WELFARE IMPLICATIONS OF RENEWABLE ENERGY COMMUNITIES. INDIVIDUAL VERSUS COLLECTIVE APPROACH

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Abstract

Decentralized solutions of resource consumption build on the theory of commons to define governance rules for resource usage and remuneration (Olstrom, 2010). This paper identifies the energy surplus as being the common to be regulated within a community by means of decentralized sharing rules, and by the State with supporting schemes. Collective self-consumption is described analytically by the relationships between taxes, feed-in-tariffs and market prices to highlight the main attractiveness of communities that is the energy in excess from the other participants. Yet the welfare improves only if the excess of energy is sold within the community below the market price, and outside the community at feed-in tariffs that are not regressive with the community size. By using French solar data and user profiles for residential and tertiary sectors, the model shows divergent interests when based only on the long-run cost of the common: the tertiary sector records net benefits if household selling price all taxes included is below market rates, while households find no financial motivation to join the community compared to an individual self-consumption case. The welfare improves if the sharing rule of the common includes also the opportunity cost, which adapts in this way the current one-size-fits-all policy to the performance of the community.

Keywords welfare, self-consumption, energy community, commons, regulation, market, rules.
JEL classification Q2, Q41, L51, D63.

1. Overview

The research on renewable energy self-consumption contains a large variety of advanced methods of analysis of the social implications and technical design of individual and collective projects (Capper et al., 2022). Stakeholders get involved into energy projects for different motivations, upon various dimensions of the ecological and energetic crisis that trigger their emergence (Heuninckx et al., 2022). New business models and forms of social organisations have been developed around collective energy projects, largely dependent on the regulatory and policy context (Busch et al., 2021) and on the definition of community, i.e. some 183 concepts in Bauwens et al. (2022). In the field of economics, several thought schools have depicted the concept of communities to explain the socio-ecological interest of organisations with collaborative economy and social solidarity economy (Sebi and Vernay, 2020); the institutional changes and distributional impacts with industrial economics (Clastres et al., 2019); the interplay between regulatory instruments and market signals with environmental economics (D'Adamo et al., 2022); the welfare effect with development economics (Berthélemy, 2016); or organisational rules with ecological economics and public choice theory (Ostrom, 2010).

This paper builds a framework of analysis of the interactions between regulation and market, such as to understand the rational attractiveness of energy communities. By means of microeconomics, a solar-based energy community facing supply scarcity is analysed from the perspective of the self-governance problem applied to the common represented by the energy in surplus. The option to use the surplus within the community instead of selling it on the market is the main motivation to join the community, where the governance rules should solve the problem of sizing and benefit sharing.

In Europe, the first motivation to enact energy self-consumption has been the opportunity to attract private investments into renewable energy projects and to attain targets set on renewables (Directives EU 2018, 2019). From the demand perspective, the self-consumption can encourage a more responsible behaviour of the consumer, with energy efficiency and sobriety effects (Liang et al., 2022). In other countries in Africa and Asia, energy self-consumption and energy communities can promote rural electrification planning and a wider access to renewables (Berthélemy, 2016).

The concept of energy community covers different configurations of size, technology and actors managing more or less complex network infrastructure for producing and selling energy (Iazzolino et al., 2022). Ideal energy communities define a governance model of renewable energy clusters based on the complementarity of energy inputs and users demand (Lowitzsch et al., 2020); moreover, they might include bidirectional energy flows and flexibility options of storage and demand response (Volpato et al., 2022). Among reasons to join communities, beyond environmental concerns, most of self-consumption projects are triggered by financial interests and high retail prices[1] that mostly explain the large number of solar projects in Germany, Denmark, Italy or Spain. In Europe, it is estimated that by 2030, some 50 GW of wind power and 50 GW of solar power could be owned by energy communities (more than 17% of the wind and solar installed capacity; European Commission, 2016), and that by 2050, half of the EU households could produce renewable energy or be involved in energy communities (Kampman et al., 2016).

In front of power market inefficiency to solve climate externality issues, the regulator has introduced targets on renewables, and complemented the market operation with capacity markets, green certificates or feed-in tariffs (Barnea et al., 2022). Yet the market and the State action remain insufficient in front of climate change emergency, hence new models of governance are necessary (Wolsink, 2020). In the case of the electricity, centralized governance of power plants and network is opposed to decentralized solutions of power generation, smart grids and micro-grids, where economies of scale oppose to institutional arrangements optimally tailored to specific local energy sources and user profiles. Despite the lack of economies of scale, energy communities organised as micro-grids have the advantage of increasing the share of renewables and the demand response initiatives. Yet, in countries with historical central network connecting all consumers and micro-grids as well, the governance of the electricity network, building on collective financial participation, has features of a common good, where

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[1] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics

decentralized solutions for power generation are a challenge for the use of the central network (Clastres et al., 2019).

While several theories can be used to study the concept of commons, such as transaction costs and game theory, we restrain the frame to institutional arrangements which are possible with decentralized communities. From an institutional point of view, the energy generated within the community has the features of common good as long as the property rights on the energy resource are well defined within the community, and rules of governance can efficiently manage conflicts (Ostrom, 2010). The public choice theory finds fertile ground with application to electricity communities, by adding communication within the community (Wolsink, 2020): smart meters allow tracing flows such as to reduce overharvesting of common-pool resources against penalty, where the common pool is the energy generated by the community. The initial financial investment of participants forming the community allows framing the properties of rivalry and exclusivity of the common good: the community gives exclusivity to its members and any use of the resource diminishes the use by another member, thus generates a reward to its owner and a cost or penalty to its user; the common pool cannot be overharvested because it is automatically managed by smart meters and it is restricted to the surplus of the resource only.

The main contributions of this paper are in terms of insights into economic interactions and market regulation of energy communities. We depict the formal relationship between taxes, tariffs and the market price that allows electricity self-consumption to turn into a collective trade according to administrative instruments and economic rules. The energy in surplus is the decentralized common good described in Ostrom (2010), yet it adds a centralized common good that is the network, paid by all consumers, which is used by the community as well. Two welfare conditions are defined such that the community to be economically and socially sustainable: 1) the well-being improves for all community participants and 2) the community does not affect the welfare of the consumers outside the community. The surplus sharing rules together with the regulation of the access to the grid will be the key conditions of the interaction between participants and consumers outside the community. Empirically, the paper contains an inductive approach to explain the economic rationality of individuals to join the community, and builds a deductive approach to analyse the assumptions of behavioural change of going from individual to collective self-consumption. The project viability being policy tool dependent, we apply the case study to the French regulation, with solar and user data in the district Pays de la Loire. By means of scenarios on self-consumption rates, we show that the surplus regulation influences the existence of the community and regulates its size.

In the remaining part, Section 2 presents the main types of communities and develops rational individual and collective self-consumption models. Section 3 presents the empirical case study applied to the French context. Section 4 analyses the policy implications derived from the model application. Final section concludes and opens work perspectives to both theory and applications.

2. Methods

First we separate individual self-consumption from collective self-consumption. Simple self-consumption is related to the single end-user who produces renewable energy for self-consumption and for market selling (Iazzolino et al., 2021. Forms of end-user energy projects have evolved with the development of renewable technologies and the State subsidies, from total or partial selling of power at feed-in-tariff, to leasing or renting a power generator and to net metering[2] (Botelho et al., 2021). More power market segments have been open to citizens, such as self-consumption with demand response services (Canizes et al., 2022), as a way to improve the efficiency of the energy system by conditioning profitability on smart energy consumption. The development of smart-metering has sustained the emergence of virtual self-consumption: the energy fed into the grid by participants is simultaneously consumed by other end-users, as part of the same building or geographically distant from each other,

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[2] Net metering is a model contract with self-consumption, where the power in excess injected into the grid is accounted for future flows withdrawn from the network, hence exempted from taxes of using the grid.

through a trade platform or peer-to-peer (Sousa et al., 2019). To some extent this represents a form of collective self-consumption where the trade is the prior feature of the energy community.

The concept of energy community is complex in the sense that it is based on various forms of energy generation and consumption, with a strong social dimension for decision-making (Bauwens et al., 2022). It supposes interpersonal trust, thus small-scale spatial distribution of members who communicate and know each other; they are involved in a voluntary and collaborative way, hence in a distinctive manner from market and the State. From the grid point of view, the main advantage of energy communities with renewable projects is that it reduces the risk of injecting a large flow of energy that cannot be absorbed locally, provided that all participants are located in the same area of injection (CRE, 2019). Yet, more commercial forms have emerged with the extension of the collective use of the energy surplus from citizens located in other cities and more broadly including large energy companies (Frieden et al., 2021). The extension of the community perimeter adds more complexity to the way the network fees are distributed at local and national scales (Fonteneau, 2021). When the network cost is covered mainly by fees from flows rather than by fixed charges, self-consumption might reduce the utility income from reduced energy withdrawn, creating missing money issues and higher compensating fees from general consumers (Clastres et al., 2019).

We explore next the economic frame of the energy self-consumption function of the market tariffs and State subsidies.

2.1. Individual self-consumption programme

We assume an end-user installing solar panels who consumes in priority energy from panels, and next sells the electricity in surplus and buys electricity from the market in the absence of solar input, automatically, by means of smart meter.

The prosumer *i* involved in individual self-consumption defines the utility based on yearly cash flow CFI_i that is the revenue from selling the electricity in surplus (*ES*) at feed-in tariff rate (*T*), minus the bill of the electricity withdrawn from the network (*E*) at market rate including taxes (*p*) net of the electricity self-consumed (*ESC*), minus the cost of solar panel evaluated at the average value (*lcoe*) of the energy produced each year (*PV*), minus costs with network fees and abonnement (*AI*):

$$CFI_i = ES_i \times T - p \times (E_i - ESC_i) - lcoe_i \times PV_i - AI_i \tag{1}$$

This follows the principle of net billing where the energy fed into the grid has a different monetary value from the energy withdrawn (Dufo-López and Bernal-Agustín, 2015). The equation shows also that the energy withdrawn from the grid diminishes with the energy self-consumed which makes decreasing the revenues of the grid operator from taxes τ included in the market price, *p*. In order to keep constant these incomes, an adjustment of the abonnement is suggested following Clastre et al. (2019), assuming all variable charges passed on the fixed fees (*AI*). At *A0* the abonnement level before self-consumption, the following identity ensures the grid operator budget neutrality:

$$\tau \times p \times E_i + A0_i = \tau \times p \times (E_i - ESC_i) + AI_i \tag{2}$$

Noting the difference between abonnement levels with $\Delta A = AI_i - A0_i$, we obtain:

$$\tau \times p \times ESC_i = \Delta A_i \tag{3}$$

Equations (3) ensures that revenues for grid operator remain constant, and that the welfare of the general consumers remains constant as well, without additional charges due to self-consumption. The abonnement of the prosumer $A1$ will increase with the missing revenues from taxes which are not paid on the energy self-consumed.

Rewriting the equation (1) based on the energy flow type and on the balance $PV_i = ESC_i + ES_i$, we obtain the cash flow as the net gain from selling the energy surplus, the bill saving from self-consumption, net of investment cost, related to the initial bill, minus abonnement:

$$CFI_i = ES_i \times (T - lcoe_i) + ESC_i \times (p - lcoe_i) - p \times E_i - A1_i \tag{4}$$

2.2. The self-consumption community programme

Within the community, participants install individual solar panels and have their own meter as initially, such as to give the choice of either an individual model or collective self-consumption, hence not constrained by a collective solar power generator. The prosumer consumes his own solar energy in priority as initially, but buys next the energy in surplus from the community, and ultimately buys individually electricity from the grid. Any energy in surplus within the community is sold *collectively* to the market as a single entity. The community has the features of a virtual community from the point of view of solar panel configuration: flows are traded virtually within the community, and physically self-consumed individually. The community is based on the heterogeneity of user profiles of power consumption and solar panel size.

The yearly cash flow CFC_i of prosumer i within the community is the following:

$$CFC_i = ES1_i \times p_i^{sc} + ES2_i \times TC - EBC_i \times p_{j,tax}^{cc} - (E_i - ESC_i - EBC_i) \times p_i - AI_i - lcoe_i \times PV_i \qquad (5)$$

Where

$ES1_i \times p_i^{sc}$ is the energy surplus sold within the community at price p_i^{sc}

$ES2_i \times TC$ is the energy surplus sold to the market at feed in tariff TC

$EBC_i \times p_{j,tax}^{cc}$ is the energy bought from the community prosumer j $(j \neq i)$ at price $p_{j,tax}^{cc}$. In this way, any community prosumer *i* pays taxes on the energy consumed from the community, and in contrast sells the energy in surplus net of taxes, based on the principle that taxes are set on consumption and not on selling activities.

Note that taxes being set on the community trade as well, the market price rate does not change in the community model compared to the individual self-consumption case, *p*, yet the set *i* or *j* will apply to differentiate the tariff type by consumer size with respect to the contract power.

$(E_i - ESC_i - EBC_i) \times p_i$ is the energy bill for the electricity withdrawn from the market.

The following constraints hold:

- $PV_i = ES1_i + ES2_i + ESC_i = ES_i + ESC_i$ (6)

The total solar power generation is split in the energy self-consumed, the energy consumed by the community and the energy in surplus sold to the market, or by short, is the sum between the energy in surplus (*ES*) and the energy self-consumed individually and collectively (ESC).

- $\sum_{i=1}^{N} ES1_i = \sum_{i=1}^{N} EBC_i$ (7)

The total electricity bought from community members is equal to the surplus sold to community members.

- $EBC_i \leqq E_i - ESC_i$ (8)

A prosumer cannot buy from the community more that he needs.

The equation (5) can be written:

$$CFC_i = ES1_i \times (p_i^{sc} - lcoe_i) + ES2_i \times (TC - lcoe_i) + EBC_i \times \left(p_i - p_{j,tax}^{cc}\right) + ESC_i \times (p_i - lcoe_i) - p_i \times E_i - AI_i \qquad (9)$$

The rational prosumer joins the community as long as the welfare is higher in the community than in individual self-consumption:

$$CFC_i > CFI_i \qquad (10)$$

By assuming budget neutrality for grid operator, we can simplify (10) as follows:

$$ES2_i \times (T - TC) + ES1_i \times (T - p_i^{sc}) < EBC_i \times \left(p_i - p_{j,tax}^{cc}\right) \qquad (11)$$

Equation (11) is the condition that the prosumer welfare improves if the loss in selling the surplus to the market, *ES2*, at community rate *TC* instead of initial feed-in tariff *T*, plus the difference of selling the surplus *ES1* to the community at an average cost, p^{sc}, lower or higher than the initial feed-in tariff *T*, depending on the size of the individual PV generator, need to be compensated by the benefit of buying energy from the community at price, $p_{j,tax}^{cc}$, instead of the market price, p_i. This rule represents the decentralized rule of governance of the community, with various solutions that can be issued through negotiation among members. This highlights that a given energy community cannot fit the central institution framework where “one size fits all” policy applies to all empirical cases (Olstrom, 2010), given the particular local profiles of solar power and user demand.

Equation (10) includes the condition that the welfare of general consumers, outside the community, remains unchanged: any network missing revenue from collective self-consumption (*EBC*) is compensated by taxes set on prosumer's j selling price, $p_{j,tax}^{cc}$. The welfare of the prosumer improves only due to the community operation, and not to lower fees on the electricity withdrawn from the grid. Inside the community, the use of central network is paid by the community members while trading. The intervention of the regulator with taxes set on the use of the central network shows that the relationship among community members cannot be based on institutional arrangements only, but on hybrid forms with market and the State that together ensure economically viable model of communities.

3. Empirical case

The case study applies to the French solar energy self-consumption, based on the legislative process set in 2017, later enriched with the development of citizen energy cooperatives, smart-grids and energy communities (Fonteneau, 2021). The French Energy and Climate Law defines the concept of self-consumption, total or partial, individual or collective, on different scales of districts, limited to 2 km and 3 MW of power generation (French Government, 2017, 2021). Different supporting schemes have been designed such as feed-in tariffs and call for tenders, adapted to different plant sizes, locations and rules of power selling and sharing (CRE, 2021), regularly updated (CRE, Opendata).

The collective self-consumption can benefit of tax reduction such as to encourage the deployment of renewables on one hand, and additional fees while using the network such as to protect general customers against overcharges, on the other hand (RTE, 2019; CRE, 2018). The potential of self-consumption is estimated to some 40 GWp (RTE, 2019), among which 50,000 up to 200,000 sites with self-consumption are the target for 2023 (PPE, 2020). In the residential sector, the technical potential for large solar panel installations is estimated to some 10 GWp, and more generally, irrespective of the size, 10 to 20 GWp are the target for 2035 (RTE, 2019). In July 2022, some 166,000 sites provide solar power with self-consumption, cumulating 1 GWp, among which 65% have less than 3 kWp and 23% between 3-9 kWp[3].

This case study contains key questions usually met for practical applications; yet, specific solar and demand inputs along with model simplifying assumptions, draw a regional specific vision of French energy communities. Two types of end-users are considered, a household with large electricity consumption including electric heating (RES11 type subscribing power rating of 6 kVA), and an administrative building in the tertiary sector (ENT3 type connected at more than 250 kVA). The annual consumption of the household is about 12000 kWh and the solar generators have different testing scales of 3 kWp, 6 kWp and 9 kWp, at a cost of 2000 €/kWp. The tertiary building has an annual consumption of 483,600 kWh and a solar panel installation of 100 kWp at 1000 €/kWp, tested at upper scales of 200 and 300 kWp.

The regulatory frame is the self-consumption option with the energy surplus sold to an aggregator, such as EDF, at regulated tariffs. Three levels exist at date, in relation with the scale of the technology: 100 €/MWh for solar installations lower than 9 kWp; 60 €/MWh for solar generators between 9 kWp and 100 kWp; and for technology between 100 and 500 kWp, the tariff is of 100.3 €/MWh for the first 1100 kWh and 40 €/MWh for the remaining flows (CRE, Opendata). These tariffs are guaranteed for 20 years, yet we maintain the same rate over the entire project lifetime of 25 years, as the household and the tertiary activity will sell the surplus to another aggregator or to the market anyway. The power price while withdrawing from the network is 174 €/MWh for households and 138 €/MWh for the tertiary sector, assumed to increase by 4% per year[4].

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[3] https://www.statistiques.developpement-durable.gouv.fr/publicationweb/460

[4] https://www.service-public.fr/particuliers/actualites/A15480

Data is documented from French distribution system operator, Enedis[5], for the two consumer types[6], and solar inputs are documented by the French transmission system operator, RTE[7] for the region of Pays de la Loire. The choice of the region is based on supporting local policies for wind and photovoltaic energies such as to attain the target of positive energy region by 2050.[8] The data covers all 17,526 half-hours of the year 2018 for both power demand and solar power potential that amounts to 1200 full load hours per year. Three cases are discussed with concern to size and best investment options, testing the individual approach of each household and tertiary activity, and the collective frame for best size and energy sharing strategy.

Household self-consumption. The rate of self-consumption varies with the scale of solar panels installed, from 46% at 9 kWp of solar panels to 89% for smaller scale, of 3 kWp (Fig. 1). The simulations do not integrate the demand-response options, despite an important potential that can improve the self-consumption rate with 6 up to 10 points, based on usages such as hot water and washing machine; hence the energy in surplus, the key factor of power trade analysis, is the residual flow between the solar energy potential and the historical demand. Based on current rates of feed-in tariffs, the highest self-consumption rate comes with the highest profit as well, showing that the regulator encourages self-consumption rather than the solar installation size. In short, based on profit criterion only, the household tends to select 3 kWp of solar panels, which have a time of return of 15 years, lower than other studies assuming lower investment costs or higher energy capacity factors (Iazzolino et al., 2022).

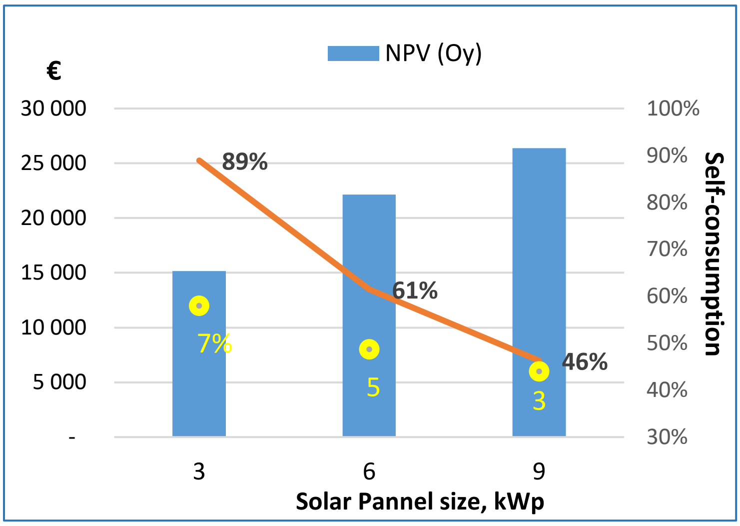

Fig. 1. Sizing options for prosumers household with individual self-consumption

Tertiary building self-consumption. Similarly to households, the tertiary building shows the same trend (Fig. 2), such as to minimize the solar installation (100 kWp) and maximize the self-consumption rate (92%). The rate of return on investment (12%) is higher than for households (6%), due to differences in bill savings at larger tertiary consumption than for household, and to differences in the solar cost and economies of scale on larger roofs, and to a lower extent, to different energy surplus volumes (8 MWh for services versus 2.1 MWh for households).

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[5] https://www.enedis.fr/open-data

[6] The household corresponds to RES11_Base profile described by the DSO with voltage level between 6 kVA and 36 kVA, and the tertiary building to ENT3 profile, i.e. a voltage level between 1 kVA and 50 kVA.

[7] https://www.rte-france.com/eco2mix/telecharger-les-indicateurs

[8] https://www.paysdelaloire.fr/sites/default/files/2022-04/1_rapport-objectifs_sraddet-approuve.pdf

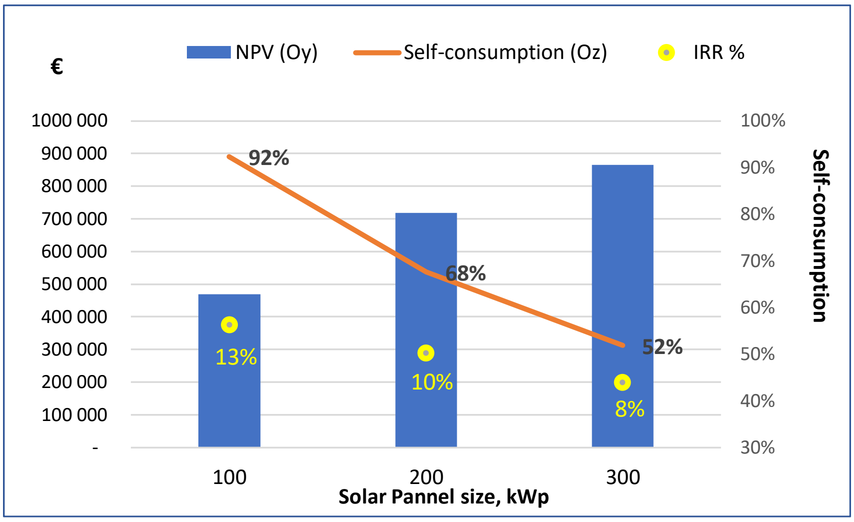

Fig. 2. Sizing options for the tertiary building with individual self-consumption

Household-Tertiary community. Empirical projects show that there is no evidence on the composition of a community, as the aggregation of participant types is different from one project to another. Collective self-consumption models being physically limited to a given perimeter and dependent on the energy resource and user type, identifying the optimal community size is impossible. Yet, calculus in Iazzolino et al. (2022) result in optimal household profile matching between 3000 and 5000 participants in Italy; and high energy cost reduction for communities made of at least five families in Parra et al. (2015).

Our numerical application tests the community made of tertiary building and twelve identical households, calibrated based on the surplus generated by each prosumer type. Results show that each actor is interested in the surplus generated by the others (Table 1): the household maximizes the profit rate at large tertiary solar installation (300 kWp) and low household solar panel size (3 kWp); similarly, the tertiary building maximizes profits at high household solar panel size (9 kWp) and low own solar investment (100 kWp). The trade of energy within the community increases with the scale of the surplus.

Table 1. Collective self-consumption financial indicators at different sizing options

	Collective self-consumption					**Individual self-consumption**			
Size, kWp	**Household**		**Tertiary**		**CE Trade**	**Household**		**Tertiary**	
(Household, Tertiary)	**NPV, €**	**IRR**	**NPV, €**	**IRR**	**MWh/yr**	**NPV, €**	**IRR**	**NPV, €**	**IRR**
(3 x12, 100)	6 096	6.3%	243 961	13.1%	2.0	6 262	6.5%	229 014	12.5%
(3x12, 200)	7 381	7.5%	354 469	10.3%	3.8			334 591	9.9%
(3x12, 300)	**8 789**	**8.7%**	408 226	8.5%	7.9			383 743	8.0%
(6x12, 100)	5 668	3.3%	257 538	13.6%	10.3	7 990	4.5%	229 014	12.5%
(6x12, 200)	6 528	3.7%	354 761	10.3%	1.6			334 591	9.9%
(6x12, 300)	7 006	4.0%	405 420	8.4%	1.7			383 743	8.0%
(9x12, 100)	3 491	1.4%	**272 839**	**14.0%**	20.1	8 228	3.3%	229 014	12.5%
(9x12, 200)	4 729	1.9%	359 538	10.4%	4.4			334 591	9.9%
(9x12, 300)	5 101	2.1%	406 310	8.4%	1.4			383 743	8.0%

Three main factors impact the behaviour of community participants:

- *The users' consumption profiles*. The homogeneity of households results in similar consumption and energy in surplus profiles at the same periods. The tertiary building has important surplus energy flows, but mostly correspond to the same surplus periods as for households, therefore the trade direction within the community is from households towards tertiary (Fig. 3).
- *The sharing key of the common*. The sharing key is here the average cost of the energy produced by solar panels, which is different with the scale of the installation: 120 €/MWh for household's panels, and 90 €/MWh for tertiary panels. By buying the surplus at average rate instead of the

market price of 138 €/MWh, the tertiary pays the household rate and makes energy bill savings. The household buys the power from tertiary at average cost of 90 €/MWh instead of market price of 174 €/MWh. Yet, this trading mechanism excludes here taxes on the network and on trading, hence including taxes the business plan might change radically.

- *The regulation*. The community excess of energy comes from both households and tertiary building. For instance, a community made of 3 kWp per household and 100 kWp respectively, generates a total surplus of 2 MWh per year which matches the tertiary needs (1.5 MWh/year) and household power needs (0.5 MWh/year), and some 10.3 MWh/year sold to the market by the households (2.7 MWh) and tertiary activity (7.6 MWh) at fixed rate of 60 €/MWh. This tariff is fixed and relates to the scale of the community (136 kWp), hence lower than the initial rate of household while selling the surplus in individual self-consumption, i.e. at tariff of 100 €/MWh. The energy savings the household records are not compensated by the tariff losses due to solar installation scale upgrading, thus their welfare diminishes.

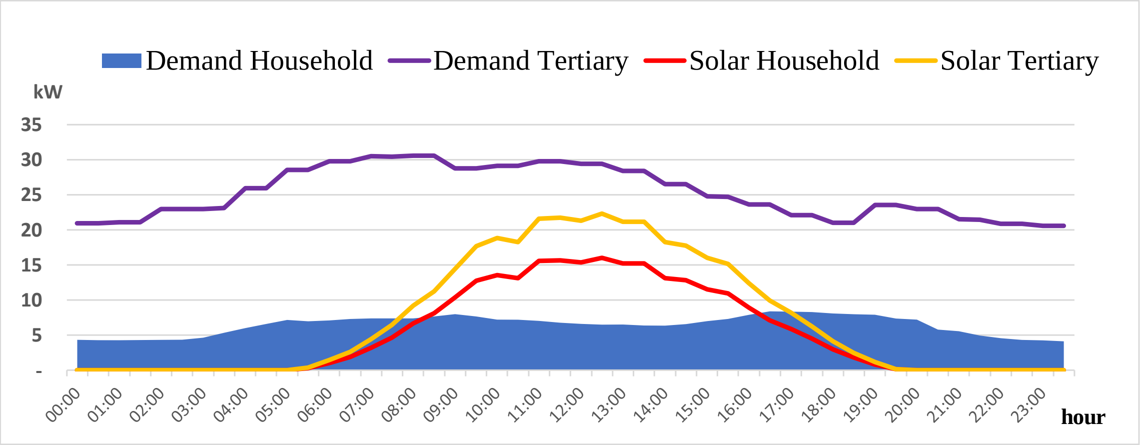

Fig. 3. Half-hour profiles of solar energy supply (172 kWp) and power consumption in July, by user

The energy traded within the community is the largest (20 MWh/year) in case of high solar panel installation of households (9 kWp per house) and low solar panel on tertiary building (100 kWp). This case is the most welfare losing for households and could be the most profitable for tertiary in case of taxes plus solar cost below the market price.

4. Policy Implications

Despite difficulties to generalize the energy community composition, some insights can be drawn with concern to solar plant sizing, energy surplus sharing and the access to the grid.

1° Solar plant sizing. The regulator can control the size of solar panel by means of the valuation of the surplus generated (Fonteneau, 2021). Prosumer's investment cost is recovered by feed-in tariffs and bill savings, making the financial model dependent on three elements: the market power price, the rate of self-consumption and the feed-in tariff. The higher the market price is, the higher the incentive to increase self-consumption is, triggering also demand side management. A low to zero feed-in tariff for the surplus would encourage solar equipment sizing with total self-consumption; a high level of feed-in tariff, e.g. higher than the average cost of the solar energy, would incentivize large solar generators; a feed-in tariff equal to the power market price (net-metering) would bring only a complement to the investment; or a level lower than the market price (net-billing) would downgrade the solar panel sizing.

The current regulation tends to prioritize self-consumption against self-production rate maximisation, since the selling tariff of the energy in surplus decreases from 100 €/MWh to 60 €/MWh for solar panels exceeding 9 kWp. This incentivizes households to size panels to their power needs if based on monetary motivation (CRE, 2018). On the other hand, this is a result rather than a target of the regulator, as basically the motivation is to encourage the demand-side management options that increase the power usage during the sunny periods and decreases thus the energy in surplus (Fonteaneau, 2021).

The regressive feed-in tariff of the energy in surplus is not compensated either by the subsidy paid to panel installation, despite its progressive rate with the plant size. Among social planner motivations to encourage energy self-consumption, the general benefits pointed out in the literature are the renewable deployment, increased energy autonomy and independence, carbon emission reduction, innovation, and improved energy efficiency (Heuninckx et al., 2022). More particularly with concern to energy communities, the motivations of the planer is the same as for individual self-consumption, to accelerate the deployment of renewables and to encourage large-scale initiatives with potential replicability of the projects, while insuring a reasonable return on investment of participants (CRE, 2018).

The French regulation makes tax reduction for network fees in individual self-consumption but in the case of collective self-consumption, members use the public network thus they pay more fees than in individual self-consumption. From the business point of view, the collective model is less attractive than the individual case. Other options could compensate the tax difference loss such as the collective self-consumption platforms with a market operator buying the electricity from the market and not from an aggregator at fixed rate.

2° Sharing rules. Most of the collective self-consumption in France involve local authorities such as administrative buildings sharing the surplus with tertiary buildings, small enterprises, cultural institutions, but rarely with households. Other forms of sharing are from social landlords willing to supply green energy to their tenants, and large energy companies developing micro-grids based on collective self-consumption (Hampikian, 2017). The current regulation contains provisions for feed-in tariffs for small to medium solar installations (< 500 kWp), while larger solar generators can apply to calls-for-tenders or to sell the power on the market. The feed-in-tariff being regressive with the size of the community formed by the aggregation of prosumers, small-scale prosumers lose the advantage of selling the surplus at high levels. To take this into account, the regulator considers the option for households to apply two feed-in tariff levels, one related to individual self-consumption and one related to the collective self-consumption, but in this case the household does not beneficiate of tax exemption as in the individual self-consumption (CRE, 2018, page 17). In this way, the selling rule of the community surplus would integrate the opportunity cost of renouncing to the individual self-consumption.

The surplus of the community can be distributed following several combinations of volumes and costs, the most common being sharing the volume as a function of the participants' demand, and selling the community surplus to participants at a tariff rate function of the initial investment cost, i.e. at the average cost of the selling participant. The model presented at section 2 applied to the household-tertiary case sets the following conditions of welfare improvement:

- **Household (*h*) utility:**

$$ES2_h (TC - T_h) + ES1_h (lcoe_h - T_h) + EBC_h (pmarket_h - p_{sv}) > 0 \tag{12}$$

Replacing Th with the household feed-in tariff of 100 €/MWh, TC with the large scale feed-in tariff of 60 €/MWh, the household long-term cost of solar panel of 120 €/MWh, the market price of household of 175 €/MWh and the long-term cost of solar panel of large solar installation on the tertiary building of 90 €/MWh, the equation gives:

$$ES2_h (60-100) + ES1_h (120 - 100) + EBC_h (174 - 90 - Tax_{sv}) > 0$$

Which gives:

$$20\ ES1_h - 40\ ES2_h + (84 - Tax_{sv})\ EBC_h > 0 \tag{13}$$

The surplus sold to the market $ES2_h$ at reduced feed-in tariff should be compensated by the surplus sold to the community and also bought from the community within the proportions set by the last equation. Note that the revenue from the energy sold to the community is positive if taxes set on the community price are lower than market price net of average cost of solar from tertiary sector.

- **Tertiary (*sv*) building utility:**

$$ES2_{sv} (TC - T_{sv}) + ES1_{sv} (lcoe_{sv} - T_{sv}) + EBC_{sv} (pmarket_{sv} - p_h) > 0 \tag{14}$$

For solar installation of 100 kWp, Tsv = 60 €/Mwh, and TC depends on the feed-in level (TC < Tsv). For bigger solar capacity, TC and Tsv depends on injection to the grid. Numerical parameters are *TC* = Tsv for all solar panel installation (<100 kWp), with a feed-in tariff of 60 €/MWh, the services long-term cost of solar panel of 90 €/MWh and the market price of 135 €/MWh, which results into:

$ES1_{sv}\ (60 - 90) < EBsv\ (135 - 120 - Tax_h)$ or

$$(15 - Tax_h)\ EBsv + 30\ ES1_{sv} > 0 \qquad (15)$$

For taxes higher than 15 €/MWh, the business model is less interesting at current prices of 135 €/MWh. If taxes are about 100 €/MWh as today, the tertiary market price should by at least 220 €/MWh to make profitable the combination between the tertiary building with households. In this way only, it is more interesting to buy within the community at a solar panel cost and to sell the surplus at a level covering the long-run cost of the panel than at low feed-in tariff. Equations 13 and 15 form the boundary of negotiation that are made possible due to the limited number of community actors.

3° Regulation of the network. The analysis of the network configuration opposes generally large scale centralized network over long distances to small-scale micro-grids, with solutions depending on economies of density and energy resource endowment (Berthelemy, 2016). Yet individual solar panels have low power potential to cover household or tertiary energy needs thus micro-grids cannot substitute to central network. The problem then is the management of a variety of micro-grids connected to the central grid where individuals put their resources in common and might contribute to the central network operation in an efficient way. The framework of Ostrom (2010) applies when individuals forming a community communicate through a trade platform for instance and find decentralized optimal solutions defending the collective interest rather than non-cooperative equilibria summing their individual interests.

The analysis of cost and benefits of self-consumption communities remains complex with concern to the impact on general consumers. The energy community operating in a limited area is clearly reducing the distance of transport and distribution of electricity, but in practice the algorithm of distributed flows in France is already based on distance minimization, thus avoided loss with communities is considered by the French TSO, RTE, as being negligible (DGEC, 2014). Similarly, the advantage of the community that aggregates several consumption profiles and flattens the net demand, is considered to be already taken into account while optimizing grid flows. Therefore any reward of this profusion effect needs an additional benefit to the already existing effect, otherwise the impact on the general consumers could be expensive. To date, network losses are the only real and valid recognized benefit from grid perspective (Iazzolino et al., 2022). According to the French Transmission System Operator, solar self-consumption does not reduce the peak load, which occurs particularly in winter time, even after the implementation of demand management measures; therefore self-consumption has currently no significant effect on the French network sizing (RTE, 2019).

At currently low scale of self-consumption, cross-subsidies between self-consumers and general consumers are low, e.g. a few euros annually (Cluster et al., 2019), yet losses for the distribution system operator could be significant due to lower variable charges, e.g. some millions of euros. This deficit could be reduced by increased fixed part (the abonnement *A* in our model) for large firms (*A* increases by 14% in Cluster et al., 2019) and residential consumers (> 130%).

Conclusions

Decentralisation of renewables involving citizens into both production and consumption of energy comes with new rules of governance based on prior criteria of proximity and social interactions. Their complexity makes difficult the definition of common rules to all energy communities, therefore empirical studies are called for understanding the self-governance. This paper explores theoretical views on institutions and the commons (Ostrom, 2010) and the application to a solar energy community connected to the central power grid allowed building the boundary of rules of negotiations. By means of a French numerical case study, we identify participant arrangements that share the energy in surplus put in common within the community according to individual welfare criteria. As the community remains connected to the central grid, these social arrangements are insufficient to operate the community and needs to be complemented by government rules in terms of network fees. We obtain a set of solutions sustaining the existence of polycentric governance of the community, yet the active involvement of participants is necessary such as to turn the analytical rule into practice and institution.

The economic model we analysed is based on moderate return on investment in line with the French regulation norms of *normal* profits (CRE, 2019). The theory of institutions consider that the rationality of communities is to renounce to market rules but not in favour to other merchandising opportunities, i.e. community profits, but as the opportunity of individuals to involve within the energy management and to contribute to solving the social dilemma of climate change and resource scarcity. Yet the diversity of participants asks for a limited size of community such to make the negotiation effective.

Our empirical case shows that the simplest financial case for the grid operator is applying similar variable charges to prosumers and to general consumers, and to set increased fixed fees to compensate the missing revenues from self-consumption. For the prosumer, the simplest case is trading with participants having similar power contracts such as to make comparable tax regimes and to play on the surplus flow instead of solar panel costs, hence on the heterogeneity of profiles among similar activities. The variety of consumption and production situations makes necessary more research on the energy community in order to simplify contractual rules in the presence of heterogeneous individuals. Clarifying payoff rules along with the distribution of the surplus are among our work perspectives in this field.

Communities connected to the national grid can operate based on their self-governance rules, but the dependence on the consumers outside the community makes them subject to national rules through taxes and values that the society is based on, such as the electricity national solidarity with concern to the quality of supply (RTE, 2019), network tariff equalization (CRE, 2018) and anti-communitarian behavior (Fonteneau, 2021). So far the community models prevent private network establishment by residential users in favor of the exploitation of the public distribution network (Iazzolino et al., 2022). Yet community models prove viable as long as they remain connected to the grid, despite high levels that the decision-making of prosumers and communities may attain.

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