Designing renewable energy production at district scale: a sensitivity analysis

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Abstract

Distributed renewable energy systems are commonly viewed as a main lever to decarbonize the urban environment. The European Union introduced directives to make sharing of local renewable energies among numerous end-users possible, hence facilitating development at scales larger than a single building. However, a lack of long-term feedback and increased complexity of such projects overshadows the advantages, which as a result deters the interest of investors. However, if it were possible to provide reliable design recommendations for shared renewable energy systems at the district scale, backed by thorough performance and risk estimates, the pace at which distributed renewable energy systems are deployed throughout cities could be significantly enhanced. This study proposes a workflow to model a district operating under a collective self-consumption framework and to perform a sensitivity analysis on a large range of parameters, in order to identify the key ones that must be thoroughly investigated to guarantee accurate techno-economic feasibility assesments.

Highlights

- Collective renewable energy systems simulation.
- Techno-economic assessment from a feasability point of view.
- Identification of influential uncertain parameters at early design stages.

Introduction

The built environment being responsible for about 40% of global greenhouse gas (GHG) emissions (Global Alliance for Buildings and Construction. 2019), the decarbonation of cities is a key factor in tackling the climate crisis. The European Union (EU), which aims to reduce GHG emissions by 55% and to reach at least 40% of renewable energy by 2030, plans on transitioning the grid from centralized to decentralized energy systems with high shares of renewable energy (European Commission. 2021). Several EU directives introduced concepts that help member countries to define frameworks in which integrating local distributed renewable energy systems would be facilitated, such as the renewable energy communities (REC), citizen energy communities (CEC), and collective self-consumption (CSC). The EU leaves a degree of leeway for the transposition of its directives to each country and their specific policies. In France, REC and CSC are often assimilated together. The idea behind the CSC corresponds specifically to the action of collectively consume locally produced renewable energy (Frieden et al. 2021), which is the focus of this paper. In France, the CSC framework makes it possible for participating end-users to share energy through the public grid (2 km maximum distance between 2 participants), which grandly facilitates the implementation of shared energy sources as no secondary grid is required. Despite its advantages, such as higher absorption capacity of locally produced energy thanks to dispatching the energy to more end-users with potentially diverse load profiles (Vivian et al. 2022), the CSC concept is still fairly new. The lack of long-term feedback and the added complexity for the project development undermines the confidence of developers in taking that path. Moreover, some research works showed that certain goals in shared energy projects may conflict, like cost minimization and self-consumption maximization (Reis et al. 2022), or financial benefits of a PV production manager and those of end-users (Duchesne et al. 2019). Hence, depending on the project and its priority goals, design recommendations may vary considerably. The objective of our work is to provide tools that help verify and ensure techno-economic feasibility at a design phase, in order to support developers willing to implement CSC in their projects.

At early design phases, many parameters may still be unknown to a certain extent, which increases uncertainty on estimated performances. Undeniably, there is a strong interest in identifying the crucial parameters that can potentially make or break the success of a CSC project, so that relevant risk analysis can be performed. This paper focuses on a sensitivity analysis (SA), leveraging the Morris method, with the aim to identify the most influential parameters on financial viability for investors, and economic benefits for end-users.

Many research works have investigated similar topics recently. An extensive amount of studies, like the work from D’Adamo et al. (2022), showed the importance of the economical context, organisational aspects of an energy community, as well as investment decisions for electricity generation and storage systems, for the profitability of shared energy projects. The impact of more intrinsically random parameters, such as climatic conditions and energy demand, or end-users’ profiles, are also studied, though to a lower extent (Duchesne et al. 2019, D’Adamo et al. 2022; Tercan et al. 2022). However, most studies perform SA on a limited number of parameters with a standard one-at-time (OAT) method (Duchesne, Cotnélusse, and Savelli 2019; D'Adamo, Gastaldi, and Morone 2022; Tercan et al. 2022). The aim is usually to explore the way certain parameters can influence the outcomes of shared energy projects in general, with a few possible scenarios, usually classified as "pessimistic", "optimistic", and "probable". Some studies used optimisation methods to guide design choices in order to maximize selected objectives (Tercan et al. 2022), which is an effective way to enhance project performances. However, optimizations are usually performed in later phases of a project design, when the decision whether to implement district scale systems or not has already been made. Another limitation is the deterministic optimisation (some parameters will remain unknown over the project lifetime). One way to overcome this issue is to perform optimization under uncertainty (Mavromatidis, Orehounig, and Carmeliet 2018). The approach in our work adopts a feasibility point of view for specific projects that are still in early stages of design. Important project orientations, such as the implementation of district energy systems, are decided in relatively early phases, even though a considerable number of parameters and assumptions are still uncertain. For example, when buildings are not existing yet, let alone inhabited, key data like electric loads are not readily available and must be simulated. But then HVAC systems may not be precisely specified, the economic context may not be fixed yet as well, which results in an increasing number of variable input parameters. Nonetheless, reliable assessments must be given to investors/developers to encourage them in implementing a higher share of renewable energies, despite the added complexity. A standard OAT method may come as insufficient to conduct a comprehensive SA on larger sets of parameters, so the Morris method is used instead.

Finally, the purpose of the current work is to develop tools and methods compatible with a workflow for practitioners who intend to model and evaluate specific "real-world" projects at a design phase. This requires UBEM tools that can model buildings and energy systems from said projects with relevant inputs and outputs to emulate a CSC operation and that can be easily coupled with a large-scale sensitivity analysis. The present approach is original by its feasibility point of view, which can be later leveraged in guaranteeing district energy performances at early design stages when major decisions must be made.

Firstly, the paper introduces the case study, then the urban building energy modelling (UBEM) methods, as well as energy allocation within the CSC simulation and the financial analysis, and lastly the results are presented and discussed.

Case study

The idea for the case study is to apply the proposed method on a typical district development project where a CSC framework could be applied. The recently built Les Groues district in the city of Nanterre, close to Paris, France, is chosen. This district is divided in 5 blocks, each one composed of about 4 buildings, mostly for residential purpose, with a few commercial spaces on the ground floors. For the present work, one of those blocks is studied, with 4 buildings of about 7 floors each, composed only of apartments. The total apartment surface is about 9600 m², resulting in 132 apartments of 70 m² in average.

The viewpoint taken here is that a preliminary design is already intended, in terms of size and shape of buildings, types of HVAC systems, and targeted PV power, and for which developers seek to estimate the potential outcomes that would result from implementing a CSC scheme. In other words, view it as if some design choices (assumptions) were made to comply with building codes and labels, but the exact sizing of some building components and systems will be carried out later, so techno-economic assumptions may vary to a certain extent between the early design and operational phases. For this case study, the main assumptions are the following:

- Project location: Nanterre, France. Weather files representative of the past 20 years from the Vélizy-Villacoublay station are used.
- Energy performance of the buildings in line with current French building code (RE2020).
- Central heating and semi-accumulative domestic hot water (DHW) produced by electric air-to-water heat pumps (AWHP). Each building has 2 AWHPs, one for heating and one for DHW.
- PV production sized to comply with the French BEPOS label (positive energy building label).
- The power plant is financed and managed by a dedicated entity, acting as an additional energy supplier for residents.

Methods

The aim of our work is to provide methods and tools to evaluate the performance of a CSC framework within a district at a design phase. The workflow shown in Figure 1 is employed:

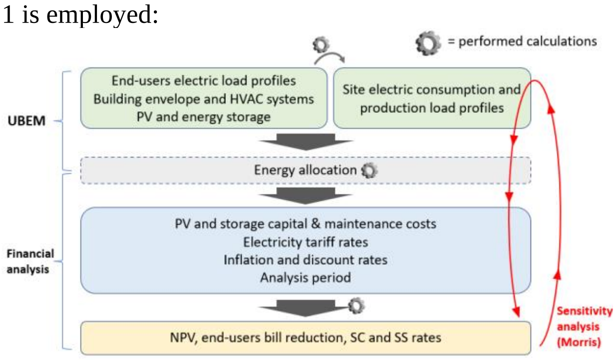

Figure 1: Proposed methodology

Urban building energy modelling (UBEM)

The complexity of modelling energy use and production at district scale is that key information, such as electric energy consumption, is generally missing at early design stage. Using only measured data from other projects is not always suitable, as load profiles may significantly vary from one project to another based on design choices, such as what kind of systems will be implemented for heating and domestic hot water, and if they will be powered by electricity. Sizing of said systems may influence load profiles. Hence, the modelling of the buildings is generally necessary. CSC being often thought about for projects involving many buildings, the modelling tools need to be suitable for larger scales. Additionally, disaggregated load profiles are required to observe energy sharing at different scales, from district or building level to end-user level. And finally, in order to account for energy exchanges, a fine temporal resolution is required. In the case of CSC in France, the accounting time step is of 30 minutes. Our modelling methodology is based on a bottom-up approach, which gives the most flexibility in terms or degree of precision with which a project is modelled. Although a "top-down" approach may reduce considerably calculation times, it is not as suitable to work with finer spatio-temporal resolutions and disaggregated data (Johari et al. 2020).

End-users' electric load profiles

This sub-model concerns the electricity consumption of end-users, which corresponds to domestic electricity uses in the current case study. As mentioned earlier, in order to account for energy exchanges at the end-users' scale, disaggregated data with a fine temporal resolution is needed. Moreover, a wide variety of load profiles is required in order to better apprehend the diversity of energy consumption habits among end-users and avoid overly coincident loads. This implies the use of probabilistic load profiles. Lastly, the load profiles must be coherent with the context, representative of a French population in our case. The CREST demand model (Richardson et al. 2010), a stochastic model built on Time of Use Surveys (TUS) allows the generation of load profiles with a temporal resolution of up to 1 minute. It is an open-source model that is widely cited in the literature (Dabirian et al. 2022). This model also generates end-users' presence, which is useful for adding metabolic loads in the thermal model. Hence, the CREST demand model has been selected. Although the model was built on British TUS, several works proved that it can be adapted to the context of another country. Similarly to Wills et al. (2018), we adjusted the model's statistical data, such as average annual consumption per dwelling, number of people per dwelling, electric appliances ownership and use intensity, so as to make it coherent with a French context. The model was then validated with measured data from a study in which about 100 French dwellings were surveyed (Figure 2).

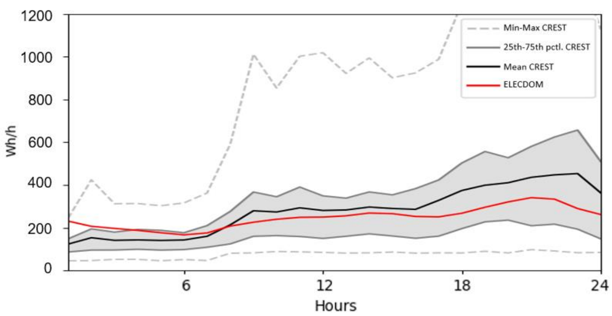

Figure 2: Comparison of a mean daily load profile modelled with CREST with measured data (ADEME. 2021)

Thermal loads

Thermal loads include heating and domestic hot water (DHW). Modelling those is required when electrical systems are used, such as heat pumps. Depending on the size of a district, and whether energy systems providing heating and DHW are mutualized, certain simplifications may be applied to lower the computational costs while keeping a sufficient degree of precision (Garreau. 2021). Thus, the thermal model needs to be flexible enough to work at various spatio-temporal resolutions. Building components included in the thermal simulation are:

- The building and its envelope, including walls (but excluding internal partitions) and windows with their respective thermal characteristics, ventilation and infiltration, thermostat settings, and thermal zoning. For the considered size and number of buildings, one thermal zone per floor corresponds to an adequate compromise between precision and computing costs.
- Internal heat gains, including metabolic loads and dissipated power from electric appliances. Profiles generated by CREST are used here.
- Central AWHP for space heating, which is modelled as a coefficient of performance defined as a function of the outdoor air temperature, applied to ideal heating loads.
- DHW systems, including an AWHP, a stratified storage tank (modelled with 6 nodes), and a recirculation loop of hot water (modelled as a non-adiabatic insulated pipe).

Baseline values and more information on modelling those parameters are shown in Table 1. The simulation is run with a 15 minutes timestep. The URBANopt tool (El Kontar et al. 2020), has been selected for our work. The thermal simulation is based on EnergyPlus, which is a widely used and proven modelling tool. What makes it particularly convenient is the degree of spatial and temporal precision being directly defined by the modeller. Moreover, it is an open-source tool, providing easier interoperability with other tools.

Electricity generation

The electricity production comes from rooftop solar PV. EnergyPlus simple PV model was used, which converts incident solar radiation to electricity using a user specified static efficiency coefficient for PV cells and inverter (i.e., 18% and 98% in our baseline case). PV panels are directly integrated in the building models on the highest rooftops.

The collective battery energy storage system (BESS) is implemented in post process with a python code. It takes as inputs an effective storage capacity, storage losses (including charge/discharge efficiency, 95% in our case), and the electric consumption et production load profiles. The operation mode consists on absorbing surpluses of energy when the production exceeds the total consumption, and discharging when consumption exceeds total production. However, it is important to note that BESS are not necessarily financially relevant in CSC projects in France, when used only to maximize self-consumption rates. The added costs, an already potentially high self-consumption rate without energy storage, and attractive feed-in tariffs surpluses of energy injected to the grid, make it harder for a BESS to be profitable. Therefore, both cases, with and without a BESS are evaluated separately.

Energy Allocation

In shared energy schemes, a distinction of physical and financial flows of energy is made, especially when there is no separated grid dedicated to exchange the locally produced electricity (Dudjak 2021). From the French legislation's point of view, the CSC framework is actually a contractual way of sharing energy rather than a physical one. Since the technical sizing and operation of the electric grid is out of the scope of the present work, only the financial layer of energy exchanges is observed here.

French residential smart-meters report every 30 minutes to the grid operator the quantities of electricity consumed by each participant, and the quantities of simultaneously produced electricity that are available for them. Then, the quantities of locally produced energy are allocated to each participant based on a key of repartition (KOR), which is a rule collectively defined at the start of a CSC operation. The most common KORs are so called default dynamic (also known as prorate of consumption) and static (such as equal sharing). The first one consists of providing to each participant at each time step a share of the simultaneously produced energy, defined by a coefficient equal to his consumption over the sum of all consumptions at that timestep. For the static KOR, the coefficients are defined once, and then remain unchanged until eventual further notice. The default static coefficients are based on equal sharing, but it could also be defined by prorate of investment. Various KORs have been investigated in the literature, and there is technically no limitation to defining a KOR, as long as it can be performed on the regulatory timestep, and that the calculation is transparent (Mustika 2022). An alternative KOR is a hybrid between prorate of consumption and static KORs, where first an equal share of energy is distributed to all participants, and eventual "left-overs" are then distributed on a prorate basis. Additionally, a KOR can determine whether the locally produced energy is allocated in priority to a collective energy use, such as central DHW, or firstly to end-users and then for collective uses. This parameter is called here "uses priority". Because only the financial layer is being investigated, the energy allocation can be simulated in post process, meaning after generation of electric consumption and production load data. This approach avoids the need for co-simulation, thus reducing the complexity of the simulation tool. The energy allocation simulation is performed with a python code.

Financial analysis

The energy simulation introduced above is run over a one-year period. However, one year is not relevant for a financial analysis where longer-term factors come into play, such as inflation and discount rates. Consequently, the financial analysis is performed over a 20-year period. Although a PV panel's lifespan averages at 25 to 30 years, generally investors seek return on investment on a shorter term, hence selecting a shorter period. The observed financial KPIs are the Net present value (NPV), and mean annual savings the CSC provides to end-users:

- the NPV mainly concerns the entity investing and managing the PV power plant. The NPV is defined by the following formula:

$$NPV = \sum_{n}^{Nb_{years}} \left(\frac{PV_{income}(n) - PV_{OPEX}(n_0) * (1+i)^n}{(1+r)^n} \right) - PV_{CAPEX} \qquad (1)$$

With r and i being the discount rate and inflation rate respectively, n the year, n_0 the first year, and Nb_{years} the analysis period. The PV_{income} is the received income from selling PV electricity to users and injecting surplus to the grid. PV_{CAPEX} and PV_{OPEX} are investment and maintenance costs respectively. A positive NPV means a return on investment has been achieved.

- End-users mean annual savings (AS), are defined as:

$$AS = \frac{1}{Nb_p * Nb_{years}} \sum_{p}^{Nb_p} \left(Bill_{with\ PV}(p) - Bill_{\frac{w}{o}PV}(p) \right) \qquad (2)$$

With p for participant, Nb_p the number of end-users participating in the CSC, Nb_{years} the number of years the analysis is carried over (20 in this case). $Bill_{with\ PV}$ and $Bill_{w/o\ PV}$ are the invoices related to end-users' electricity purchases, respectively when the project is equipped with PV, and the case without it as reference.

While the energy simulation is performed once and over a year period in order to obtain load profiles, the PV production load is altered each year of the financial analysis in order to account for the loss of efficiency of the PV systems (-0.5%/year). Accordingly, the BESS charge and discharge as well as the energy allocation are recomputed each year.

Sensitivity analysis

Considering the amount of simulation inputs considered, the Morris method is leveraged as it covers efficiently a larger experimental design than a regular OAT approach, and it requires significantly lower computing resources to run than global sensitivity methods (Rivalin et al. 2018). The number of trajectories and levels is a compromise between precise results and computational costs. A combination of 10 trajectories and 4 levels is applied, which is commonly used in the literature (Franczyk 2019). A reasonably higher number of trajectories and levels did not bring significant gains in precision. Table 1 summarizes the design of experiment, and the categories in which the parameters fall in. The variation ranges are determined as possible changes between the design and operational phases of the project. As such, the range of variation for each parameter is linked to the level of confidence the modeller has in its potential to vary until the operational phase is reached.

As mentioned previously, the assessed KPIs are the NPV for the investor, average end-users' annual savings, but also global self-consumption (SC) and self-sufficiency (SS) rates are observed.

Category	Colour code	Index	Parameter	Baseline values	Variation range	Details / assumptions
PV power plant		1	Installed PV power	140 kWp	-20% / +20%	The variation ranges are defined by potential changes between the design and operational stages, for example unplanned slight variation of usable roof area, rated efficiency, disposition of PV panels.
		2	Panels orientation	0° (south)	-45° / +45°	
		3	Panels tilt	30°	-20° / +20°	
Building design		4	Insulation level	Uwalls 0.2 W/m².K Ufloor 0.2 W/m².K Uroof 0.125 W/m².K Uwindows 1.7 W/m².K	-20% / +20%	Range of variation accounting for slight changes that may occur between the design and operationnal phases, as well as a potential decrease in performance due to human error during construction.
		5	Window to floor area ratio	19%	16% / 22%	Building code requires a minimum of 16,7%, and rarely goes over 22% to reduce risk of overheating during summer
		6	Rated COP for space heating AWHP	4	3,5 / 4,5	Common values observed on the market, for rated evaporator and condenser temperatures of 7°C and 35°C respectively
		7	Rated COP for DHW AWHP	4	3,5 / 4,5	
		8	HW storage tank	3000 L for a building with 30 standard appartments	Nb apts * 100 / Nb apts * 150	If the type of DHW production might be known at design stage (instanteanous, semi-accumulative, accumulative), the exact volume of the storage tank is generally not determined yet. According to the COSTIC, an institution publishing recommendations for building HVAC design, sizing of the volume of semi-accumulative HW storage tank can be determined by multiplying the number of standard appartments in the building by a factor between 100 and 150. The power of the heating systm is then calculated accordingly to the volume of the storage tank.
		9	BESS capacity	No BESS and 200 kWh	200 kWh / 400 kWh	For the present case study, a 200 kWh BESS increases increases the SC rate rate by about to 84%, compared to 62% in the case without BESS. 400 kWh BESS maximizes the SC rate up to 94%. The case witouh a BESS is also analyzed.
Energy allcoation		10	KOR ratio	0%	0% / 100%	0% correspond to a KOR fully based on prorate of consumption. 100% cooresponds to a fully hybrid KOR, which is based on an egalitarian allocation first, and then a prorate allocation of surpluses to participants that can still receive energy. 50% corresponds to a case where 50% of the energy is allocated with a prorate of consumption KOR and 50% with a hybrid KOR.
		11	Uses priority ratio	0%	0% / 100%	0% corresponds to an energy allocation in priority to end-users. 100% corresponds to an energy allocation in priority for collective uses (DHW in our case). 50% corresponds to half of the produced energy allocated to end-users, and the other half to collective uses. The surplus from one category can be allocated to the other, as long as respective volumes of consumptions have not been fully covered yet.
Electricity tariffs		12	CSC electricity tariff	0.140 €/kWh	-20% / +20%	In order to make a CSC attractive for end-users, the local tariff should be lower than the average grid tariffs, but also high enough for the project to be profitable for the investor/manager of the PV power plant. A ratio of 80% of the grid tariffs for individual end-users is selected as baseline. The variation range applies for the first year of the analysis. The CSC tariff is not subject to inflation in this study, to adress the fact that the price of locally produced electricty is much less exposed to variation linked to geopolitical events than larger scale energy markets. In that sense, it provides a protection against inflation on energy prices for end-users. Although, this tariff may slightly increase in the reality, due to maintenance costs being affected by general inflation over time. VAT are not included.
		13	Grid tariffs	0,174 €/kWh (individual end-users) 0,131 €/kWh (condominium association)	-20% / +20%	Values based on French governmental statistics. The tarifs are considered as flate rate. An increased of about 20% has been observed between 2021 and 2022. The variation range applies for the first year of the analysis. The tariff increase over the next yars is is accounted for with the inflation rate. VAT are not included.
		14	Feed-in tariff	0,110 €/kWh	-20% / +20%	Based on current regulatory feed-in tariffs. They've been increasing recently, with a 13% increase between 2021 and 2022. VAT are not included.
Investment & maintenance costs		15	PV CAPEX	1100 €/kWp	1000€/kWp / 1500€/kWp	Observed values in benchmarks and reports on the costs of renewable energy systems (ADEME, NREL, Fraunhofer institute)
		16	PV OPEX	16 €/kWp/year	15€/kWp/year / 20€/kWp/year	
		17	BESS CAPEX	700 €/kWh	600€/kWp / 1000€/kWp	
		18	BESS OPEX	15 €/kWp/year	15€/kWh/year / 20€/kWh/year	
Economic context		19	Discount rate	5%	4% / 6%	Usual discount rate and variation range used by the ADEME for rooftop PV power plant within the 100 - 500 kWp range
		20	Inflation rate	2%	1,60% / 2,40%	According to the French national statistics institute, the inflation rate over the past 5 years is about 2%. The standard error over the past 30 years is about 18%, hence a variation range of -/+ 20% of the baseline value used here.
End-users energy habits/ behaviour		21	Average annual electric load per dwelling per year	2200 kWh/year	-20% / +20%	Baseline value determined from national statistics and surveys from ADEME (2021)
		22	CSC participation rate	80%	-60% / +100%	End-users are free to accept joining a CSC operation, and also leaving it later. An surveys led by IFOP, a French statistics institute, showed that 86% of the French population have a positive opinion about solar PV
		23	Thermostat setpoint	20 °C	18°C / 22°C	Typical range of observed thermostat setting
Solar ressources		24	solar radiation	1150 kWh/m²/year	-2% / +2%	The range of variation is based on the standard error of the annual radiation measurement on a horizontal surface over a period of 20 years at the station PARIS - ORLY weather station (geographically close to the case study localization), which is around 1.5% according to the data from the WRDC, and rounded to 2%

Table 1: Summary of the design of experiment used for the sensitivity analysis with the Morris method.

Results

A baseline case was first simulated, without performing the Morris SA, in order to verify that the model works properly. The energy simulation, that generates load profiles, runs with a 15 minutes timestep. Figure 3 shows electricity consumption and production load profiles for a winter and a summer day (for all 132 apartments). During winter, the BESS systems is less used as most of the production is directly absorbed by consumption, resulting in high SC rates, even up to 100% like for the example hereunder. However, on a summer day, production exceeds consumption, so battery charging cycles are observed, until full capacity is reached, and then discharging cycles once the production levels go below the consumption levels, until there is no stored energy left.

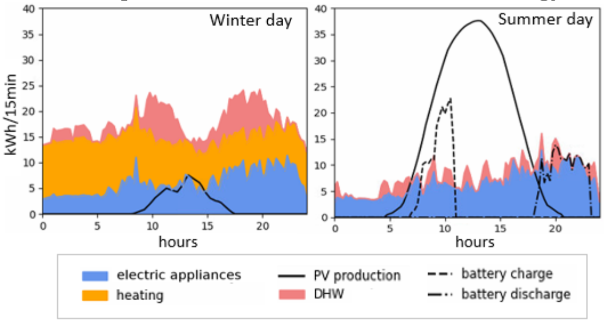

Figure 3: Consumption and production load profiles over a winter and a summer day, with a 200kWh BESS.

Figure 4 illustrates the breakdown of electricity purchases for end-users participating in the CSC project, with a KOR based on prorate of consumption, and a hypothesis of 80% of residents participating in the CSC. The amount of end-users in relation to the available PV power results in a relatively low share of received local energy per participant. However, an annual invoice reduction in the range of 6% to 10% can be observed. Despite seeming low, this may be considered as attractive for end-users, as they actually perceive benefits without investing in the PV powerplant. They simply purchase electricity from the PV plant at a lower tariff than the grid tariffs. The impact of the KOR can be noted as well. The present KOR rewards end-users with higher energy consumptions. A hybrid KOR would first equally allocate energy to all participants, thus incentivizing them to reduce their energy consumptions.

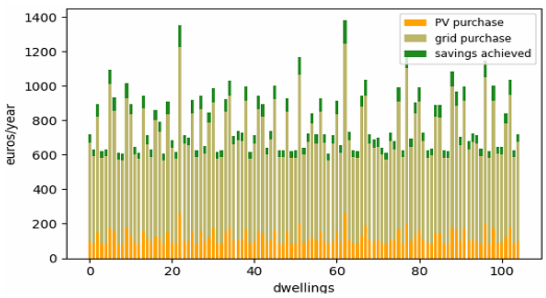

Figure 4: Participating end-users' electricity purchases breakdown, under a prorate of consumption KOR.

Despite the observed benefits for end-users, the project is likely to see the light of day only if the investor/manager of the PV power plant achieves a return on investment in a reasonable amount of time. Figure 5 shows the cumulated NPV over the years, for cases with and without a BESS. As discussed earlier, with the current legislations around the energy in France, deploying a BESS in a CSC operation may not be profitable. the simulation results here show that the high feed-in tariffs substantially mitigate the benefits brought by investing in a BESS, and the augmented cashflow does not cover the higher supplementary costs. Nonetheless, this applies to the present day, as BESS systems currently represent a high investment cost, but they are likely to decrease considerably in the next decade (Jülch 2016). The obtained self-sufficiency (SS) rates are 85% and 62% respectively for the cases with and without BESS. The energy storage improves substantially the SS rate, however it proves to be not profitable, making it in the end a less attractive option for the investor, despite the advantages for end-users. In the case without the BESS, the NPV becomes positive between the years 12 and 13, meaning a return on investment is achieved. Thus, end-users and investors perceive benefits, the project seems viable. Although these are the outcomes of single simulations, this is where the SA comes into play in order to identify the most influential parameters that could significantly alter those results if they happen to vary.

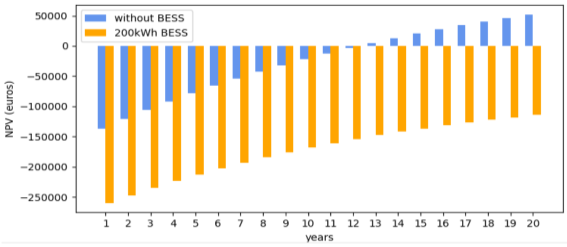

Figure 5: Evolution of cumulated NPV over the analysed period, for cases with and without BESS (200 kWh capacity for the latter).

The next step is performing the SA with the Morris method. Here again, two cases are studied: with and without BESS. Basically, in early design phases, the choice whether a BESS system will be deployed or not may have not been made yet, but as observed, the impact of this design decision is clearly significant and the variation range between zero to a sufficient storage capacity to get reasonable improvement of SC and SS rates may overshadow the impacts of the rest of parameters. Hence it was decided to study two variations of the case study. Table 2 summarizes the elementary effects ($\mu*$) estimated by the SA for both cases. The higher the $\mu*$ value for a given parameter, the more sensitive the model is to that parameter. The financial/economic parameters category proves to be overall the most influential for both the NPV and end-users bill reduction, at the exception of BESS capacity which actually appears to be the most impactful parameter. However, the BESS is linked to high additional investment, which understandably has an important impact on financial KPIs. Technical systems parameters, like the COP of the AWHP, show relatively little impacts. This implies that when there is already a general idea of the systems that will be deployed in a project, the uncertainties related to the exact systems specifications have a relatively low impact on the project's performances. This might not be the case when major shifts in design choices may still happen, for which larger ranges of variation on the corresponding parameters should be used. Certain parameters that can impact end-users' benefits, are negligeable for the investor. This is the case of participation to the CSC rate, or the chosen KOR which directly affect the shares of energy allocated to each participant. Nonetheless, the way the energy is allocated between participants does not affect the energy supplier, since the CSC tariff is the same for all users. Feed-in tariffs being relatively high in our case (which expresses the government's policies to encourage the deployment of PV), a decrease of on-site self-consumption has a limited impact of the supplier's revenue. This may significantly change in a context where feed-in tariffs are much lower, or inexistant. Variation in PV sizing and residents' energy consumption habits have minor impacts on financial KPIs, but affect the rate of on sites renewable energy consumption (SS and SC rates).

Figure 6 shows the graph of $\sigma(\mu^*)$, for the case without a BESS. This case is chosen here for the purpose of better readability, as the impact of BESS capacity exceeds largely the effects of the rest of parameters. A rather low degree of non-linearity is observed, implying that the parameters are not likely to gain impact by interaction with other parameters.

		Without BESS				With BESS			
Param. Index	Parameters	NPV (€)	End-user savings (€)	SC rate (pp)	SS rate (pp)	NPV (€)	End-user savings (€)	SC rate (pp)	SS rate (pp)
1	PV total power	11320	10	13%	4%	19782	23	13%	9%
2	PV orientation	10950	2	2%	1%	15483	2	1%	1%
3	PV tilt	9517	1	2%	1%	9765	1	2%	1%
4	Building Uvalue	116	0	0%	0%	17	0	0%	0%
5	Window to floor ratio	357	0	1%	0%	95	0	0%	0%
6	AWHP COP (heating)	353	0	0%	1%	26	0	0%	2%
7	AWHP COP (DHW)	764	5	1%	0%	369	4	1%	1%
8	DHW tank volume	458	1	0%	0%	57	0	0%	0%
9	BESS capacity	-	-	-	-	200002	6	8%	3%
10	KOR	0	14	0%	0%	5	40	0%	0%
11	Uses priority	0	8	0%	0%	11	8	0%	0%
12	CSC tariff	79544	55	0%	0%	112533	91	0%	0%
13	Grid tariff	70820	27	0%	0%	100768	37	0%	0%
14	Feed-in tariff	25402	0	0%	0%	9603	0	0%	0%
15	CAPEX PV	71702	0	0%	0%	68909	0	0%	0%
16	OPEX PV	10558	0	0%	0%	10657	0	0%	0%
17	CAPEX BESS	-	-	-	-	123000	0	0	0
18	OPEX BESS	-	-	-	-	21144.2	0	0	0
19	Discount rate	27301	0	0%	0%	18112	0	0%	0%
20	Inflation rate	2414	14	0%	0%	7867	22	0%	0%
21	mean annual cons./dw	10300	10	12%	0%	3863	15	8%	3%
22	CSC participation rate	10050	9	14%	4%	8224	23	8%	11%
23	Thermostat setpoint	1532	3	3%	4%	170	2	0%	8%
24	Annual solar radiation	8409	1	1%	0%	10007	2	1%	1%

Table 2: Elementary effects (μ) results for cases with and without BESS.*

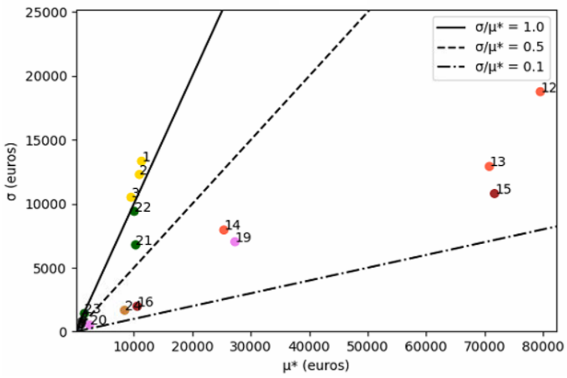

Figure 6: Elementary effects (μ) and interactions (σ) on the NPV (without BESS). See Table 1 for Colour codes.*

Discussion

For energy modelers who take responsibility for the design recommendations they provide, it is crucial to identify the key parameters that influence the performances of a project, to then focus on them when leading uncertainty analysis, since including all parameters of a model may be computationally too expensive. The presented case study corresponds to an emulation of a design phase of a district development project, where the question of implementing a CSC scheme is at stake. It is assumed here that general design choices were already made, nonetheless some details may still vary between the design and operational phases, such as the exact efficiencies of various building components/systems, the actual effective area available for solar panels, or the precise economic context. The sensibility analysis shows that the cost-effectiveness from the investor's point of view is highly sensitive to economic assumptions, which seems logical. However, the uncertainty on technical parameters has a rather limited impact since the variation ranges remain reasonably close to the intended design. End-users' behavior related parameters (average level of consumption, participation to the CSC rate) also have a limited impact on the project's profitability. This is explained by high feed-in tariffs for this scale of installed PV power, so a decrease in the collective SC rate may not put the return on investment in jeopardy. As a result, the modeler may grant less effort on analyzing the variability of those less significant parameters. However, those results cannot be directly translated to other projects. For example, feed-in tariffs may be lower in smaller projects, or in different contexts. As already discussed, implementing a BESS is not necessarily profitable in CSC projects in France nowadays, however this may change in the future. Then, major design changes, like using gas or biomass boilers instead of heat pumps, may also bring different results. The district in this study is essentially residential, so load profiles among end-users are relatively homogeneous, hence the uncertainty on this parameter has a limited impact. But this might not be the case in mixed-use districts, where commercial or office spaces are included, and where energy profiles may be considerably more diverse. These additional variations are out of the scope of this paper, but this highlights the need for future works to investigate a larger panel of projects in order to draw generalizable conclusions.

Lastly, the sensitivity analysis shows that the impact of the studied parameters varies based on the KPIs that are observed. Therefore, eventual uncertainty and risk analysis carried out afterwards for guaranteeing performances must be oriented towards the right sets of parameters depending on the objectives of a project.

Conclusion

The current paper presented a workflow to, first of all, model a district operating under a CSC framework and then to perform a sensitivity analysis using the Morris method. The proposed workflow intends to help an energy modeler to identify the key parameters that must be thoroughly investigated to provide accurate and reliable techno-economic feasibility assessments. The case study showed that for project where buildings' main design choices were already made, small variation of technical input data are not likely to change the outcomes in terms of cost-effectiveness for investors. Hence, economic assumptions are the key parameters to focus on in order to reliably estimate the NPV. However, when looking at other KPIs, such as benefits for end-users or SC and SS rates, other parameters become important, such as end-users' energy consumption and involvement. In this sense, a KPI for greenhouse gas emissions should also be implemented, to lead the analysis beyond the sole economic performance of projects, which will be the topic of future work. Further enhancement to the workflow will also include the integration of uncertainty and risks assessment methods based on the outcomes of the sensitivity analysis.

Finally, the results from the current case study cannot be directly translated to other projects yet. As discussed in this paper, results may vary if a district features commercial uses, or less buildings and residents, or different systems for heating for instance. Therefore, variations to the case study should be addressed in future works in order to verify whether different results would be obtained for different district types and designs.

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