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Multi-agent simulation of collective self-consumption: impacts of storage systems and large-scale energy exchanges

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Abstract

Collective self-consumption (CSC) is often presented as an approach for better energy management. This paper proposes a multi-agent and multi-level model to analyze the impact of CSC in the residential sector. It considers human activity as the core of electricity consumption in the household. In addition to a co-simulation between a multi-agent model of human activity and a thermal model, we added a layer to simulate interactions within an association of households, together with collective means of production and storage. This model was used to perform various studies. First, CSC configurations with individual and collective storage were simulated. The results highlight the impact of individual and collective means of storage on the way energy is consumed, exchanged, charged or discharged in the group of households and within each household. Finally, a large structure including energy exchanges between a set of households (neighborhood) forming a CSC was modeled. The results clearly show the impact of energy exchange between neighborhoods on the overall CSC.

Keywords: *Multi-agent simulation, human activity, collective self-consumption, storage systems*

29 1. Introduction

30 The residential sector is the largest consumer of electricity in the world (23 000 TWh in 2017¹). This
31 consumption is mostly based on fossil resources, which are characterized by their limited availability and their
32 negative consequences on the environment and their role in climate change. To reduce the carbon footprint,
33 the development of renewable energies (RE) is widely supported in this sector.

34 Generating one's own energy using a local source (e.g., photovoltaic panels, windmills) and consuming all or a
35 part of this energy is called *individual* self-consumption (ISC) (Luthander et al., 2015; Matallanas et al., 2011).
36 This way of producing and consuming energy is being developed around the globe, especially the use of
37 photovoltaic panels in the residential sector². However, only 25% to 40% of this energy is consumed by the
38 producers and the surplus is generally sold to an electricity supplier (Luthander et al., 2015). This impacts the
39 electricity transport and distribution operators, who have to perform load balancing, which in turn leads to
40 additional costs and is less and less sustainable at a large scale (Tarroja et al., 2013) and is therefore an
41 obstacle to the development of ISC.

42 Several solutions exist today to accelerate the development of self-consumed energy. Luthander et al. (2015)
43 proposed the use of storage systems in order to stagger the use of the electricity produced, or to apply
44 demand-side management (DSM) to stagger the use of some appliances during the periods of energy
45 production. The use of individual storage systems, like batteries, to store the excess electricity and use it when
46 the local energy production is low is well developed alongside ISC. In addition to these individual strategies,
47 both Tushar et al. (2018) and Yaagoubi & Mouftah (2017) suggested sharing or exchanging the locally
48 generated energy between households. This is called *collective* self-consumption (CSC), and enables
49 households to absorb the excess energy produced by other households. CSC consists in regrouping households
50 so that the excess production is exchanged between the households of a neighborhood. Even if, from a physical
51 point of view, the energy distribution is continuous and accomplished by the electricity distribution network,
52 the energy exchange operations and the resulting financial flows in CSC are performed on a contractual basis,
53 at regular time steps. CSC operations can be set up in various ways by varying the available means of
54 production or storage, the contractual organization of energy exchange and the characteristics of the

¹ <https://www.iea.org/>

² <https://www.solarpowereurope.org/>

55 households (such as the type and composition of families, the characteristics of the built environment, the
56 electrical appliances available, etc.). Until now, however, only a limited variety of CSC configurations have been
57 analyzed in real settings, hence the need for a simulation to study the diversity of possible cases.

58 In order to develop new CSC operations, CSC stakeholders such as building owners, property developers, urban
59 communities, energy providers and network operators need to be informed about the various ways RE can be
60 consumed and exchanged between households. Our approach, based on the SMACH project (*Simulation of*
61 *Activity and Consumption in Households*) (Reynaud et al., 2017), consists in using multi-agent simulation (MAS)
62 to study the energy consumption in households and the way energy can be exchanged in a CSC operation. The
63 originality of this work lies in the fact that it considers human activities and their interactions as the principal
64 spur for energy needs, and the driver of energy consumption and energy exchange. The energy needs and
65 excess consumption of each household are strongly dependent on the characteristics of their inhabitants, such
66 as household composition, and daily activities. This makes the SMACH approach a suitable tool to study CSC
67 while taking into consideration the diversity of residential energy consumption.

68 In the next section, we will present related work on the simulation of human activity and energy exchange. In
69 the third section, we present the SMACH platform that we used to simulate the human activity and the
70 electrical consumption of the households. In the fourth section, we will describe a multi-agent multi-level
71 model for the simulation of CSC that addresses the limitations identified in the literature. Various cases studies
72 and their results are described in Section 5 to illustrate the genericity and the possibilities offered by our model.
73 The first focuses on the different impacts of individual and collective energy storage within a CSC association.
74 The second case study examines how energy is exchanged in a new, sustainable neighborhood with a collective
75 solar farm. The last case study illustrates the capacity of our model to simulate energy exchange not only
76 between households but also between different groups of households. Finally, future work will be discussed in
77 Section 6.

78 2. Background

79 2.1. Simulation of human activity

80 Planning and sizing CSC operations in the residential sector requires a precise knowledge of electricity
81 consumption in each household. However a realistic simulation of electricity consumption needs to take into

82 account the activity of its inhabitants (Carlucci et al., 2020; Happle et al., 2018). An insufficient level of detail in
83 the modeling of human activity can lead to serious discrepancies between simulated and measured electricity
84 consumption (Clevenger & Haymaker, 2006; de Menezes et al., 2012; Norford et al., 1994; Soebarto &
85 Williamson, 2001).

86 Human activity is complex, with four principal features that must be taken into consideration in order to
87 simulate it precisely and derive a precise evaluation of energy consumption in households. First, human activity
88 is characterized by a strong variability (Kang & Scott, 2010) from one individual to another (*interpersonal*
89 *variability*) but also for a same individual (*intrapersonal variability*) (Bakaloglou & Charlier, 2019; Feldman &
90 Pentland, 2003). Human activity is characterized by repetitive phenomena, called *routines*, through which
91 individuals organize their activity at a low cognitive cost (Salembier et al., 2009). Finally, human activity is
92 characterized by its collective dimension, characterized by cooperation between individuals who live together
93 (Haradji et al., 2012). This cooperation is achieved through information exchange and communication between
94 individuals.

95 Several approaches that simulate human activity have been described in the literature, most of them combined
96 with building energy models in order to calculate the energy needs of a building associated with heating, air
97 conditioning, Domestic Hot Water (DHW), artificial lighting and ventilation (Fang et al., 2014; Kim & Moon,
98 2009; Yuan et al., 2017). The *deterministic model* which simulates human activity through fixed schedules and
99 deterministic rules (Abushakra et al., 2004; Happle et al., 2017) or the *stochastic models* use a probabilistic
100 approach to simulate dynamic decision-making (Happle et al., 2018). But these kinds of models do not take into
101 account all the characteristics of the human activity like the variability or the collective dimension or human
102 activity (Gaetani et al., 2016).

103 The *Multi-agent models* represent inhabitants of households by autonomous entities, the agents, which
104 interact in a given environment. Reynaud et al. (2017) highlighted the capacity of multi-agent simulation (MAS)
105 to simulate reactive and adaptive individuals who are able to collaborate to perform various tasks. MAS is
106 therefore considered as a more relevant approach that increases the realism of simulated human activity
107 compared to deterministic and stochastic models (Amouroux et al., 2013; Chapman et al., 2018; Ferreri et al.,
108 2015; Kashif et al., 2013). **SMACH platform, described in Section 3, is based on three components namely (1) a**
109 **population generator based on national census data, (2) a MAS to simulate human activity (Amouroux et al.,**

110 2013), and (3) a co-simulation with a building energy model. SMACH applies a holistic approach that takes into
111 account the four principal aspects of human activity we presented, in a comprehensive manner and simulates
112 human activity and decision-making as the determining factors in energy consumption. However, local
113 production, energy storage, energy exchange and CSC have not yet been implemented in these models.

114 2.2. Simulation of energy exchange

115 Energy exchange in CSC can take different forms, and two categories of exchange are generally distinguished in
116 CSC modeling: distributed energy exchange and centralized energy exchange.

117 In **distributed energy exchange**, trading operations take place directly between producers and consumers
118 without going through a third party, households directly transmit the necessary information to each other to
119 exchange energy. For example Lee et al. (2014) and Yaagoubi & Mouftah (2017) use game theory to represent
120 these kind of energy exchange. On the contrary in **centralized energy exchange**, some of the decisions
121 concerning energy exchange are taken by a third party. The goal of this third party is to distribute energy
122 between the households according to precise rules. For example, Vytelingum et al. (2010) proposed the
123 creation of an energy market based on a continuous double auction in which buyers and sellers simultaneously
124 make offers to buy and sell. The market distributes energy in order to satisfy the offers as much as possible.

125 In CSC, an important distinction must be made between the physical layer (responsible for the distribution of
126 energy, i.e., the physical energy that actually transits on the electricity network), and the contractual layer
127 (responsible for the contractual and financial organization of energy exchange between households).
128 Experiments on CSC in the field rely on this distinction, as illustrated by Mengelkamp et al. (2018), who
129 described these two layers in the implementation of a CSC in Brooklyn. In their experiment, the centralized
130 contractual layer takes the form of an energy market, similar to the one described by Vytelingum et al. (2010).
131 Given this distinction, the model we propose focuses on the simulation of the contractual layer, which can be
132 applied to any organization of the physical layer. We call a **collective organization of energy exchange** a
133 situation where a central entity (e.g., a marketplace) is responsible for contractual energy exchanges. We call
134 an **individualized organization of energy exchange** a situation where households exchange energy directly,
135 without the intermediary of a central entity. Current CSC experiments usually use a collective organization of
136 energy exchange (Mengelkamp et al., 2018).

137 Our contribution, presented in this article, is a multi-agent multi-level model that can be used to study different
138 ways to organize the contractual layer of exchange in a group of CSC households. This model is built upon the
139 SMACH multi-agent platform of human activity and therefore consider human activity to compute the energy
140 consumption of the households which is a key data to perform energy exchanges. Such a consideration is not
141 taken into account in the existing CSC model. Moreover, as we will show, our model is able to simulate and
142 study numerous CSC configurations in terms of population, storage and production equipment, or in the way
143 energy is exchanged between households, which is not the case for models presented in the literature. The
144 model presented in this paper focuses on the collective organization of energy exchange, with the presence of
145 a central entity responsible for managing the contractual layer, as this organization is the one commonly used
146 today in field experiments.

147 3. SMACH and single-building consumption simulation

148 We used the SMACH platform to simulate human activity and the electricity consumption of households that
149 formed a CSC. The SMACH platform combines three components in order to simulate a realistic electricity
150 consumption.

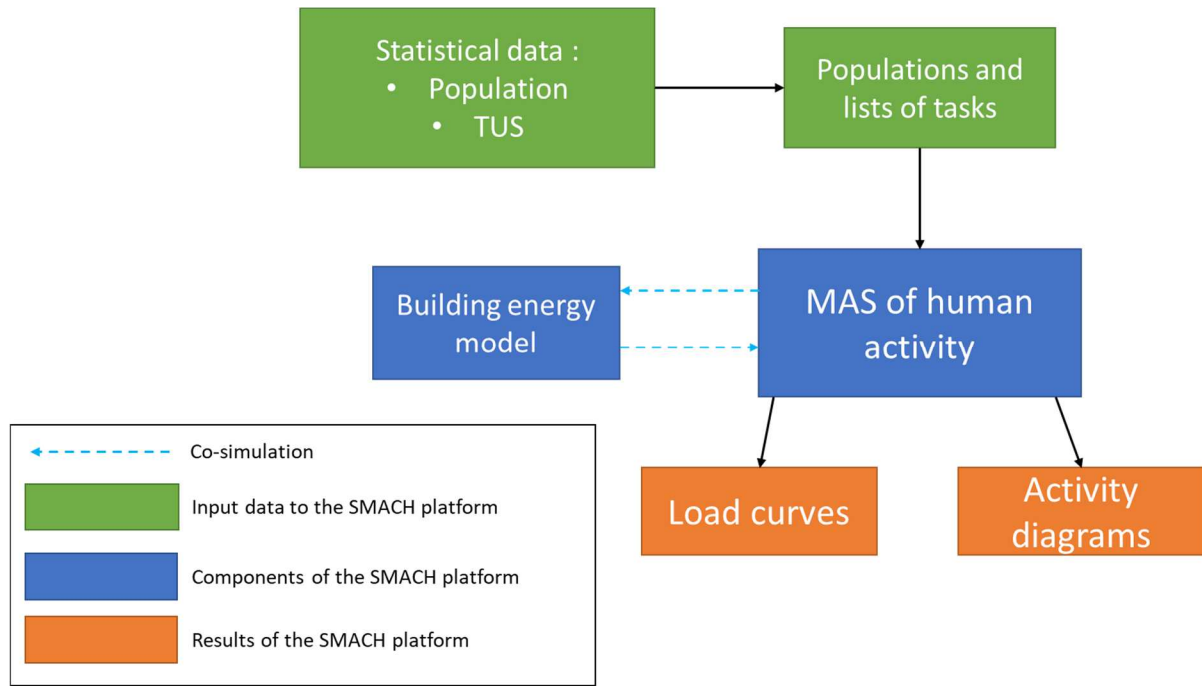
151 The first component of the SMACH platform is the Population Generator. By using national census and energy-
152 related data, it creates synthetic populations that are statistically representative of the studied area (e.g., a city,
153 a region, a whole country). Each generated household is characterized by a family profile, the age, gender and
154 socio-professional category of each individual, their electricity tariffs, the type of heating and DHW energy
155 available (electrical or non-electrical), a set of electrical appliances, as well as a building with a given surface
156 and energy performance. Moreover, for each inhabitant of each household, the generator provides a
157 provisional daily and weekly schedule containing a list of tasks that an individual tries to perform. For this
158 purpose, SMACH uses data from the *Time Uses Surveys (TUS)*, carried out in France between 2009 and 2010
159 (Reynaud et al., 2017). These surveys consist in 27000 notebooks, on which the 18500 participants wrote their
160 current activity every 10 minutes over a complete week and weekend day. From these TUS notebooks, SMACH
161 builds a provisional schedule consistent with the profile of each inhabitant of the household. All these elements
162 form a static description of the daily life of a household. However, the provisional schedule alone is not enough
163 to forecast the activities of each simulated individual: these will be decided by the individuals themselves
164 during the multi-agent simulation.

165 The second component of SMACH is the MAS of each household. The model transforms the static description
166 of the household into a dynamic simulation of human activity. Each inhabitant is represented by an agent, and
167 the MAS simulates their activity at a 1-minute time step. The result of this simulation is an activity diagram
168 describing, at each moment of the simulation, the activity performed by an inhabitant, and in which location.
169 The 1-minute time step was chosen by the developers of the platform in order to account for realistic human
170 activity and interactions between individuals. A time-step greater than 1 min could lead to a lack of precision in
171 the simulation of human activity, while an inferior time step does not significantly improve the realism of the
172 activity but leads to longer simulation times. During a SMACH simulation, the agents select a task to perform in
173 their provisional schedule at each time step. The selection is based on a level of dynamic priority. The priority
174 of a task changes depending on associated parameters like duration, preferred time step or rhythm. Other
175 factors like energy price, the availability of an electrical appliance or the actions of the other inhabitants also
176 influence a task's priority level. Each activity performed by an occupant of the household is linked to the use,
177 programming or control of one or more electrical devices, thus resulting in an energy consumption metered at
178 each time step. The load curve of the household is therefore a consequence of the activities performed.

179 The last component of the SMACH platform is a co-simulation between a multi-zone thermal energy model and
180 the MAS. This co-simulation provides a precise computation of the indoor temperature for each zone of the
181 building, impacted by parameters and variables such as the exterior air temperature, how well the building is
182 insulated, the presence of the occupant in each room and the nominal power of electrical heaters. The
183 buildings are modeled with the BuildSysPro Modelica library³ developed by EDF (Plessis et al., 2014). The co-
184 simulation between the multi-agent system of human activity and the thermal building model is achieved using
185 the FMI (Functional Mock-up Interface) standard (Plessis et al., 2014). The building energy model was validated
186 using laboratory and field data, and compared to the IEA BESTEST benchmarks (Judkoff & Neymark, 1995).

187 **Figure 1 presents the interaction between the three components of the SMACH platform.**

³ <https://github.com/EDF-TREE/BuildSysPro> accessed 21/01/2020



188

189

Figure 1 : Schematic representation of SMACH platform and its components

190

A specific approach was devised to validate the human-centered approach of SMACH for the simulation of both

191

activity and energy consumption, at both the individual and aggregated level. First, the capacity of the model to

192

faithfully reproduce realistically human activity was verified in a cognitive ergonomics field study using

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participatory simulations with real households who were able to manipulate a dedicated SMACH human-

194

computer interface (Amouroux et al., 2014). The SMACH load curves were also compared to the metered load

195

curves of the same households and shown to be within acceptable confidence intervals. Secondly, a

196

macroscopic study was performed with 100 simulated households to verify that the simulations reproduced

197

relevant indicators at the aggregated level when compared to TUS data (e.g., average duration of the activities

198

per day, the number of repetitions for each activity and of a sequence of activities). Finally, aggregated load

199

curves of 1000 simulated households representative of Metropolitan France were compared to the annual and

200

weekly profiles used for the assessment of injection and withdrawal flows on the public distribution network

201

(DSO open data). This work validated the values and dynamics of the simulated load curves, which were

202

representative of the energy consumption in the residential sector (Reynaud et al., 2020, in French).

203

The SMACH platform is therefore a useful basis for studying CSC as it already incorporates a robust simulation

204

of human activity and the ability to represent statistically representative households. We therefore propose to

205

consider CSC as a multi-level construction, based on inhabitants in households who themselves participate in

206 an energy exchange organization between households. SMACH is used to simulate the first two levels of the
207 CSC (individual human activity and household-level activities). We extended it to 1) incorporate individual self-
208 consumption (ISC) into the SMACH platform, and 2) model the energy exchange between households, as well
209 as the energy exchange between groups of households.

210 4. Model of collective self-consumption

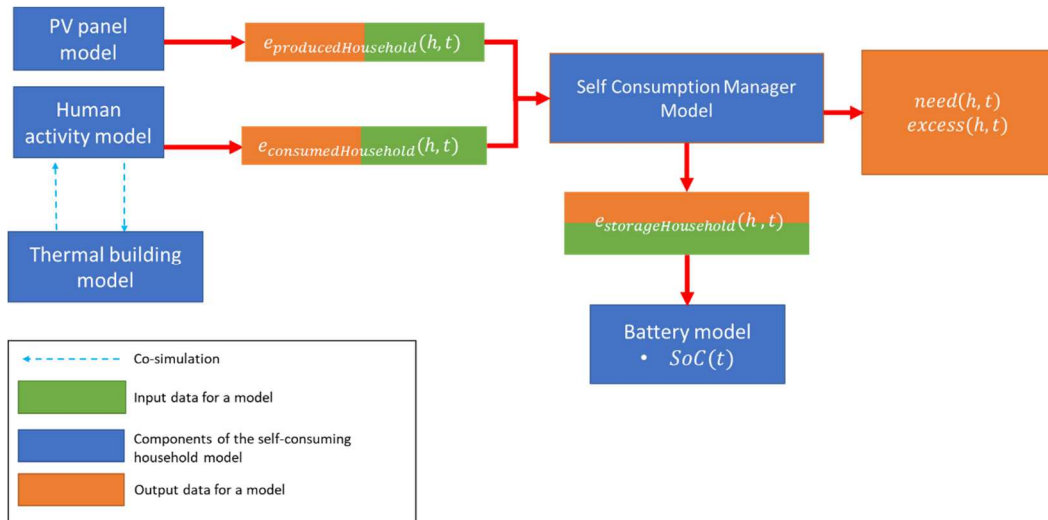
211 In this section we present a multi-agent four-level model to simulate CSC. In the first level, we simulate the
212 individual activity of the inhabitants using the SMACH platform. The second level is a MAS which simulates the
213 interaction between the inhabitants and the electrical appliances in the household to calculate the load curve
214 of the household. In order to simulate ISC, we adapted this level by attributing a means of local energy
215 generation and storage to households, and including a calculation of the amount of energy that is produced
216 locally, and then charged or discharged at each simulation time step. We will present this ISC model in section
217 4.1. The third level of our model, which is also a MAS, simulates the contractual energy exchange between
218 households. In this level, a third-party entity carries out the contractual energy exchanges and the computes
219 financial flows by following the rules for a given CSC configuration. It is presented in section 4.2. The fourth
220 level of our model simulates energy exchange between different groups of households already using CSC. This
221 level is also a MAS which works like the third level of our model.

222 4.1. Simulation of individual self-consumption

223 To simulate ISC, we first adapted the SMACH platform so that each household could produce, charge and
224 discharge energy. The households were equipped with means of local energy production. In the current model,
225 this production was obtained using a model of photovoltaic (PV) panels. The PV panels were modeled with the
226 BuildSysPro Modelica library. Like the building, the PV panels were co-simulated with the MAS of human
227 activity using the FMI standard. The model simulates crystalline silicon type PV panels and computes the PV
228 panel temperature, electrical power generated and the cumulative PV production based on the work of Martin
229 & Ruiz (2001) and Luque & Hegedus (2003). The PV panels are characterized by their surface, their tilt and their
230 orientation. The model calculates the power produced by the PV panels at each simulation time step using the
231 meteorological data associated with the location studied: outdoor temperature, wind direction and speed as
232 well as solar radiation.

233 The energy storage systems were simulated by a battery model with a linear charge and discharge curve. Such
234 models have already been used to study the impact of storage systems with ISC (Munkhammar et al., 2013;
235 Weniger et al., 2014). The batteries are characterized by their maximum capacity and the amount of energy
236 they can charge or discharge at each simulation time step. Charging or discharging energy impacts the battery's
237 State of Charge (SoC). At each time step, the SoC, noted $SoC(t)$, is computed according to the quantity of
238 energy that is charged or discharged.

239 To manage the produced, consumed, charged and discharged energy, we developed a new entity in the
240 household called the Self-Consumption Manager (SCM). The purpose of this manager is to compute the result
241 of all energy-related operations within a household at each simulation time step. Thus, using the household's
242 consumption, production and the SoC, the SCM calculates the household's energy needs and any excess, and
243 the amount of energy that is charged or discharged from the battery. The SCM can carry out various ISC
244 strategies on the energy produced by the household or its individual battery. For example, a household can
245 decide to use all of its energy production for itself and only exchange the excess energy it can't consume or
246 store. But it can also decide to exchange all its energy production, regardless of its own consumption. An
247 intermediate strategy could be to set the ratio of energy available for external exchanged based on a given ISC
248 rate. Formally, for a simulation time step t , $e_{consumedHousehold}(h, t)$ is the amount of energy consumed by a
249 household h and $e_{producedHousehold}(h, t)$ the amount of energy produced by the PV panels. With this
250 information, and knowing the battery SoC, the SCM computes $e_{storageHousehold}(h, t)$, the quantity of energy
251 charged or discharged from the individual battery of the household accord to the battery usage policy. Then,
252 with these values, the SCM computes $need_{household}(h, t)$ and $excess_{household}(h, t)$, the energy needs and
253 surplus, respectively, for a household h calculated for the simulation time step t . These values are used to
254 perform the energy exchange operations in the third level of the model. The precise functioning of the SCM
255 and the various associated equations are detailed by (Albouys-Perrois, 2021). The Figure 2 shows the different
256 models that compose the complete model of a household practicing ISC with the different input and output
257 data.



258

259

Figure 2 : Model of a self-consuming energy household

260

4.2. Simulation of collective self-consumption

261

We named the third level of the model an *association* of households, where the CSC operations are carried out.

262

An association can also produce, charge or discharge energy using the collective means of production and the

263

collective means of storage. An association is therefore composed of households, one or several collective

264

means of production, one or several means of storage and a third-party entity which will perform the

265

contractual energy exchanges between the households.

266

We denote H for "Households", the set of households in an association. For each simulation time step t , we

267

can evaluate $excess_{household}(h, t)$ and $need_{household}(h, t)$, which are the needs and the energy surplus of a

268

household h calculated by its SCM.

269

The collective means of energy production and storage use the same model as their individual counterparts

270

presented in the previous section. For an association and a simulation time step t , $E_{producedAsso}(t)$ is the

271

amount of energy produced by all the collective PV panels, $E_{ChargedAsso}(t)$ the amount of energy charged and

272

$E_{dischargedAsso}(t)$ the amount of energy discharged from the collective battery.

273

In an association, the *Local Exchange Place* (LEP) is the third-party entity responsible for the energy exchanges

274

between households. To perform these energy exchanges, the LEP inputs are:

275

- The quantity of energy produced by the collective means of production;

276

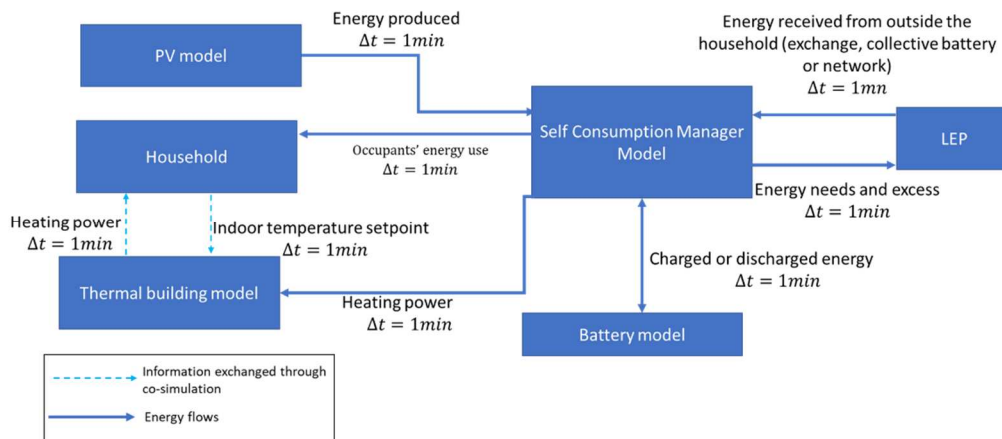
- The surplus energy produced but not consumed by every household;

277

- The energy needs for every household;

278 • The amount of energy discharged from the collective means of storage.

279 With these values, the LEP first exchanges the energy produced by the collective means of production and the
280 energy surplus of the households, according to the exchange policies defined below. Then, the LEP distributes
281 the energy discharged from the collective means of production between the households. As CSC is modeled as
282 a contractual operation, CSC simulation consists in the computation of the energy allocation **after** the energy
283 has been used by the different households and electrical devices at the physical level. The simulation platform
284 therefore uses two-time steps. **Simulation time step t** triggers the calculation of the quantities of energy
285 consumed, produced, charged or discharged depending on human activity, local energy production and storage.
286 This corresponds to the physical aspects of the simulation performed by the SMACH platform at a 1-minute
287 time step. The Figure 3 present the different energy flow chart of a self-consuming household performed at
288 this time-step but also the information exchange between the thermal building model and the household (the
289 human activity model).



290

291 *Figure 3 : Energy flow chart of the self-consuming household*

292 **The counting time-step c** triggers the computation of the contractual energy allocation according to the
293 aggregated results of the previous accounting period the LEP is responsible to aggregate these values. This
294 second time step is a parameter whose value was set to 15 minutes, a common value in Europe for smart
295 meters.

296 To calculate the allocation of the energy produced within the association, the LEP follows a set of contractual
297 rules called **energy exchange policies**. The architecture of the CSC model means it can be used to study any
298 type of exchange policy, as long as the rules are formalized and implemented in accordance with the

299 requirements of the model. We defined and implemented three different exchange policies based on the most
300 common policies identified by CSC experts and the work of Bonnardot et al. (2020, in French):

- 301 • A *proportional* exchange policy in which the LEP allocates a quantity of energy that is proportional to
302 the energy needs of each household;
- 303 • A *fixed rate* exchange policy where households receive a fixed share of the total available energy;
- 304 • A *competitive* exchange policy where households make offers to buy and sell (quantity of energy and
305 price). In order to manage these offers, we implemented a first price sealed-bid auction model
306 (McAfee & McMillan, 1987) in which the LEP plays the role of an auctioneer.

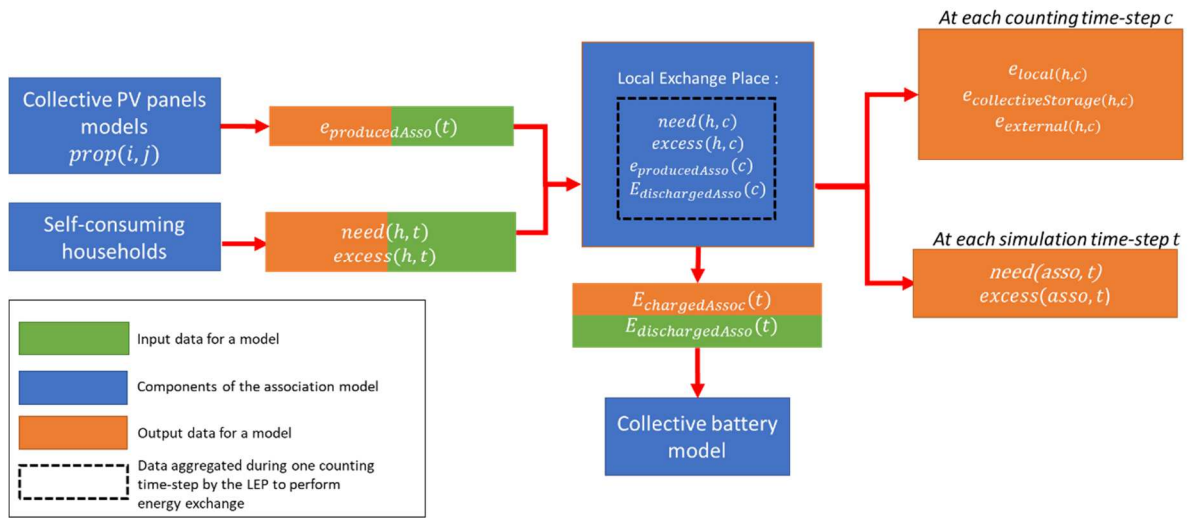
307 In order to divide and share the energy discharged from the collective batteries, the LEP follows a set of rules
308 called a **collective storage policy**. In a similar way, any type of collective storage policy can be implemented.
309 We defined a single collective storage policy, namely a **proportional collective storage policy**. With this policy,
310 the LEP divides the energy discharged from the collective batteries in proportion to the energy needs of each
311 household.

312 With these sets of rules, the LEP computes the following value for each household h in the association, at each
313 counting time step c :

- 314 • $e_{local}(h, c)$: the amount of energy produced locally and received by a household. This value is
315 computed using the exchange policy of the LEP;
- 316 • $e_{collectiveStorage}(h, c)$: the amount of energy received by a household from the collective means of
317 storage. This value is computed using the collective storage policy of the LEP;
- 318 • $e_{external}(h, c)$: the amount of energy consumed by a household that comes from a source that is
319 external to the association. In the model this energy is provided by the electricity providers of the
320 households.

321 Moreover, the association computes its own energy surplus and needs for each simulation time step.
322 $excess(asso, t)$ and $need(asso, t)$ are the energy needs and excess production of the association $asso$ for the
323 time step t . These values make it possible to establish invoicing at the level of the association, and in some
324 cases to study the energy exchanges in detail, and the impact of CSC policies on the consumption of the
325 households and the association. The Figure 4 presents the different elements that compose the complete

326 model of an association with the different input and output data. In this figure we also show at which time step,
 327 the different values related to the CSC operations are calculated.



328

329

Figure 4 : Model of the Association to perform CSC

330

4.3. Energy exchange between multiple associations

331

At the level of a CSC association, the excess energy that cannot be exchanged or stored is usually sold to a relevant third party such as an electricity provider. This is the case in our three-level model. However, associations of households will be limited in size, and a city or region might be composed of several associations. Energy exchange between associations could therefore be a way to maximize the consumption of locally produced energy without selling it back to the grid. We decided to add a fourth level to our model in order to simulate inter-association energy exchange. Similar to energy exchange within an association, energy exchange between associations is managed by a third-party entity that we call the **Central Exchange Place (CEP)**.

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339

The goal of the CEP is to evaluate the needs and excess energy of several associations at each counting time step c , and to exchange the excess energy between associations. To perform these exchange operations, the CEP follows its own specific exchange policy. When an association receives energy through an inter-association exchange, the energy is exchanged between the households of the association by its LEP according to the exchange policy defined by the association. Figure 5 illustrates a configuration in which three associations exchange energy.

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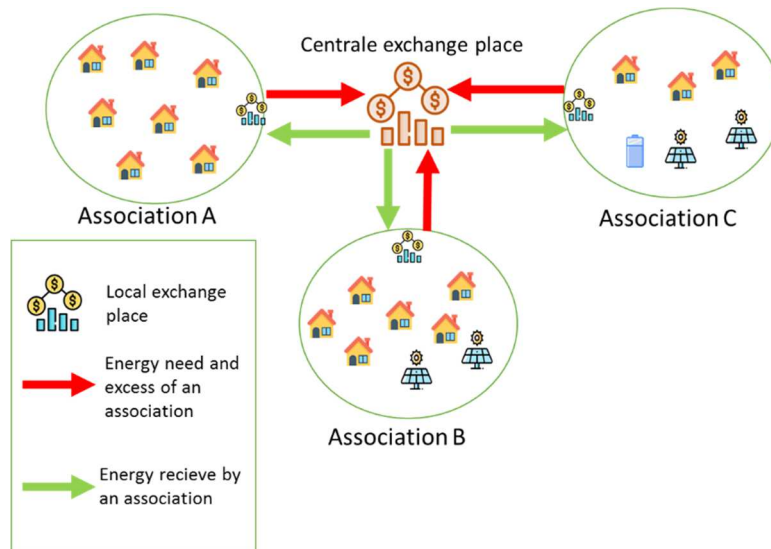


Figure 5 : Example of an organization for inter-association energy exchange

Formally, a CEP takes in input:

- $need(asso, c)$: the energy needs of an association $asso$ at the end of a counting time step c ;
- $excess(asso, c)$: the excess energy produced by an association $asso$ at the end of a counting time step c .

For each association $asso$, the CEP computes $e_{exchangeExtAsso}(asso, c)$, the amount of energy received by an association at the end of a counting time step c .

Finally, the addition of levels to this CSC model can be repeated indefinitely and used to create large structures in which energy is exchanged at several levels, *i.e.* from the home to the city.

5. Results

~~In this section, we will present three different case studies to illustrate the capacity of the model to simulate and study various CSC configurations.~~ Currently, the study and understanding of the different mechanisms of CSC are major challenges for the main players in the energy world. Indeed, the transition to CSC will raise new questions about the ways in which energy is consumed, exchanged or the impact of storage systems on the consumption or activity of inhabitants... The main objective of the model developed here is to simulate CSC configurations to address these major questions. The CSC model in this paper therefore allows experts in the field to characterize and simulate numerous configurations with the aim of proposing and validating hypotheses or answering scientific, technical or economic questions related to CSC. To highlight the

364 possibilities offered by this model, we present in the following the results of 3 different case studies based on
365 the same reference situation in terms of population but with changes in the means on energy production or
366 storage inside the association. In the first study, we assessed the impact of individual and collective storage
367 systems on the electricity consumption of an association of CSC households. In the second study, we analyzed
368 the impact of CSC on the electricity consumption of a recent, sustainable neighborhood with high-performance
369 buildings. In the third case study, we demonstrate the capacity of our model to simulate energy exchange
370 between several associations.

371 5.1. Simulation parameters

372 The parameters of the model were sorted into three categories.

373 The **Population** category comprises the parameters that describe the household, the inhabitants, the building,
374 and the electrical appliances. This category also defines the ISC equipment in each household, *i.e.* the presence
375 of a PV panel or an individual battery and their parameters.

376 The **Collective Equipment** category includes the parameters of the collective means of production and the
377 collective means of storage within an association.

378 The **Energy Exchange** category contains the energy exchange policy that the LEP will follow to exchange energy
379 within an association. It defines the policy for the exchange of locally produced energy as well as how to
380 manage the collective means of storage.

381 5.2. Reference situation and performance indicators

382 The results presented in the first two case studies are based on the same reference situation, *i.e.*, an
383 association composed of 100 households. The population and buildings of the association were generated with
384 the SMACH platform with the following characteristics:

- 385 • *Building type*: apartment;
- 386 • *Building insulation*: statistical distribution based on French thermal regulations, chosen from 1982 to
387 2012;
- 388 • *Electrical heating*: statistical distribution between electrical and non-electrical heating in France;
- 389 • *DHW production*: distribution between electrical and non-electrical DHW production based on
390 heating type and electricity tariffs;

- 391 • *Population*: statistically representative of French households based on census data;
- 392 • *Location*: city of La Rochelle, France.

393 This reference situation represents a typical French population living in an apartment. We located the
394 reference situation in the meteorological area of La Rochelle, situated in the South-West of France, a region in
395 which many PV panels have been installed.⁴ The simulation was performed over a year. This allowed us to
396 observe the impact of seasonal weather on human activity and decision-making, electricity consumption, as
397 well as local energy production. The three energy exchange policies defined in Section 4.2 were simulated.

398 To analyze the results, we used two indicators in their instantaneous and integrated forms:

- 399 1. *Self-sufficiency rate* gives the proportion of energy consumed by a household that derives from local
400 production, energy exchange, and individual and collective storage:

$$404 \quad rate_{selfSufficiency} = \frac{consumption_{local}}{consumption_{total}} \quad (1)$$

401 where $consumption_{local}$ is the quantity of energy consumed that was produced by PV panels, or
402 derived from an individual or collective means of storage, and energy exchange; and
403 $consumption_{total}$ the total energy consumed by a household;

- 405 2. *Self-consumption rate* gives the proportion of energy produced locally and directly consumed by the
406 association or by the household:

$$408 \quad rate_{selfconsumption} = \frac{consumption_{local}}{production_{total}} \quad (2)$$

407 where $production_{local}$ is the quantity of energy produced by one association or household.

409 These two indicators have already been used in order to analyze ISC at the scale of households (Castillo-Cagigal
410 et al., 2010; Luthander et al., 2015) but also to study CSC at the scale of the neighborhood (Vinyals et al., 2018).
411 Other metrics exists to analyze self-consumption (Salom et al., 2011), but self-production and self-sufficiency
412 rates are widely used to analyze ISC and CSC, that is why only these two indicators are considered in this paper.

⁴ <https://resources.solarbusinesshub.com/solar-industry-reports/item/global-market-outlook-for-photovoltaics-2014-2018>

5.3. Impact of individual and collective storage systems on electricity consumption

With this first case study, we compared the impact of individual and collective storage on electricity consumption within an association. Based on the reference situation, we defined and simulated three different CSC configurations. In all of them, 50 households within the association were equipped with individual 3.5-kilowatt peak (kWp) PV panels. We chose to equip only 50 households as, according to Luthander et al. (2015), a household, **equipped with PV panels**, consumes between 30% and 40% of its energy production, suggesting that an energy surplus would be available for exchange between households. In the second case study, households owning PV panels were also equipped with individual batteries. Each battery could store 14 kWh of energy. The maximal electrical charge or discharge power was 5 kW. We used the following battery management rule: if the energy produced by the PV panels of the household was lower than its energy consumption, then the battery discharged energy to meet the needs of the household. Otherwise, the battery was charged from the excess energy produced by the PV panels. In the third case study, the association was equipped with a collective battery. The collective storage capacity was 700 kWh i.e., equal to the entire storage capacity of individual storage. The maximal charge or discharge power of the collective battery was 250 kW.

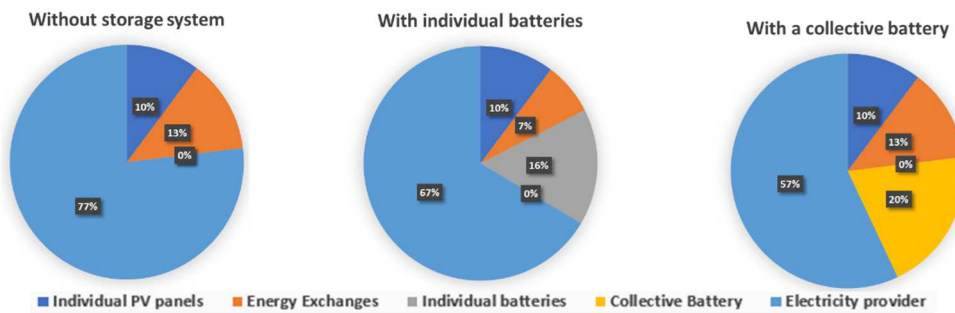
	Self-consumption	Self-sufficiency
ISC	21%	10%
CSC without battery	48%	23%
CSC with individual batteries	70%	34%
CSC with collective battery	90%	43%

Table 1 : Annual values of self-sufficiency and self-consumption of the association for ISC and CSC without energy storage, with individual batteries and with a collective battery with a proportional exchange policy

Table 1 gives the values of self-production and self-consumption for the association without energy exchange (ISC) and for the three case studies (CSC without and with storage systems). Using individual or collective storage systems resulted in an improvement in both self-consumption and self-production in the association, i.e., more of the energy produced locally was consumed directly by the association. The self-consumption and self-sufficiency values were the same for the 3 exchange policies we modeled because all three allocated all the energy that could be consumed within the association. It is worth noting that, for an equivalent capacity and charge/discharge power, collective storage produced higher self-consumption and self-production. This is because all the households in the association could benefit from collective energy storage, in contrast to

437 individual storage, where only 50 households had access to collective storage. Over a year, only **21 MWh** of
 438 energy were not consumed or stored in the association with a collective battery, which is an improvement
 439 compared to the CSC without a battery (**107 MWh**) and the CSC with individual batteries (**61 MWh**).

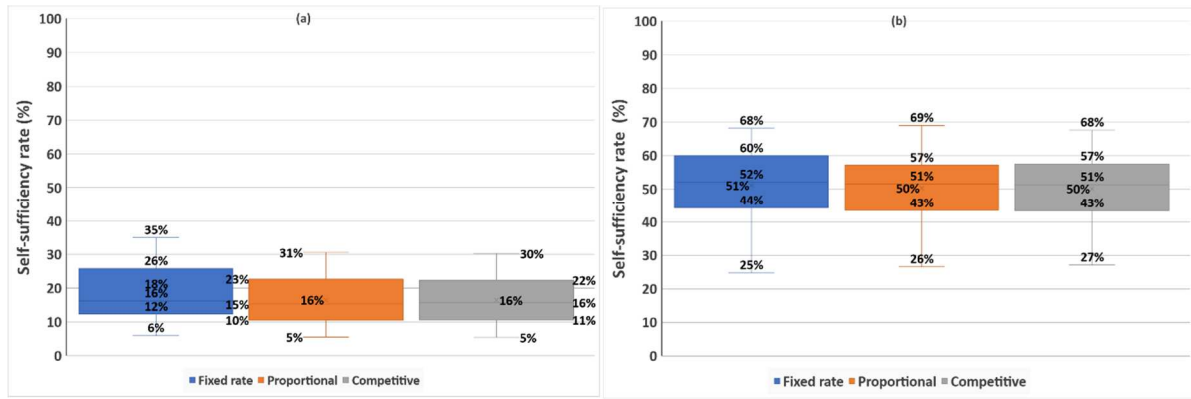
440 Figure 2 shows the origin of the energy consumed by the households in their association. The use of individual
 441 storage negatively impacted energy exchange by lowering the quantity of energy exchanged between the
 442 households. Indeed, without individual batteries, **13%** of the energy consumed came from exchanges
 443 compared with only **7%** after the installation of individual batteries. On the other hand, a collective battery did
 444 not impact the quantity of energy exchanged and more energy was consumed from the collective battery than
 445 from the individual batteries.



446

447 *Figure 6 : Origin of energy consumed in the association without storage systems, with individual batteries and with a*
 448 *collective battery*

449 To study the impact of the individual and collective batteries on energy consumption at the household level,
 450 we first analyzed the self-sufficiency of the 50 households that did not possess PV panels. Figure 7 presents the
 451 distribution of this indicator for these households for each exchange policy. This box-plot representation
 452 displays the minimum and maximum self-sufficiency, the upper and lower quartile, the median value, and the
 453 mean. Figure 4 on the other hand, presents the self-sufficiency for the household owning PV panels for each
 454 exchange policy.



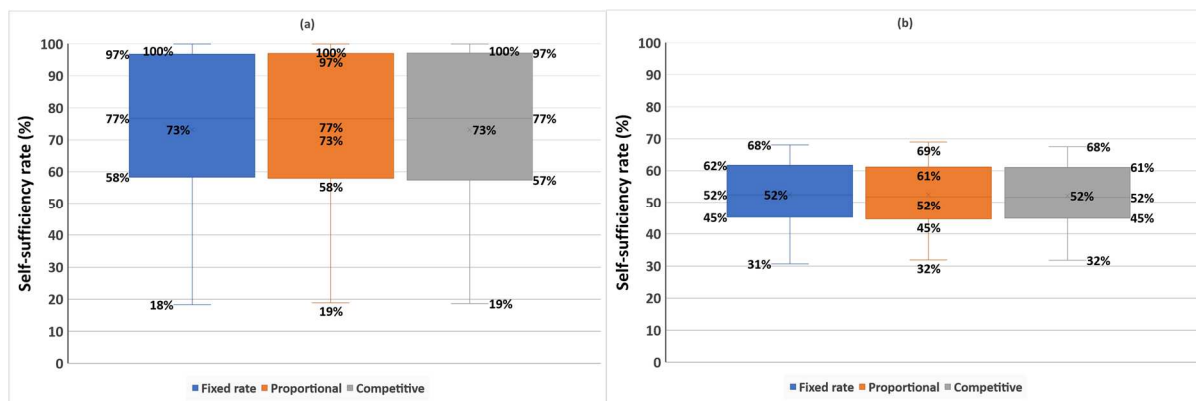
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Figure 7 : Distribution of annual self-sufficiency levels for a household without PV panels
 (a) in an association with individual batteries
 (b) in an association with collective batteries



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Figure 8 : Distribution of annual self-sufficiency levels for a household with PV panels
 (a) in an association with individual batteries
 (b) in an association with collective batteries

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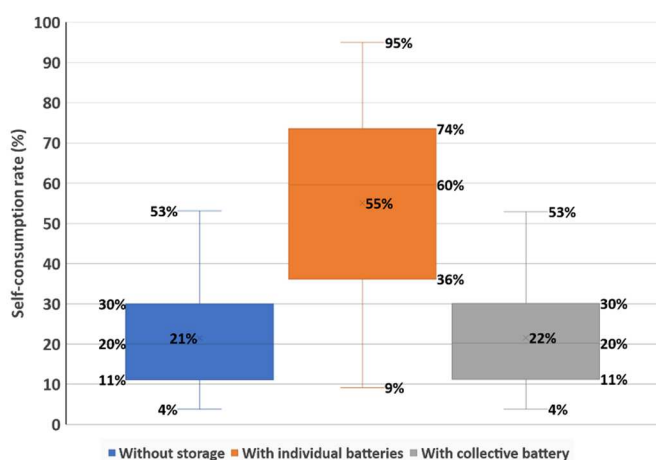
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For the three exchange policies, it is clear that the use of individual batteries led to lower self-production for households without PV panels than with a collective battery. For example, with a proportional exchange policy, the average self-production went from **16%** with individual storage to **50%** with collective storage. On the other hand, the self-sufficiency of a household with PV panels was higher with individual storage than with collective storage. For example, with individual batteries, for some households, annual self-sufficiency was close to 100%. However, these are households with neither heating nor electrical DHW production and therefore with a relatively low electricity consumption. Moreover, the use of individual batteries resulted in large differences between the self-sufficiency levels within the association. For instance, for a proportional exchange policy, the mean self-sufficiency of the households owning individual PV panels and **owning** individual battery was **77%** (Figure 8) compared with **16%** (Figure 7) for a household without individual PV

473 panels and **owning** individual batteries. However, there was no such difference between the households of the
 474 association.



475

476 *Figure 9 : Distribution of self-consumption levels for households with PV panels*

477 Figure 9 shows the self-consumption in the association for the households equipped with a PV panel. It is clear
 478 that using individual batteries significantly improved the quantity of energy produced which is self-consumed
 479 by these households. Mean self-consumption varied from **20%** without storage to **60%** with individual batteries.
 480 These results are in accordance with those in the literature dealing with the use of individual storage systems
 481 for ISC or CSC (Braun et al., 2009; Munkhammar et al., 2013). However, the use of collective batteries in the
 482 association did not impact the self-consumption of the household owning PV panels. Indeed, this indicator only
 483 takes into account the energy that comes from the individual systems (batteries and PV panels) of the
 484 households. The self-consumption values were therefore identical to a configuration without collective storage.
 485 This study shows how individual and collective storage can impact CSC operations and indicators. Individual
 486 batteries can greatly increase the self-consumption and self-sufficiency of households that own them to the
 487 detriment of households without production and storage equipment, which then receive a lower share of
 488 locally produced energy. In contrast, the use of collective batteries makes it possible to distribute excess energy
 489 among all the households in the association, and so a greater share of the local energy can be consumed within
 490 the association. With collective storage the differences between the self-production of the households in the
 491 association were smaller compared to an association with individual batteries.

492 5.4. Impact of CSC and collective energy production on the electricity consumption of a sustainable
493 neighborhood

494 In this case study, we analyzed how CSC with a collective means of production impacted the electricity
495 consumption of a sustainable neighborhood. This type of neighborhood is characterized by the use of one or
496 more sources of renewable energy, low energy consumption and a low carbon footprint. To simulate this
497 sustainable neighborhood, several parameters from the reference situation were changed:

- 498 1. The buildings were energy efficient, in conformity with the French building thermal regulation
499 standards of 2012 (Le Muet & Machner, 2012), which improved the properties of a building (e.g.,
500 better thermal insulation).
- 501 2. Heating systems and DHW tanks that were previously modeled with resistive heating did not consume
502 electricity from the grid, but used another energy source (wood or gas, for example) which is not
503 included in the electricity consumption simulated by our model. Heat-pump based heating and DHW
504 systems have not yet been modeled.
- 505 3. The association was equipped with 100 kWc collective PV panels.

506 Moreover, for this case study we only simulated proportional and fixed-rate exchange organizations. Indeed,
507 although a competitive exchange policy is not incompatible with a collective PV panel, this case study was
508 inspired by a real CSC experiment in France⁵ which did not look at competitive exchange policies.

509 First, the simulation results highlighted the positive impact of the neighborhood's performance on the
510 electricity consumption of the association. Indeed, the annual electricity consumption of the entire
511 neighborhood decreased from 438 MWh (from the case studies of section 5.3) to 164 MWh.

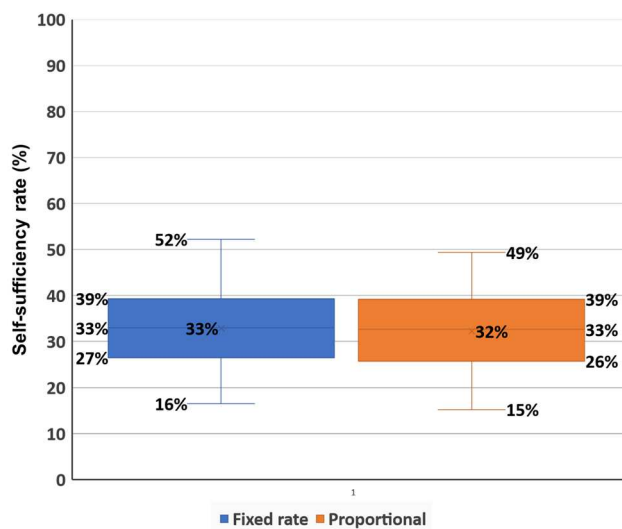
	Self-consumption	Self-sufficiency
Proportional exchange policy	43%	46%
Fixed rate exchange policy	43%	45%

512 *Table 2 : self-consumption and self-sufficiency values of a sustainable neighborhood equipped with collective PV panels*

513 The values given in Table 2 show that self-sufficiency and self-consumption in the association were almost
514 identical for the two exchange policies we implemented. By comparing the second row of Table 1 (an

⁵ <https://www.energetica-india.net/news/edf-installs-frances-largest-collective-self-consumption-pv-project>

515 association with individual PV panels without storage systems) with the results from Table 2, the self-
 516 sufficiency varied from 45% to 46% compared to 23% in Table 1. However, it is also clear that self-consumption
 517 did not really change from Table 1 to Table 2. This means that the households consumed less energy from the
 518 energy provider, but they did not consume more local energy compared to an association with individual PV
 519 panels without storage. Indeed, by creating a sustainable neighborhood we only reduced the total electricity
 520 consumption of the households without changing their consumer habits, which is why self-consumption at the
 521 scale of the association was similar between this case study and the reference association with individual PV
 522 panels and without energy storage (section 5.2).



523

524 *Figure 10 : Distribution of self-sufficiency of sustainable neighborhood households*

525 Looking at the distribution of self-sufficiency between the households shown in Figure 10, the exchange policy
 526 did not impact the quantity of energy received by the households of the association. The main reason is that
 527 the annual electricity consumption of the households in the association (**164 MWh**) was close to the quantity
 528 of energy produced by the collective PV panels during the same year (**120 MWh**). Thus, the distribution of self-
 529 sufficiency values was similar for the two exchange policies. In this case, during the day the collective PV panels
 530 produced enough electricity to power the households of the association most of the time and the energy
 531 exchange policy did not fundamentally impact the quantity of energy received by each household.

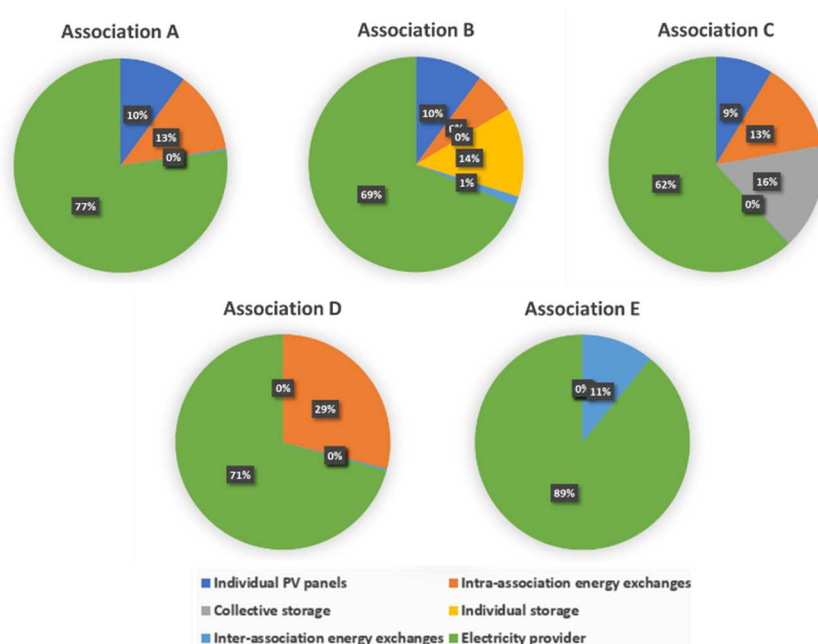
532 However, even if the production and the consumption in the association were similar, there was still **52 MWh**
 533 of energy produced by the collective PV panels which was not consumed by the households of the association

534 and which had to be sold to the electricity provider. Nevertheless, the use of individual or collective batteries
535 could allow the association to consume all or part of this surplus energy.

536 5.5. Inter-association exchange

537 For this case study, we focused on the impact of inter-association exchange on the electricity consumption of
538 several associations. We simulated 5 CSC associations of 20 households each. Each association was
539 characterized by specific parameters to represent different ways of consuming, producing and storing energy.

540 For **association A** 10 households were equipped with 3.5 kWp PV panels. For **association B**, 10 households
541 were equipped with 3.5 kWp PV panels and an individual battery with a capacity of 14 kWh, and an electrical
542 power of 5 kW. For **association C**, 10 households were equipped with a 3.5 kWp PV panel. This association was
543 also equipped with a collective battery with a capacity of 140 kWh and an electrical power of 50 kW. For
544 **association D**, the buildings were high performance and built according to the French thermal regulation
545 standards of 2012; these households did not use resistive heaters or DHW production. The goal of this
546 modification was to reduce the electricity consumption. This association was also equipped with collective 20
547 kWp PV panels. **Association E** did not have any energy production or storage equipment. These 5 associations
548 used a proportional exchange policy to exchange energy. This is also the exchange policy used by the CEP for
549 inter-association energy exchange. Figure 11 shows the origin of the energy consumed by the different
550 associations.



551

552

Figure 11 : Origin of energy consumed by the five associations

553

Associations A, B, C and D received only a small share of energy from inter-association exchange. Indeed, these

554

associations already produced energy at the same time and therefore wanted to exchange their excess energy

555

concurrently. However, of these 4 associations, association B received more energy from inter-association

556

exchange than the others. This is due to the presence of individual batteries, which reduced the amount of

557

energy potentially exchangeable between the households of the group.

558

Association E was the largest consumer of energy from inter-association exchange because it had no means of

559

producing energy. Inter-association exchange therefore allowed it to reduce its consumption of energy from

560

the network. In all, **11%** of the energy it consumed came from the production of other associations.

561

It will be of great interest to set up studies at different scales, from the neighborhood to the city, for example.

562

With inter-association exchange, it will be possible to study the impact of the social, economic and

563

technological differences between associations on energy exchange.

564 Conclusion

565

In this paper, we presented a multi-agent and multi-level model to simulate CSC in the residential sector while

566

taking into account the activity of the inhabitants. Specifically, we modeled the contractual layer of the CSC,

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responsible for energy exchange in the form of a metering operation. The first two levels of our model simulate

568

human activity and electricity consumption of the households through the SMACH platform, to which we

569 added ISC mechanisms. This allowed us to obtain a realistic energy consumption profile by co-simulating a MAS
570 of human activity and a building thermal model. The third level, the association of households, is also a MAS
571 that was used to simulate energy exchange between households. The fourth level of the model allowed a
572 simulation of energy exchange between associations. One originality of this CSC model for the residential
573 sector is that it relies on a realistic simulation of human activity and household electricity consumption. To our
574 knowledge, the incorporation of human activity in a CSC simulation has not yet been included in the various
575 studies dealing with the simulation of CSC.

576 The case studies in this paper highlighted the capacity of the model to simulate various CSC configurations and
577 energy exchange policies. The first case study presented in this paper focused on the different impacts of
578 collective and individual storage systems on the electricity consumption of CSC households. The results showed
579 that, at the scale of the association, the use of collective batteries increased the quantity of energy produced
580 locally that is consumed by the households when compared to the use of individual batteries. It also reduced
581 the consumption of energy from the electricity provider. These results also showed the importance of taking
582 into account the objectives of households when setting up a CSC in an association. For an association where
583 the objective is only to increase self-consumption, the use of individual storage systems is, according to our
584 results, a solution to consider. On the other hand, within an association seeking a form of equity in terms of
585 self-sufficiency between households, the use of a collective storage system is a more appropriate solution. The
586 second case study focused on a sustainable neighborhood characterized by low electricity consumption. The
587 results showed that the exchange policy did not impact the self-sufficiency of the households when their
588 electricity consumption was similar to the electricity production within the association. Nevertheless, the
589 excess energy, i.e. not consumed by the association, was still high, even for a sustainable neighborhood. The
590 third case study highlighted the capacity of the model to simulate energy exchange between associations with
591 different characteristics. With such simulations it becomes possible to simulate associations with different
592 social, economic or technical characteristics. Thus, the model can be used to simulate CSC at different scales
593 such as a group of districts, a city or several nearby towns.

594 These first contributions to CSC simulation leave several questions unanswered for the development of a
595 general framework for studying CSC configurations. The next step is to consider the impact of CSC on the
596 energy policy *within households*, i.e. their preferences and decision-making related to the use of electrical

597 appliances. In fact, residents could choose to adapt their activities to skew the use of certain electrical devices
598 such as the washing machine to be in line with the availability of renewable energy. We started to work on this
599 question by developing a skewing strategy in SMACH, but we still need to validate these simulated decision-
600 making processes with field data in real CSC campaigns. Likewise, we are starting to set up policies for the use
601 of storage systems in SMACH, for example with strategies for charging or discharging energy depending on the
602 price of electricity in the group. The impact of energy exchange between households and associations on the
603 energy policy of the association itself must also be considered. An association is a legal entity that will take
604 decisions, for example on the way the collective means of production or storage are used within the
605 association. The cost of storage systems, whether individual or collective, will also be a factor to be considered
606 in this perspective and may therefore impact decision-making at the household or group level. **Indeed, for the**
607 **current version of the model, we consider the energy coming from individual battery free of charge for the**
608 **household owning them. However, it's important to consider the relatively high-cost of battery storage system**
609 **(Hafiz et al., 2018) in terms of installation but also the operation of such system. In case of individual storage**
610 **systems, storage cost must be considered by the inhabitants or by an algorithm which can automatically**
611 **manage the charge or discharge operations of the battery (Arora & Chanana, 2014). For collective batteries,**
612 **the storage costs could be charged to the residents in accordance with the energy they consume from shared**
613 **storage systems through various pricing strategies. The model of the present study should allow to implement**
614 **and test various alternative costs for individual and collective storage systems. Furthermore, the**
615 **implementation and operation of the local exchange place has a cost that must be taken over by the**
616 **households. Two kinds of cost for such systems were identified. First, the operating costs of the local exchange**
617 **place itself and the gain wanted by the operators of the local exchange place. Some authors already consider**
618 **such cost while calculating a price paid by each household for the energy exchanged (Wu et al., 2015). The**
619 **second cost is linked to the physical energy network not currently taken into account by the model.**
620 **Nevertheless, some authors consider an energy transmission cost for each exchange operation realized in a**
621 **group of household practicing CSC (Wu et al., 2015; Yaagoubi & Mouftah, 2017). An extensive simulation of**
622 **the costs paid by each household in an association considering storage costs is an important step that we must**
623 **consider in the future versions of the model.**

624 Other longer-term perspectives can be considered, namely the incorporation of CSC in an environment with
625 dynamic price offers, or the use of electric vehicles as a source of energy consumption but also of energy
626 storage. The modeling of an association in which households and buildings of the tertiary sector (e.g. a
627 supermarket, offices, hotels) using CSC could also be a way to enrich our model. Indeed, the geographical
628 proximity of buildings in the residential and tertiary sectors, particularly in cities, makes them good candidates
629 for energy exchange. The aim is to build a comprehensive approach articulating these different interactions at
630 different scales, and to validate these simulations by evaluating not only energy consumption but also the
631 behavior associated with energy exchange. As with SMACH, this work will be part of a research program on the
632 multi-agent simulation of energy use in households, which requires a strong multidisciplinary approach
633 combining computer science, cognitive ergonomics, statistics, economics and building energy modeling.

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