities for ECs and can help with the inclusion of ECs to the energy system. The analysis provides interesting results for policymakers, as results point out that with the current available sharing coefficients, the incentive to form mixed energy communities is not given. If this is aimed for, different sharing coefficients are needed. In addition, the results show how the distribution of the investment costs and the choice of sharing coefficient impacts the profitability of the members, which is an important insight for future ECs.

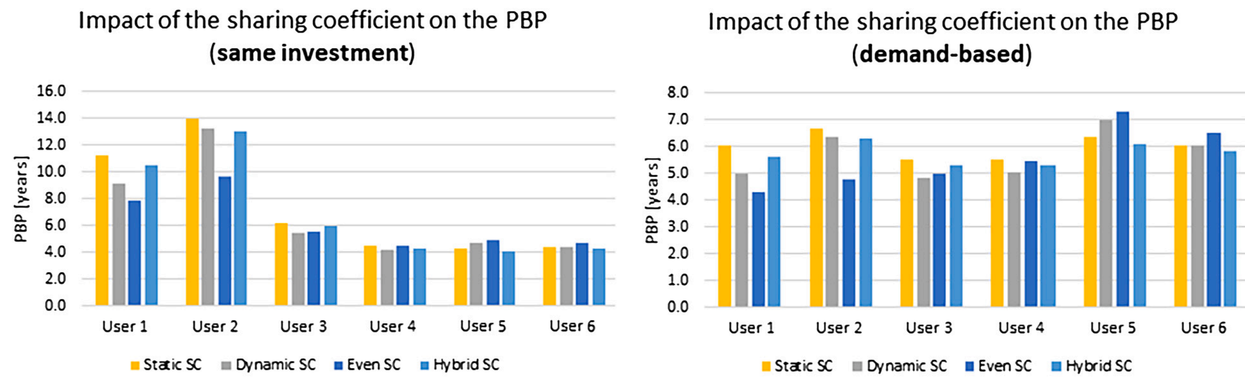


Fig. 14. Payback periods (PBP) in scenario 1.

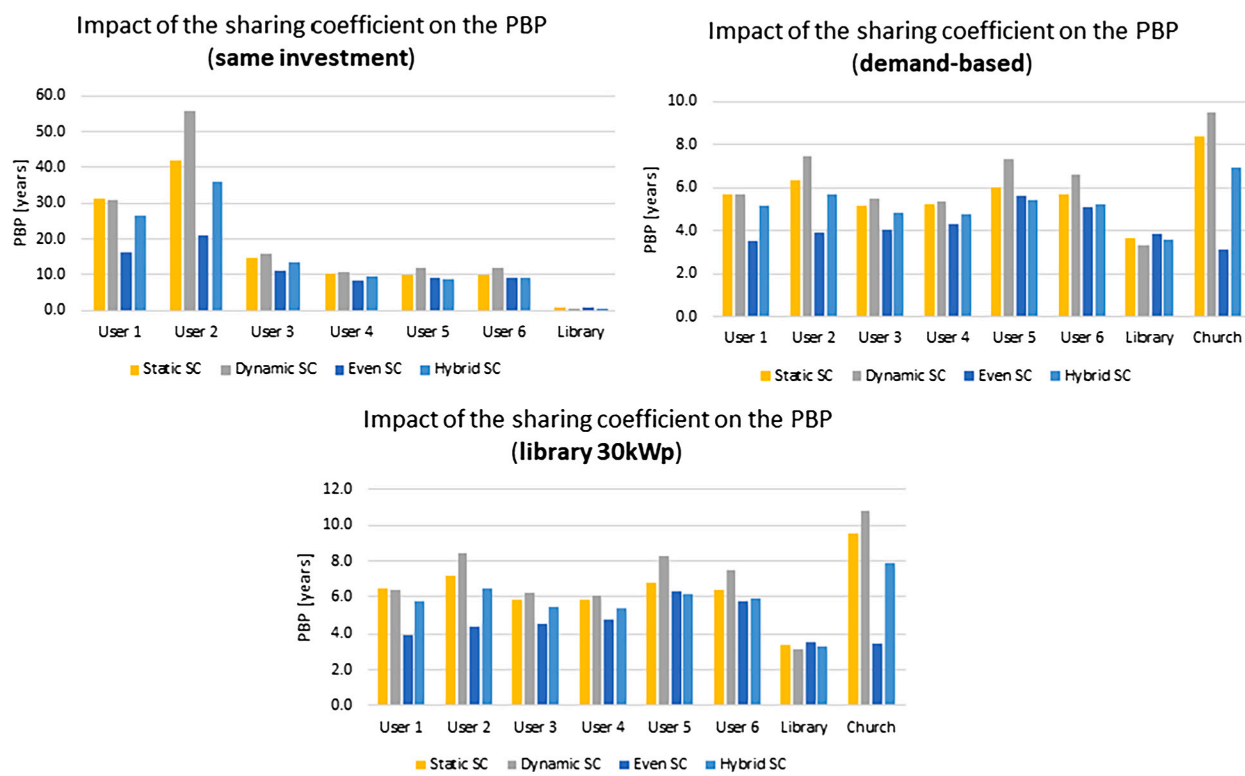


Fig. 15. Payback periods (PBP) in scenario 2.

The following paragraphs will discuss additional topics and limitations.

First, it is possible that the applied sharing coefficient leads to changes in the energy usage behaviour of households, which might change the generated savings of the member. For example, with the static sharing coefficient, it is likely that some households have excess electricity, due to a higher share of assigned electricity than their demand, while others do not get enough to cover their electricity need. In our setup, households with excess electricity sell it directly to the grid, although other households in the community could use it. This is the main difference to the hybrid sharing coefficient where distributing excess electricity to other community members is possible. As a result, when an EC applies the static sharing coefficient households could use smart energy consumption tools that, for example, switch on the washing machine when excess electricity is available. However, including this possibility would be beyond the scope of the paper, as this would need an additional optimization algorithm that maximizes the savings of EC members. Nevertheless, this topic leaves room for further research.

Second, another important issue that has to be considered is that the data of the library were collected from another location than the remaining EC members. Due to the fact that in the Spanish pilot area no data for commercial entities with a high demand was available, we had to use data from the pilot side in Croatia. In addition, the recording periods differ. The data of the residential members and the church were recorded from 01/2021 to 12/2021 and library data were collected from 08/22 to 08/2023. This can lead to slightly different results than when using data from the same area, as for example the electricity demand might differ according to other weather conditions of the area. For example, during a very hot day in Spain the remaining members have a higher electricity demand because of an increased usage of an air condition which is not reflected in the load profile of the library when the same day was cooler in Croatia (and the other way around). In addition, it might also be possible that the COVID pandemic and country specific regulations impacted the load profile in contrast to a situation when no pandemic takes place.

Third, another limitation of this analysis is that we assumed that electricity prices and the demand of the community members stay constant over the lifetime of the PV plant. We decided to do this for two reasons. First, at the moment it is very unclear how the electricity prices will change in the upcoming years as a result of the situation of Ukrainian war. Second, increasing electricity prices would clearly influence the expected savings as the higher the electricity price are, the higher are the estimated savings.

Another drawback of this study is that we only investigate two energy community setups located in Spain. In general, Spain has very beneficial premises for photovoltaic investment, and so it is very likely that the results are worse when analysing sharing coefficients in another European country. In addition, no grid tariffs are applied within the 500 m radius of an energy community. In contrast, other countries have no or only limited reductions in the grid tariffs when electricity is shared within an energy community. Overall, a country comparison would have gone beyond the scope of this paper, although the simulation model would be able to analyse any type of energy community in any country. Future research may extend this analysis and compare different European countries and their national framework and how the discussed sharing coefficients differ.

5. Conclusion

The presented study analysed the impact of different sharing coefficients on the economic benefits of the members of an energy community by applying a Monte Carlo simulation approach in combination with a time series approach to simulate load profiles. Summarizing, it could be shown that choice of the sharing coefficients do not have a significant impact on the overall profitability of an energy community, but highly impacts the individual economic benefits of the members.

It is shown that the total electricity consumed and sold within the community, and therefore also the SCR and SSR, do not differ between the dynamic, hybrid or even sharing coefficient. The only sharing coefficient that allows for a slightly lower exchange is the static sharing coefficient. However, for individual member savings, the chosen sharing coefficient impacts the results. There are considerable differences between the analysed EC setups, which are a residential member only setup and a residential and commercial member setup. The average savings of the residential members are significantly lower in the mixed setup, except when the even sharing coefficient is applied, as this sharing coefficient benefits low demand members. The same is true when comparing the SSRs of the households. Overall, the results show that for residential members, it only makes sense to form an energy community with commercial members when the even sharing coefficient is applied. This implies that in a real-world energy community, a sharing coefficient similar to the even sharing coefficient would be necessary to form mixed energy communities. This is essential, as an energy community with residential and commercial members is more efficient than an energy community only containing households, as the SSR and SCR are significantly higher. This leads to a higher degree of autarky, higher savings and a more efficient use of solar energy.

By using a simulation model in combination with a time series model, we were able to show realistic insights regarding the impact of sharing coefficients. One advantage is that we do not only present a snapshot of a fictive energy community but provide additional insights that are often impossible to discover through real-world experimental and theoretical analysis alone. The analysis does not only show the distribution of the expected savings of each member, but also by how much the expected savings can vary and what the worst case might be. Especially when talking about renewable energy sources, this is crucial, as the amount of produced energy heavily depends on exogenous factors like the weather.

Summarizing, the presented work contributed to the actual discussion on ECs and which influence the applied sharing coefficient might have on the members. The introduced simulation model as well as the results give additional insights and may be used for further scientific work on energy communities and stakeholders deploying ECs.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Simulation model

We start with the definition of households in an energy community. There are N households which are observed over a time horizon T. In this setup there is only one big PV plant where the production is defined as $S_{EC}(t)$. Each household has an electricity demand at each point in time presented by $D_n(t)$ and can consume produced electricity of the PV plant. This consumed electricity is defined as $C_n(t) = min(D_n(t), S_{EC}(t) * \delta_n)$ where δ_n defines the share of the produced electricity the household can use. In addition, $D_{EC}(t)$ defines the demand of an energy community at point in time t which can be presented as

$$D_{EC}(t) = \sum_{n=1}^{N} D_n(t). \tag{A1}$$

The overall demand and supply of the community over the observed time horizon is denoted as

$$\begin{aligned} S_{EC} &= \sum_{t=1}^{T} S_{EC}(t) \\ D_{EC} &= \sum_{t=1}^{T}\sum_{n=1}^{N} D_n(t). \end{aligned} \tag{A2}$$

There are five different electricity prices: (i) the normal grid tariff depending on the hour in which the electricity is needed (P_{Grid}), (ii) the price a member receives when selling electricity to the grid (P_{FI}), (iii) the price a member pays when receiving electricity directly from the EC, (iv) the price a member receives when selling electricity to the community (P_{Sold}), and (v) the price a member pays when buying electricity from other members (P_{Buy}). The bill of the energy community members is defined as follows

$$B_n = \sum_{t=1}^{T} C_n(t) \cdot P_{EC}(t) + CE_{n,Buy}(t) + GE_{n,Buy}(t) + CE_{n,Sell}(t) + GE_{n,Sell}(t) \tag{A3}$$

where $C_n(t)$ is the electricity directly consumed from the PV, $CE_{n,Buy}(t)$ and $CE_{n,sell}(t)$ are the costs and revenues of buying or selling in the community and $GE_{n,Buy}(t)$ and $GE_{n,Sell}(t)$ are the costs and revenues from buying or selling to the grid. These are defined as

$$CE_{n,Buy}(t) = R_n(t) \cdot R^n_{IMP}(t) \cdot P_{Buy}(t) \tag{A4}$$

$$GE_{n,Buy}(t) = R_n(t) \cdot R^n_{IMP}(t) \cdot P_{Grid}(t) \tag{A5}$$

$$CE_{n,Sell}(t) = R_n(t) \cdot R^n_{EXP}(t) \cdot P_{Sold}(t) \tag{A6}$$

$$GE_{n,Sell}(t) = (R_n(t) \cdot R^n_{EXP}(t) \cdot P_{FI}(t) \tag{A7}$$

where $R_n(t)$ represents the remaining electricity of each household and has a negative value if excess electricity is available and a positive value if the household still needs electricity. In addition, $R^n_{IMP}(t)$ has the value 1 if the household has to import electricity and otherwise 0 and $R^n_{EXP}(t)$ has the value 1 if the household has excess electricity and otherwise 0.

A.1. Static and dynamic sharing coefficients

In this simulation setup the households get a certain share ($\delta \in [0,1]$) of the production. The remaining electricity at point in time t that the consumer needs are defined as

$$R_n(t) = D_n(t) - \delta_n(t) \cdot S_{EC}(t). \tag{A8}$$

The sharing parameter δ depends on the yearly (static) or hourly (dynamic) demand of the member and has following forms

$$\begin{aligned} Static : \delta_n &= \frac{D_n^{yearly}}{D_{EC}^{yearly}} \\ Dynamic : \delta_n(t) &= \frac{D_n(t)}{D_{EC}(t)}. \end{aligned} \tag{A9}$$

Depending on the sharing coefficient δ, $R_n(t)$ can be positive or negative. If $R_n(t)$ is negative, it means that the share of the production is larger than the electricity demand and the excess electricity will be sold at market price ($P_{FI}(t)$) to the grid. If $R_n(t)$ is positive, the households have a higher electricity demand than the produced electricity and have to buy electricity from the grid at price $P_{Grid}(t)$. This means if

$$\begin{aligned} R_n(t) > 0 &\rightarrow R^n_{IMP}(t) = 1 \\ R_n(t) <= 0 &\rightarrow R^n_{EXP}(t) = 1. \end{aligned} \tag{A10}$$

$R^n_{IMP}(t)$ and $R^n_{EXP}(t)$ have length T and the value 1 or 0 depending on the sign of $R_n(t)$. Therefore, the consumed electricity from the power plant is defined as

$$C_n(t) = min\{D_n(t), S_{EC}(t) \cdot \delta_n(t)\}. \tag{A11}$$

The electricity bill of household n has the following form

$$B_n = \sum_{t=1}^{T} C_n(t) \cdot P_{EC}(t) + GE_{n,Buy}(t) + GE_{n,Sell}(t). \tag{A12}$$

The reference scenario for the households is given by

$$B_n^{Ref} = \sum_{t=1}^{T} D_n(t) \cdot P_{Grid}(t). \tag{A13}$$

A.2. Hybrid sharing coefficient

Next, we show the case when the hybrid sharing coefficient is applied. This implies that the excess electricity can be shared within the community. Therefore, $R_n(t)$ has the form

$$R_n(t) = D_n(t) - \delta_n(t) S_{EC}(t), \tag{A14}$$

where $C_n(t)$ is defined in the same way as for the dynamic and static sharing coefficient. The only difference is that $\delta_n(t)$ is different. In this setup δ_n depends on the investment costs of the community member

$$\delta_n(t) = \frac{Investment_n}{\sum_{i=1}^{N} Investment_i}. \tag{A15}$$

The variables $R^n_{EXP}(t)$ and $R^n_{IMP}(t)$ are defined in the same way as before. Overall, the billing scheme of household n at time t is defined as

$$B_n = \sum_{t=1}^{T} C_n(t) \cdot P_{EC}(t) + CE_{n,Buy}(t) + GE_{n,Buy}(t) + CE_{n,Sell}(t) + GE_{n,Sell}(t). \tag{A16}$$

Here the costs and revenues of selling and buying electricity become

$$CE_{n,Buy}(t) = \alpha_n \cdot R_n(t) \cdot R^n_{IMP}(t) \cdot P_{Buy}(t) \tag{A17}$$

$$GE_{n,Buy}(t) = (1 - \alpha_n) \cdot R_n(t) \cdot R^n_{IMP}(t) \cdot P_{Grid}(t) \tag{A18}$$

$$CE_{n,Sell}(t) = \gamma_n \cdot R_n(t) \cdot R^n_{EXP}(t) \cdot P_{Sold}(t) \tag{A19}$$

$$GE_{n,Sell}(t) = (1 - \gamma_n) \cdot R_n(t) \cdot R^n_{EXP}(t) \cdot P_{FI}(t), \tag{A20}$$

where α and γ depend on the amount of electricity the energy community needs or has to sell. In this setup, two additional parameters regulate how much of the excess electricity is sold to other members (γ) and how much electricity is sold to the grid (α). These parameters are necessary to assure that each member has the same right to sell electricity to the community as $P_{Sold} > P_{FI}$. That means three cases are possible which define the values of α and γ:

1. Electricity still needed equals the available electricity which implies that
$C_{Needed}(t) = C_{Excess}(t)$.
2. Electricity still needed is smaller than the available electricity which implies that
$C_{Needed} < C_{Excess}(t)(t)$.
3. Electricity still needed is larger than the available electricity which implies that
$C_{Needed}(t) > C_{Excess}(t)$.

Therefore, we need to know the available and needed electricity in the community, which are given by

$$C_{Excess}(t) = -\sum_{n=1}^{N} R_n(t) \cdot R^n_{EXP}(t) \tag{A21}$$

and

$$C_{Needed}(t) = \sum_{n=1}^{N} R_n(t) \cdot R^n_{IMP}(t). \tag{A22}$$

A.2.1. $C_{Excess}(t) = C_{Needed}(t)$

Again, α_n and γ_n are equal to 1 and the bill at this point in time is reduced to

$$B_{nBuyer}(t) = C_n(t) \cdot P_{EC}(t) + CE_{n,Sell}(t) \tag{A23}$$

$$B_{nSeller}(t) = C_n(t) \cdot P_{EC}(t) + CE_{n,Sell}(t). \tag{A24}$$

A.2.2. $C_{Excess}(t) > C_{Needed}(t)$

Here, α has the value 1 while the value of γ depends on the excess electricity. The bill of household n at time t has the following form

$$B_n(t) = C_n(t) \cdot P_{EC}(t) + CE_{n,Buy}(t) - (CE_{n,Sell}(t) + GE_{n,Sell}(t)). \tag{A25}$$

Here, we have to define a sharing parameter to determine which amount of the excess electricity of a household is used in the community and which part is sold to the grid. As one can charge a higher price within the community than the market price each member wants to sell as much as possible in the community. Therefore, a fair sharing parameter is needed and so we assume that each household sells the same amount of its excess electricity to the community and to the grid. For this, we define the parameter γ

$$\gamma = \frac{C_{Needed}(t)}{C_{Excess}(t)}. \tag{A26}$$

A.2.3. $C_{Excess}(t) < C_{Needed}(t)$

Here γ has the value 1 while the value of α depends on the available electricity. The bill of household n at time t has the following form

$$B_n(t) = C_n(t) \cdot P_{EC}(t) + CE_{n,Buy}(t) + GE_{n,Buy}(t) - CE_{n,Sell}(t). \tag{A27}$$

We have to define a sharing parameter to determine which amount of the excess electricity of a household can be bought from the community and which part of the needed electricity has to be bought from the grid. As the price within the community is lower than the grid price each member wants to buy as much as possible from the community. To have a fair sharing parameter we assume that each household buys the needed amount of electricity from the community and the grid. Here, we present three possible definitions of the sharing parameter α. Again, α can be defined as equal percentage of the need that can be served by the community. In this case, α is defined by

$$\alpha = \frac{C_{Excess}(t)}{C_{Needed}(t)} \tag{A28}$$

Reference scenario for the households

$$B_n^{Ref} = \sum_{t=1}^{T} D_n(t) \cdot P_{Grid}(t) \tag{A29}$$

$$B_n^{Ref\,PV}(t) = \sum_{t=1}^{T} C_n(t) \cdot P_{EC}(t) + GE_{n,Buy}(t) - GE_{n,Sell}(t). \tag{A30}$$

A.3. Even sharing coefficient

In this setup, the produced electricity is distributed dependent on the lowest demand. The members receive electricity depending on their electricity need in kWh and there are several rounds until all member's electricity needs are satisfied or the entire produced electricity is distributed. In the first step, each member gets the same amount of electricity which is the smallest demand at time t ($min\{D_n(t)\}$) or the entire production divided by the number of members N ($\frac{S_{EC}(t)}{N}$). If

$$\frac{S_{EC}(t)}{N} \cdot N > min(D_n(t)) \cdot N \tag{A31}$$

all members get electricity equal to the smallest demand of the energy community ($min\{D_n(t)\}$). In contrast, if

$$\frac{S_{EC}(t)}{N} \cdot N < min(D_n(t)) \cdot N \tag{A32}$$

there is not enough electricity to give all members $min\{D_n(t)\}$ and therefore production is divided by the number of members ($\frac{S_{EC}(t)}{N}$). After that, the algorithm checks if all members are served or if the entire production is distributed. If not, the next round starts. This is repeated until no member needs any more electricity or until the entire production is distributed. In the case where all members are served and there is still electricity left, the excess electricity is sold to the grid. The revenues from the feed-in are equally distributed among all members at the end of the billing period. The algorithm of this sharing coefficient is described in the following pseudo code:

Algorithm 1 Even Sharing Coefficient.

$D_n(t)' \leftarrow D_n(t)$
$S'_{EC} \leftarrow S_{EC}(t)$
loop over all time steps t:
min value $\leftarrow$ 10000
wert $\leftarrow$ 0
while $S'_{EC}(t) > 0$ and $sum(D'_n(t) > 0)$ **do**
loop over all members n to find the minimum demand:
  if $D_n(t)' = 0$ **then**
    next
  wert $\leftarrow$ wert + 1
  if $D_n(t)' <$ min value **then**
    min value $\leftarrow D_n(t)'$
loop over all members n to share the electricity:
  if $D_n(t)' = 0$ **then**
    next
  $D_n(t)' \leftarrow D_n(t)'t - min(\frac{S'_{EC}(t)}{wert}, \text{minvalue})$
  $S'_{EC}(t) \leftarrow S'_{EC}(t) - min(\frac{S'_{EC}(t)}{wert}, \text{minvalue}) \cdot wert)$
$B_n(t) \leftarrow D_n(t)'t \cdot Price_{Grid} + (D_n(t) - D_n(t)'t) \cdot Price_{EC}$
$B_n^{Ref}(t) \leftarrow D_n(t) \cdot Price_{Grid}$

The electricity bill of household n has the following form

$$B_n = \sum_{t=1}^{T} C_n(t) \cdot P_{EC}(t) + GE_{n,Buy}(t) + \frac{S_{EC}(t)' \cdot P_{FI}(t)}{N} \tag{A33}$$

where $S_{EC}(t)'$ is the remaining electricity of the production which is sold to the grid. When using the even sharing coefficient the revenues from the feed-in of the excess electricity are equally split among the members. Reference scenario for the households

$$B_n^{Ref} = \sum_{t=1}^{T} D_n(t) \cdot P_{Grid}(t). \tag{A34}$$

Nomenclature

P_{Grid}	Price of electricity from the grid
P_{FI}	Price of electricity when fed in
P_{Sold}	Price when selling to community members
P_{Buy}	Price when buying from community members
P_{EC}	Price of electricity produced by the EC
δ_n	Sharing coefficient of household n
D_n	Electricity demand of household n
D_{EC}	Electricity demand of the EC
S_{EC}	Electricity supply of the EC
S_n	Yearly savings of household n
B_n	Yearly bill/costs of household n
B_n^{Ref}	Yearly reference bill/costs of household n when not being part of the EC
$S_{n,kWh}$	Savings per kWh
SC	Sharing coefficient
E_{Con}	The amount of electricity consumed
E_{Sold}	The amount of electricity sold
$Investment_i$	Investment costs of households n
PBP	Pay back period
SCR	Self-consumption rate
SSR	Self-sufficiency rate
C_{EC}	Yearly total amount of electricity that is consumed by the member
$CE_{n,Buy}$	Costs when buying electricity in the EC
$CE_{n,Sell}$	Revenues when selling electricity in the EC
$GE_{n,Buy}$	Costs when buying electricity from the grid
$GE_{n,Sell}$	Revenues when selling electricity to the grid
R_n	The remaining electricity after receiving electricity according to the sharing coefficient
R^n_{IMP}	Remaining electricity that has to be imported
R^n_{EXP}	Excess electricity that can be sold to other members or the grid
α, γ	Parameters that regulate how much of the excess electricity is sold to other members and how much electricity is sold to the grid
C_{Needed}	Total remaining electricity the EC needs after sharing electricity
C_{Excess}	Total excess electricity the EC has left over after sharing electricity
$B_{n,Buyer}$	Bill of the buyer in the EC
$B_{n,Seller}$	Bill of the seller in the EC
C_n	Electricity that member n directly consumes from the PV
$C_{n,total}$	Total electricity that member n receives from the EC

Appendix B. Figures and tables

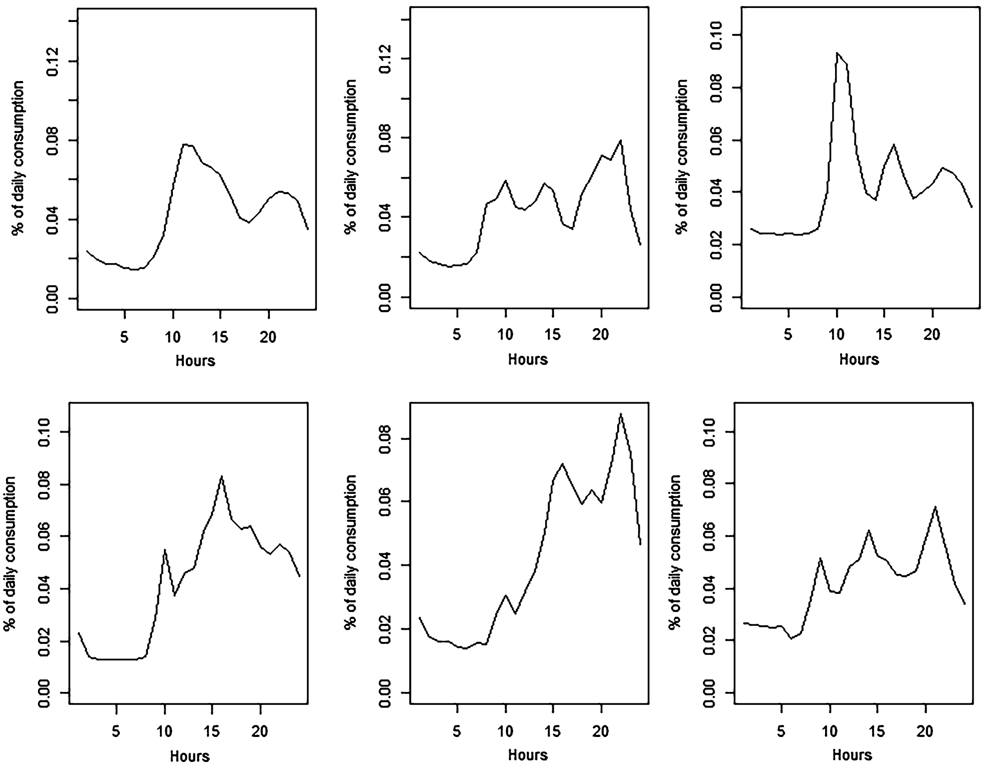

Fig. B.1. Average day - Household 1 (upper left), Household 2 (upper middle), Household 3 (upper right), Household 4 (lower left), Household 5 (lower middle), Household 6 (lower right).

Table B.1
Overview of the savings in scenario 1.

	H1	H2	H3	H4	H5	H6
Static						
Minimum	414.92	364.64	682.23	839.66	910.14	878.68
1st Quartile	463.33	398.94	736.31	953.61	1,003.14	974.11
Median	481.50	414.36	762.85	992.89	1,044.89	1,012.54
3rd Quartile	500.50	430.74	790.60	1,033.78	1,088.18	1053.86
Maximum	557.80	474.09	853.82	1,187.28	1,221.50	1173.46
Dynamic						
Minimum	479.90	371.08	760.36	891.78	837.49	867.40
1st Quartile	541.03	414.75	822.51	1,032.14	931.32	974.71
Median	561.25	429.66	851.40	1,072.43	965.42	1,010.39
3rd Quartile	581.83	445.52	881.89	1,114.03	1,000.67	1,047.57
Maximum	663.87	497.00	953.86	1,270.35	1,128.84	1,184.00
Hybrid						
Minimum	457.24	393.22	722.24	915.79	978.15	939.00
1st Quartile	490.97	419.35	761.91	994.65	1,045.92	1,012.48
Median	507.33	433.67	787.11	1,029.87	1,085.56	1,048.05
3rd Quartile	524.53	448.81	812.97	1,066.55	1,127.13	1,086.27
Maximum	569.20	478.00	856.72	1,171.54	1,205.32	1,174.77
Even						
Minimum	550.90	471.94	752.33	866.55	821.77	830.85
1st Quartile	605.25	515.03	802.48	975.66	900.34	923.18
Median	629.22	539.03	828.78	1,007.65	932.17	954.28
3rd Quartile	655.71	564.37	855.93	1,040.87	965.28	985.97
Maximum	720.23	614.73	910.95	1,166.14	1,049.64	1,080.25

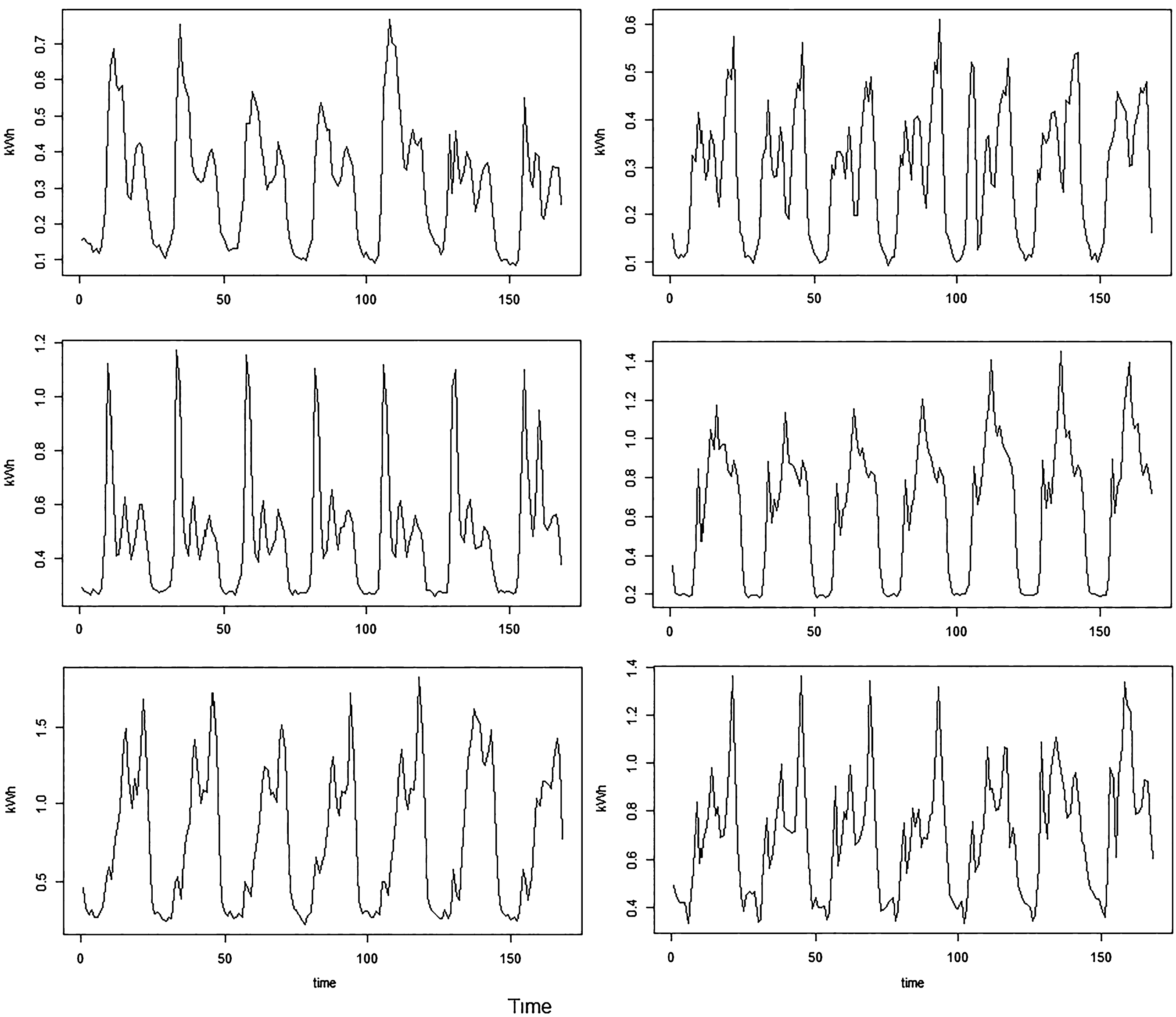

Fig. B.2. Average week - household 1 (upper left), household 2 (upper right), household 3 (middle left), household 4 (middle right), household 5 (lower left), household 6 (lower right).

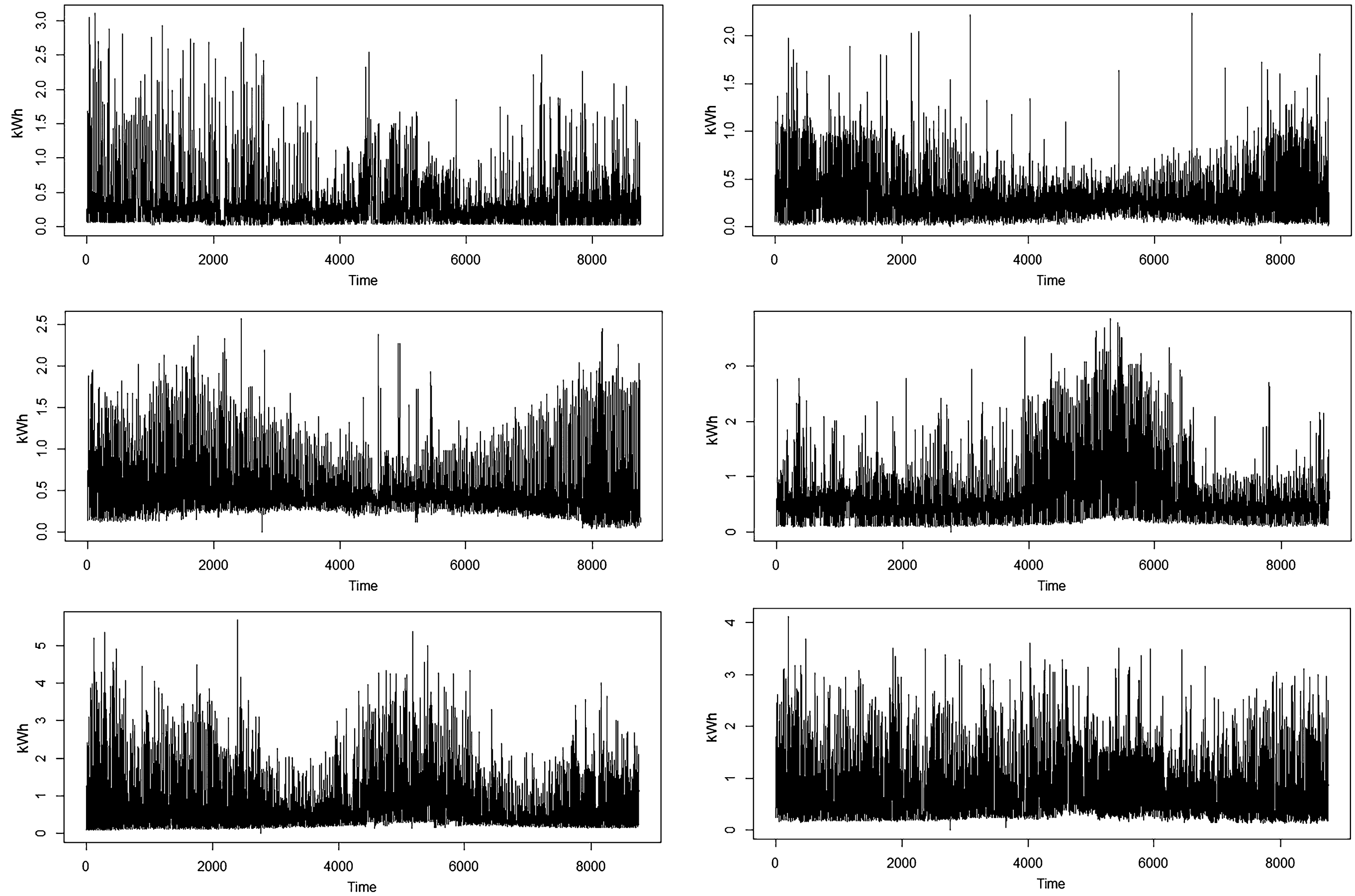

Fig. B.3. Yearly consumption - household 1 (upper left), household 2 (upper right), household 3 (middle left), household 4 (middle right), household 5 (lower left), household 6 (lower right).

Table B.2
Overview of the savings in scenario 2.

	H1	H2	H3	H4	H5	H6	church	library
Static								
Minimum	370.93	332.46	626.21	724.85	824.23	783.19	174.42	9,938.92
1st Quartile	421.08	362.93	673.04	865.70	906.79	884.15	191.43	10,541.58
Median	437.63	376.85	697.66	902.29	944.38	919.12	199.98	10,965.66
3rd Quartile	454.75	391.45	723.19	940.01	982.76	955.78	208.87	11,376.12
Maximum	503.85	427.28	779.22	1,087.89	1,092.93	1,072.82	229.73	11,997.07
Dynamic								
Minimum	370.18	288.22	587.49	723.95	675.87	687.16	163.39	10,993.50
1st Quartile	425.38	323.64	639.82	843.33	776.55	784.01	179.97	11,555.15
Median	440.14	334.97	661.28	876.12	804.57	812.54	186.10	11,931.29
3rd Quartile	455.64	346.48	682.88	909.69	832.73	841.49	192.33	12,303.77
Maximum	524.49	391.64	742.07	1,061.38	929.28	956.42	211.38	12,947.17
Hybrid								
Minimum	431.42	374.62	683.95	863.68	947.48	902.06	207.74	10,239.33
1st Quartile	463.63	396.91	717.33	943.42	1,004.28	961.00	219.42	10,831.65
Median	475.81	406.47	736.02	969.52	1,029.65	985.37	224.82	11,221.58
3rd Quartile	488.97	417.08	755.83	997.99	1,057.72	1,012.68	230.92	11,600.64
Maximum	522.09	442.03	793.51	1,094.86	1,120.05	1,079.87	244.44	12,191.18
Even								
Minimum	540.52	458.65	756.68	888.54	863.34	856.84	317.89	9,761.26
1st Quartile	606.69	512.76	819.03	1,022.45	960.67	967.21	364.42	10,283.62
Median	644.16	550.55	858.48	1,065.87	1,003.04	1,008.51	401.85	10,517.87
3rd Quartile	686.39	592.35	901.04	1,110.84	1,049.63	1,053.80	442.59	10,722.21
Maximum	768.15	656.83	976.76	1,276.99	1,167.38	1,176.46	504.57	11,193.01

Table B.3
Yearly savings of the static and dynamic sharing coefficient in scenario 1 - 5% quantile of the VaR analysis.

Year	Static						Dynamic					
	H1	H2	H3	H4	H5	H6	H1	H2	H3	H4	H5	H6
1	499.53	432.62	799.30	1,011.34	1,097.00	1,054.91	574.41	442.36	890.15	1,086.32	996.34	1,032.44
2	495.37	430.39	795.70	1,002.71	1,088.81	1,048.79	571.75	441.64	884.80	1,075.99	990.82	1,025.39
3	493.60	428.26	791.65	999.32	1,083.38	1,040.22	569.01	437.55	879.92	1,075.97	979.45	1,020.13
4	491.66	424.95	788.26	992.58	1,073.60	1,034.44	563.83	436.43	875.58	1,069.22	980.64	1,013.29
5	487.22	423.34	783.25	986.88	1,067.79	1,024.92	560.50	432.57	868.99	1,064.44	972.18	1,010.62
6	484.96	419.07	777.94	986.68	1,062.11	1,022.46	557.72	430.26	865.74	1,055.20	965.25	1,006.98
7	481.33	416.51	774.39	977.06	1,055.08	1,012.73	554.08	428.10	861.01	1,049.85	959.57	1,000.92
8	479.40	414.76	768.96	975.67	1,046.97	1,007.14	550.16	424.45	855.84	1,043.45	955.21	995.09
9	476.86	411.79	765.04	962.77	1,042.23	1,003.32	550.93	423.87	850.56	1,034.34	951.53	987.58
10	472.71	409.80	759.35	959.73	1,032.92	993.48	544.07	422.07	845.01	1,031.44	943.17	983.54
11	470.39	406.23	755.77	956.58	1,026.89	989.26	541.23	418.29	840.01	1,026.57	938.48	979.04
12	467.65	404.22	751.25	945.40	1,022.78	982.75	539.47	414.99	835.77	1,016.98	933.66	969.46
13	463.57	402.00	747.95	945.58	1,012.00	978.70	536.03	413.73	830.06	1,015.00	929.01	964.33
14	462.19	398.93	742.86	934.73	1,005.87	969.09	533.81	410.96	824.62	1,008.67	925.14	961.03
15	458.32	397.76	739.65	930.12	1,001.03	962.33	529.49	408.48	821.52	1,003.47	920.44	953.55
16	457.30	394.50	735.69	922.12	992.97	960.46	527.21	407.19	818.01	997.45	911.47	953.45
17	453.69	392.12	730.84	918.79	987.55	950.60	525.34	404.54	811.79	989.42	910.54	947.51
18	450.59	389.52	726.63	912.49	981.41	949.07	520.57	402.53	808.65	985.77	901.68	941.66
19	447.68	387.86	723.02	910.15	973.75	939.88	517.74	400.43	804.76	980.10	898.21	933.80
20	445.40	385.66	717.22	904.30	969.39	937.18	514.94	397.41	799.30	972.30	893.06	931.23
21	442.70	382.67	714.93	897.14	961.58	930.55	513.71	396.32	794.88	970.57	889.63	924.02
22	439.24	381.08	710.74	892.56	957.29	922.55	510.12	394.28	791.09	965.83	886.21	920.36
23	437.08	378.37	706.48	884.02	952.80	916.31	508.25	391.48	785.84	961.66	878.62	914.69
24	433.19	375.82	702.07	883.96	945.87	912.92	503.73	390.05	782.38	955.10	873.61	908.71
25	432.92	374.32	698.04	878.75	938.54	905.22	502.08	387.23	777.38	951.75	869.94	904.35

Table B.4
Yearly savings of the hybrid and even sharing coefficient in scenario 1 - 5% quantile of the VaR analysis.

Year	Hybrid						Even					
	H1	H2	H3	H4	H5	H6	H1	H2	H3	H4	H5	H6
1	529.71	455.42	827.46	1,070.64	1,146.54	1,098.48	661.70	576.94	869.56	1,022.32	968.29	979.25
2	526.87	452.79	823.04	1,065.06	1,139.41	1,091.20	657.11	572.38	862.50	1,020.06	964.45	975.64
3	524.07	450.75	818.80	1,058.51	1,133.84	1,085.84	652.42	568.01	858.77	1,007.94	956.60	969.22
4	521.17	448.17	813.79	1,051.92	1,126.45	1,081.06	648.16	563.73	854.40	1,007.36	952.25	964.16
5	518.03	445.73	809.95	1,046.34	1,119.16	1,073.81	644.96	559.40	849.28	1,001.70	947.59	958.78
6	515.18	443.09	806.39	1,041.97	1,113.08	1,067.78	639.10	555.69	845.74	998.33	942.06	953.44
7	512.96	440.33	801.11	1,034.92	1,105.25	1,061.15	635.87	551.32	839.73	993.14	934.99	950.67
8	510.02	437.73	797.20	1,030.22	1,099.70	1,056.30	630.89	547.11	836.93	988.74	932.28	946.91
9	506.71	435.66	793.66	1,024.47	1,092.50	1,049.87	626.84	543.38	831.65	979.43	925.61	940.10
10	504.22	433.11	789.04	1,015.71	1,086.83	1,043.94	623.32	538.41	827.37	975.55	919.89	934.99
11	501.79	431.04	785.11	1,011.86	1,079.98	1,037.85	618.28	534.88	823.15	974.25	914.79	929.84
12	499.36	428.46	780.38	1,008.61	1,074.50	1,031.36	615.14	530.49	818.81	969.10	909.45	925.67
13	496.88	426.12	777.25	1,001.16	1,067.55	1,024.96	611.36	527.44	813.60	965.37	906.98	921.73
14	494.21	423.74	772.59	994.72	1,060.95	1,020.62	605.82	522.42	809.41	956.00	899.74	915.95
15	491.76	421.24	769.04	990.82	1,053.55	1,014.51	602.97	518.30	805.95	954.89	894.29	912.71
16	488.03	418.92	765.35	984.35	1,049.30	1,009.39	600.54	515.59	801.40	952.00	888.86	906.52
17	486.22	416.76	760.94	980.98	1,042.38	1,004.06	595.33	511.35	798.53	943.88	884.14	901.26
18	483.37	414.55	756.72	972.89	1,036.02	998.89	591.30	507.32	793.86	937.96	879.67	896.85
19	481.51	412.79	753.10	970.04	1,031.30	992.00	586.46	505.35	788.57	939.69	875.65	892.68
20	478.52	410.61	749.50	962.78	1,023.78	986.22	583.99	500.20	784.99	931.04	871.57	885.83
21	475.67	407.71	745.94	957.43	1,016.76	980.19	580.24	496.15	780.99	927.22	865.75	884.80
22	473.90	406.24	741.43	951.84	1,011.77	973.41	575.30	493.68	776.82	924.34	858.85	878.90
23	470.87	404.02	737.93	947.17	1,005.27	969.41	572.08	490.53	772.93	917.98	853.91	871.41
24	468.50	401.46	734.60	941.05	999.84	963.70	569.27	485.99	769.22	913.29	850.94	867.39
25	466.03	399.31	729.49	935.92	993.41	957.81	565.79	482.20	766.27	907.91	846.13	863.97

Table B.5
Yearly savings of the static sharing coefficient in scenario 1 - 5% quantile of the VaR analysis.

Year	Static							
	H1	H2	H3	H4	H5	H6	Lib	Church
1	454.92	393.31	732.95	917.25	988.96	950.04	11,623.51	211.89
2	451.41	390.01	729.91	911.02	982.49	948.01	11,570.02	210.75
3	448.30	388.62	725.45	905.54	973.33	941.13	11,483.57	209.34
4	445.68	386.01	720.57	903.62	968.03	936.89	11,433.93	207.83
5	443.33	384.30	716.22	894.33	964.69	927.42	11,359.95	206.57
6	441.09	381.79	713.01	890.33	955.78	922.66	11,294.87	204.73
7	437.70	379.23	709.69	884.40	949.34	917.65	11,235.78	203.44
8	435.45	377.53	706.02	879.85	944.57	910.97	11,173.55	202.11
9	432.96	375.05	701.68	872.47	939.53	902.90	11,104.11	200.64
10	430.89	372.42	696.87	864.63	931.96	901.79	11,042.58	199.07
11	427.69	370.18	693.08	863.40	926.71	893.00	10,980.49	197.99
12	424.27	368.20	688.39	857.76	918.97	890.28	10,902.55	196.49
13	422.32	365.74	684.89	850.72	913.00	884.32	10,845.51	195.22
14	420.30	364.63	681.43	847.43	908.57	877.74	10,771.23	193.91
15	416.96	361.98	677.26	841.86	900.40	873.39	10,707.09	192.52
16	415.83	360.03	673.67	835.27	897.89	867.76	10,638.80	190.84
17	411.28	357.03	669.68	831.02	891.84	863.65	10,569.10	189.83
18	409.96	354.70	665.89	827.12	885.77	856.89	10,508.00	188.71
19	407.58	353.26	661.80	823.18	878.87	853.43	10,436.85	187.64
20	405.22	350.46	657.22	818.88	874.61	847.74	10,367.33	185.87
21	401.79	348.97	653.87	812.41	869.11	842.99	10,300.03	184.58
22	399.11	346.26	649.87	807.30	863.83	835.22	10,228.28	183.38
23	396.59	344.13	645.98	801.99	856.99	833.43	10,160.11	181.97
24	394.10	342.06	642.59	798.00	852.66	826.86	10,084.51	180.60
25	392.60	340.56	639.17	794.47	844.86	820.24	10,019.38	179.37

Table B.6
Yearly savings of the dynamic sharing coefficient in scenario 2 - 5% quantile of the VaR analysis.

Year	Dynamic							
	H1	H2	H3	H4	H5	H6	Lib	Church
1	446.08	342.95	685.60	873.67	819.59	822.01	12,524.58	191.76
2	443.96	340.63	682.96	870.26	815.86	819.46	12,463.72	190.46
3	440.86	339.19	679.85	868.82	811.42	815.34	12,405.18	189.33
4	437.92	337.17	676.57	861.93	808.67	809.72	12,335.46	188.39
5	436.48	335.67	671.70	856.44	803.86	805.40	12,278.84	187.62
6	433.43	334.25	668.83	851.37	800.83	801.59	12,209.25	186.45
7	431.15	332.52	664.47	846.11	796.64	796.91	12,151.01	185.94
8	429.80	331.02	662.20	842.88	792.23	795.04	12,102.36	184.41
9	428.49	329.58	657.92	841.25	786.99	791.32	12,037.90	183.23
10	424.84	327.03	654.70	835.20	783.92	783.94	11,975.51	182.98
11	423.40	325.46	651.99	832.94	778.89	780.73	11,927.66	181.87
12	421.04	323.94	647.71	827.31	775.71	778.47	11,855.67	181.37
13	419.98	321.91	645.30	824.82	771.11	774.82	11,803.29	179.94
14	417.57	320.51	642.53	818.86	766.92	772.65	11,735.97	178.77
15	415.41	318.38	638.49	812.59	760.93	767.11	11,692.50	178.23
16	412.33	317.30	634.63	811.99	758.95	761.51	11,622.44	177.05
17	410.88	315.94	631.92	806.53	755.36	757.05	11,544.79	176.38
18	409.41	313.27	628.52	800.22	751.27	752.52	11,508.05	175.34
19	407.84	312.82	625.66	795.77	747.98	748.49	11,444.12	174.50
20	404.11	310.28	621.26	789.63	743.79	742.59	11,392.69	173.39
21	402.87	308.46	618.39	790.46	739.68	740.58	11,322.79	172.15
22	400.34	306.82	617.08	784.74	734.89	735.85	11,261.43	171.67
23	398.02	305.07	611.86	780.15	729.71	733.23	11,198.92	169.95
24	395.92	303.14	608.28	778.89	724.78	727.35	11,138.96	169.70
25	394.07	302.65	606.09	770.14	719.60	723.68	11,087.18	168.66

Table B.7
Yearly savings of the hybrid sharing coefficient in scenario 2 - 5% quantile of the VaR analysis.

Year	Hybrid							
	H1	H2	H3	H4	H5	H6	Lib	Church
1	491.56	420.78	766.21	997.45	1,068.82	1,018.10	11,826.23	233.67
2	489.52	418.65	762.28	991.66	1,062.94	1,013.12	11,768.19	232.57
3	486.52	416.99	759.04	988.30	1,058.27	1,007.19	11,716.87	231.66
4	484.71	415.17	756.00	984.72	1,053.42	1,003.80	11,652.42	230.52
5	482.96	413.07	752.28	979.43	1,048.00	999.63	11,586.33	229.31
6	480.69	411.52	748.44	975.02	1,043.52	995.02	11,534.46	228.30
7	478.42	409.93	744.92	968.85	1,039.07	990.50	11,476.20	227.49
8	475.46	408.27	741.77	964.00	1,033.74	985.58	11,410.08	226.23
9	473.68	406.19	739.35	960.39	1,029.62	981.59	11,353.82	225.31
10	471.72	405.15	735.65	955.33	1,025.96	977.34	11,288.56	224.18
11	470.46	402.81	732.96	951.59	1,020.74	973.48	11,233.88	223.15
12	467.78	401.37	729.90	948.12	1,016.50	968.88	11,160.25	222.56
13	466.39	399.58	727.19	945.29	1,011.92	964.85	11,105.83	221.49
14	464.64	398.47	723.94	939.30	1,009.35	961.77	11,054.14	220.57
15	462.06	396.27	720.60	935.29	1,002.84	958.76	10,982.82	219.60
16	460.45	395.24	718.23	933.60	1,000.19	952.86	10,929.71	219.00
17	458.72	393.68	715.20	930.07	995.88	951.95	10,868.13	218.21
18	456.89	392.21	711.97	922.69	992.90	945.76	10,797.21	217.46
19	455.15	390.98	709.73	921.30	989.30	942.03	10,738.83	216.40
20	452.91	389.55	706.18	918.65	986.10	939.20	10,679.76	215.75
21	451.08	387.92	703.86	913.08	982.48	935.22	10,620.58	214.84
22	449.79	386.80	701.00	908.99	978.35	931.64	10,552.30	213.91
23	447.27	384.98	697.96	906.07	974.90	928.49	10,492.42	213.15
24	445.51	383.58	694.66	901.88	970.94	924.30	10,426.85	212.36
25	444.51	382.24	692.86	899.25	966.92	920.90	10,365.67	211.60

Table B.8
Yearly savings of the even sharing coefficient in scenario 2 - 5% quantile of the VaR analysis.

Year	Even							
	H1	H2	H3	H4	H5	H6	Lib	Church
1	707.74	619.81	928.10	1,101.27	1,064.41	1,059.24	10,771.11	475.28
2	700.33	612.88	920.89	1,091.86	1,054.62	1,052.83	10,745.02	467.77
3	689.81	605.62	911.62	1,088.26	1,047.42	1,044.27	10,714.97	461.22
4	685.54	599.20	905.09	1,074.91	1,036.51	1,035.55	10,679.91	454.21
5	677.40	591.16	898.36	1,073.43	1,033.18	1,027.30	10,644.60	446.02
6	670.87	583.98	891.47	1,065.99	1,023.01	1,021.24	10,616.34	440.07
7	663.65	577.43	884.15	1,055.77	1,015.76	1,014.70	10,583.66	432.77
8	657.66	570.21	878.25	1,051.48	1,006.37	1,005.35	10,554.45	425.39
9	649.10	563.63	871.32	1,042.99	999.34	999.11	10,517.80	420.05
10	643.64	556.59	862.74	1,037.35	993.22	992.10	10,484.67	412.93
11	636.89	550.50	856.19	1,027.49	985.62	983.08	10,456.42	406.57
12	630.36	544.54	849.47	1,018.67	978.72	976.89	10,422.97	399.89
13	623.80	536.65	841.55	1,016.08	969.47	971.24	10,390.08	393.46
14	618.36	530.75	835.38	1,011.15	964.20	964.10	10,351.32	388.01
15	613.31	524.81	830.09	998.06	956.55	956.28	10,317.91	381.92
16	605.54	518.41	823.57	994.11	949.20	950.98	10,279.94	375.39
17	599.37	512.80	817.19	986.90	944.10	944.30	10,234.44	370.23
18	594.16	507.63	810.21	980.78	937.62	938.86	10,206.41	364.49
19	587.92	500.99	805.32	973.57	930.37	931.77	10,155.68	358.61
20	582.56	495.62	798.94	967.45	925.08	926.65	10,126.26	352.89
21	575.84	489.42	793.62	963.71	916.65	917.16	10,087.05	347.57
22	570.56	484.57	787.28	959.48	910.73	914.78	10,044.23	341.38
23	565.34	480.07	782.72	951.04	905.98	905.63	10,000.00	337.86
24	561.22	473.96	777.59	944.88	898.15	898.82	9,960.64	331.96
25	554.89	469.84	771.63	943.55	892.08	893.61	9,900.36	326.74

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