Assessment of an internal combustion engine micro-CHP operation for different office buildings performance scenarios

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Abstract

This paper presents the results of a sensitivity analysis performed on a real office building of 3500 m² coupled with micro-CHP system in addition to a gas boiler and a hot water storage. We compare equipment performances for four envelope characteristics corresponding to four construction periods (based on building thermal regulations) in France (before 1980 to 2012). The results obtained by simulating the building combined with the heating plant model in Dymola/Modelica environment show good correlation between the electrical peak load and production (most of the time, the consumption is higher than production). With the micro-CHP, the production plant satisfies correctly the thermal needs and the temperature is comfortable for all office floors. These results are encouraging and can be used by practitioners and engineers to design, to size and operate efficiently micro-CHP.

Background and state of the art

Building sector is the largest single energy consumer in Europe with approximately 40 % of the energy use. European institutions are looking for solutions to increase energy performance at all levels. Upgrading and combining heating equipment such as boilers (potential base of 100 million devices in Europe) with high efficiency technologies such as micro combined heating and power (micro-CHP) is a double option to optimize the energy consumption.

Micro-CHP systems are becoming essential in order to take full advantage of the available primary energy. This system produces simultaneously heat and electricity and enables recovery of heat resulting from electricity generation by using it to satisfy the thermal building needs.

Studies on the feasibility of micro-CHP technologies in different countries such as Magri et al. (2012) and Barbieri et al. (2012) indicate that satisfactory results can be achieved, enabling reductions in primary energy consumption. Gas micro-CHP with internal combustion engines (ICE) are considered the most mature and reliable products on the market.

Combinations of building/energy systems/use include relatively complex physical phenomena difficult to treat. Dynamic simulation is a flexible solution to study this behavior. Recent works in the topic of micro-CHP modeling such as Bonabe de Rouge et al. (2016), Dorer and Weber (2009) indicate that providing comprehensive information on the micro-CHP sizing methods, hydraulic and building integration is required. For example, the size of the storage which could influence the operating hours and the losses, or the control strategy of the micro-CHP/auxiliary boiler, are interesting parameters to be investigated in order to optimize the system integration. Furthermore, the literature on these issues is more extensive for residential than commercial buildings.

Finally, Kelly et al. (2008) also mentioned the possibility for micro-CHP to be a part of Highly Distributed Power Systems (HDPS). Therefore, it could be turned ON through a third party signal based on need for power supply. Evaluation of opportunities for HDPS control could help shaping additional micro-CHP benefits.

Objectives

Therefore, the aim of this article is to evaluate, quantify and give insights to further develop techniques for proper sizing of micro-CHP equipment. This will also help to explore technical or integration problems which have to be overcome in order to adapt this system to real office building market. The chosen method is based on the modeling and simulation of a real office-building and its systems.

Building modeling assumptions

The modeled case study is a real office-building composed of 5 floors (3500 m²). The model encompasses 8 thermal zones defined as a welcome area on the first floor, technical areas and office areas for all floors from first to fifth floor.

Thermal zones usage definition

The defined thermal zones can be gathered in three types of use: offices, welcome and technical areas. Each type of use is parameterized in terms of schedule, ventilation, heat gains, heating and cooling temperature set points. The paper is focusing on the heating period. Thus, the cooling systems assessment will not be presented further in the paper.

<u>Schedules</u> are defined for occupancy, ventilation, lighting and other loads (such as computers for instance) in each thermal zone. The schedules are used in all occupied thermal zones (welcome and office areas). Thus, the occupancy is defined according to Figure 1 assuming it is

identical for all weekdays except weekend for which no occupancy is taken into account (office-building).

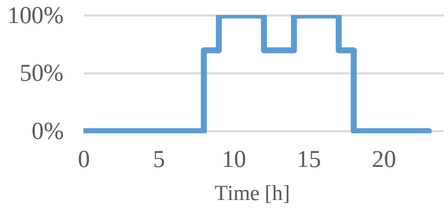


Figure 1: Five identical weekdays' occupancy schedule

The ventilation is considered ON from 8a.m. to 8p.m. during the weekdays only. The lighting system is considered turned ON from 6a.m. to 8p.m. during the weekdays only. The other loads are defined according to Figure 2 during the weekdays and 10% during the weekend.

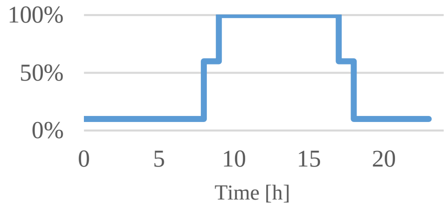


Figure 2: Five identical weekdays' other loads schedule

The ventilation airflow is calculated in all the thermal zones including the permeability of the building envelope and the mechanical ventilation with heat recovery. Permeability of the thermal zone is characterized by an airflow defined according to (1) at the outside air characteristics:

- external temperature and density (ρ_{air} in $kg.m^{-3}$)
- mass flow rate ($\dot{m}_P$ in $kg.s^{-1}$) which is computed as a function of the nominal permeability mass flow rate ($\dot{m}_{Pnom}$ in $m^3.h^{-1}.m^{-2}$) and the building envelope surfaces with heat losses (S_o in m^2).

$$\dot{m}_P = \frac{\dot{m}_{Pnom}.\rho_{air}.S_o}{3600} \qquad (1)$$

The mechanical ventilation system (with heat recovery) is characterized by:

- a heat exchanger efficiency (η_{HX}) according to (2) and depending on the thermal zone temperature (T_{room}), external temperature (T_{ext}) and temperature of the supply air (T_{HX}).

$$\eta_{HX} = \frac{T_{HX} - T_{ext}}{T_{room} - T_{ext}} \qquad (2)$$

- a supply air mass flow rate into the thermal zone through the heat exchanger ($\dot{m}_{HX}$) (during occupancy $\dot{m}_{HXocc}$ has a value of 7261 $m^3.h^{-1}$ while during unoccupied period $\dot{m}_{HXinocc}$ has a value of 315 $m^3.h^{-1}$) and a schedule of occupancy specific to each thermal zone (δ_{occ} = 1 if the thermal zone is occupied and 0 otherwise).

$$\dot{m}_{HX} = \dot{m}_{HXocc}.\delta_{occ} + \dot{m}_{HXinocc}.(1 - \delta_{occ}) \qquad (3)$$

The heat gains are computed for each thermal zone. They are separated into radiative (Q_{rad} in $W.m^{-2}$) and convective parts (Q_{conv} in $W.m^{-2}$). They depend on the occupancy, lighting and other loads.

- Heat gains due to occupancy ($Q_{occupancy}$ in $W.m^{-2}$) are proportional to heat emissions per occupant ($Q_{occupant}$ = 90 W), the occupancy rate schedule ($S_{occupant}$) and a number of occupants per square meter ($N_{occupant}$) specific to each thermal zone (detailed in Table 1).

Table 1: Thermal zone occupation ratio

Type of thermal zone	$N_{occupant}$ ($occupant.m^{-2}$)
Welcome area	0.1
Office area	2
Technical area	0

Finally, heat gains due to occupancy are computed as follows:

$$Q_{occupancy} = Q_{occupant}.N_{occupant}.S_{occupant} \qquad (4)$$

These heat gains and evenly separated between radiative and convective parts.

- Heat gains due to lighting (Q_{light} in $W.m^{-2}$) are considered 100 % radiative and are obtained from the real behavior of the building. Thus, available real measurements (see Figure 3) of electric loads (lighting, office equipment, others) in the building management system are analyzed. Data extraction is performed and electric power due to lighting is attributed to building thermal zones as inputs.

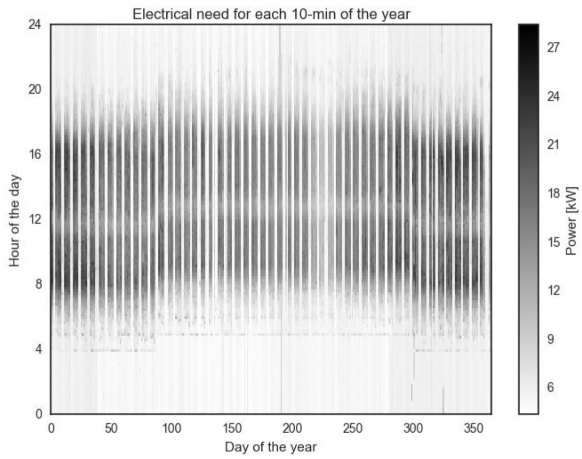


Figure 3: Annual offices zones real building electric load

- Heat gains from other loads ($Q_{otherLoads}$ in $W.m^{-2}$) result of the ratio $Q_{equipment}$ = 16 $W.m^{-2}$ and load rate schedule as defined in Figure 2 ($S_{equipment}$). These heat gains are also considered 100 % radiative.

$$Q_{otherLoads} = Q_{equipment}.S_{equipment} \qquad (5)$$

To sum up, the radiative and convective heat gains are defined according to (6) and (7):

$$Q_{rad} = 50\ \%\ Q_{occupancy} + Q_{light} + Q_{otherLoads} \qquad (6)$$

$$Q_{conv} = 50\,\%\, Q_{occupancy} \qquad (7)$$

The heating temperature setpoints (Table 2) are defined in order to control the room temperature. During the year, a heating period is set up. Every week, the "day" setpoint heating applies from 6 a.m. to 9 p.m. during the weekdays and "night/weekend" setpoint for the rest of the day and all day during the weekend.

Table 2: Heating temperature setpoints

	Heating
Day	21 °C
Night/Weekend	16 °C

Four building study cases

The modeled building is then adapted to different energy standards, corresponding to energy performance of a French building built before 1980, during 1980-1999, 2000-2011 or 2012. Some adaptations are performed for the heating periods to ensure thermal comfort for building's occupants and to be closer to reality (older and less efficient buildings need a longer heating period). Thus, for "Before 1980" and "1980-1999" buildings, the heating period is defined from the 1st of October to the 30th of May. For "2000-2011" and "2012" buildings, the heating period is defined from the 1st of October to the 30th of April. The ventilation system is also adapted according to the building construction period. These changes are summarized in Table 3 following the notation defined in the previous section.

Table 3: Ventilation configurations

	Before 1980	**1980-1999**	**2000-2011**	**2012**
$\dot{m}_{Pnom}$ $(m^3.h^{-1}.m^{-2})$	2	1.6	1.2	0.8
η_{HX}	-	-	0.5	0.7

Walls and windows characteristics (Table 4) are selected in order to ensure adequate performance level for the envelope.

Table 4: Building envelope characteristics

	Before 1980	**1980-1999**	**2000-2011**	**2012**
Ext. walls	Concrete 20 cm			
	PSE 0 cm	PSE 1.9 cm	PSE 6 cm	PSE 16 cm
Int. walls	Concrete 12 cm			
Ext. floors	Concrete 20 cm			
	PUR 0 cm	PUR 3.5 cm	PUR 8.5 cm	PUR 14.7 cm
Int. floors	Concrete 20 cm			
	-	-	PSE 4.5 cm	PSE 15 cm
Int. ceilings	Concrete 17 cm			
	-	PUR 1.9 cm	PUR 9.3 cm	PUR 23 cm
Windows	SG 3 mm	DG1 4 / 6 / 4 mm	DG2 4 / 8 / 4 mm	DG3 4 / 15 / 4 mm

Where : PSE = Polystyrene; PUR= Polyurethane; SG = Single Glazing with U-value of frame of 3.8 $W.m^{-2}.K^{-1}$; DG1 = Double Glazing with U-value of frame of 3.8 $W.m^{-2}.K^{-1}$; DG2 = Double Glazing with U-value of frame of 3 $W.m^{-2}.K^{-1}$; DG3 = Double Glazing with U-value of frame of 1.4 $W.m^{-2}.K^{-1}$

These four buildings are then simulated during a full year. First results for heating needs allow to size the thermal plant and thermal zones emission systems. Heating needs are illustrated in Figure 4. The more efficient the building is, the lower its heating needs are.

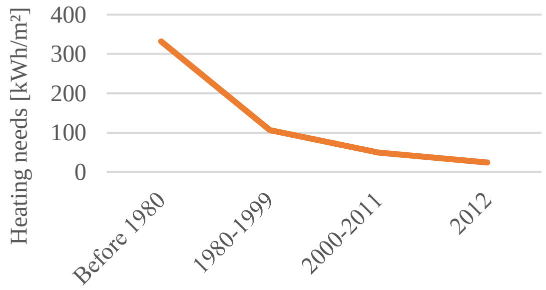


Figure 4: Heating needs for building cases

Plant modeling assumptions

The building model is connected to a heating plant model including components such as micro-CHP, auxiliary boiler, thermal storage system, hydraulic loop, control strategies and variable internal loads.

Dynamic micro-CHP model

The micro-CHP unit is an internal combustion engine (ICE) providing thermal and electrical power to the building. The micro-CHP is a 7.5 kW_{el} and 20 kW_{th} unit based on reciprocating engine technology. It runs at 1500 rpm for a gas consumption of 30 kW (HHV) at nominal operating conditions. It is capable of load modulation down to 50 % of nominal power to adapt its thermal capacity to building needs and lower the risk of short ON/OFF cycles. This particular micro-CHP unit adopts heat recovery thanks to condensing exhaust water and a variable speed pump. It is thus particularly efficient at low inlet water temperature.

Grey-box modeling: The model relies on a grey-box approach. It intends to represent operation of micro-CHP systems keeping in mind that it is governed by physical laws but simplifying and/or grouping multiple phenomena with equations mixing physics and empirical parameters. While it requires limited experimental investigation to identify calibration parameters, advantages are a better computational time and no need to describe all the physical phenomena. Grey-box models are largely adopted for annual simulation coupling building and systems as showed in IEA Annex 42 works. Thus, this paper uses this approach.

Micro-CHP model: Andlauer (2011) and then Bouvenot et al. (2015) developed a model for a 1 kWel Stirling engine (SE)-based micro-CHP unit. The model includes both steady state and transient operations for electrical, thermal and gas power as shown in Figure 5. Bouvenot et al. (2015) extended their work to a wood-pellet steam engine. Recently, Bonabe de Rougé et al. (2016) adapted this model for power modulation and calibrated parameters for the ICE-based unit investigated in this paper.

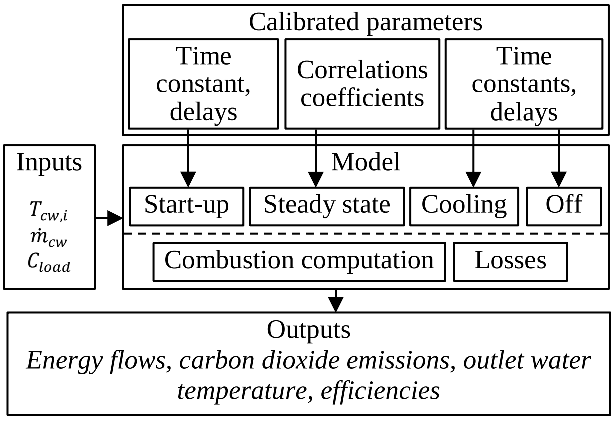


Figure 5: Architecture of dynamic micro-CHP model

Steady state operation: Linear equations including parametric correlations coefficients *a*, *b* and *k* describe steady-state operation for each power flow as a function of nominal capacity (P_{fuel}^{nom} in the case of fuel/gas input), inlet water temperature $T_{cw,i}$ and water mass flow rate $\dot{m}_{cw}$. *Nom* subscript indicates arbitrary nominal values. Load level C_{load} is added to the original algorithm to model ICE modulating behavior. Equation (7) illustrates fuel consumption computation.

$$P_{fuel} = P_{fuel}^{nom} + a\left(T_{cw,i} - T_{cw,i}^{nom}\right) + b\left(\dot{m}_{cw} - \dot{m}_{cw}^{nom}\right) + k\left(1 - C_{load}\right) \quad (7)$$

Linear equations for exhaust temperature, condensing water mass flow rate and combustion computation allow computing both sensible and latent exhaust heat losses.

Transient operation: Exponential form equations and delays describe thermal production during start-up and cooling phases. The model represents electrical production and gas consumption with delays and ideal rising/falling edge as transient behaviors for these variables are found to be negligible during experimentation.

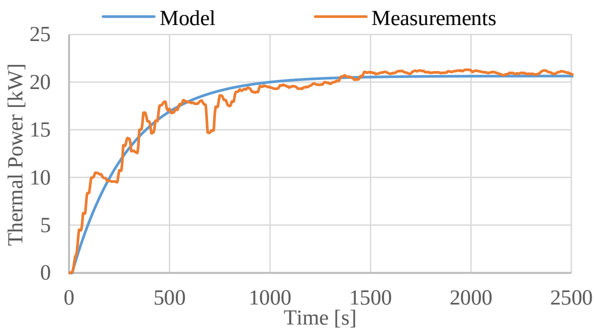


Figure 6: Measured and modeled thermal power during a start-up phase

Parameter calibration: An experimental test bench for micro-CHP unit enables to observe or evaluate temperature, water flow rate and power flows at various operating conditions. A calibration process allows calibration of each parameter for steady state and transient operations. Figure 6 is an example of calibration results for thermal power during start-up and Figure 7 an example of calibration results for steady state operation and 50 °C inlet water temperature.

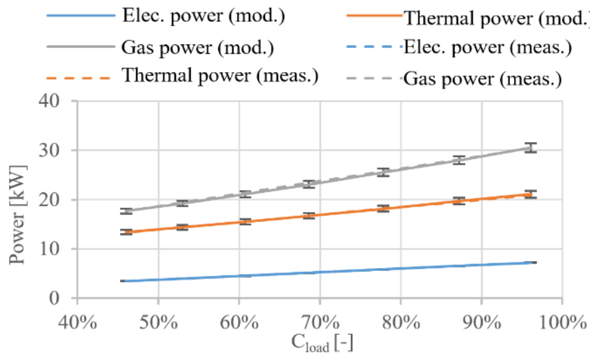


Figure 7: Measured and modeled gas consumption, electrical and thermal production for different load levels for 50 °C inlet water temperature

Full model of the plant

The full plant (see Figure 8) includes a micro-CHP unit, an auxiliary boiler and a thermal storage tank. Pumps and splitters are also used to connect the components together.

The micro-CHP model described before is used and the other components of the plant originate from the Modelica Buildings library (Wetter et al. (2015)).

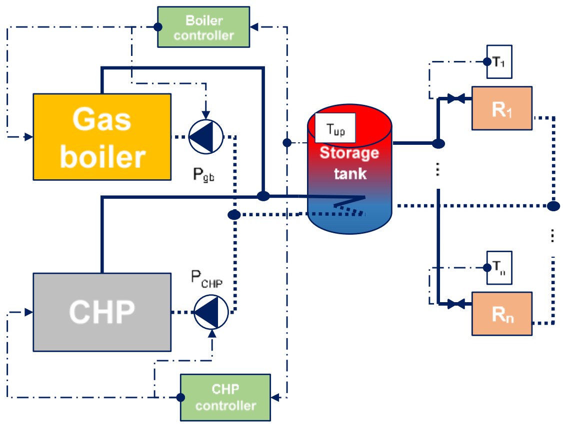


Figure 8: Plant model scheme

The reference control of the micro-CHP unit is based on building thermal needs. The micro-CHP unit operates in priority to heat the water storage tank. A hysteresis is set up and permits to turn ON the micro-CHP unit when the water storage tank temperature is below 55 °C until the temperature reaches 60 °C again.

The parameters defining the behavior of the boiler unit are described below:

- Nominal thermal power of this unit depends on the building case (see Table 5).
- The operating range of the boiler unit is from 20 % to 100 %.

Table 5: Boiler power for the four building cases

Building	Before 1980	1980-1999	2000-2011	2012
Boiler power [kW]	417	263	158	107

- The control of the equipment is defined based on its thermal behavior. The boiler unit operates as a back-up to heat the water of the storage tank only during the heating period. A hysteresis is set up which turns on the boiler unit when the water storage temperature is below 52 °C until the temperature reaches again 57 °C.

The storage tank unit is a hot water storage volume with heat exchanger. In our study case, a volume of 2000 L is selected as reference. A variable speed pump moves hot water through radiators equipped with thermostatic valves integrated in our plant scheme. The valves are controlled as a function of the zone temperature, (T_i). Two pumps, one for the gas boiler (P_{gb}) and the other for the micro-CHP pump (P_{CHP}) are integrated in the plant model as well.

Simulation cases

The full plant is combined to the building model and a sensitivity analysis is performed in order to determine the "best fit" for a specific micro-CHP unit.

Sensitivity analysis assumptions

For each of the four building performance levels, representative of old and recent French office buildings, 7 heating system configuration cases are simulated. These configurations are described below:

Conventional supply (without micro-CHP): this case considers the building without micro-CHP, only a boiler covers the heating needs of the building. National electricity grid supplies electrical needs.

Reference: the reference case with micro-CHP gathers all assumptions described in "plant modeling assumptions" section without modification.

Hysteresis: a third case focuses on the choice of alternative thresholds for the hysteresis between boiler and micro-CHP. The boiler thermal control is defined in this case with a hysteresis between 55 °C and 59 °C and the micro-CHP thermal control is defined between 58 °C and 62 °C.

Storage volume: an additional case consists in modifying the volume of the storage tank. Instead of 2000 L of storage capacity, 1000 L water storage is introduced.

Inertia: this case enables to study the impact of heat emitters' thermal inertia. This case doubles the reference value for every emitter in the building.

"Max tank use" and "hybrid" controls: two cases are defined in order to modify the control of the micro-CHP unit.

- "Max tank use" control allows the micro- CHP unit (but not the boiler) to run until the tank top temperature reaches 90 °C to "unlock" the full potential of the storage. The return temperature must not violate the security limit (of 70 °C).
- Then a "hybrid" control is proposed. Reference control is applied but, in the case of spot market electricity price being higher than a threshold value (50 €/MWh), "max tank use" control is allowed. Spot market electricity price hypothesis are explained thereafter.

Spot market electricity price

We use EPEX spot market electricity price to trigger the operation of the micro-CHP in "hybrid control" case. High prices usually reflect high national electrical demand periods during which micro-CHP electricity production may be useful.

Figure 9 illustrates the electricity price variation (€/MWh, red curve) and outside temperature (°C, green curve) for one week of January (Monday 4th to Sunday 10th). It shows similar profiles for all weekdays with peak prices during the morning and the evening. On the contrary, during the night and in the middle of the day, the electricity price falls.

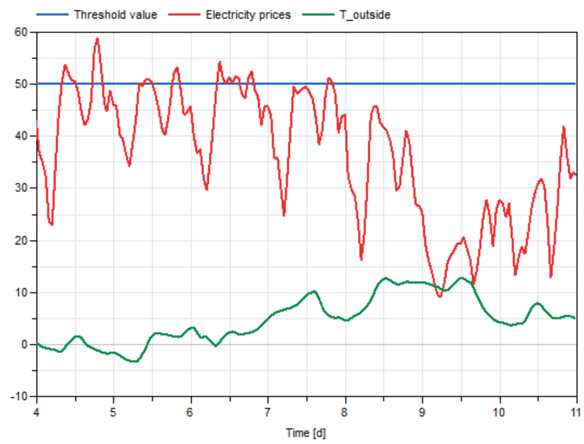


Figure 9: Spot market electricity price during a week in January 2015 and outside temperature

Furthermore, by comparing every day of the week, we can see price goes down during weekend. This can be explained by lower commercial activities, especially in office buildings and industry, which are large electricity consumers. In addition, we can notice that the morning peak is shifted in time by about half an hour. Besides, on this particular week, outside temperature on Friday is warmer than the other days. As national electricity consumption is impacted by weather conditions (especially in France), electricity price is also reduced.

Metrics

To compare performance between simulation cases, multiple metrics are introduced. These metrics are described below.

Primary Energy consumption (PE) of all cases is deducted from gas and electrical Final Energies (FE), consumed or produced by the building energy system. Dynamic models of boiler and micro-CHP provide final gas consumption (FE_{boiler}^{gas}) and electrical production (FE_{CHP}^{el}) while 10-min electrical load data give annual electrical need (FE_{need}^{el}).

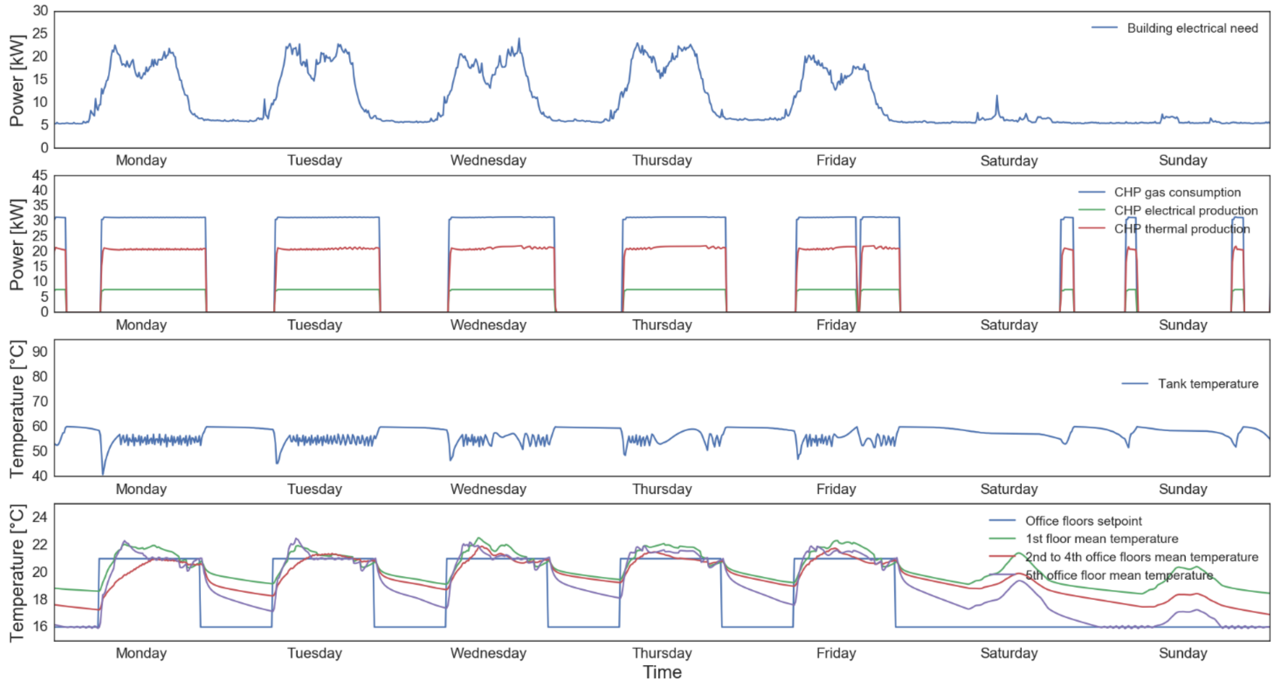


Figure 10: A week (#3) of operation during winter for "2012" building and "reference" system case

A common approach is to compare primary energy consumption for a conventional (subscript *conventional*) energy supply system (gas boiler and national electricity grid) and an alternative (subscript *alternative*) micro-CHP-based supply system. Relative primary energy savings (PES) are defined in (8) :

$$PES = \frac{PE_{conventional} - PE_{alternative}}{PE_{conventional}} \quad (8)$$

Primary energy consumption of the conventional system is given in (9) :

$$PE_{conventional} = FE_{boiler}^{gas} . f_{PE}^{gas} + FE_{need}^{el} . f_{PE}^{el} \quad (9)$$

Primary energy consumption of the alternative system (including micro-CHP) is given in (10) :

$$PE_{alternative} = (FE_{CHP}^{gas} + FE_{boiler}^{gas}) . f_{PE}^{gas} + (FE_{need}^{el} - FE_{CHP}^{el}) . f_{PE}^{el} \quad (10)$$

f_{PE}^{gas} refers to the primary energy conversion factor of natural gas and f_{PE}^{el} to the primary energy factor for electricity. Typical values for France are respectively 1.0 and 2.58. Equation (10) implies:

- Produced micro-CHP electricity displaces grid electricity import from central electrical power plant with transport and distribution losses.
- The same primary energy factor applies for exported and self-consumed micro-CHP electricity production. We do not take into account that self-consumed electricity also avoid low-voltage distribution network losses compared to exported electricity. This is a conservative choice even if different primary energy factors could be used.

A common strategy to increase primary energy savings consists in producing as much electricity as possible as its primary energy factor is higher than gas.

Self-consumption, self-production, electrical coverage

Self-consumption (SC) is the ratio between electricity production consumed on-site and total electricity production. Self-production (SP) is the ratio between the electricity production consumed on-site and total electricity needs. Electrical coverage (EC) is the ratio between total electricity production and electricity needs. Together, these ratios enable to represent the autonomy of the building and the concomitance of production and needs.

Thermal coverage (TC) is the share of total heat production covered by micro-CHP heat production. Its value depends on both micro-CHP maximal thermal power versus building thermal needs and its operation.

Relative peak reduction represents the relative reduction of building electricity consumption for each 10-min time step thanks to the introduction of micro-CHP in the building. This ratio is useful to give insights about how it could be helpful to install a micro-CHP from the point of view of electricity grid manager.

Results and discussion

A selection of 28 configurations (building, system and control) are simulated for a year with Dymola/Modelica. The present section intends to describe the operation of the micro-CHP plant coupled with the building and compare performances thanks to the specific metrics described before. First, we focus on the 2012 building with reference system case to illustrate the operation of our system. Then, we compare simulation results for the four building insulation levels using the reference system.

Finally, a sensitivity analysis for the 2012 building is illustrated.

"Reference" system with 2012 building case analysis

This section describes operation of the building including micro-CHP during a typical winter week (third week of the year, from Monday to Sunday) in the "reference" case for the most insulated building (2012).

Top of Figure 10 shows an electrical base power consumption of about 6 kW which is present during the night and peak load usually occurs from about 9 a.m to 5 p.m. As well, electrical production occurs during opening hours because of higher heating setpoints. There is a good visual correlation between peak load and production. Most of the time, electrical consumption is higher than local production meaning high self-consumption ratio. Figure 10 illustrates that micro-CHP always operates at full load when turned ON. Small and fast variations of tank sensor temperature indicates the backup auxiliary boiler maintains the tank setpoint.

Analysis of Figure 10 illustrates that the operation of the micro-CHP is almost continuous during a winter day except for the fifth day around 4 p.m: warmer external temperature and more solar gains lead to less heating needs. On this particular day, micro-CHP has to stop around 4 p.m because the tank reaches the temperature setpoint. We also observed that three shorter starts-up are necessary during the weekend to maintain setback temperature for the top floor. Globally, the production plant satisfies thermal needs and ensure thermal comfort in every office floors. At last, morning warm-up leads to fast tank temperature drop meaning that it is discharged to quickly reach the comfort temperature (before 9 a.m) in all the office floors.

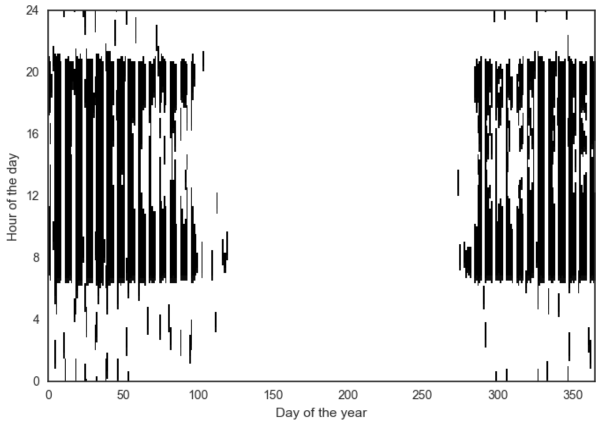


Figure 11: Operating state of micro-CHP for each 10-minutes of the year in the reference case for a 2012 building

Figure 11 represents the operation of the micro-CHP through the year as a carpet plot. Left and right sides of the chart are winter days, upper and lower sides are nights. The unit operates mainly during opening hours (for the "reference" control in the most insulated building). Periodic white vertical lines represents weekend days during winter. During these days, the micro-CHP is mainly turned OFF but it briefly operates during the coldest periods. The operation is typically interrupted from 11 a.m to 17 p.m during the mid-season as thermal needs are less important.

Results comparison for "Reference" system with 4 different building cases

We now compare plant operation for the four buildings cases. The cogeneration unit size is fixed so that the best level of thermal needs can be determined for this particular engine. The four cases are compared for the same "reference" control. Finally, the same specific electrical load is kept for all cases and previously introduced metrics are studied below.

<u>Primary energy savings</u>

Figure 12 shows that the micro-CHP can operate much longer (1734 h vs 5444 h) in the oldest building case. Indeed, the operation is almost continuous during winter months including night periods. As a result, the micro-CHP offers the highest primary energy savings in that case thanks to a high annual electricity production.

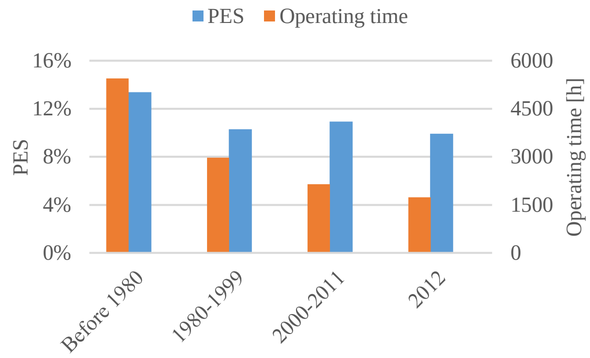


Figure 12: Primary Energy Savings and micro-CHP operating time for "reference" case

<u>Self-consumption, self-production, electrical coverage</u>

Figure 13 shows that the electrical self-consumption is always superior than 85 %, with an increasing trend for the newest buildings.

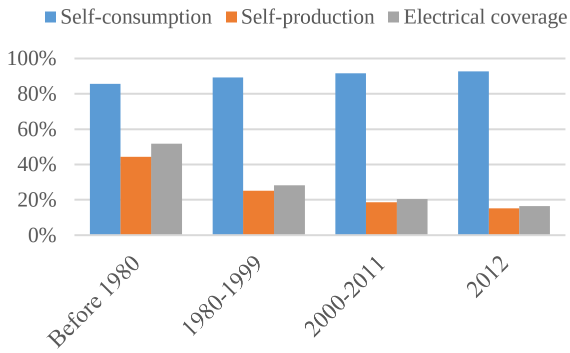


Figure 13: Self-consumption, self-production and electrical coverage for "reference" case

The reason is that micro-CHP sometimes operates at night especially in the oldest buildings (higher thermal needs). However, at night, electrical load is lower leading to electricity export.

As the self-consumption is similar for all cases, the self-production and the electrical coverage mainly depend on the operating time of the micro-CHP unit. That is why they decrease for newest buildings. For the oldest building, the local electrical production represents about 50 % of the total electricity consumption while it only represents 15 % for the newest building.

Thermal coverage

The opposite trends happen for thermal coverage versus electrical coverage (see Figure 14). The less heat the building consumes the more the micro-CHP is able to cover thermal needs. While theoretical maximal annual heat production of the micro-CHP (20 kW at full load through all year: 175 MWh) is about 1.5 times greater than annual heat demand of the 2012 building (~110 MWh). The constrained maximal power and the thermal dynamics with restricted thermal storage leads to limited thermal coverage.

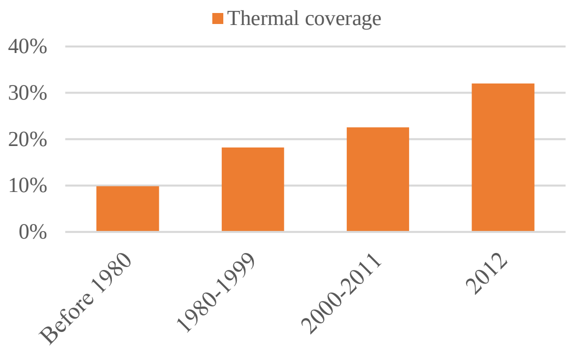


Figure 14: Share of heat production produced by the micro-CHP (thermal coverage)

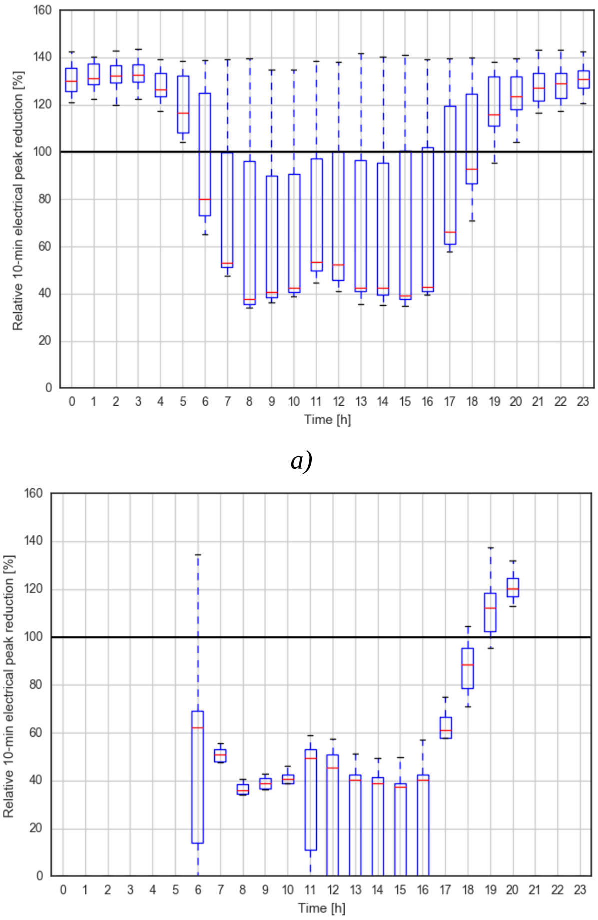
Electrical peak reduction

Statistical distribution of the relative electrical peak consumption reduction is illustrated (see Figure 15) during the month of January for the oldest (a) and newest (b) buildings. Peak reduction greater than 100 % means that electricity is exported to distribution grid. For each vertical bar, the box extends from the lower to upper quartile values of the data, with a red line at the median. The whiskers extend from the box to show the range of the data. Short bars represent a tight distribution of peak reduction values. For example, at 8 p.m both buildings are always exporting electricity to the grid. This could be significant to the grid if a large number of buildings are able to shave imports during high national electricity demand (typically at 7-8 p.m during winter months because of electric heating in France).

In the newest (2012) building, the micro-CHP mainly shaves peak demand during the day (no bars at night) while we see continuous operation and peak shaving for the oldest building: bars do not cross zero. At night, electrical needs of the buildings are almost constant and quite low, thus, relative peak shaving is always higher during these periods.

Analysis

Comparisons between different thermal load levels show that thermal needs strongly influence operation of the micro-CHP and its interactions with electrical network. This is mainly due to “reference” control, consisting in following thermal load of the building. Different control strategies or system parameters could modify micro-CHP behavior. They are investigated thereafter.



a)

b)

Figure 15: Distribution of relative electrical peak reduction during January for oldest (a) and newest (b) buildings

Sensitivity analysis for the 2012 building case

This section presents results comparison for a given building with various storage sizes, controls and emitters. The 2012 building shows greater sensitivity to modifications of control, storage and emitters, thus, we present this case below. For oldest buildings, control and systems have less impact.

Hybrid control typical week of operation

To illustrate how the micro-CHP operates in “hybrid control” mode, Figure 16 shows a week of micro-CHP operation, electricity needs and spot market prices together with water storage temperature.

Multiple “hybrid control events” (price greater than 50 €/MWh) can be observed. Standard storage tank setpoint temperature is 55/60 °C but the tank temperature increases up to 90 °C in about 3 to 4 hours when prices are greater than 50 €/MWh. Typically, these events take place during the morning or in the evening. Even if the building rooms temperature setpoint drops at 9 p.m (resulting in no thermal needs), micro-CHP continues to run until the tank is fully loaded. As high prices usually

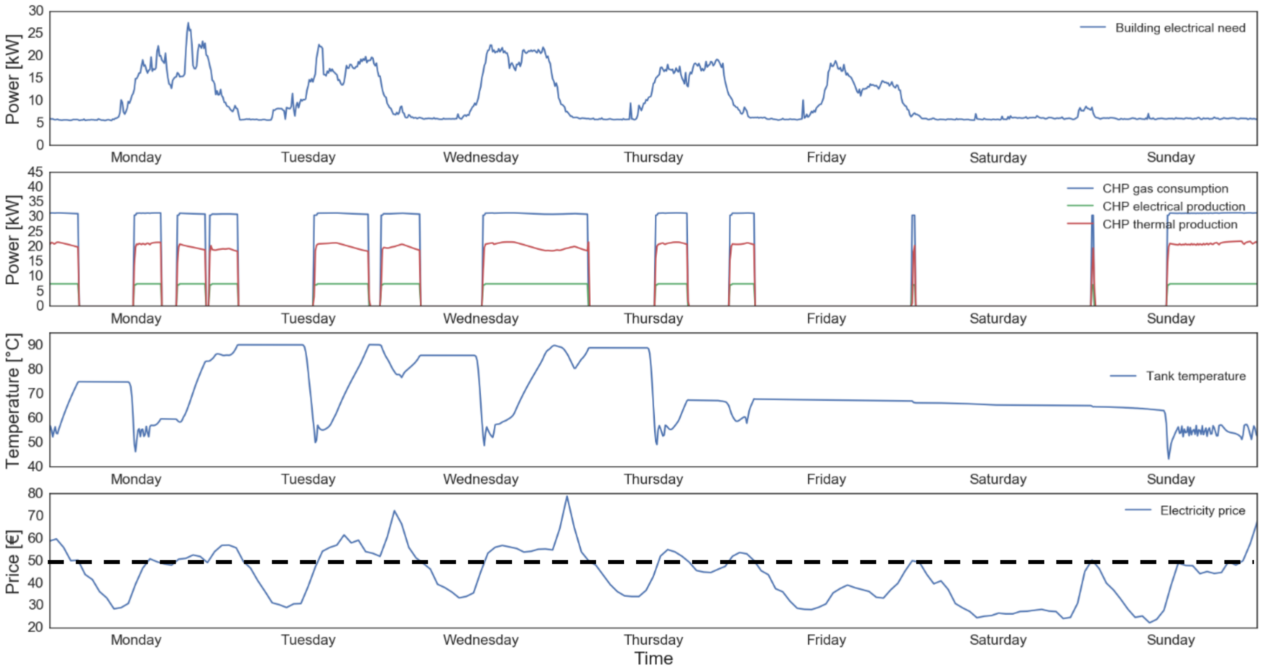


Figure 16: A week (#42) of operation during winter for "2012" building and "Hybrid control" system case

occur when national demand is high, there is a very good correlation between CHP operation and national demand whatever the building thermal needs are.

<u>Primary energy savings</u>

The highest PES is obtained for the "max tank use" control strategy (see Figure 17). This strategy results in an unlimited "hybrid" control where the micro-CHP loads the tank to the limit whenever it can whatever the electricity price is. Therefore, micro-CHP operating time is 43 % longer than the "reference" case; this allows higher annual electricity production. This control strategy is the only one to enable the newest building PES to exceed oldest building PES.

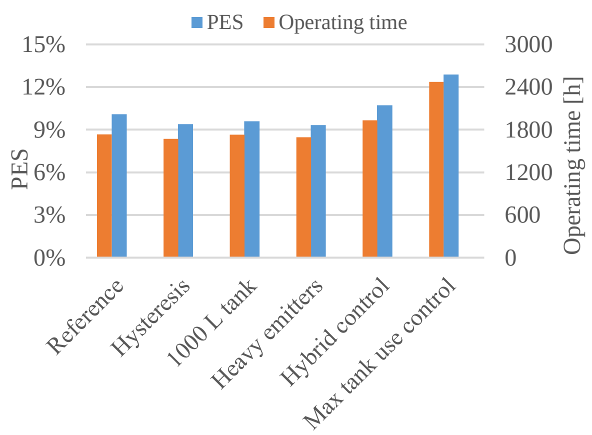


Figure 17: Primary Energy Savings and micro-CHP operating time in 2012 building case

Hybrid control is close to "reference" case: for a threshold value of 50 €/MWh only a few hundreds of hours of hybrid strategy are possible.

Modifying hysteresis or emitters slightly decreases PES. Decrease of water storage volume also reduces PES as it decreases the ability of the micro-CHP to produce electricity by lowering operating time. The auxiliary burner thermal production increases in these cases instead of the micro-CHP.

<u>Self-consumption, self-production, electrical coverage</u>

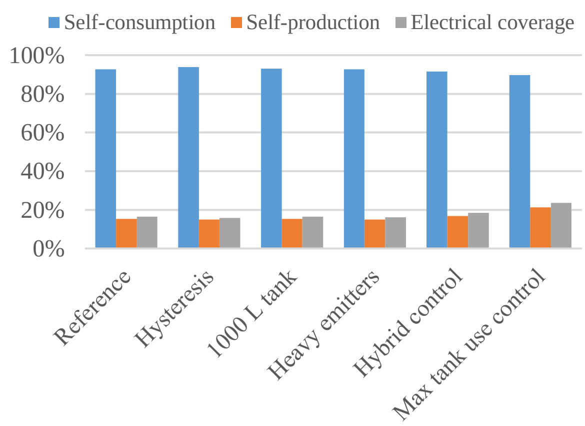
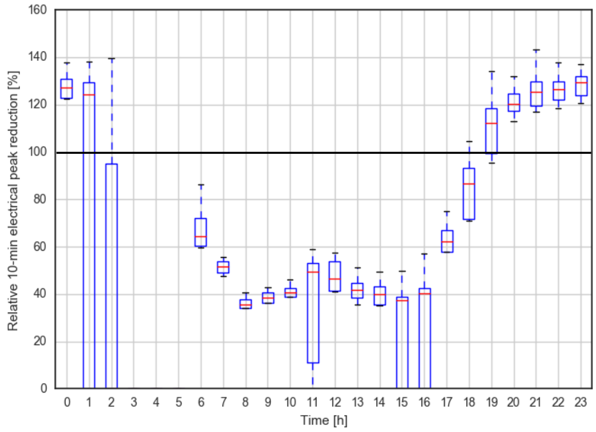


Figure 18: Self-consumption, self-production and electrical coverage for 2012 building case

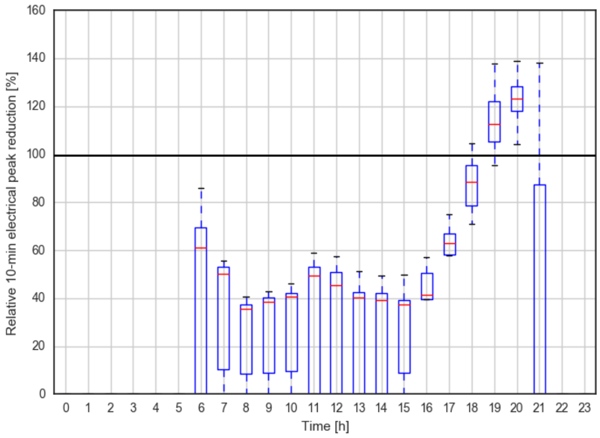
Figure 18 shows that self-consumption ratio of the "max tank use" control case is lower than all other cases. Actually, micro-CHP unit more often operates in the evening (outside of opening hours). Consequently, the electricity production can occur when electrical needs are low and a part of the electricity production is exported to the distribution grid.

<u>Electrical peak reduction</u>

The "max tank use" control strategy enables the building to be a net electricity exporter from 5 p.m to midnight during January (see Figure 19) as peak reduction values distribution is tight at these hours. This building could therefore participate in reducing electrical network peak load. In the "hybrid" control, almost no price event is triggered during January, thus the operation is more limited to the opening hours. Finally, distributions of peak reduction values are wide from 6 a.m to 3 p.m meaning that the micro-CHP is less used compared to the previous case.



a)



b)

Figure 19: Distribution of relative electrical peak reduction during January for "max tank use" (a) and "hybrid" (b) control

Conclusion

This paper intended to present results obtained from a dynamic simulation model of a micro-CHP plant coupled to an office building model with various thermal needs, systems (storage and emitters) and controls. As thermal and electrical loads of office buildings are different from residential buildings and not often considered in literature, this work could help enlarging the potential market of micro-CHP with new insights.

This paper showed that primary energy savings for an office building integrating a micro-CHP unit mostly depend on annual thermal need versus nominal power (sizing) and type of control, especially for low thermal needs. For the highest thermal demand building, the micro-CHP is running most of the time whatever the type of control is.

This study could be completed by an economic evaluation of micro-CHP installation according to thermal needs and control strategy. Especially, attention could be focused on potential cost savings due to dynamic electricity price control events. For instance, the micro-CHP would run when the price of electricity consumed by the building is high.

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