Task 3.3.2 – Investment opportunities for the residential consumer

Julien Garcia Arenas, Patrick Hendrick, ULB

1. Introduction

The objective of task 3.3.2 was to conduct a techno-economic analysis of investment opportunities for residential consumer, considering the recent evolution of the energy prices, the renewable technology costs, and the introduction of the injection tariff in Flanders. To this end, a software tool was developed to model and solve a consumer-centric optimization problem for a home multi-energy system (MES) to supply electricity and domestic heat demands. This tool is then applied to 2 typical case studies to perform a cost-benefit analysis considering investments in renewable technologies compared to keeping business-as-usual (BAU) with a classic home energy supply. For each case study, scenarios are optimized, and the solution of the mathematical program is compared to its reference BAU, by estimating economic performance indicators sur as NPV. In total, 100 individual input scenarios, generated using the improved building stock model of task 2.2.3 are considered per case study; with the objective to analyze the impact of slight variations in terms of building envelope performance and building use/occupancy on the investment opportunities for a same typical household in Flanders. The output results of these individual scenarios will also be compared against the results of only using a single average scenario. Finally, this single average scenario (the average of the 100 individual input scenarios), is used to conduct sensibility analyses over the electrification rate of the optimal solution, over the gas price, the injection tariff, and the discount rate of the project. These results will be analyzed and interpreted to understand what the optimal technology choices are for typical Flemish households, and to quantify the costs and benefits related to such investments.

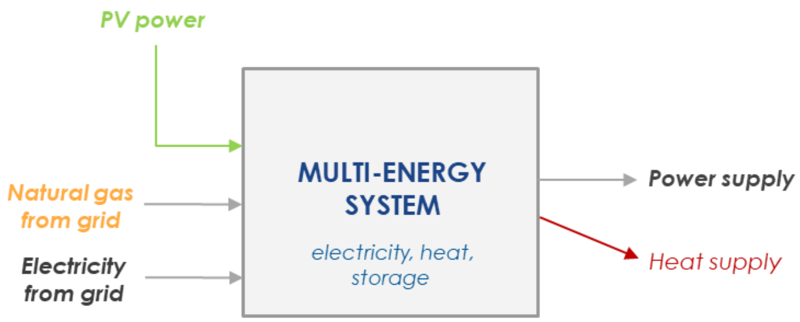

Figure 1 : schematics of the energy vectors of the MES

The rationale of this task is that, while it is increasingly acknowledged that consumers will play a central role in achieving European climate change objectives, it remains challenging to determine the most suitable investment options for self-energy generation with a favorable return on investment. This challenge has been further emphasized with the end of the renewable energy compensation system in Flanders, which has been replaced by the feed-in tariff. Initially, having an electricity meter allowed for easy sizing of a photovoltaic panel installation: the aim was to produce the same amount of kilowatt-hours as consumed annually, resulting in a zero-electricity bill. However, since 2023, the feed-in tariff has altered the value proposition of locally produced electricity compared to consumed electricity, thereby encouraging increased self-consumption, particularly with the use of battery storage. Additionally, determining the most suitable system for reducing emissions associated with heating and domestic hot water demand is also a challenge. While optimizing the energy performance of a residence is the first step, it appears that electrifying heat production is a promising solution. Certain emerging business models, such as heat pump boilers and heat buffer tanks, have also become particularly attractive since the recent energy crisis, marked by unpredictable increases in natural gas and electricity costs.

The innovative aspect of this work lies in jointly analyzing the investments required to supply the electricity and heat needs of a dwelling, where locally generated renewable electricity can be self-consumed, stored, and even converted into heat if deemed more advantageous by the optimization tool. It is also possible to store this heat for future heating requirements. Conducting a techno-economic analysis of such an energy system is quite complex and necessitates the development of a software optimization tool capable of modeling the multi-energy system and determining the optimal choice and sizing of renewable technologies to be installed to minimize the energy bill. This study is conducted within the current context of Flanders, specifically considering a typical single-family Flemish dwelling, with energy prices and billing based on the Flemish region grid tariff structure.

2. Description of the investment model

This investment model is a mathematical optimization program formulated as a linear program performing the economic dispatch of a home energy supply system. It involves input/output equations representing the energy supply system under consideration. The program optimizes energy flows over a year with a 15-minute time step based on constraints and a objective function to be minimized. This tool therefore performs the centralized planning and operation of the system under study to determine the optimal selection and size of the involved technologies such that the total costs are minimized. It assumes a perfect forecasting of the energy demands as well as the production profiles of the intermittent renewable technologies as well as a perfect availability of the units all year round.

The multi-energy system modeled in this study is presented in Figure 2. It involves three energy vectors (electricity, natural gas, heat) and three energy supply sources: electricity and natural gas from the grid, as well as electricity generated by the photovoltaic panels installed on the building's roof. Additionally, two converting technologies (air/water electric heat pump (EHP- and a residential gas boiler) and two storage technologies (Li-ion battery and heat buffer tank) are considered. The energy needs of the system are the electricity consumption, the space heating, and the domestic hot water demands.

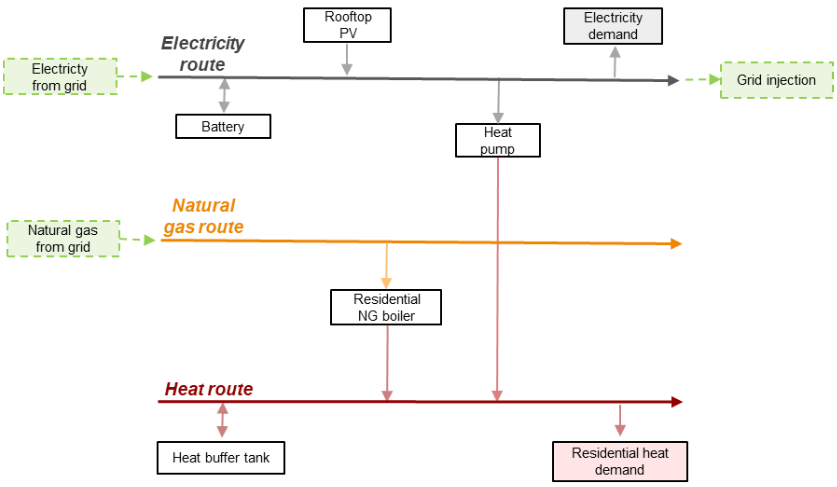

Figure 2 : schematic overview technologies and energy vectors (left) and features (right) of the model

The heat pump technology is an electric air/water heat pump radiator heating, equipped with an embedded domestic hot water (DHW) tank, therefore converting electricity into heat to provide both space heating et DHW demands. It is also assumed that the EHP is equipped with inverter technology to be able to modulate its output power.

The heat storage buffer tank can be installed in addition to the EHP. It is used to increase the volume of water in the heating system, and allows for the heat pump to produce and store heat for later use in the day, acting like a battery that shifts the load for heating system. The heat storage tank is equipped with spiral coil heat exchanger to enable storage for domestic hot water along with space heating.

For a considered timestep, PV production can be used to supply the electricity demand; any excess can be stored in the battery, injected back to the grid, or converted into heat via the heat pump; this generated heat can be used to supply the heat demand, or can be stored in the heat buffer tank. On the other hand, any residual electricity demand can be supplied by discharging the battery, or by importing electricity from the grid. The residual heat demand can be supplied by the heat pump converting electricity discharged from the battery, or imported from the grid, or by the existing residential gas boiler importing natural gas from the grid.

2.1 Model overview

A schematic overview of the customer-centered investment model structure is presented in Figure 2. It presents all the data used as input to the model, and the results obtained:

- The inputs include the description of energy vectors, the available production (renewable and conventional) and storage technologies and their associated technical and economic parameters, the system's economics, energy demands to be supplied, as well as the optimizer's objective function and model constraints.
- The outputs resulting from the optimization, such as the selection and optimal sizing of the considered technologies; the optimal operation of energy production and storage for each quarter-hour of the year, the contribution of each unit to energy supply; and the economic performance of the solution envisaged, such as investment and operating costs, and NPV at the end of the project.

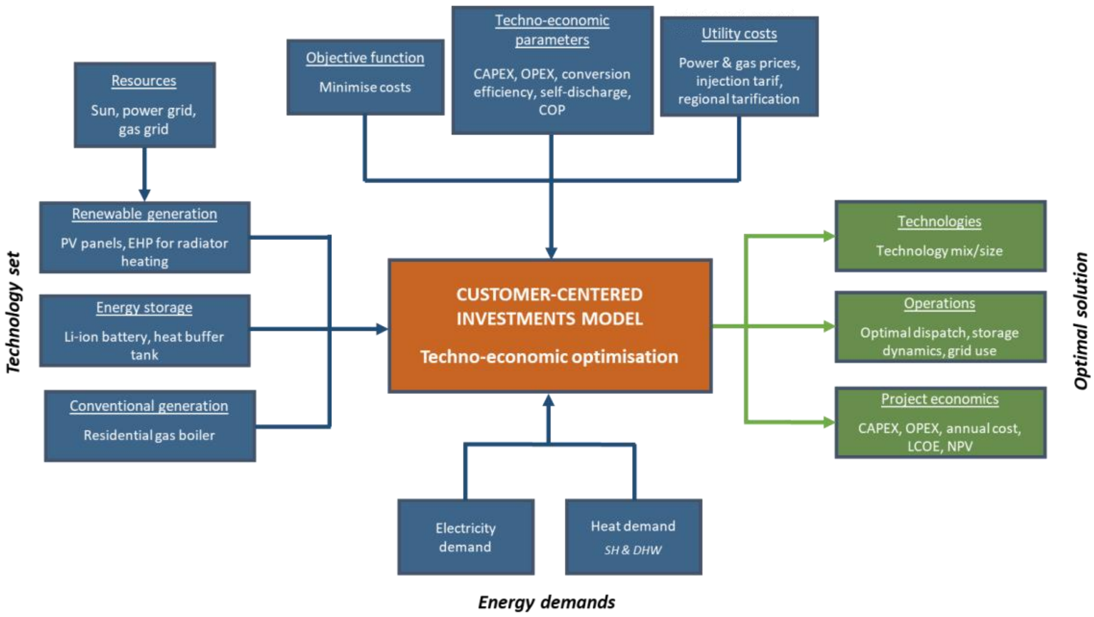

Figure 2 : schematics customer-centered investment model structure

2.2 Model equations

The model equations are adapted from a EPOC publication[1]

1) Sets

Four sets are introduced in the mathematical model: the simulation time interval I, containing the 35040 time-steps of 15 minutes; the set of energy carriers E= {elec, CH_4, heat}; the set of generating technologies G = {EHP, boiler}; and the set of storage technologies S = {Battery, buffer tank}.

2) Converting technologies

For each time step *i* in the simulation interval I, the operation and constraints of converting technologies *g* (i.e. the electric heat pump and the natural gas boiler) are described as follow:
$\forall\, i \in I$,

$$P(i)_g^{e\prime} = \eta_g^{e\prime} * P(i)_g^e \qquad (1)$$

$$P(i)_g^{e\prime} \leq K_g \qquad (2)$$

Where $P(i)_g^e$ and $P(i)_g^{e\prime}$ are respectively the consumption of the carrier *e* and the production of the carrier *e'*, both expressed in kW. Equation 1 states that such technologies allow to switch from an energy vector into another considering the efficiency $\eta_g^{e\prime}$ to convert *e* into *e'*. In equation (2), K_g is the installed capacity of the technology *g*, that sets an upper value on its output.

Regarding the EHP unit, $\eta_g^{e\prime}$ is replaced by *COP(i)*, the coefficient of performance (COP) of such systems, a variable parameter that depends on the temperature of the heat source $T^{source}(i)$ and sink $T^{sink}(i)$ through the year. The following formulation[2] is used compute $COP(i)$ of an air source EHP for radiator heating:

$$COP(i) = 6.08 - 0.09 * \Delta T + 0.0005 * \Delta T^2 \qquad (3)$$

$$\Delta T(i) = T^{source}(i) - T^{sink}(i) \qquad (4)$$

$$T^{source}(i) = 40°C - 1.0 * T^{amb}(i) \qquad (5)$$

Note that, for a air source EHP, $T^{source}(i) = T^{amb}(i)$, the ambient temperature at timestep *i*. This input ambient temperature profile is extracted from the time-series profiles dataset generated in Task 2.2.3.

3) Energy storage

For each energy carrier $c \in C$, the set containing the 4 energy carriers, it is common to model the dynamics of its associated storage unit by updating its state of charge (SOC) for each time step, by considering self-discharge of the battery along with the charging and discharging efficiencies (resp. η_c^e and η_d^e) as follow $\forall\, i \in I$, ∀ e ∈ E:

[1] Garcia Arenas, J.; Hendrick, P.; Henneaux, P. Optimisation of Integrated Systems: The Potential of Power and Residential Heat Sectors Coupling in Decarbonisation Strategies. *Energies* **2022**, *15*, 2638. https://doi.org/10.3390/en15072638
[2] Ruhnau, O., Hirth, L. & Praktiknjo, A. Time series of heat demand and heat pump efficiency for energy system modeling. *Sci Data* **6**, 189 (2019). https://doi.org/10.1038/s41597-019-0199-y

$$SOC(i)_s^e = (1-\delta_s^e) * SOC(i-1)_s^e + \eta_C^e * P(i)_c^e - \frac{P(i)_d^e}{\eta_d^e} \quad (6)$$

$$SOC(i)_s \ \leq \ \kappa_s^e \quad (7)$$

$$P(i)_{,c}^e \leq \ K_s^e \quad (8)$$

$$P(i)_{s,d}^e \leq \ K_s^e \quad (9)$$

$$\kappa_{battery}^{elec} = \Gamma_{battery}^{elec} \ * K_{battery}^{elec} \quad (10)$$

Equation (9) shows that, to compute the current SOC of the technology *s*, the previous SOC is multiplied by a self-discharge coefficient δ_s^e, then the charging and discharging powers $P(i)_c^e$ and $P(i)_d^e$ are respectively added and subtracted considering their associated efficiencies.

Moreover, the installed energy capacity κ_s^e in (10) is setting a maximum value on the SOC of the storage technology *s*. In equation (11) and equation (12), the installed power capacity of the storage technology *s,* K_s^e is used to constraint the power flowing in or out of the storage. Equation (13) is deals with the inter-dependencies of the energy and power components of a battery using the coefficient Γ_s^{elec}. This coefficient is assumed equal to 2 in this study.

4) Energy balance equations

The MES model comprises 3 energy balance equations (resp. for electricity, heat and CH_4) that must be respected for each time step, one equation for each energy carrier. The left-hand side of these equations corresponds to the production of energy carrier *e* while the right-hand side focuses on its consumption.

$\forall \ i \in I,$

$$P(i)_{pv}^{elec} + P(i)_{bat,d}^{elec} + P(i)_{grid}^{elec} \ = \ P(i)_{demand}^{elec} + \ P(i)_{EL}^{elec} + P(i)_{EHP}^{elec} + P(i)_{bat,c}^{elec} + P(i)_{injection}^{elec}$$
(11)

$$P(i)_{boiler}^{heat} + \ P(i)_{EHP}^{heat} + \ P(i)_{buffer,d}^{CH_4} = \ P(i)_{demand}^{heat} + \ P(i)_{buffer,c}^{heat}$$
(12)

$$P(i)_{grid}^{CH_4} = P(i)_{boiler}^{CH_4}$$
(13)

The PV electricity production at timestep *i,* $P(i)_{pv}^{elec}$*,* is determined by multiplying the installed capacity of the PV installation by a typical production profile for Belgium, normalized for 1kWc. This input profile, as well as the electricity and heat demand profiles, is extracted from the time-series profiles dataset generated in Task 2.2.3.

5) Economics and objective function

The total cost of the MES can be divided in two contributions, the total investment costs Ξ_{tot} and the total operating costs Θ_{tot} . Ξ_{tot} are determined by (17) considering the unit capex of the technology $t \in T$ and its installed capacity. As stated in (15), the contributions to Θ_{tot} over the time interval *I* are the total fixed and variable operating costs (resp. FOM and VOM) for all the technologies, and the annual energy bill $C_{energy\ bill}$. In order to only have annual costs in the objective function (14), Θ_{tot} is annualized following (16) as a function of the lifetime N and the discount rate D of the project. Finally, the net present value at the end of the project is computed by equation (18), considering the annual cash flows and the initial investment costs.

$$minimise(Obj = \Xi_{tot}^{annualised} + \Theta_{tot}) \tag{14}$$

$$\Theta_{tot} = \sum^{t \in T}(FOM_t * K_t + VOM_t * \sum^{i \in I} P(i)_t^e) + C_{energy\ bill} \tag{15}$$

$$\Xi_{tot}^{annualised} = \frac{D}{1-(1+D)^{-N}} * \Xi_{tot} \tag{16}$$

$$\Xi_{tot} = \sum^{t \in T}(capex_t * K_t) \tag{17}$$

$$NPV = -\Xi_{tot} + \sum^{n \in N} (\frac{cash\ flow_n}{(1+D)^n}) \tag{18}$$

3. Case studies

3.1. Description of the 2 case studies

Now that the mathematical model is described, it is necessary to obtain a reliable input dataset to represent a typical single-family building in Flanders. However, since every individual house and family is different, it is not straightforward to estimate the characteristics of a typical single-family dwelling in Flanders. It was deemed useful to consider at least two case studies when modeling a typical household:

- Firstly, a renovated four-façade, single-family house with a PEB rating of A to B,
- Secondly, the same building, but in need of renovation with a PEB rating ranging from C to D.

These case studies were selected to highlight the differences in investment opportunities between a renovated and a non-renovated building, in terms of initial costs and profitability. Indeed, due to the different building envelope performances, the energy demands will be significantly different from one case study to the other.

Moreover, within each case study, one can understand that typical energy demands are difficult to estimate (i.e. two typical renovated houses will differ slightly in terms of building envelope and building use/occupancy). Hence, a dataset of a 100 representative power and heat demand profiles is used per case study to be more representative of the considered building stock, each profile varying according to the following considerations:

1. **Case study 1: renovated buildings (fabric renovations and gas boiler upgrades)**:

This set of single-family dwellings are renovated with an average EPC label of A. Gas remains the main heating fuel although the dwellings have high efficiency boilers. Other simulation parameters remain the same as that for the non-renovated buildings.

- U-value Roof: [0.15 W/m^2K – 0.40 W/m^2K]
- U-value Window: [1.4 W/m^2K – 2.1 W/m^2K]
- U-value External Wall: [0.32 W/m^2K – 0.56 W/m^2K]
- Heater Burner Efficiency: [0.88 – 0.92]
- Heater Thermal Efficiency: [0.85 – 0.90]
- Number of People: [3 -5]
- Lighting efficiency: [1.27 W/m^2 – 2.11 W/m^2]
- Electric Equipment Use/Design: [70 W – 90 W]

2. **Case study 2: non-renovated buildings with no heat pumps and no rooftop PVs**:

   This set of single-family dwellings are non-renovated buildings with an average EPC label between C and D. Gas is the main fuel in such dwellings, providing space heating and domestic water demand. These dwellings contain standard electric equipment including interior lights, dishwasher, television, washing machine and interior equipment such as laptops. The average number of occupants in such dwellings is taken as 3. Different electricity and gas consumption profiles are generated by varying the following parameters.

   - U-value Roof: [2.5 W/m^2K – 4 W/m^2K]
   - U-value Window: [3.7 W/m^2K – 4.8 W/m^2K]
   - U-value External Wall: [3 W/m^2K – 4.5 W/m^2K]
   - Heater Burner Efficiency: [0.55 – 0.7]
   - Heater Thermal Efficiency: [0.6 – 0.7]
   - Number of People: [3 -5]
   - Lighting efficiency: [4 W/m^2 – 5 W/m^2]
   - Electric Equipment Use/Design: [102 W – 150 W]

On the other hand, the climatic conditions such as the ambient temperature and global irradiation profiles are kept constant, meaning that in every scenario, the building is exposed to the same external temperature profile while heating, and every PV installation has the same production profile.
Therefore, each of the 100 scenarios per case study will consist of a subset of the 5 following yearly time-series with a 15-minute resolution:

a. Electricity consumption profile
b. Space heating consumption profile
c. Domestic hot water consumption profile
d. PV on-site generation profile
e. Dry-bulb temperature profile

Those profiles are used as input of the optimization model. Along with techno-economic parameters presented in the next section, those profiles are crucial to represent with accuracy the context of the study, consequently increasing the reliability of the output results.

4. Techno-economic parameters

In this section, the value of each techno-economic parameter used in the optimization model is described. Table 1 summaries the parameters of the considered technologies, while Table 2 summaries the values of the components of the tariff structure used to compute an energy bill in Flanders.

For a PV installation alone, the capex is between 1600 – 2000 €/kWc (set to 1600 to account for the 700€ bonus per installation in 2023 in Flanders). If a battery is installed, the additional costs are 600€ per kWh. Note that these costs are estimated for a single-phase electric system; if a three-phase system is considered, the costs are increased to 1800 – 2200 €/kWc, and to 800 €/kWh for the battery.

The modelled HP parameters are for an existing single-family house with radiator heating, comes with a DHW tank as well as a direct electrical immersion heater to complement the heat production during cold temperatures (low COP values). The investment costs of the EHP are considering a 400€ bonus per installed kW in 2023 in Flanders.

MAIN TECHNO-ECONOMIC PARAMETERS

Technology *unit*	Efficiency 1	Capex $\frac{€}{kW(h)}$	FOM $\frac{€}{kW}$	VOM $\frac{€}{kWh}$	Ref.
PV (residential)	-	1600	12,8	0	A,B
Air/water HP	COP(i)	1043*	32,5	0	A,B
Battery (indiv.)	0.98 (c) 0.97 (d)	600	5,4	2	A,B
Heat buffer tank	1	410	50/unit	0,006	A,B

*the cost includes a 400eur/kW installation bonus from Flanders administration in 2023
A : Danish Energy Agency technology catalogs ; B : consultation of the Belgian market in 2023

Table 1: Summary of the main techno-economic parameters of technologies

Note that the capex costs include the installation costs. The discount rate of the project is set to 4%, and the economic lifetime to 25 years with no residual value.

Moreover, a maximum capacity constraint of PV capacity is set to 10kW, corresponding to a 17m^2 roof area. Similarly, due to footprint limitations for the heat storage buffer tank, a maximum capacity constraint of 35kWh is applied, corresponding to a 1000l tank capacity with a temperature elevation of 30°C. A typical size for the buffer tank is around 60-160l, corresponding to 2.1-5.6 kWh storage.

Additionally, the productivity of a typical Belgian PV installation is set to 1056 kWh per kWc installed; the COP of the air/water heat pump for radiator heating in determined every time step by equations (3), (4) and (5), as a function of the ambient temperature input profile; The self-discharge coefficient of the battery is set to 0.1%/day, and the energy losses by heat dissipation in the heat buffer tank to

2.1%/hour. Finally, the interdependency ratio between energy and power ratings of the battery is set to 2, meaning that a 10kWh battery has a charge/discharge power of 5kW.

The annual electricity bill is estimated based on the use of a bi-directional digital meter. Hence, for each timestep, the electricity flowing in and out of the building is measured and billed with its *time-of-use* tariffication (here, day/night tariffication is considered). The average monthly peak is also estimated to determine the capacity tariff, consisting in the average of the 12 monthly peaks measured by the smart meter.

ENERGY BILL COMPONENTS (Flanders)	UNIT	VALUE	COMMENT	SOURCE
Average electricity grid tariff			**transport & distribution costs incl. 6% VAT, incl. regional contributions**	
capacity tariff	EUR/kW/y	43.2967	*Based on the average of the 12 recorded monthly peaks. Averaged value of flemish DSOs' tariffs.*	VREG
total proportional term (day)	EUR/MWh(day)	40.4734	*Average value of flemish DSOs' tariffs*	VREG
total proportional term (night)	EUR/MWh(night)	28.7255	*Average value of flemish DSOs' tariffs*	VREG
digital meter data collection	EUR/year	14.53	*Average value of flemish DSOs' tariffs*	VREG
injection tariff	EUR/MWh	0	*For grid users with decentralised production <= 10kVa*	VREG
maximum annual grid tariff	Eur/MWh	203.548		VREG
Average electricity commodity tariff			**Incl. 6% VAT**	
annual abonnement fee	EUR/year	63.36	*Average value of fixed price energy contract offers for Flanders during spring 2023*	
consumption (day)	EUR/MWh(day)	238.5	*Average value of fixed price energy contract offers for Flanders during spring 2023*	
consumption (night)	EUR/MWh(night)	189.7	*Average value of fixed price energy contract offers for Flanders during spring 2023*	
injection (day)	EUR/MWh(day)	-70.7	*Average value of fixed price energy contract offers for Flanders during spring 2023*	
injection (night)	EUR/MWh(night)	-36.9	*Average value of fixed price energy contract offers for Flanders during spring 2023*	
flemish renewable energy contribution	EUR/MWh	22.5		VREG
Average natural gas grid tariff			**transport & distribution costs incl. 6% VAT, incl. regional contributions**	
fixed term	EUR/year	71.41	*Average value of flemish DSOs' tariffs*	VREG
total proportional term	EUR/MWh	8.45	*Average value of flemish DSOs' tariffs*	VREG
meter data collection	EUR/year	12.63	*Average value of flemish DSOs' tariffs*	VREG
Average natural commodity tariff			**Incl. VAT**	
annual abonnement fee	EUR/year	49.4	*Average value of fixed price energy contract offers for Flanders during spring 2023*	
consumption	EUR/MWh	77.6	*Average value of fixed price energy contract offers for Flanders during spring 2023*	
Federal taxes			**Incl. 6% VAT**	
energy contribution tax for electricity	EUR/MWh	2.04167		CREG
energy contribution tax for natural gas	EUR/MWh	1.05767		CREG
special excise tax on electricity	EUR/MWh	50.3288	*Term replacing the federal contribution tax since January 2022*	CREG
special excise tax on natural gas	EUR/MWh	8.72	*Term replacing the federal contribution tax since January 2022*	CREG

Table 2 : Summary of the values of the components of the tariff structure used to compute an energy bill in Flanders.

Since many DSO are operating in Flanders, an average tariff was computed to compute the grid tariffs components of the energy bill. Similarly, the commodity costs are average values for a fixed price energy contract in Flanders, based on a market analysis in spring 2023.

Note that, since March 2023, the decision to keep a 6% VAT rate instead of 21% was made by the Belgian government for an indeterminate period.

5. Methodology

As explained earlier, two case studies are studied, each case study involving a dataset of 100 individual scenarios, representing the same building with slight variations in energy performance and building use/occupation. Each scenario consists of 5 time-series profiles, used as input context for the optimization tool.

For each scenario, the profitability of the investment opportunity will be determined and compared against its reference. The reference of the individual scenario consists of applying the same inputs, but the optimization model is simplified such as it represents the BAU situation: using electricity and natural gas from the grid to supply the energy needs. Consequently, the annual cash flows resulting from the cost differences between the individual scenario and its reference are used to compute the NPV of the project, following equation (18).

Additionally, for each case study, an average scenario is created, corresponding to a subset of the "averaged" energy demand profiles, each profile resulting from the average of the 100 individual profiles. This average scenario is also used as input of the tool, and the associated results are compared against the results of the 100 individual scenarios. Once the deviation of the results of this scenario compared to the others individual ones, it is also used to perform the sensibility analyses.

Hence, several results are presented in section 6 for each case study:

- The plot of the costs of each individual scenario for the case study, along with the size of each technology of the resulting energy supply system. These results are presented in the format of error bars representing the average and standard deviation of the 100 individual solutions. The output result of the average scenario is also plotted to highlight its deviation from the average of the 100 individual solutions.
- A more detailed plot of the CAPEX and the OPEX (and their components) of the optimal investment opportunity while considering the average scenario, and the comparison with its average reference scenario counterpart to determine the NPV.
- Still considering the average scenario, sensibility analyses are conducted to evaluate the impact of 4 techno-economic parameters:
    1. the natural gas price, varying from 30€/kW to 150 €/kW
    2. the electrification rate of heating, with a natural gas use decreasing from -0% to -100%
    3. the discount rate, varying from 3% to 8%
    4. the injection tariff, varying from a factor 0.5 to 2.5.

  For each sensibility analysis, the evolution of the resulting technology mix of the solution is also presented as a function of the varying parameter.

6. Results

6.1 Results of case study 1 – PEB A

The 4 upper-left error bars of Figure 3 hereafter represent the average and deviation of the optimal capacity of the renewable technologies resulting from the optimization of the 100 individual scenarios of the renovated single-family dwelling case study. The optimal sizing resulting for the optimization of the average scenario is presented with a red cross. The 4 bottom-left graphs represent the average and deviation of the initial CAPEX, the energy bills, and the NPV of the project after 25 years. The 2 graphs on the right represent the annual costs of the BAU references scenarios, only consisting of energy bills since no initial investment is required.

First, it is observed that, while there is a need to provide consequent initial investment, investing in a PV-battery-heat pump-buffer tank system is profitable today, with an a NPV around 12000€ after 25 years. It is also observed that the output results when considering the optimization over the average scenario are quite accurate compared to the average of the 100 individual outputs, although a consequent 7.2% error is observed when determining the NPV with the average scenario.

Considering a total simulation time divided by 100, using the average scenario comes with a good trade-off between accuracy and computational burden.

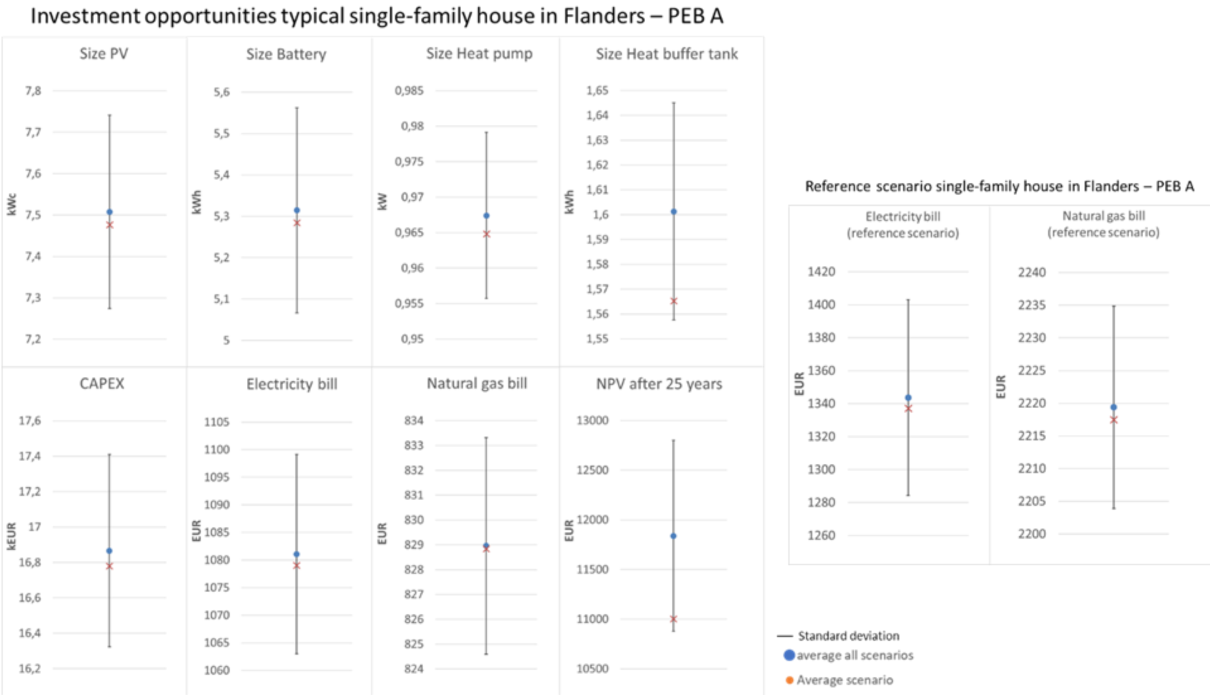

Figure 3 : Output results of all scenarios from case study 1 : technology set sizing, CAPEX, energy bills, and NPV

Moreover, compared to the BAU reference scenario, investing in 7-8kWc PV, 5-6kWh battery, 1kW heat pump and 1.5-2kWh heat buffer (corresponding to a 46l capacity) is decreasing the annual electricity bill of around 20%, and the annual gas bill of more than 62%. However, the size of the heat pump seems a bit too low at first, but when it is understood that the heat pump works in combination with the existing natural gas boiler, similarly to a hybrid heat pump/gas boiler system this size range is acceptable. In such hybrid combination, the heat pump is expected to provide heat most of the time, and the gas boiler acts as a back-up during high demand, cold ambient temperatures periods.

To conclude, investing in a PV-battery-heat pump-buffer tank system is profitable, but an accurate and optimal sizing is required to avoid underestimate the installed capacities (and related additional costs) of each technology. For example, it is not necessary to maximize the PV capacity of the roof, it is neither optimal to choose the bigger size capacity for the battery. Considering the alternative heating system, after working on the renovation of the building envelope, replacing the gas boiler with a consequent heat pump with heat buffer storage installation doesn’t guarantee the highest return on investment nowadays, even considering the high energy prices. The results of this study suggest investing in a hybrid heat pump/gas boiler system with buffer tank instead.

Analyzing Figure 4 one can observe that the largest component of the CAPEX of the investment opportunity remains the PV - battery installation. Despite the Flemish bonus when installing a heat pump system in 2023, the heat pump system costs might be underestimated due to simplifications in the optimization model : indeed, the typical size of the heat pump system related to the techno-economic parameters being 5kW, downsizing the system capacity leads to unrealistically low investment costs (that decreases linearly with the capacity decrease).

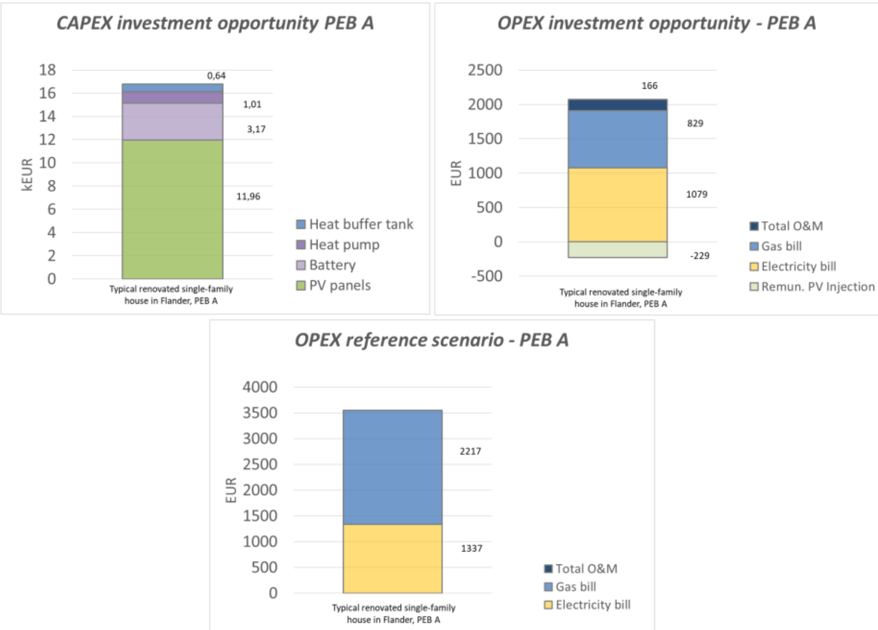

Figure 4 : Detailed output results of the average scenario of case study 1, compared to its reference scenario

Additionally, the 229€ remuneration due to PV injection to the grid suggests that, among the 7.9MWh PV production, more than 60% is consumed locally. When comparing the energy bill against the reference scenario, we understand again that, even with the consequent electrification of the heat supply enabling a substantial gas bill reduction, the resulting electricity is still lower than keeping BAU.

Now focusing on the sensibility analysis over the natural gas use in the optimal system configuration (Figure 5), one understands that electrifying the home energy supply up to 66% can be done without any significant change in terms of NPV (at least with the 2023 heat pump installation bonus), and a complete electrification leads to a NP reduction of less than 15% after 25 years. Electrifying heat supply also means that one must increase the PV capacity from 7.5 to 8.5kWc, and the slight decrease in the size of the battery, along with the increase in heat pump and buffer tank capacities, suggest that the PV energy is more likely to be directly converted into heat and stored for later use instead of being electrochemically stored.

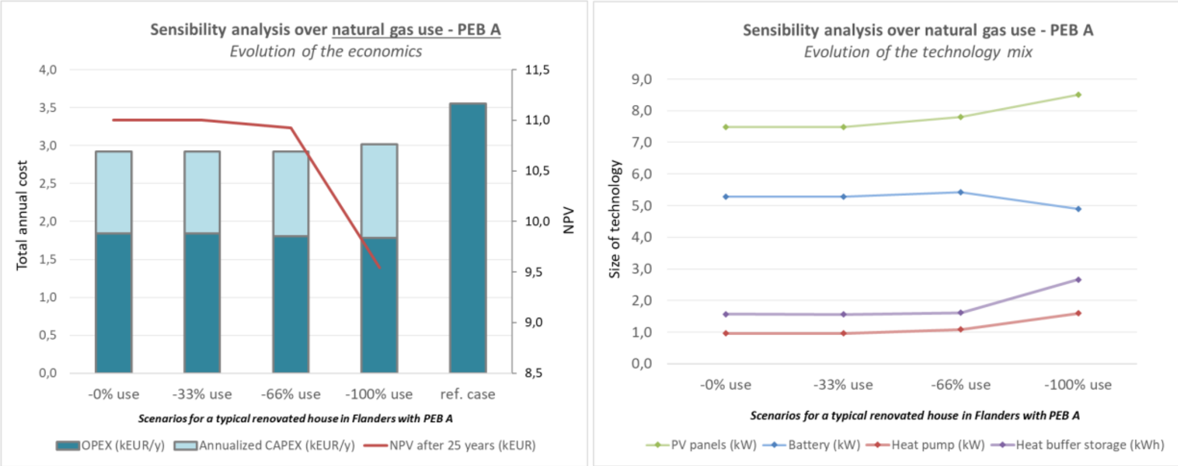

Figure 5 : Sensibility over the natural gas use for the average scenario for case study 1

The results of the sensibility analysis of the natural gas price (Figure 6) highlight that if the natural gas price decreases to its pre-energy crisis value, it represents a threat to the electrification of home heat supply. It is indeed observed the installed capacity of the heat pump and the buffer tank is marginal for natural gas price lower than 60€/MWh. However, those technologies rapidly increase in capacity along with the PV capacity once the natural gas price is incrementally increasing above 60€-70/MWh. This suggests again that electrification becomes sufficiently competitive against conventional generation technologies, especially in the actual energy context.

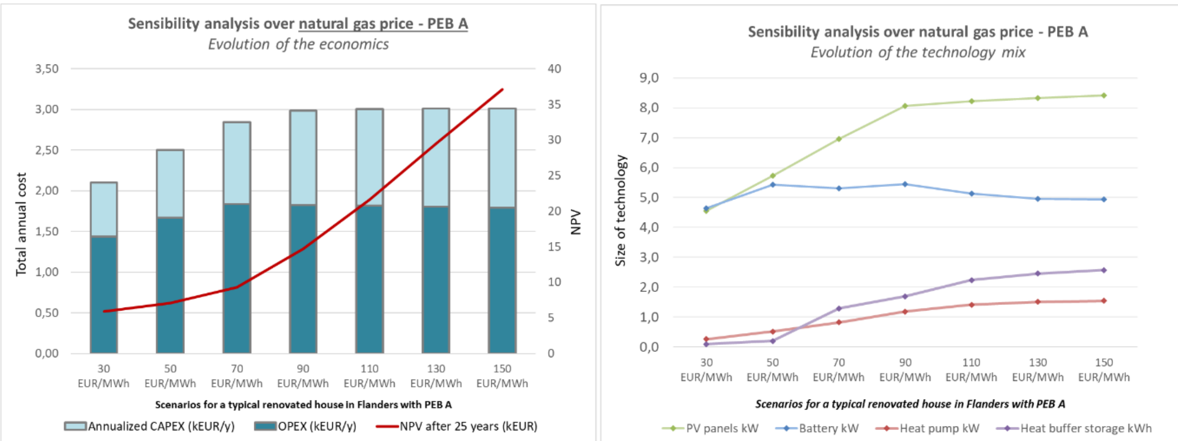

Figure 6 : Sensibility over the natural gas price for the average scenario for case study 1

Figure 7 clearly highlights that the discount rate is an important parameter to control while considering investments in renewable energy systems: the dramatic decrease in PV and battery capacities (i.e. the largest components of the initial investment costs) represent a loss of interest in producing and consuming its own energy when short-term loans rates are not interesting. Another conclusion is that, even if the NPV after 25 years is attractive, it is crucial to enable consumers to afford the project’s substantial initial investment.

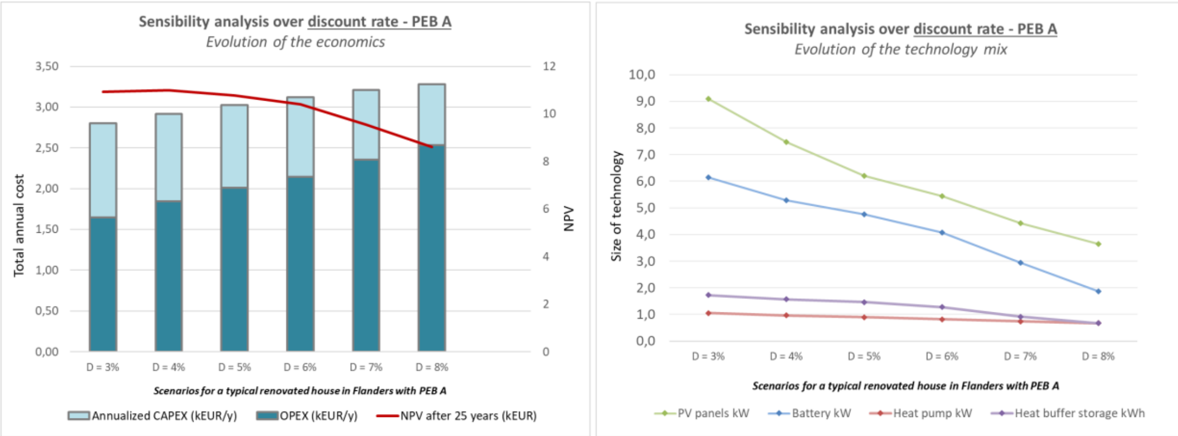

Figure 7 : Sensibility over the project discount rate for the average scenario for case study 1

Finally, Figure 8 clearly shows that increasing the injection tariff increases substantially the profitability of the project, but there is a adverse counterpart regarding the local use of energy: the PV production keeps increasing until the 10kW maximum capacity is reached, then the installed capacity of the other technologies decreases to make room for grid injection. Consequently, while the injection tariff is a good incentive to increase profitability of PV systems, it has the counterpart to not induce a rational consumer behavior, and generates a non-rational use of energy because the investor produces large amounts of renewable energy but still consumes natural gas.

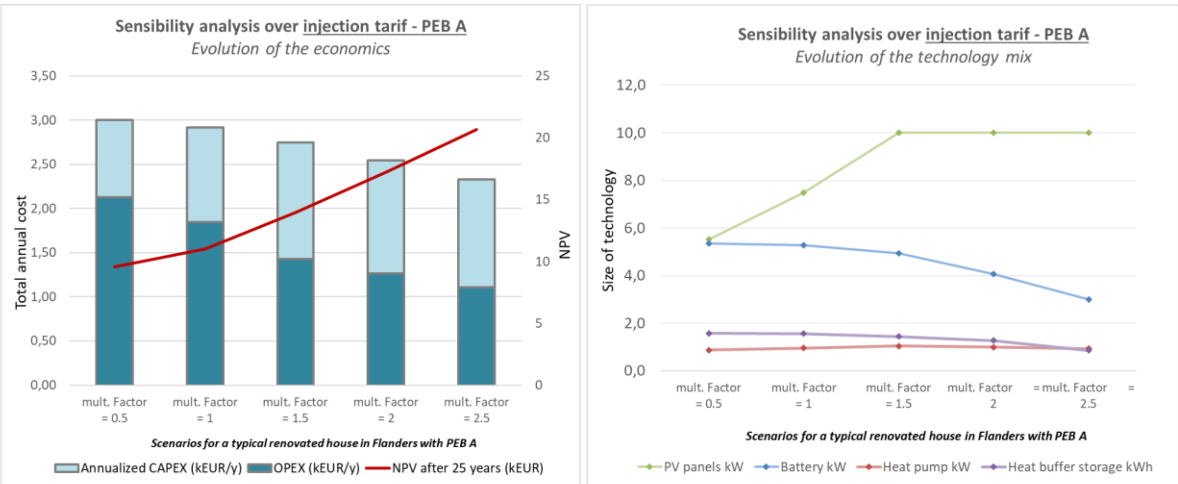

Figure 8 : Sensibility over the injection tariff for the average scenario for case study 1

6.1 Results of case study 1 – PEB C-D

Now considering the typical non-renovated building, the same observations as for the previous case study apply. A larger energy system is however required, inducing a larger initial investment to handle as well as a larger footprint required, both can become non-negligible challenges for the consumer. The sensibility analyses over the injection tariff and the natural gas price highlight limitations on the increase of profitability as the maximum PV capacity is quickly reached, which is logical since larger energy consumption induce larger amount of renewable energy to be produced. Lower returns on investment are also observed at the end of the economic lifetime of the project, meaning that investments in alternative energy supply systems for buildings to be renovated are less attractive, especially regarding the high initial CAPEX.

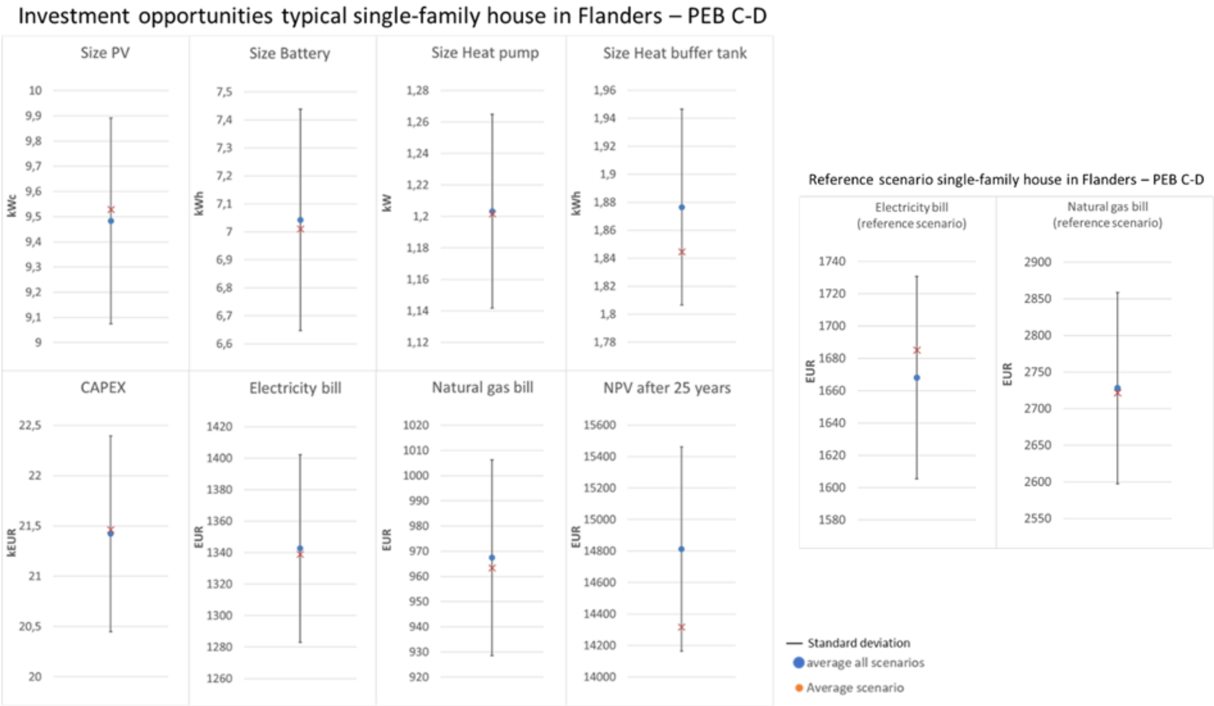

Figure 9 : Output results of all scenarios from case study 2 : technology set sizing, CAPEX, energy bills, and NPV

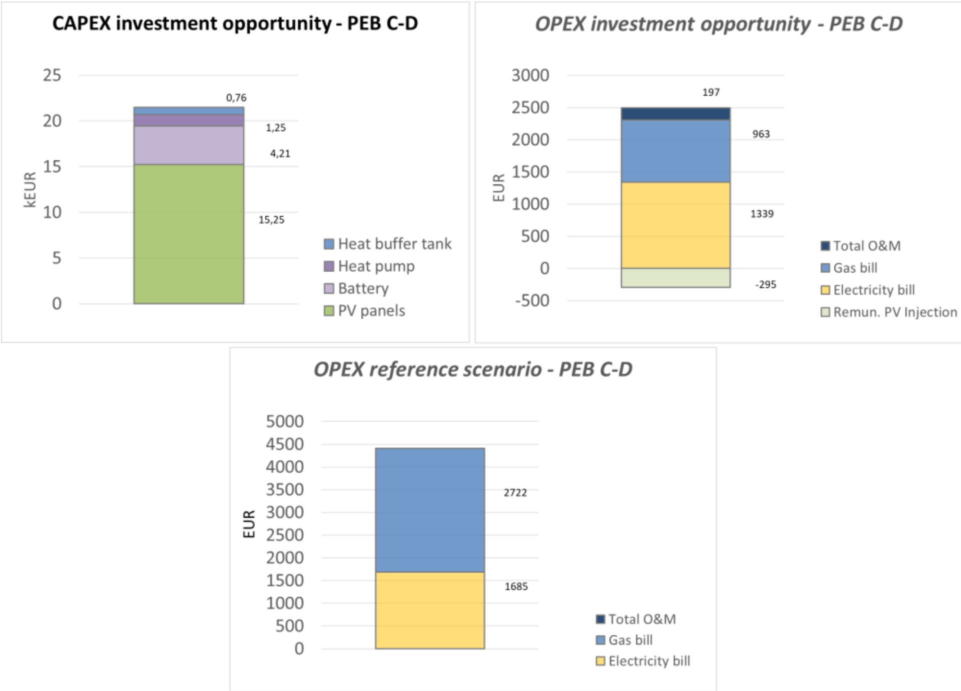

Figure 10 : Detailed output results of the average scenario of case study 1, compared to its reference scenario

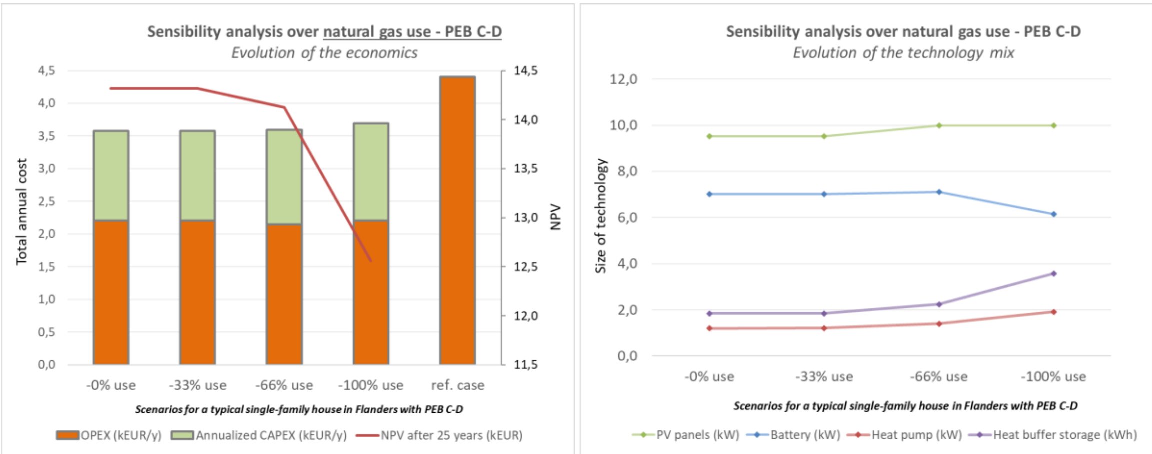

Figure 11 : Sensibility over natural gas use for the average scenario for case study 2

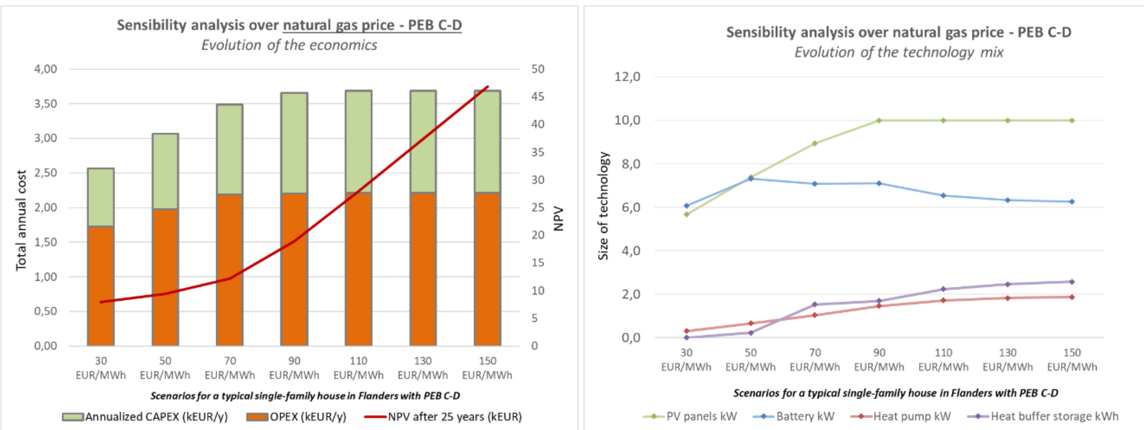

Figure 12 : Sensibility over the natural gas price for the average scenario for case study 2

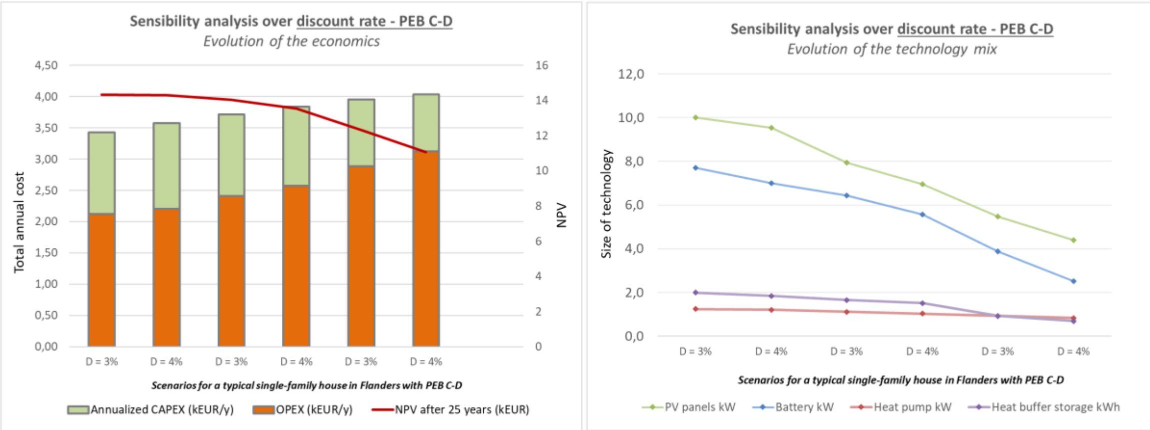

Figure 13 : Sensibility over the project discount rate for the average scenario for case study 2

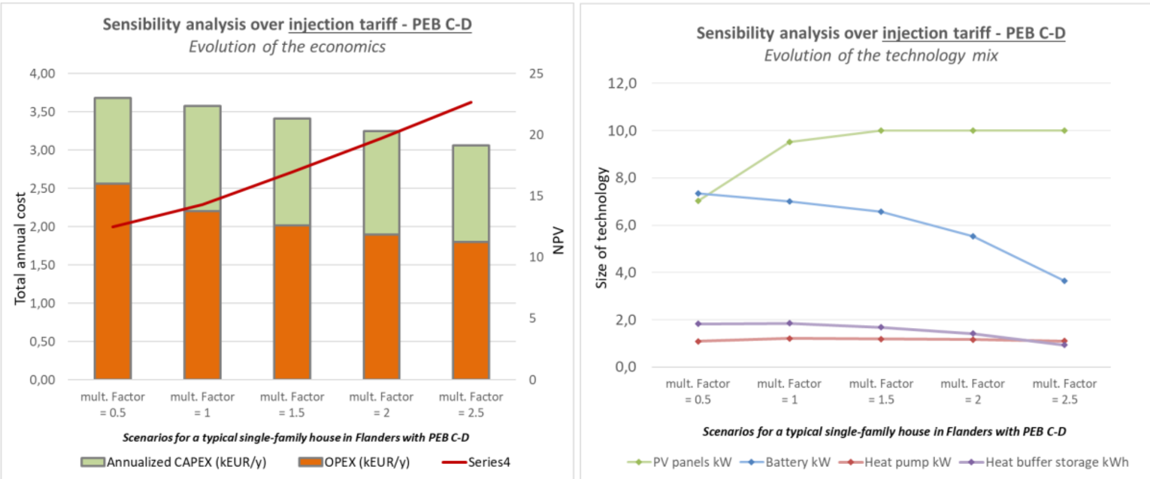

Figure 14 : Sensibility over the injection tariff for the average scenario for case study 2

7. Conclusion and further improvements

To conclude on this techno-economic analysis of consumer's investment opportunities in renewable energy supply systems, several observations are worth mentioning:

- The first step is to renovation before investing in a renewable energy supply system.
- With the introduction of the injection tariff, the optimal sizing does not consist in maximizing its PV production anymore. Investing in a hybrid heat pump/natural gas boiler represents a good investment opportunity compared to replacing the existing gas boiler. Investing in a larger storage system can potentially inefficiently increase the costs of the project.
- The current energy context is enabling the profitability of PV-battery-heat pump-heat buff tank systems, but a further decrease in the natural gas price represents a threat.
- Electrifying 2/3 of the heat energy supply is feasible without significantly compromising the profitability of the project, however, further increasing this electrification rate is not an optimal solution.

- While such energy systems are profitable in the long term, it is important to enable consumers to afford the initial investment cost, for example by accessing low-rate short term loans.
- While incentives on the injection tariff increase significantly increase the profitability of such projects, it is not an efficient signal to induce a rational use of energy.

Regarding further improvements, while the use of an average scenario generated robust output results compared to individual scenarios, it could be interesting to further analyze robustness when varying the climatic conditions: the question of whether renewable energy system sized based on an average climatic scenario is still optimal and robust while operated on varying individual climatic scenarios remain unanswered at the end of this study. Moreover, improvements regarding the cost evaluation of undersized systems for technologies such as heat pumps could help generate more accurate and optimal output results, for example by replacing the constant unit capex per kW by a linear evolution of the unit capex as a function of the installed capacity.