Energetic Analysis Of The Coupling Between A µCHP Production And A Semi- Stationary Electrical Storage System (Electrical Vehicule) Shared With A Residential Building

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Abstract

Some works deal with the simulation of the coupling between µCHP systems and buildings but the literature reveals that electric storage systems are poorly integrated inside codes that emulate this coupling. Only Alanne et al. (2010), Bianchi et al. (2013), Cao et al. (2014), Alahäivälä et al. (2015) and Balcombe et al. (2015) incorporated an electrical storage system and none integrates an electrical vehicle.

A numerical tool has been developed in TRNSYS to realistically and dynamically simulate the interactions between micro combined heat and power (µCHP) systems, a residential building and the electric grid. This tool includes in particular data driven µCHP models on a gas Stirling engine and a wood pellet Rankine engine, physical models of energy storage systems and realistic 1 min time step stochastic generators energy loads (heat, DHW and electricity).

Electrical mobility takes advantage of a possible mutualisation: an electrochemical battery used for an electric mobility application can be regarded as a semi-stationary storage that is disconnected from the building during travel and reconnected to return.

This study shows the relevance of the coupling between electric personal mobility (electric vehicles (EV) or plug-in hybrid EV (PHEV)) and a µCHP electricity production in a joint context and recent growth of these two technologies in France by assessing increases on electrical self-consumption rates, electrical self-production rates and electrical coverage rates. Besides, the tool also shows the equivalent full stationary battery that offers EV oversized batteries between 10 and 20 % of the nominal maximum state of charge.

The lasting contribution is the numerical platform developed in TRNSYS.

Introduction

The opportunity to combine an electrical vehicle (EV) with a µCHP system has several advantages:

- cost: the electric storage is "free" from the perspective of the building because the battery is shared between EV and coverage of building electrical needs;
- compatibility and sustainability of EV batteries (> 20 kWh_{el}) with the loads of the building (< 10 kWh_{el}) on average in France) : that involves low depths of discharge DOD and that limits the cycling degradation effects;
- the balance between the availability of the storage system (morning, evening, night) and the presence of occupants in buildings: presence which correlates the consumption of electricity (lighting, appliances, *etc.*);

Simulation

TRNSYS tool

A numerical platform has been developed in previous works in the TRNSYS environment (Bouvenot et al. (2015)). Various systems, input parameters and control strategies have been integrated with the objective of simulating the coupling between a µCHP (a gas Stirling engine here) system and a residential building as realistically as possible. Particular attention has been paid to the modelling of the thermal storage buffer tank, the modelling of the electrical storage systems, the regulation strategies and the stochastic and realistic modelling of DHW and electrical needs. This platform is composed of different elements represented on Fig. 1 where five fluxes are highlighted: the electrical flux, the heat flow, the fuel flow, the economic flow and the flow of CO_2 emissions.

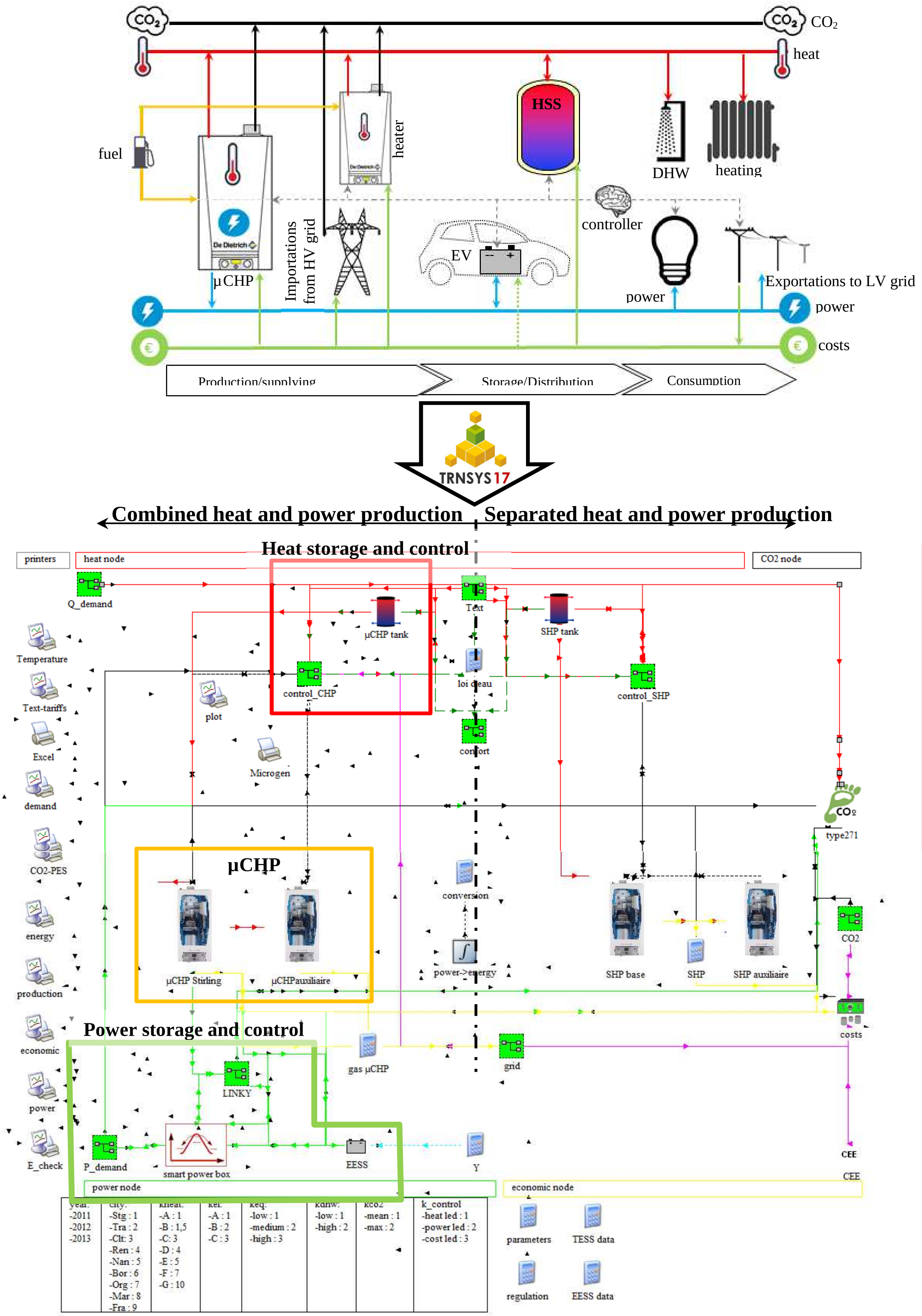

Figure 1: Principle scheme of the numerical tool and TRNSYS shape and links.

This platform distinguishes the systems (µCHP, auxiliary generator and storage systems) and interactions with the building (needs for heating / domestic hot water (DHW) and specific electricity) and the grids (low voltage (LV) distribution and high voltage (HV) transport grid). These different elements have been modelled individually in previous works (Bouvenot (2014)). We now mainly describe the model linked to the electrical loop.

Electrical energy storage system (EESS)

As part of a vehicle to home (V2H) strategy, the electrical energy storage system (EESS) selected is a lithium-ion type electrochemical battery that equips most of the current EVs. The modelling approach is chosen such that the characteristics of the model are generic and retain a physical meaning; *i.e.* they are applicable to other electrical storage technologies (mainly inertia flywheels and compressed air storage systems). The purely physical modelling of electrical storage systems is beyond the scope of this study due to the diversity of physical phenomena encountered (mechanical, chemical, thermodynamic, *etc.*) and the complexity of the modelling of these systems. For example, the physical modelling of an electrochemical battery requires the equation of chemical diffusion in electrodes, chemical reactions, reaction kinetics, internal electrical resistance, *etc.* (Darkovich et al. (2015)). Four characteristic quantities emerge:

- The state of charge SOC characterized by an initial state SOC_0, the minimum admissible states of charge SOC_{min} and maximum SOC_{max}, a thermosensible variation (SOC(T)) and by its aging (decrease of the capacity with the cycles)
- Specific powers: maximum discharge power $P_{d,\ max}$, maximum load power $P_{c,\ max}$, calendar losses P_{cal} and standby power P_{sb},
- the efficiencies of charge η_c and discharge η_d,
- cycling (cycles over lifetime) *n*: fixed or variable parameter depending on depth of discharge DOD (*cf.* Fig.2).

The tool use the characteristic of SAFT Lithium-ion battery described on Fig. 2 t model the semi stationary EESS.

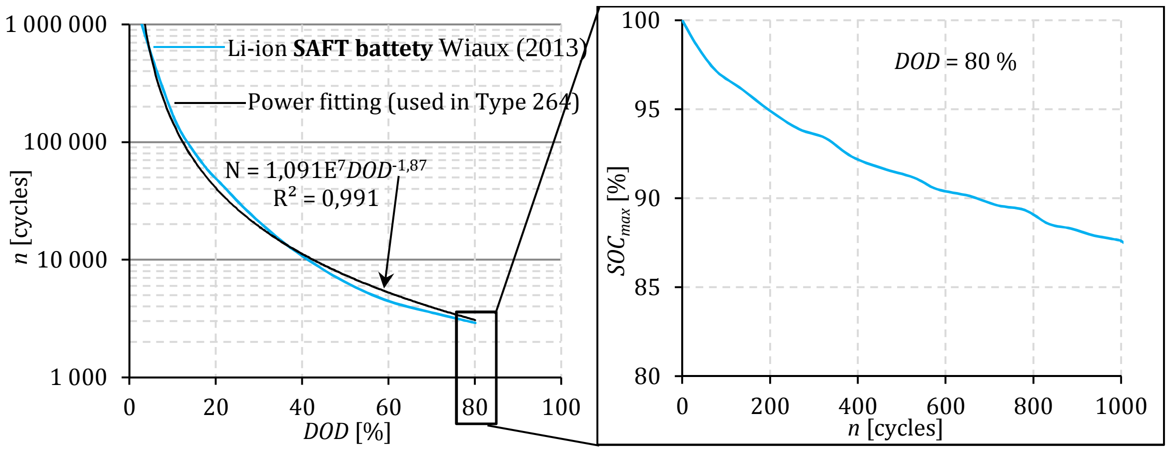

Figure 2 : Impact of *DOD sensibility on cycling and impact of full cycling on SOC_{max}.*

For electrochemical batteries, temperature dependence for capacity can be very large according to Wiaux (2013) or Eddahech (2013), and is often neglected for applied studies and annual dynamic thermal simulations. This assumes a dynamic thermal modelling too complex to implement to obtain this temperature. The rate of charge or discharge may also have a significant impact. Indeed, the efficiencies of charge and discharge are in principle dependent on this kinetic but are difficult to model with little effort. In contrast, under a very slow regime, self-discharge will penalize the balance sheet. The significant impact of discharge depth and cycling on the lifetime of batteries can be easily taken into account by empirical correlations and aging coefficients ΔSOC (see Fig. 2). A small depth of discharge (<10%) can lead to multiplying nominal cycling up to 1,000.

A specific type has been modelled under TRNSYS (type 264) in order to take into account the different parameters previously identified. It should be noted that TRNSYS offers a battery type (the "Type 47") but this one refers to a lead-acid battery. This simplified model does not consider all the physical phenomena involved during the charging or discharging phases (self-discharge, cyclability, *etc*.). Table 1 gives the values considered in the numerical platform and the following equations presents the base of the numerical modelling strategy of the electrical batteries.

Table 1 : ESS model parameters.

Definition	Type	264
Nominal *SOC*	SOC_0 [kWh$_{el}$]	0 - 20
Minimum relative *SOC* accepted	SOC_{min}[%]	20
Maximum relative *SOC*	SOC_{max} [%]	100
Capacity reduction linked to cycling effect	ΔSOC [kWh$_{el}$/cycle]	$\frac{0{,}2.SOC_0}{n_{max}}$
Energy density	E_{spe}[Wh$_{el}$.kg^{-1}]	150
Specific power	P_{spe}[W$_{el}$.kg^{-1}]	1 000
Maximum power	P_{max} [%.j^{-1}] (charge or discharge)	$P_{spe}\frac{SOC_0}{1000\,E_{spe}}$
Calendar losses	P_{cal}	0,2 [%.j^{-1}]
Charge efficiency	η_c [%]	95
Discharge efficiency	η_d [%]	100
Maximum number of cycles	n_{max} [cycle]	n_{max} = 1,091E^7$DOD^{-1,87}$

Charge and discharge losses P_{loss}:

$$P_{loss} = (1-\eta_c)P_c + (1-\eta_d)P_d + P_{cal} \quad \text{with } P_c \text{or } P_d \le P_{spe} \tag{1}$$

State of charge *SOC* of the battery at i^{th} time step for the n^{th} cycle:

$$\begin{gathered} SSOC^0 = SOC(t=0) = SOC_{nom} \\ SOC_{max} = SOC_{nom} - \Delta\mathrm{SOC}(\overline{DOD}).n \\ SOC^i = SOC^{i-1} + \left(P_c^i - P_d^i - P_{loss}^i\right).\Delta t \end{gathered} \tag{2}$$

$$\text{with } SOC \le SOC_{max}$$

Two electrical storage applications are possible: stationary (or static) storage and embedded / semi-stationary storage *via* batteries integrated with electric or hybrid vehicles. In the second case, type 264 is modified to add a presence scenario (freely modifiable: here from 7 pm to 7 am every day): VE is considered as a stationary storage which is disconnected from the building during and reconnected on return.

On the economic level, Balcombe (2015) details the investment costs of a stationary storage by Li-ion battery according to a specific state of the art to this quantity. In particular, they integrate the costs of auxiliaries (load controller, inverter and wiring) and installation costs. Fig. 3 gives the "power" type-fitting curve of Balcombe (2015) on the specific cost of Li-ion batteries. This correlation is used by default in the numerical platform.

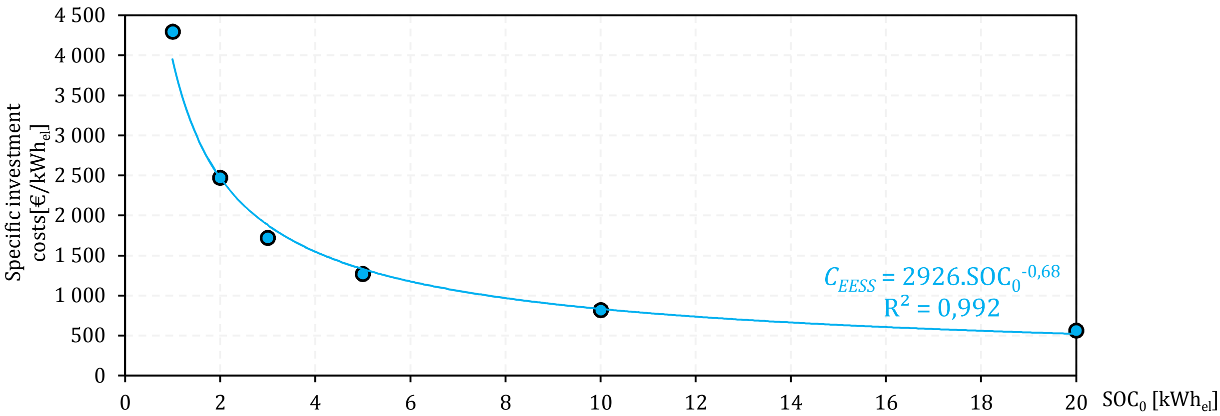

Figure 3 : Specific investment costs for stationary Li-ion batteries.

Specific electricity needs (ESS)

The specific electrical needs (excluding any electrical heating) are a crucial factor to assess the energetic, environmental and economic relevance of µCHP solutions. There are several databases for electrical needs for countries in North America or Europe specifically dedicated to studies on µCHP or micro generation (Knight (2007)). However, these data are not suited to our platform in the French context, especially about the time step, the level of detail and the geographic context, that's why we develop our own tool to generate random electrical needs profiles using a 1 minute time step. This generator is based on statistical profiles of frequency of use: "time of use" method (TOU). It aggregates the power consumption of each electrical appliance based on use probabilities depending on the time of the day, the type of day (week end or week days) and the season: it's a "bottom-up" method. The operating time is variable and follows a standard normal distribution around the mean duration. All statistics used come from the measurement campaign at European level: REMODECE (2008). The generator creates unique profiles by separating non-shifting from the shifting part, which enables intelligent energy management according to 2 input parameters: the dwelling level of appliance based on REMODECE data (low, medium and high) and the electrical appliances energy class based on the European directive 92/75/EEC. Fig. 4 gives the architecture of the procedure for determining the load curve of the stochastic generator developed and Fig. 5 shows an example of the stochastic power consumption profile generated for a winter day in the case of a high appliance level and a B energy class. This tool has been validated on aggregated national data (Bouvenot (2005)).

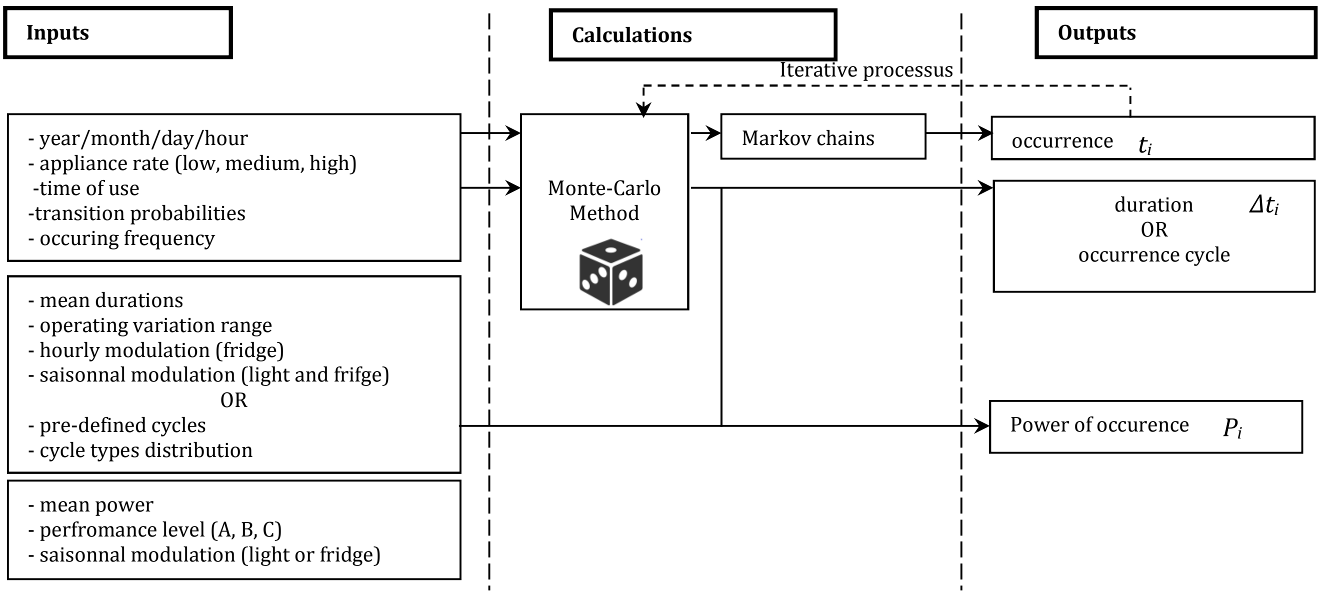

Figure 4: Specific power needs modelling architecture.

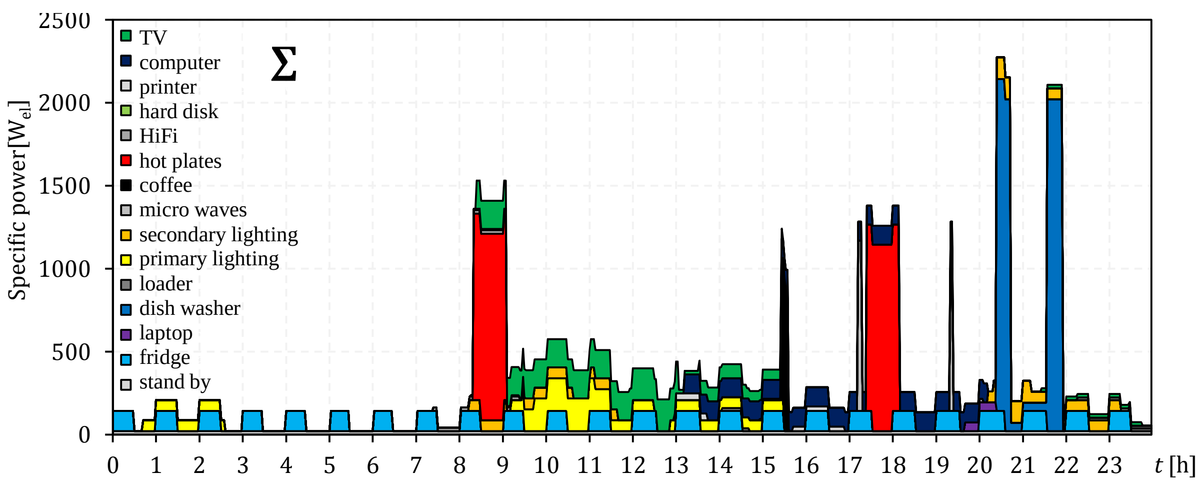

Figure 5: Stochastic needs (thermal and electrical) profiles from the "bottom-up" generators.

Discussion and result analysis

Performance indicators

Integrated in a physical environment, these electrical energy storage systems will interact with the building and the electrical grid. Several indicators make it possible to characterize these interactions:

The self-consumption rate SCR representing the self-consumed share of micro-cogenerated electricity production:

$$SCR = \frac{E_{SC}}{E_{\mu CHP}} \quad (3)$$

The self-production rate SPR (or self-sufficiency) is defined by the ratio of the micro-cogenerated electric production consumed on the total electrical needs:

$$SPR = \frac{E_{SC}}{E_{needs}} \quad (4)$$

The electric coverage CR ratio is defined by the ratio of micro cogenerated electrical production to total requirements:

$$CR = \frac{E_{\mu CHP}}{E_{needs}} \left(= \frac{SPR}{SCR} \right) \quad (5)$$

Thermal modelling strategy

The study considers a 800 W_{el} gas Stirling engine as µCHP system controlled by heat led strategy. Type 56 os used to assess the thermal needs according to the French standards in terms of heat consumption ratios (energy classes A (<50 kWh/m²), B, C, D and E (<250 kWh/m²) here). Multi nodal tank Type 534 is used for the thermal energy storage system (TESS).

Electrical supply configuration

If the VE is absent, the self-produced power is self-consumed by the building at first and the extra power is then exported to the grid. If the VE is present, the VE is used as bi directional stationary EESS. The self-produced power is self-consumed in the building at first, then it load the VE battery and finally it is exported to the LV grid. If the µCHP production is so low, power from the EV supplies the building.

Results

Fig. 6 shows the rates of self-consumption and self-production obtained as a function of the equivalent electrical storage time $\boldsymbol{\tau_{eq}}$ defined in equation 4:

$$\tau_{eq} = \frac{SOC_0}{P_{el}^{nom}} \quad (6)$$

Firstly, Fig.6 shows the energy relevance of the use of stationary electrical storage systems which make it possible to significantly increase both 2 SCR and SPR indicators. For high performance buildings (class A), their impact is more pronounced and increases from 25 to over 50% of self-consumption rates. Low heating requirements limit the operation of µCHP systems and electrical production. The result is low self-consumption and self-production rates and a significant share of electricity imported from the grid. Fig. 6 also shows that very low storage capacities (on the order of 30 minutes of equivalent storage time) are sufficient to obtain high energy indicators for high-performance buildings. In addition, oversized electrical storage has little influence on these energy indicators.

For buildings with average energy performance (class D), these systems, even at low capacity, are less relevant. Indeed, the thermal requirements allow an important operating load of the µCHP system and therefore a significant electrical production (coverage rate of 179% here). This electrical overproduction implies higher exports with a low SCR but a high SPR. In the end, if the coverage rate exceeds 100%, an electrical storage system proves to be irrelevant.

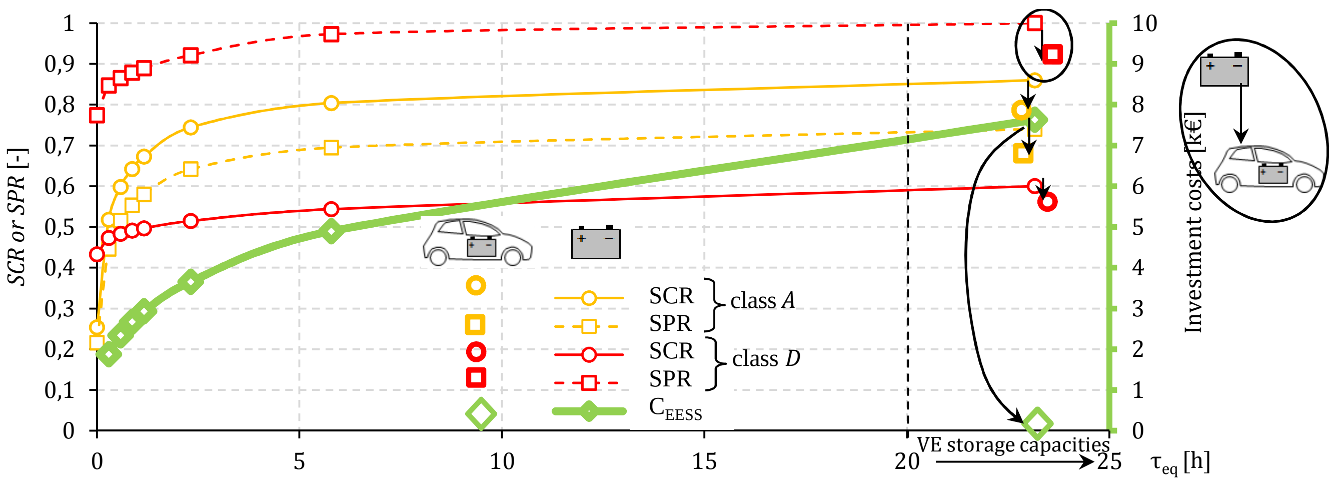

Figure 6 : Impact of electric storage capacity on energy and economic indicators.

At the economic level, the cost of investing C_{EESS} for electric batteries is given on Fig. 6. Even at low capacity, this technology remains expensive (around € 2,000 for 0.5 kWh_{el}), while the gains linked to the decrease of the consumed electricity from the grid in the most favorable case amounts to several hundred €. The use of electrical storage can only be justified in the short term by a criterion of standardization (total auto production) or by pooling the storage system with a photovoltaic system or by using an electric vehicle whose Electric battery would act as semi-stationary electrical storage and "free" from the point of view of the building. The non-permanent presence of storage batteries degrades the indicators of self-consumption and self-production by 10 to 20% with the defined scenario.

The literature on the coupling between a µCHP and a residential building shows that most authors focus either on self-consumption (mainly) or self-production (Bouvenot (2015)). It is important to correlate these two indicators in order to evaluate the coupling performance. It is, for example, easy to obtain very high self-consumption rates via a very low production (a few W_{el}) which makes it possible to be absorbed by the base of the feed continuously. On the other hand, here self-production will be very weak.

Fig.7 presents the self-consumption rate according to self-production rate in nine configurations: three types of buildings (100 m² class A, C and E) and three electrical requirements profiles representative of French consumption (household electric appliances Energy class B with three levels of equipment: low, medium and high). This constitutes the "electrical independence field ". The ideal being to reach rates of 100% for each indicator. This representation shows that micro-cogenerated electricity production is highly self-consuming in high-performance buildings but in parallel, electricity imports from the network are the strongest (low self-generation). Conversely, buildings that are more energy-intensive have lower self-consumption due to a larger micro-cogenerated electricity production, most of which is exported to the grid.

These curves show that electrical storage will be all the more relevant for high-performance buildings with low specific electrical requirements. Since the operating load of the µCHP system is limited (low thermal requirements), the probability of concomitant operation with an electrical requirement will be low. The most efficient configurations in terms of electrical independence correspond to national mean buildings in terms of thermal consumption (class C (150 kWh/m²)). Electrical storage systems make it possible to significantly increase this indicator of electrical independence. Electrical batteries will therefore make it possible to better correlate production and consumption in order to maximize self-consumption. The concordance of the rise of low-consumption buildings and electric cars thus appears as a boon for the development of µCHP via vehicle to home strategies for example.

One finds the positioning of the semi-stationary batteries of high capacities (20 kWh_{el}) corresponding to VE. This positioning makes it possible to make a correspondence between the stationary and semi-stationary (VE) capacities. Thus, a semi-stationary storage by VE allows an equivalent stationary storage of the order of 2 to 5 kWh_{el} and makes it possible to significantly increase the self-consumption and the electrical self-production of a micro-cogenerator coupled with a building.

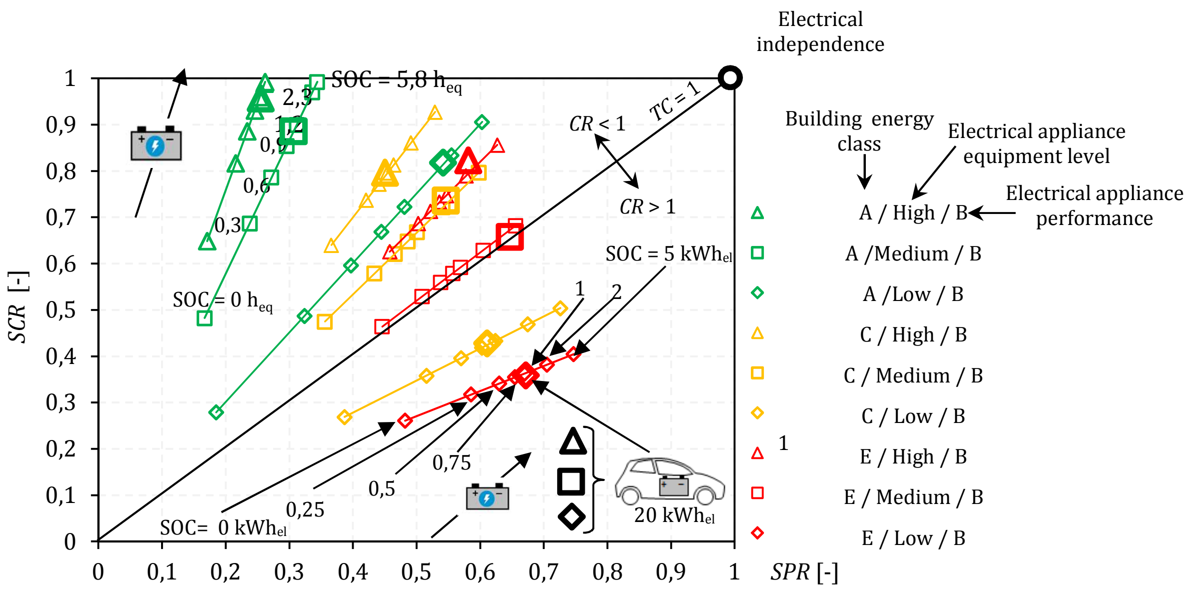

Figure 7: Electrical independence field with the influence of stationary electrical storage capacities from 0 to 5 kWh_{el} (or 0 to 5,8 h_{eq}) and correlations with EVs.

Conclusion

A numerical simulation platform has been developed in the TRNSYS environment to study the coupling between a µCHP system, a residential building, the grid and energy storage systems (TESS & EESS/EV/PEHV). It became apparent that the recent rise of individual electric mobility makes possible to pool the electric storage battery with a stationary storage application of electricity so as to obtain more interesting self-consumption and self-production rates. Despite the high capacity of VE's batteries, the intermittent presence implies a reduction in effective storage performance (indicators of SCR and SPR). However, these indicators only decrease in the order of 10 to 20% and still allow performance to be equivalent to a permanent stationary storage of the order of 2 to 5 kWh_{el}. Other studies on the supplementary aging of batteries induced by a V2H strategy, on the modification of the DOD or on the scenarios of presence have to be carried out to refine the study of this coupling. Also, the economic impact and the impact on the grid must also be better assessed. A new experimental project is running on the coupling between a gas PEM fuel cells and a lithium-ion battery in order to validate our platform and to model more precisely EESSs and to better assess the over degradation of EV batteries linked to V2H strategies.

Nomenclature

C	cost, €
DOD	depth of discharge, *%*
E	electrical energy, kWh_{el}
P	power, W
n	number of cycles, -
SCR	self-consumption rate, -
SPR	self-production rate, -
SOC	state of charge of EESS, kWh_{el}

Greek symbols

η	efficiency
τ	equivalent storage time, h

Subscripts and superscripts

c	charge
cal	calendar
d	discharge
DHW	domestic hot water
EESS	electrical energy storage system
el	electrical
eq	equivalent
EV	electric vehicle
FE	final energy
HV	high voltage
LV	low voltage
nom	nominal
PEHV	plug in electric hybrid vehicle
sb	stand by
SC	self-consumed
spe	specific
TESS	thermal energy storage system
th	thermal

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