# Value sharing in Renewable Energy Communities: an open issue

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***Abstract*—In this document we deal with the issue of value sharing in Renewable Energy Communities (RECs). These are entities composed of multiple end users (general term referring to producers, consumers, prosumers, ...) which are connected to the same public distribution grid, through which they can share energy. Despite being "virtual", this energy sharing can be assumed to reduce the energy exchanged by the REC with the national grid upstream. As such, the sharing of energy is at all effects an asset for the REC. Therefore, as a first approximation, we identify the value of a REC precisely as the energy shared by its members. The latter quantity depends on all the REC members, and it is an open question how to evaluate their contribution to the sharing of energy. In this document we describe a simple model of REC and present two methods to evaluate the contribution of each REC member to the shared energy: one utilizing concepts from game theory, while the other one being an heuristic method based on the knowledge of the system. Through simple and didactic case studies, we show how these two methods work and compare the results obtained in different situations.**

## Disclaimer



## I. Introduction

Renewable Energy Communities (RECs) are entities composed of multiple end users (general term referring to producers, consumers, prosumers, ...) which are connected to the same public distribution grid. These end users inject and/or withdraw energy into the grid through their connection points to the grid. When injections happen simultaneously to withdrawals, the energy produced and injected into the grid is considered to be consumed locally by the REC members.

This concept is defined as *energy sharing*, and the shared energy is defined as the minimum between the total injections and withdrawals. Despite being a virtual energy exchange, it can be assumed that it reduces the energy exchanged by the REC with the national grid upstream. Then, the shared energy can be considered at all effects an asset for the REC, from an energy (self-consumption and self-sufficiency), environmental (consumption of renewable energy) and economical (reduced consumption from the grid) point of view.

It is not clear, however, how to evaluate the contribution that each REC member has in the sharing of energy in the community (i.e., the value of each member). Other than being an open question, this also represents a key issue since it can be the first step in the division of economical benefits (or in the creation of business models) in RECs.

In this work we describe a simple model of REC and present two methods to evaluate the contribution of each member to the value of a REC, that, as a first approximation, is identified as the energy shared in the REC. Then, we apply both methods to simple case studies in order to show how they work, what are their peculiarities and the differences in the results obtained.

## II. Assumptions

**Section highlights**

- A REC is considered as a set of energy nodes connected to the same electricity distribution grid (Figure 1);
- The energy shared in the REC in each time step is the minimum between the total injections and total withdrawals of the nodes part of the REC;
- Energy sharing decreases the REC's exchange with the grid upstream (Figure 2).

We consider a Renewable Energy Community (REC) as a set of energy nodes distributed over the public distribution grid, each of which is identified with a single connection point with the grid (see Figure 1). Nodes inject and/or withdraw energy into/from the grid, which is measured by the meters installed at their connection points with the grid. We denote the injections and withdrawals through a connection point, respectively, $E_{\mathrm{inj}}$ and $E_{\mathrm{with}}$. Naturally, $E_{\mathrm{inj}}$ and $E_{\mathrm{with}}$ *through the same* connection point are mutually-exclusive quantities in the same time instant.

By injecting and withdrawing energy into the grid, the nodes are said to be *sharing* energy with each other. Indeed, the balance between the nodes injections and withdrawals and the energy exchanged with the national grid *upstream*[1] of the

[1]It should be noted that the REC does not own and operate its own distribution grid, therefore there is not a meter that measures the exchanges between the REC and the grid upstream, i.e. the energy exchanges are virtual.

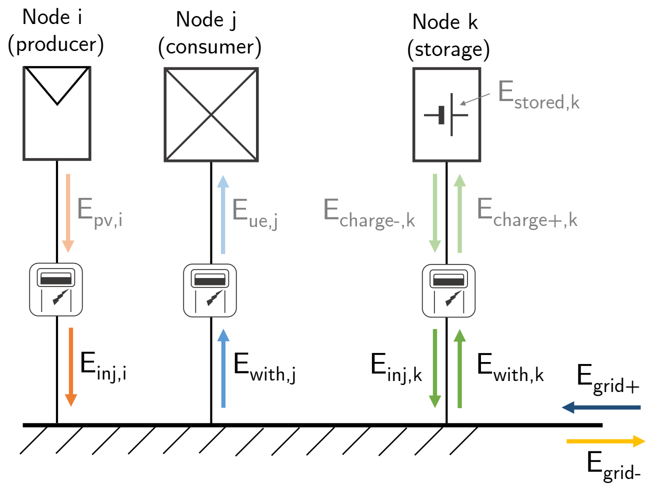


Fig. 1. Renewable Energy Community as a set of energy nodes connected to the same distribution grid.

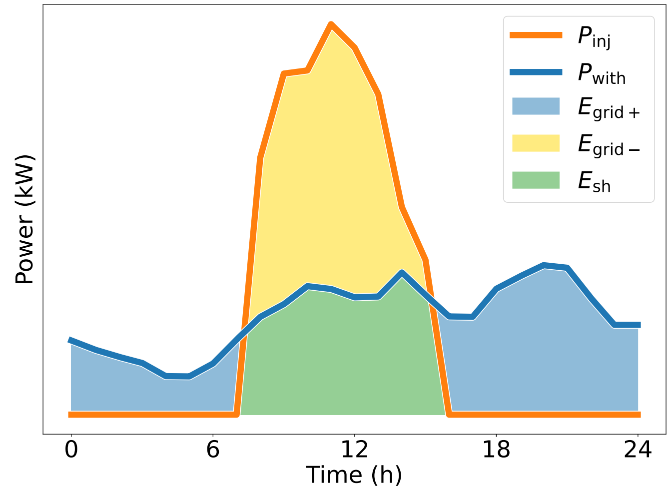


Fig. 2. Qualitative representation of energy sharing in RECs.

energy community reads as follows:

$$\sum_{\mathrm{n}\in\mathrm{N}} E_{\mathrm{with,n}} - \sum_{\mathrm{n}\in\mathrm{N}} E_{\mathrm{inj,n}} = E_{\mathrm{grid,+}} - E_{\mathrm{grid,-}}, \tag{1}$$

where $N$ is the set of nodes in the REC; $E_{\mathrm{grid,+}}$ and $E_{\mathrm{grid,-}}$ are the energy, respectively, withdrawn from and injected into the grid upstream of the REC (the term $E_{\mathrm{grid,+}} - E_{\mathrm{grid,-}}$ represents the net exchanges with the grid).

The energy balance in (1) shows that the energy exchanged with the upstream grid, respectively, withdrawn and injected, is smaller than the total withdrawals and the total injections of the nodes [1]–[5]. In particular, the difference between the total withdrawals and the energy withdrawn from the upstream grid is equal to the shared energy (the same holds for the injections). The latter quantity, $E_{\mathrm{sh}}$, is defined as follows:

$$E_{\mathrm{sh}} := \min\left(\sum_{\mathrm{n}\in\mathrm{N}} E_{\mathrm{inj,n}}, \sum_{\mathrm{n}\in\mathrm{N}} E_{\mathrm{with,n}}\right). \tag{2}$$

Figure 2 provides a qualitative example of these concepts (for graphical purposes, the total injections and withdrawals of the nodes are represented as powers, and the areas between these curves represent the shared energy and the energy exchanged with the grid upstream).

## III. Nodes Typologies

**Section highlights**

- Three types of nodes are considered: producer, consumer storage;
- Producer and consumer nodes are given synthetic injections/withdrawals profiles;
- Storage systems are operated so to minimize the net energy exchange with the upstream grid (complying with the technical constraints) (Figure 3).

The injections or withdrawals through a connection point in each time step depend on the corresponding node's characteristics. For sake of simplicity, we consider here just three types of node:

i. Producer node, which can only inject energy into the grid (Node $i$ in Figure 1);
ii. Consumer node, which can only withdraw energy from the grid (Node $j$ in Figure 1);
iii. Storage node, which can either inject or withdraw energy from the grid (Node $k$ in Figure 1).

Concerning the latter typology of node, the energy that is withdrawn from the grid is stored in an electricity storage system (charge), while the energy that is injected into the grid is taken out of the storage system (discharge).

We use here a simplified model of energy storage, whose constitutive equation is the following energy balance between two consecutive time steps $t$ and $t+1$:

$$E_{\mathrm{stored,t+1}} = E_{\mathrm{stored,t}} + E_{\mathrm{charge,t}}, \tag{3}$$

where $E_{\mathrm{stored}}$ is the energy stored inside the system (level of capacity filled), and $E_{\mathrm{charge}}$ is the energy charged into the system (when positive, discharged when negative).

Since the storage capacity ($CAP$, in kWh) is finite, then the following constraints must be met:

$$0 \le E_{\mathrm{stored,t}} \le CAP \ \forall t, \tag{4}$$

$$-E_{\mathrm{charge,max}} \le E_{\mathrm{charge,t}} \le E_{\mathrm{charge,max}} \ \forall t, \tag{5}$$

where $E_{\mathrm{charge,max}}$ is the maximum energy that can be charged/discharged in each time step. This quantity is related to the maximum rate of charge/discharge, i.e., $E_{\mathrm{charge,max}} = CAP/t_{\mathrm{min}} \cdot \Delta t$, where $t_{\mathrm{min}}$ is the minimum time of charge/discharge.

The storage systems are operated to decrease the energy exchanged with the grid upstream. Hence, the injections/withdrawals from the storage nodes are evaluated as follows:

$$E_{\mathrm{charge}} = E_{\mathrm{grid+}} - E_{\mathrm{grid-}} \tag{6}$$

Since the storage capacity is finite, then $E_{\text{charge}}$ must be recomputed in each time step in order to comply with the constraints in (4) and (5). Furthermore, if more storage nodes are present in the REC, they are first sorted by capacity and then (6), (5) and (4) are sequentially applied until, eventually, $E_{\text{grid}+} > 0$ and $E_{\text{grid}-} > 0$.

Concerning the producer and consumer nodes, simplified synthetic profiles are used to emulate the PV production (Gaussian function) and the end users consumption (constant):

$$P_{\text{pv}}(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-((t \mod 24)-\mu)^2}{2\sigma^2}} (\mu = 12, \sigma = 2), \tag{7}$$

$$P_{\text{ue}}(t) = k. \tag{8}$$

Figure 3 shows the withdrawals and injections profiles (together with the shared energy and the grid exchanges) in a REC with one node for each typology. The contribution of each node to the total withdrawals/injections are shown too.

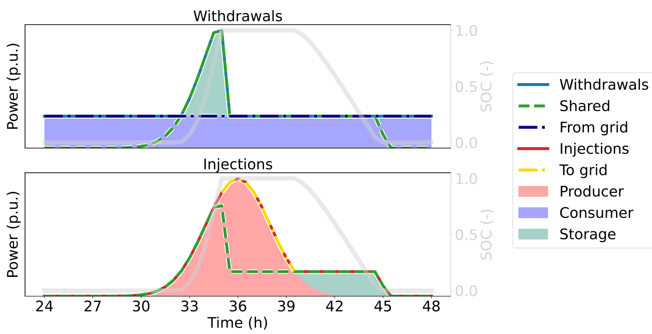


Fig. 3. Injections and withdrawals profiles when energy storage are present in the REC.

## IV. Methods

**Section highlights**

- Two methods to asses the contribution of each REC member to the energy sharing are considered;
- One method considers the energy sharing as a cooperative game and evaluates the contribution as the Shapley value;
- The second method is heuristic and divides the value (energy shared) between injections and withdrawals and then evaluates each node's value, time step by time step, by evaluating their contribution to the total injections/withdrawals.

We describe two methods to calculate the *value* that each REC member (i.e., a single energy node) brings to the REC. We don't consider the economical aspects of the initiative but only the energy ones. Therefore, we identify the value of a REC as the energy that is shared by its members. Other definitions of value can be introduced when considering the economics of the REC, e.g., the total revenues minus the total operative costs or the NPV of the investment [6], [7].

Given the didactic nature of this work, we do not consider the integral value during the horizon of the simulation, which is a scalar quantity, but rather the values in each time step of simulation, which is a vector quantity. However, the total value can be calculated by summing all the elements in the vector value.

We denote the vector value of a REC as $\vec{v}$, and therefore, we put:

$$\vec{v} = \{E_{\text{sh,t}}\}_{\text{t=1,...,T}}, \tag{9}$$

where $t$ is the index of the time step and T the time horizon of the simulation.

The contribution of each member $n$ of the REC to the total value is instead denoted as $\vec{v_{\text{n}}}$, and it must hold that $\sum_{\text{n}\in\text{N}} \vec{v_{\text{n}}} = \vec{v}$.

### A. Shapley values

We first introduce the approach adopted in [6] and [7], which comes from the Cooperative Games theory and is based on the concept of *Shapley value*. In a nutshell, this approach considers the nodes in $N$ as participants to a game (let us call it the *Energy Sharing game*). The value $\vec{v_{\text{n}}}$ of each player $n$ is equal to the player's Shapley value, which is a measure of the contribution of the player to the game. A coalition is identified by a subset of all players, and the value of a coalition is identified by the energy shared if only a subset of players are considered. Therefore, considering two extreme cases:

- If the coalition has only one player, the value is null, since at least two nodes are needed to share energy;
- If the coalition is composed of all the players in the REC, the value coincides with the value of the whole REC.

Evaluating the Shapley values of a player requires the calculation of the value of each possible coalition (subset of REC members) in which the player is not present. Then, the values of the corresponding coalition in which the player is added is calculated and the increment of value caused by adding of the player is identified. Summing this incremental value for each possible coalition leads to the Shapley value of the player. In formulas:

$$\vec{v_{\text{n}}} = \sum_{\text{S}\subseteq\text{N}\setminus\{\text{n}\}} \frac{|S|!(|N|-|S|-1)!}{|N|!} \left(\vec{v}(S\cup\{n\}) - \vec{v}(S)\right), \tag{10}$$

where S is a coalition without the player $n$; $S \cup \{n\}$ is the corresponding coalition with the addition of $n$; N is the set of all players. The term that precedes the difference of value in the coalitions $S \cup \{n\}$ and $S$ is a weight related to the possible coalitions of size $|S|$.

It should be noted that this approach requires re-evaluating the energy shared in each coalition, i.e., each possible combination of the nodes in N. The computational burden of this procedure grows exponentially with the number of nodes.

We also note that, while the injections of producer node (or withdrawals of a consumer one) do not change according to the coalition in which they are, the same does not hold for storage nodes. The latter are indeed able to adapt their injections/withdrawals in order to minimize the exchanges with the grid upstream, according to (6).

### B. Heuristic approach

We present now a heuristic approach to the calculation of each node's contribution to the shared energy. This approach stems from two considerations:

i. Energy can be shared only if nodes are are simultaneously injecting and withdrawing energy;
ii. Each node $n$ has a certain contribution to the total injections or to the total withdrawals in each time steps.

We can then divide the total vector values between the "injections" and the "withdrawals", i.e., we identify two broad values:

$$\vec{v}_{\mathrm{inj}} = \beta \cdot \vec{v} = \beta \cdot \{E_{\mathrm{sh,t}}\}_{\mathrm{t=1,\dots,T}}\,, \tag{11}$$

$$\vec{v}_{\mathrm{with}} = (1-\beta) \cdot \vec{v} = (1-\beta) \cdot \{E_{\mathrm{sh,t}}\}_{\mathrm{t=1,\dots,T}}\,, \tag{12}$$

where $\beta$ is a coefficient of division of the value that must be set depending on the weight given to the injections and those given to the withdrawals.

Since we are considering the value equal to the shared energy, it is reasonable to assume that injections and withdrawals have the same weight on the sharing of energy, i.e., $\beta = 0.5$.

Afterwards, it is possible to calculate the value of each node to the total value by evaluating, time step by time step, its contribution to the total injections and to the total withdrawals. In formulas:

$$\vec{v}_{\mathrm{n}} = \{v_{\mathrm{n,t}}\}_{\mathrm{t=1,\dots,T}}\,, \tag{13}$$

$$\text{s.t. } v_{\mathrm{n,t}} = \begin{cases} v_{\mathrm{inj,t}} \cdot \frac{E_{\mathrm{inj,n,t}}}{\sum_{\mathrm{n}} E_{\mathrm{inj,t}}}, \text{ if } E_{\mathrm{inj,n,t}} > 0, \\ v_{\mathrm{with,t}} \cdot \frac{E_{\mathrm{with,n,t}}}{\sum_{\mathrm{n}} E_{\mathrm{with,t}}}, \text{ if } E_{\mathrm{with,n,t}} > 0, \\ 0, \text{otherwise.} \end{cases} \tag{14}$$

## V. Results

We applied the two methods to different case studies in order to show their peculiarities and differences. We intentionally used simple case studies in order to make the results more interpretable. In all case studies, we normalized the production/load profiles in Figure 3 so that the *total* production and the *total* consumption in the REC in the given time horizon are equal to 1 kWh. In this way, we also consider the situation of natural self-sufficiency [1], in which the total renewable production equals the total end users consumption. We consider a time horizon of one week (however, the production and consumption profiles are stationary over the days), and a time step of half an hour ($\Delta t = 0.5$ h).

In the following, we show the profiles of injections, withdrawals and shared energy in the REC during one day of the week (for graphical purposes). Similarly to Figure 3, we use the area below the curve of the shared energy to highlight in different colors the contribution of each node to the shared energy evaluated by using the Shapley value and the heuristic approaches.

### A. REC with producers and consumers

In this case study we only consider producer and consumer nodes, without storage nodes that can modify their injections/withdrawals to increase the shared energy. By the simulation of the REC, it results that the energy shared is equal to around 0.373 kWh, which means having a self-consumption and self-sufficiency of 37.3%.

*REC with only two nodes:* We start by considering only two nodes, one producer and one consumer (see Figure 4 and Figure 5). In this case both methods split equally the contribution to the total value (shared energy) between the two nodes. In the case of the heuristic method, this is enforced by setting $\beta$ equal to 0.5. In the case of the Shapley method, this is the results of the application of (10). However, this result is trivial and does not depend on the production/consumption profiles. Indeed, in this case three coalitions are evaluated: the one with the two nodes, and the two ones with only one of the node (which have value equal to 0 by definition). Therefore the only possibility is to split the total value equally.

*REC with one producer and multiple consumers:* What happens then if we keep the same total consumption, but spread it among multiple consumer nodes present in the REC (e.g., five)? Despite the total value of the REC does not change, the value distribution evaluated with the two methods is different, as shown in Figure 6 and Figure 7. The division of value between the consumers is uniform (for both methods), since they have the same consumption profiles. However, the Shapley method gives globally more value to the producer (53.6% of the total). This is a result of how the Shapley value is calculated. By considering all possible combinations of nodes, the possibilities for the (one) producer to add value to the REC are larger. On the other hand, each consumer becomes replaceable in the game: when excluding one of them, there are other four consumers that contribute to the REC's value. We denote this as the *replaceability issue*.

*REC with multiple producers and one consumer:* The replaceability issue is even more exasperated if we consider again only one consumer (that therefore holds the total REC consumption) and five producers (see Figure 8 and Figure 9). In this case, the value distribution is unbalanced towards the consumer, but with a much larger effect (almost 70% of the value is allocated to the consumer). Figure 8 provides a possible explanation to this. During the central hours of the day, the solar production is so large that most part of the excess cannot be consumed locally in any case. This makes the producers even more replaceable.

On the other hand, the heuristic method does not change the total division of values between producer(s) and consumer(s) (but this is a quite trivial conclusion, since it is fixed a-priori), while dividing equally the values between the nodes of each typology, exactly like the Shapley method.

*First reflection:* Which way of value division is better? If we consider two existing RECs with exactly the same production and consumption profiles (in total) but with a different number of producers/consumers, how could we explain that in one case the producer get more value and in the other case the consumer do? Is this fair? On the other hand, this replaceability issue could result in an interesting feature when designing the REC. For instance, it could show that the production is too unbalanced with respect to the consumption and vice versa. Yet, how to use it if does not only depend on the profile but also on the number of players?

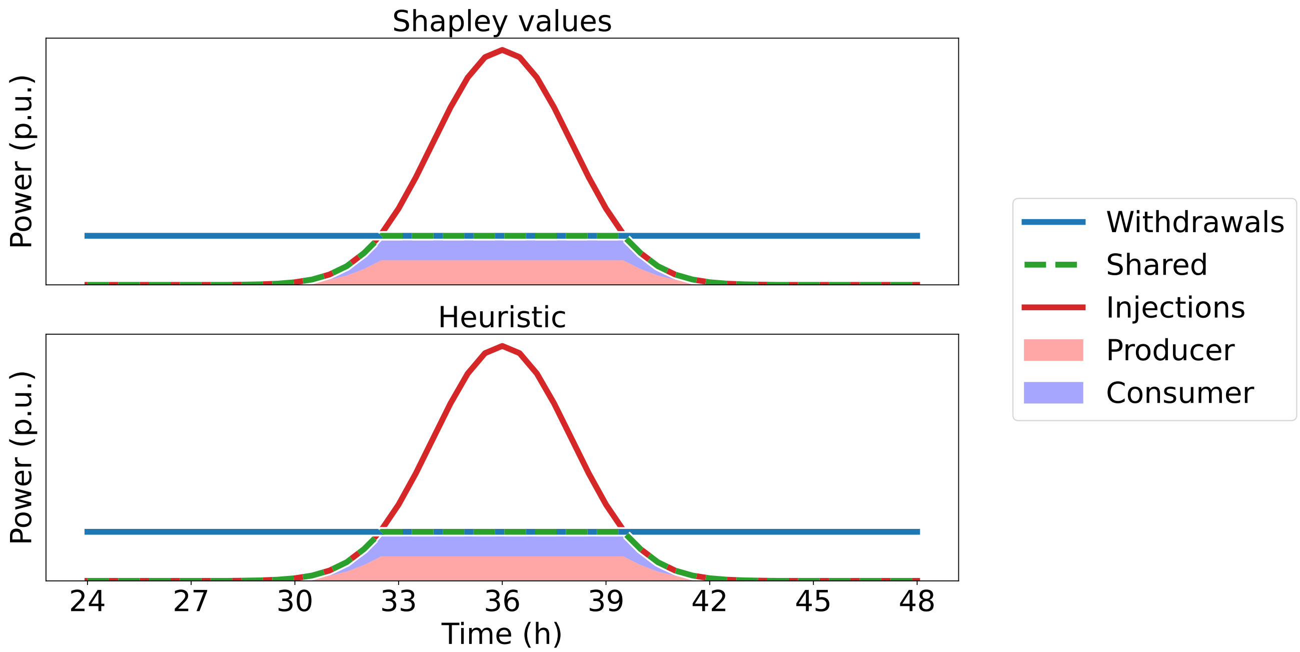


Fig. 4. Hourly value division between nodes during one day, in a REC with one producer and one consumer.

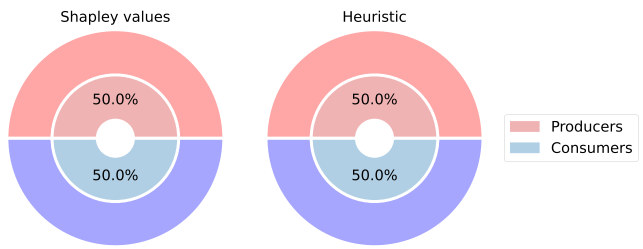


Fig. 5. Weekly value division between nodes during one day, in a REC with one producer and one consumer.

## B. REC with producers, consumers and storage

We propose one case study where a storage system is included in the REC. Given the replaceability issue of the Shapley approach highlighted in the previous paragraphs, we consider again the case in which the REC is composed of one producer and one consumer node, to which we add a storage node. The storage is sized so that the energy shared during the time horizon is doubled (i.e., 0.746 kWh). Figure 3 introduced before shows the injections/withdrawals profiles in this case study, while Figure 10 and Figure 11 show the results obtained with the two value division methods. Quite different results are obtained with respect to the value allocated to the storage node, with the Shapley method giving less value, in proportion. This result is not completely unexpected, since the storage node is able to generate value only in one of configuration out of three (excluding the ones with only one node).

On the contrary, the heuristic method divides the value in a more equal way. Moreover, the same value is given to the producer and the consumer. Most interestingly, the value given to the storage node is half of the increase in the shared energy (25% of the shared energy, which has doubled). The other half is equally split between the producer and the consumer. In fact, the storage system allows to double the shared energy, but only because the two other nodes are present in the REC. It is the author's opinion that this aspect is worth further investigation.

A closer look at Figure 10 highlights another interesting aspect of the value division obtained with the Shapley value. Indeed, the method allocates value to the producer node even when it is not injecting energy into the grid (hours from 42 to 46). This again is a consequence of how the value is calculated by considering the incremental value added by a player to each coalition.

*Second reflection:* The previous example shows that the heuristic method may provide a fairest value division than the Shapley method (at least, from the appearance). Again, is it possible to provide an answer to which of the two methods is better? Moreover, these examples only consider the energy aspects, ignoring the economics of the system. For instance, let us take the equal division of benefits between producers and consumers ($\beta = 0.5$), which sounds fair on the energy point of view. Is it yet fair from an economical point of view? If the consumers do not have any burden related to the investment, does this business model compensate enough the producer(s)? The same holds for the storage system: is the value allocated to it enough to justify the expense for its installation? While these remain open questions, it probably should be noted that, when considering the economics of the investment, a more wise choice would be not to evaluate the value of the REC only on the shared energy.

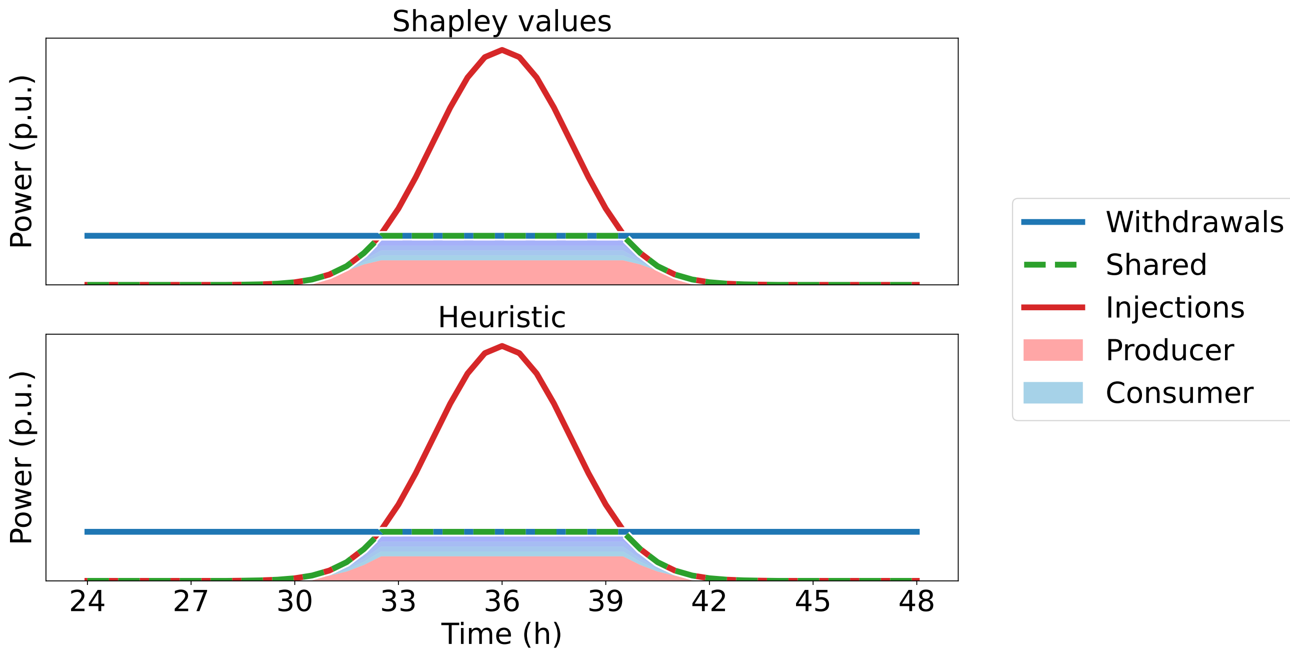


Fig. 6. Hourly value division between nodes during one day, in a REC with one producer and five consumers.

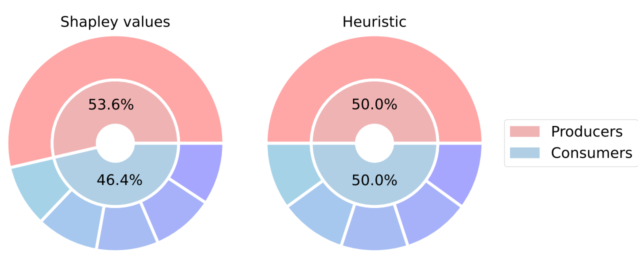


Fig. 7. Weekly value division between nodes during one day, in a REC with one producer and five consumers.

*Third reflection:* This last reflection is more of an "author's disclaimer" to highlight that, despite the coherence with the assumptions made and, possibly, the value of the results, this work lacks a proper review of the existing literature on the topic and any comparison with the published results (which are not only restricted to energy communities but also in general smart and distributed production/consumption systems and peer-to-peer energy exchange). Also, the Shapley value is not the only method applicable, as shown in [7], therefore other methods may give yet different results. However, the author believes that the topic is of relevant interest and should be treated more in detail, to provide a systematic comparison between different case studies and different methods.

## Acknowledgments


This work owes most of its essence to the efforts of Francesco Moraglio and prof. Maurizio Repetto, while the author merely provided the framework for their application and tried to present the results obtained in a comprehensive way.


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## Appendix

We provide some clarification of the weight factor used in the player's $n$ Shapley Value formula in (10), that multiplies the incremental value of the addition of the player to each subset $S$ of the players in $N \setminus \{n\}$.

In particular, we start by a "reverse engineering" of this weight factor, that we call $w$, and is calculated as follows:

$$w(S, N) = \frac{|S|! \times (|N| - |S| - 1)!}{|N|!},$$

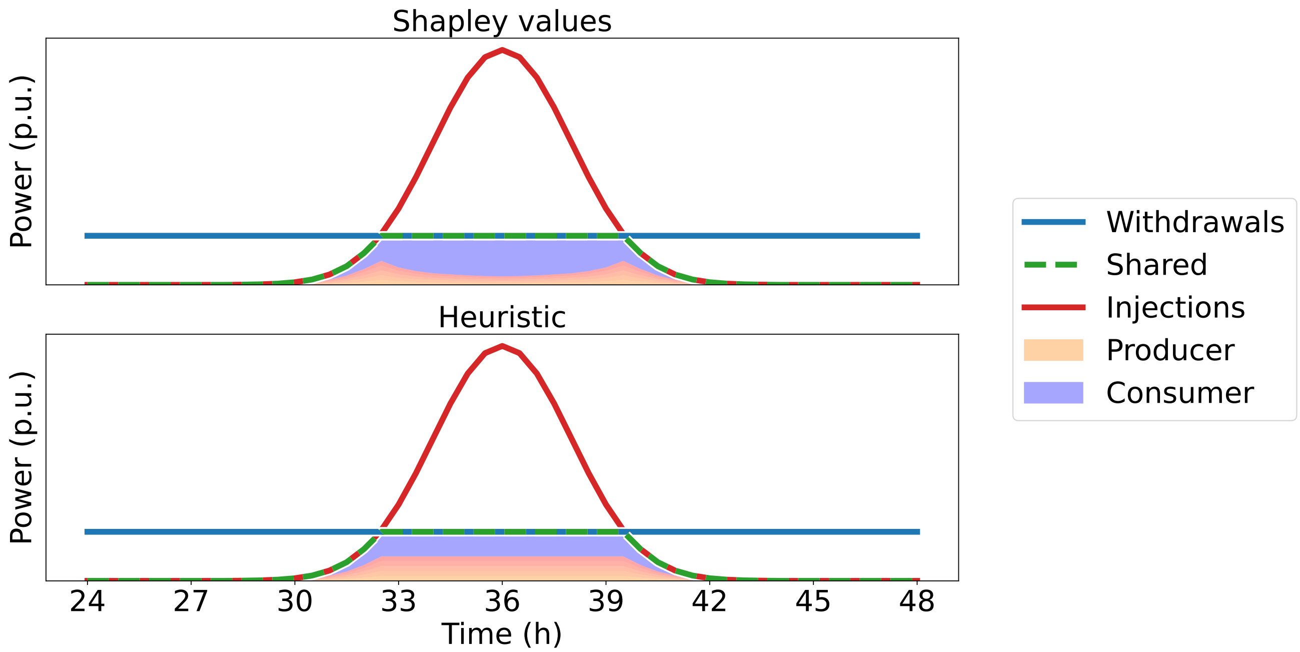


Fig. 8. Hourly value division between nodes during one day, in a REC with five producers and one consumer.

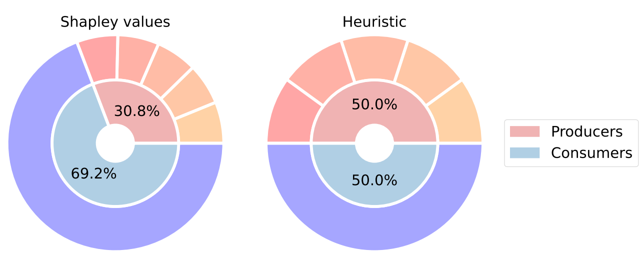


Fig. 9. Weekly value division between nodes during one day, in a REC with five producers and one consumer.

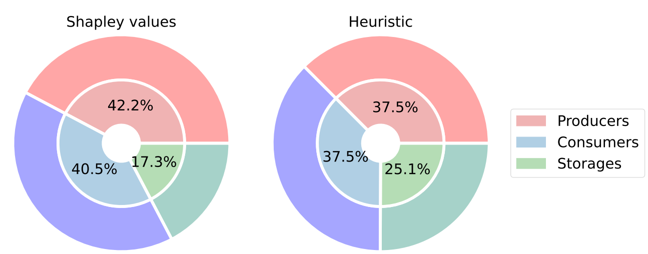


Fig. 11. Weekly value division between nodes during one day, in a REC with one producer, one consumer and one storage.

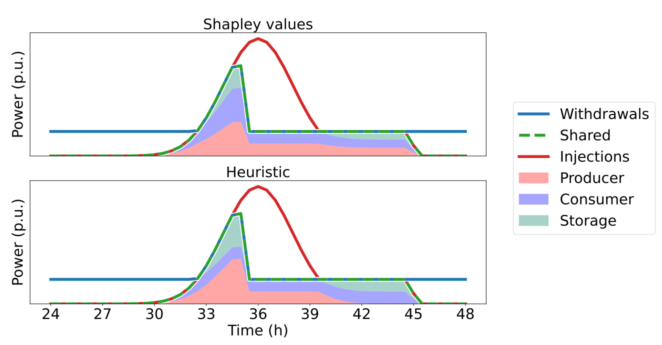


Fig. 10. Hourly value division between nodes during one day, in a REC with one producer, one consumer and one storage.

where, N is the set of all players, S is a subset of the set $N \setminus \{n\}$ (all players but $n$), and operator $|\cdot|$ is the size of a set.

We then remind from combinatorics that, given a set of size $m$, it is possible to obtain a number of possible combinations of $k$ elements of the set equal to:

$$\binom{n}{k} = \frac{n!}{k! \times (n-k)!}.$$

In our case, the set from which we can extract combinations is $N \setminus \{n\}$ (i.e., $n = |N \setminus \{n\}| = |N| - 1$) and a combination is the subset $S$ (i.e., $k = |S|$). Therefore, the number of possible combinations ($PC$) is equal to:

$$PC(S, N) = \frac{(N-1)!}{|S|! \times (|N| - 1 - |S|)!}.$$

We notice that the denominator in the previous equation is exactly the numerator in the calculation of $w(S, N)$, that we can re-write as follows:

$$\begin{aligned} w(S,N) &= \frac{|S|! \times (|N|-|S|-1)!}{|N|!} = \\ &= \frac{|S|! \times (|N|-|S|-1)!}{(|N|-1)!} \times \frac{(|N|-1)!}{|N|!} \\ &= \frac{1}{PC(S,N)} \times \frac{(|N|-1)!}{N \times (|N|-1)!} \\ &= \frac{1}{PC(S,N)} \times \frac{1}{N}. \end{aligned}$$

Finally, we just need to remind that in the calculation of the Shapley Value in (10), we sum over all the possible combinations $S$. In total, we have $N$ possible sizes of $S$ (from 0 to $|N|-1$), and, for each size $|S|$, we have $PC(S,N)$ possible combinations. Hence, the weights sum to 1.

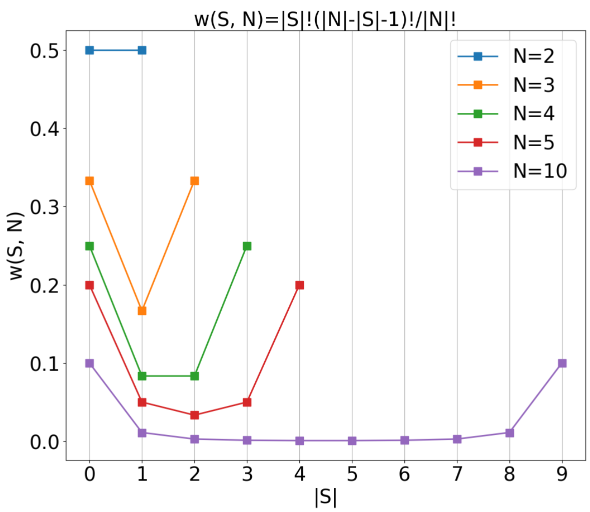


Fig. 12. Weights in Shapley Value formula for different number of players and for each possible size of the subsets.