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# Assessment and optimisation of energy consumption in building communities using an innovative co-simulation tool

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## ABSTRACT

Energy efficiency in building sector is attracting an increasing interest in the scientific community, due to its strong impact in terms of greenhouse gas emissions. In this context, the REMOURBAN H2020 project has carried out a pilot deep refurbishing work on a small cluster of 10 homes, implementing energy saving measures and a hybrid energy-supply system to satisfy the heating and domestic hot water demand. The system aims to achieve near-zero-energy homes level of performance at reasonable cost by offsetting the energy consumption with local energy microgeneration. It is designed as a local low temperature district heating system and includes ground source heat pumps, photovoltaic panels, electric and thermal energy storage devices. The management of the complex hybrid system requires a suitable control strategy to optimise the energy consumption and consequently running cost. With this purpose a co-simulation tool has been developed, coupling a model of the energy system built using Dymola-Modelica and the EnergyPlus model of the buildings. This allows to develop different control strategies aiming to reduce the energy consumption from the grid, maximize the self-consumption of photovoltaic energy and ultimately move away from fossil fuel to sustainable energy resources.

## KEYWORDS

Co-simulation tools; Hybrid Heating Systems; LTDH; REMOURBAN; Retrofitting.

## 1 INTRODUCTION

Both the European Union and the United Kingdom are on the frontline addressing the root causes of the climate change. On November 28th, 2018 the European Commission presented a long-term strategic vision for a competitive carbon neutral economy by 2050 [1] .The United Kingdom, on the other hand, is tackling and responding to climate change through “The Climate Change Act 2008 (2050 Target Amendment) Order 2019”, which states that “It is the duty of the Secretary of State to ensure that the net UK carbon account for the year 2050 is at least 100% lower than the 1990 baseline” [2].

In this scenario the research community is showing an increasing interest in buildings energy performance. This is due to the great impact that the building sector has on the energy demand, it accounts for roughly 40% of the energy demand in the European Union (EU) [3] and 36% in the world with a forecasted growth of 28% by 2040 compared to the 2015 [4]. The growing population and the rising energy demand in developing countries could lead to a 50% increase in the energy demand from buildings by 2060. A fast growing economy like China had a 5.76%

yearly increase in the carbon emissions from buildings in the last decade, with a total of 1.28 billion tons of $CO_2$ emitted in 2017 [5].

In the EU dwellings alone are responsible for 60% of building energy demand and 40-60% of this energy is used for heating [6]. In the specific case of the UK, the domestic sector accounts for around 40 $MtCO_2e$[1] on a total of 151.3 $MtCO_2e$ that represent the final consumption energy in the UK [7], the building sector is responsible for around 26% of all carbon emissions considering the direct and indirect ones[2] [8].

Research has shown that the replacement rate of existing buildings with new buildings is quite low, about 1-3% per annum [9] and therefore the 80% of the actual building stock is expected to be still occupied in 2050 [10]. At European level about two thirds of the buildings were built when energy efficiency requirements were very poor or not present at all, almost 50% of the boilers for instance were installed before 1992 and they run with an efficiency equal to 0.6 or less [11]. In this scenario, refurbishing existing buildings is a necessary path for the reduction of GHG (Greenhouse Gases) [12], the European Commission itself states that given the replacement rate an higher renovation rate is needed [13].

The Committee on Climate Change (CCC) underlines how having low-carbon heating systems is a necessary path to reach the target of zero carbon emission by 2050 [14], in the so called “Further Ambition” they highlight options for emission reduction that are likely to be needed to meet the net-zero target. In terms of refurbishment the main interventions indicated by the CCC are:

- Efficiency improvement (in terms of reduced energy demand).
- Low-carbon heating systems (i.e. heat pumps, biomethane and networked low-carbon heat).

One of the ways to achieve the total abatement needed in terms of GHG (estimated in 82 $MtCO_2e$[3]) is the full is the full electrification of the heating compartment, whereas a better fabric energy efficiency capable of deliver a 25% emission reduction [8].

The proposed research will investigate an opportunity to move away from fossil fuel sources by utilising a full electric decentralised heating system for a block of 10 homes, i.e. working not at the single building level, but at community level. This scheme aims to achieve near zero energy homes level of performance at reasonable cost by offsetting the energy consumption with local energy microgeneration.

As a platform for this research, the pilot 2050 homes deep retrofitting intervention, part of the EU Horizon 2020 REMOURBAN [15] project carried out in 10 residential homes, will be used. The new system will present a decentralized, scalable energy system, where the heating is supplied by the micro energy grid operating at low temperature, combined with the

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[1] $MtCO_2e$ are Mega Tons of equivalent $CO_2$, see 4.4 for equivalent $CO_2$ definition.

[2] Direct emissions are from sources that are owned or controlled by the reporting entity. Indirect emissions are a consequence of the activities of the reporting entity but occur at sources owned or controlled by another. Indirect emissions are currently most commonly associated with electricity use.

refurbishment of the building envelope will provide a sustainable community model for a development with minimum $CO_2$ impact.

To assess the effectiveness of the retrofitting intervention a new, innovative, co-simulation tool has been developed, the latter will not only allow to study the energy performances but also, to define better control strategies for the new energy system.

# 2 METHODOLOGY

In order to analyse the effectiveness of the refurbishment and the performances of the new full electric heating system a digital twin was developed.

Nowadays very powerful Building Performance Simulation (BPS) tools are available. Software like EnergyPlus [16], IDA ICE [17] or TRNSYS [18] perform very well in terms of annual energy analysis [19], allowing a detailed analysis of the building behaviour and related complex phenomena like the thermal zones coupling and the solar radiation effects [20].

These software on the other hand fall short when it comes to have a proper representation of the energy systems and the associated control scheme [19]. Software like Modelica-Dymola [21] (used in this research) is capable to better simulate the work of the energy systems and also to address the control needs. Dymola is an integrated environment for developing dynamic physical system models in the Modelica language and a simulation environment for performing experiments. The software uses hierarchical acausal object-oriented modelling to describe, in increasing detail, the systems, subsystems and components of a model. Physical couplings are modelled by defining physical acausal connectors and graphically connecting sub-models[22]. The Modelica language allows the systems to be described in terms of relationships rather than specific calculation orders thus removing the tedious manual task of model equation rearrangement to suit the problem being solved.

By coupling two software platforms (EnergyPlus and Dymola) it is possible to take advantage of the vast libraries implemented in EnergyPlus software (their user-friendly interface with capability to import complex geometries generated from CAD files) while using an advanced modelling tool like Dymola for an extensive and exhaustive simulation of the energy system and its controls. The latter is the real strong point of the co-simulating work, which allows us to overcome the limits of the BPS tools and stepped into the simulation and optimised control of the energy system. In this work Design Builder [23] has been selected as interface for the utilization of EnergyPlus, due to its user-friendly interface [24].

## 2.1 Co-Simulation

Co-simulation represent a technique that allows individual component models described by algebraic or discrete equations to be simulated by different simulation tools running simultaneously and exchanging data during runtime.

Co-simulation is relatively new modelling approach. In [25] the authors use EnergyPlus and Dymola for a co-simulation tool intended for the optimization of comfort levels in a demand controlled ventilation scheme. In [26] Borkowski et al. carried an optimisation study about advanced control strategies for adaptive building skins working with EnergyPlus and Dymola, the object of the investigation was a single room at an office development. Favoino et al. in [27] develop a simulation framework to evaluate the control and performance of photovoltachromic switchable glazing using in this case EnergyPlus and MATLAB platforms. A more articulated work was carried out by Yang et al. in [28], EnergyPlus and Dymola were used as part of an integrated tool chain to study a new hotel building HAVC system, with lake-source HPs. Other works use different software like NANDRAD [29] in combination with Dymola or a Building Control Virtual Test Bed (BCVTB) as a link between Dymola and EnergyPlus (or other similar software) to analyse HVAC systems, especially in terms of effective control [19]. To the best of the authors' knowledge, however, in literature co-simulation models of hybrid energy systems, operating at small district level like the one developed in this research, are not present. By using the software EnergyPlusToFMU developed by Lawrence Berkeley National Laboratory [30] a Functional Mock-up Unit (FMU) was created to couple the two software platforms, EnergyPlus and Dymola. This link package is written in Python and allows users to export EnergyPlus as an FMU for co-simulation using the Functional Mock-up Interface. The FMU imported in a software like Dymola will work as a slave to the master software (Modelica/Dymola in this case) and can utilise the interface in a standardised way exchanging data as input and output signals.

Figure 1 shows an example where the heat flow defined in the master software is used in the FMU (i.e. in EnergyPlus) to calculate the temperature in a room.

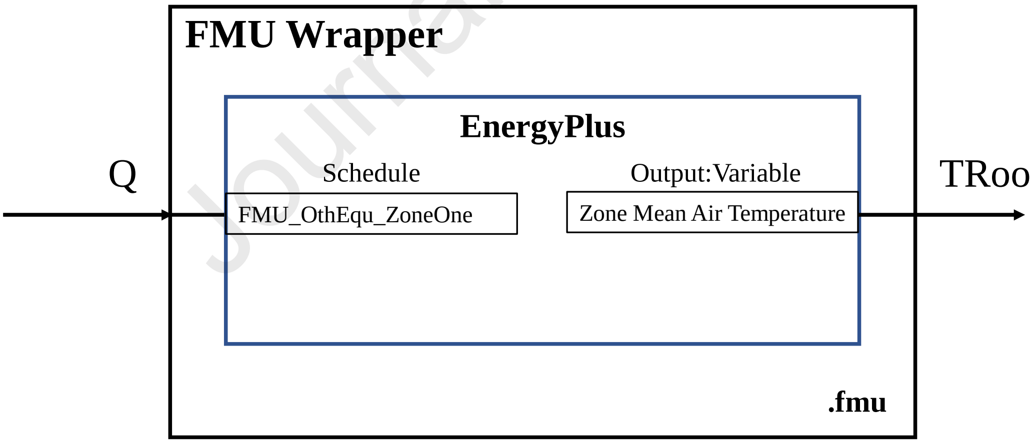


**Figure 1. FMU example**

In this research work the co-simulation is used for coupling EnergyPlus and Dymola. The latter works as a master software with EnergyPlus used to simulate the building and its energy demand, and Dymola used to simulate the energy system with all its components.

## 2.2 Pre-Refurbishment

The case study is a small cluster of thirteen homes, built in the 1960s, nine of them are terraced William Moss houses [31] and four are bungalows. Every terraced home includes a kitchen, two bedrooms, a toilet, a bathroom and a lounge, all connected by a staircase (Figure 2). The bungalows on the other hand are divided in kitchen, bathroom, bedroom and lounge.

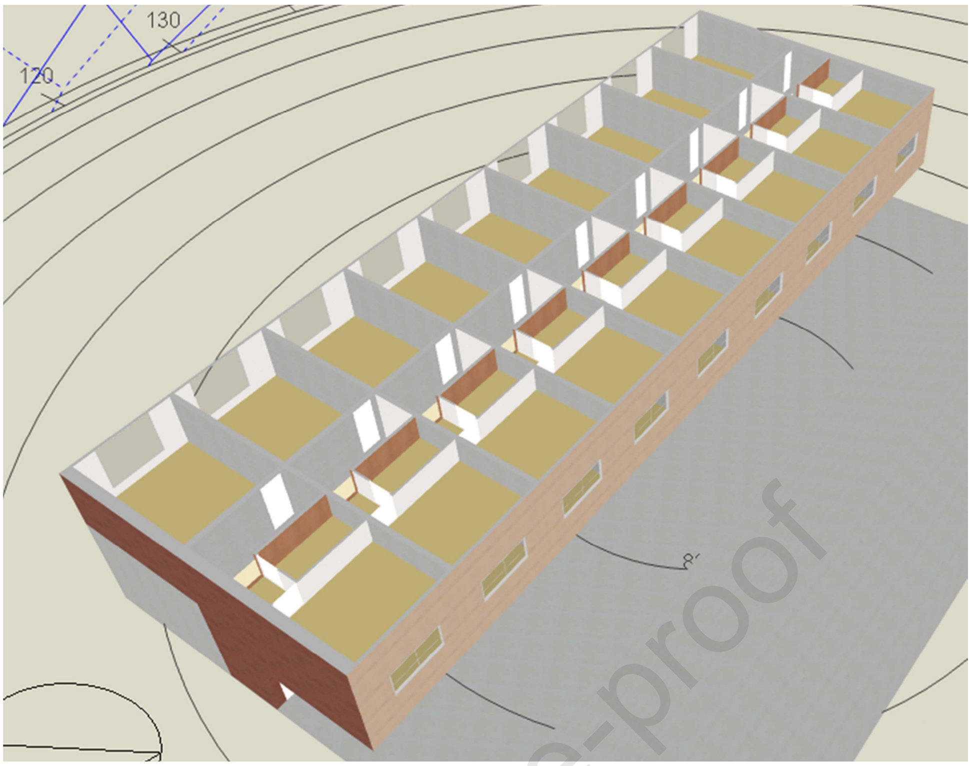


**Figure 2. Section of the main block from DesignBuilder**

The buildings have raft foundation and load bearing precast concrete panels which work also as separation between the different apartments. Storey-height infill timber frame panels were fixed between the precast panels, and tiles hung on timber battens. Although the walls were originally specified with glass fibre insulation within the timber panels, it is assumed that this has either slumped or been affected by damp and its effectiveness has been reduced. The gable end walls were cladded in bricks, and the roof was covered in concrete tiles, with an asymmetrical section and copper cladding to a vertical element facing west.


[redacted] [redacted]

**Figure 3. Back of the building before the refurbishment**

Originally in all the houses the Space Heating (SH) and the Domestic Hot Water (DHW) was provided by a combi-boiler (24kW) combined with a radiator system,

## 2.3 Post-Refurbishment

### 2.3.1 Building envelope

The refurbishing of the building has been carried out following the “Energiesprong” [32] approach, only seven of the nine houses and three out of four bungalows, own by the local housing provider have been refurbished. The privately-owned middle terrace home, one of the end-terrace homes and one of the bungalows, remain in the pre-refurbishment conditions due to the existing financial restrictions; this brings the total of the retrofitted homes to 10. The Energiesprong approach is based on the utilization of prefabricated components, so the building facades have been covered with an external wall, the end terrace walls have been refurbished and the building has now a new rooftop which incorporates a photovoltaic (PV) plant. The new façade wall, applied directly over the old one, helps to eradicate the thermal bridges and increase substantially the insulation level of the building. In Table 1 is reported the stratigraphy of the new external wall applied on the old one.

**Figure 4. Satellite view of the cluster after the refurbishment**

**Table 1. External insulation added on the old facades**

| Material | Thickness (mm) | Thermal Conductivity λ (W/mK) |
|---|---|---|
| Weatherboard | 10 | 0.14 |
| Air gap | 50 | R=0.18 (m²K/W) |
| Chipboard | 10 | 0.15 |
| Glass wool | 200 | 0.04 |
| Vapour barrier | - | - |
| Air gap | 40 | R=0.18 (m²K/W) |
| Chipboard | 10 | 0.15 |

The refurbishment of the end terrace wall consisted of polyurethane insufflation foam placed into the cavity between the external brick and the internal concreate load-bearing wall, replacing the air gap and the old EPS insulation. The roof renovations consist of a new glass wool insulation layer placed on top of the old one in this way covering also parts that were not insulated before. The total thickness of the glass wool insulation layers is now 270 mm. A new room has been added to each home by converting the external store into a garden room/new living room (the new façade wall has been installed as a front wall). Another intervention on the building envelop has been the application of a 200 mm thick glass wool external insulation on the ground floor wall and a 150 mm one on the kitchen floor. The external wall/cladding is offset manufactured and installed in a single step operation (Figure 5).

**Figure 5. Installation of a prefabricated façade module**

The work on the building envelop has reduced the infiltration value to 6 m³/(m²hr)@50Pa. The value of air changes to living rooms and bedrooms is now 0.5 ac/h (so in the lower band of the values suggested by The Chartered Institution of Building Services Engineers, CIBSE) and also, is possible to presume that the thermal bridges have been almost completely eradicated (this reduces the risk of mould). The radiators in the retrofitted houses have not been changed, it is assumed that by improving the building fabric after the refurbishment work, the energy consumption will be substantially reduced, and the old heating elements will be able to provide necessary heat. New double-glazed windows with 6-20-6 low emissivity glazing and Argon filling have been installed (Figure 6).

**Figure 6. Back façade of the building after the retrofitting**

### 2.3.2 Heating system

The heating system has been completely changed, the gas boilers have been removed and replaced by completely new, advanced, low temperature heating system. The system includes Ground Sourced Heat Pumps (GSHPs), Thermal Energy Storage (TES), Electric Energy Storage (EES). The block now is configured as a micro Low Temperature District Heating (LTDH) network.

The heat in the system is generated by two different GSHPs with a total power of 32.4 kW. One of the GSHP is used to heat the water up to 40°C the second is able to heat the water up to 65°C. The GSHPs are connected to 5 boreholes 130 m deep and they have a design COP of 4.2. The thermal storage is formed by two hot water tanks with a total capacity of 4 $m^3$ Figure 7. The hot water is supplied to the radiators at about 40°C, whereas the DHW is supplied to the users at 48°C.

**Figure 7. Photovoltaic plant and TES**

# 3 MODEL

## 3.1 Design Builder model

The first model of the case study was developed in DesignBuilder represent the 10 homes before the renovation and has been used as reference to evaluate the effectiveness of the refurbishment. In this model temperature setpoints and heating schedules were the ones recommended by “The Government’s Standard Assessment Procedure for Energy Rating of Dwellings” [33]; ventilation values are on the other hand suggested by CIBSE Guide A and by the Approved Document F: Means of ventilation (2010 edition incorporating 2010 and 2013 amendments) [34,35]. The blower door test provided the infiltration value.

The space heating system was simulated as a radiator system with combi-boilers responsible for DHW too. The consumption levels were as expected very high, due to the poor insulation and high infiltrations in the building, however the consumption value of the pre-refurbishment case must be considered conservative, as the buildings were in very poor conditions, with an irregularly distributed insulation that was in some places completely absent. A second model was developed implementing all the modifications made with the refurbishment intervention, both in terms of building envelope improvement and new energy centre, responsible for the SH and DHW production for the entire cluster. Figure 8 shows the model of the retrofitted cluster in DesignBuilder.

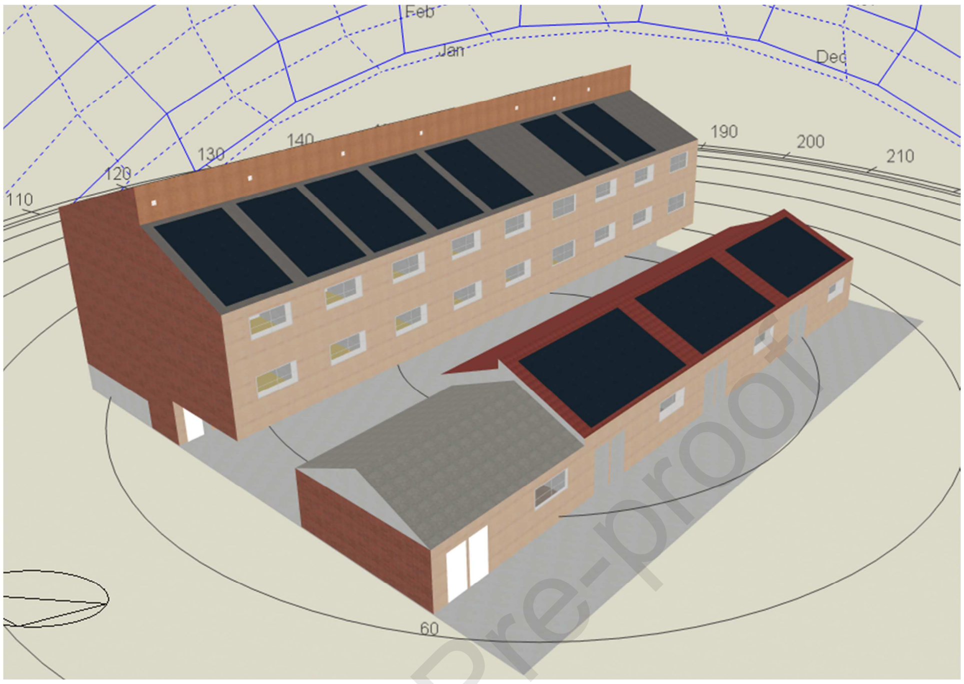


**Figure 8. Case study after the retrofitting as visualised in DesignBuilder**

## 3.2 Co-Simulation model on Dymola

Using the FMU block the model developed on DesignBuilder was imported in the Dymola environment, creating a co-simulation tool where the building performances in terms of energy demand and losses due to the envelop are simulated in EnergyPlus, whereas the entire energy system and relative control systems are implemented in Dymola (Figure 10).

The FMU provides to Dymola the values of:

- weather data;
- building heat demand (as mass flow and temperature required for SH and DHW);
- PV power generation.

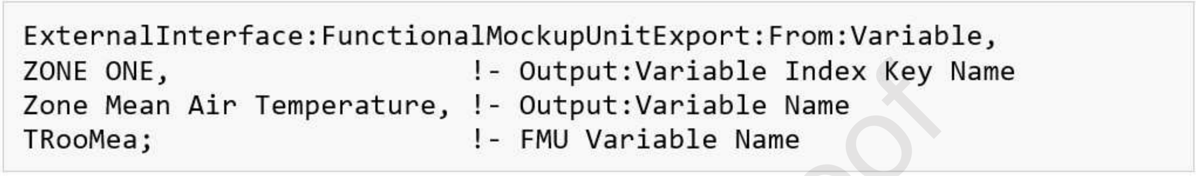
Dymola sends back to the FMU the temperature of the low and high heat storage, used to define respectively the temperature of the radiators and DHW supply. Dymola allows the maximum level of freedom in terms of control system and makes very easy to the user to carry on comparative evaluation changing different parameters.

### 3.2.1 FMU creation and mathematical description

Before analysing the computational steps in the model is worth to describe how the FMU has been created and what unique features were required for this specific study.

The FMU is generated from the EnergyPlus Input Data File (IDF) that EnergyPlus automatically creates after every simulation. The IDF file has been customised by the authors to satisfy the specific requirements of this research work.

In the IDF a script representing two infinite power boilers was implemented: one boiler is dedicated to the SH the second to the DHW. The idea behind this is to provide these two fictitious boilers with outlet temperature values calculated in Dymola for both the SH and DHW circuits. The mass flow in these two systems will be defined by EnergyPlus itself depending on the temperature value received from Dymola, this means that the heating system simulated in Dymola/Modelica will "de facto" provide the heat for the buildings simulated in EnergyPlus.



```
ExternalInterface:FunctionalMockupUnitExport:From:Variable,
ZONE ONE,                    !- Output:Variable Index Key Name
Zone Mean Air Temperature,   !- Output:Variable Name
TRooMea;                     !- FMU Variable Name
```

**Figure 9. Example of script for external interface**

To allow a two way communication between the FMU and Dymola, setting up of a so called "External Interface" is required. A specific script, similar to the one in Figure 9 has been created for every required variable, including, as aforementioned, weather data and PV energy production.

Once finalised the IDF has been converted to FMU using both EnergyPlusToFMU package and Python interpreter. At this point Energy Plus, as the slave programme {1}, is packaged in the FMU for co-simulation and Dymola as a master programme {2} supports the import of the FMU for co-simulation. Each programme solves initial value ordinary differential equations that are coupled through the FMU to the differential equations of the other programme. When for a general step $k$ EnergyPlus computes the sequence:

$$x_{1}(k+1) = f_{1}(x_{1}(k), x_{2}(k)) \qquad (1)$$

Dymola similarly computes the sequence:

$$x_{2}(k+1) = f_{2}(x_{2}(k), x_{1}(k)) \qquad (2)$$

With initial conditions:

$$x_{1}(0) = x_{1,0} \qquad (3)$$

and

$$x_{2}(0) = x_{2,0} \qquad (4)$$

To advance from time step $k$ to the next time step $k+1$ each of the two programmes uses its own integration algorithm. At the end of the time step Energy plus {1} sends its new state $x_{1}(k+1)$ to Dymola {2} and receive from Dymola the state $x_{2}(k+1)$.

Dymola as the master of the two simulation programmes imports the FMU and manages the data exchange between the two programmes. As a procedure this co-simulation scheme is equal to an Explicit Euler integration scheme [36].

### 3.2.2 Computational steps

In Figure 10 is possible to see a simplified scheme of the co-simulation tool with the data flow between the different blocks. In the energy system blog are present six sub-systems, these represent (clockwise order) the control system, the heat pumps, the thermal energy storages, the boreholes and the battery block that is comprehensive of its own battery control system.

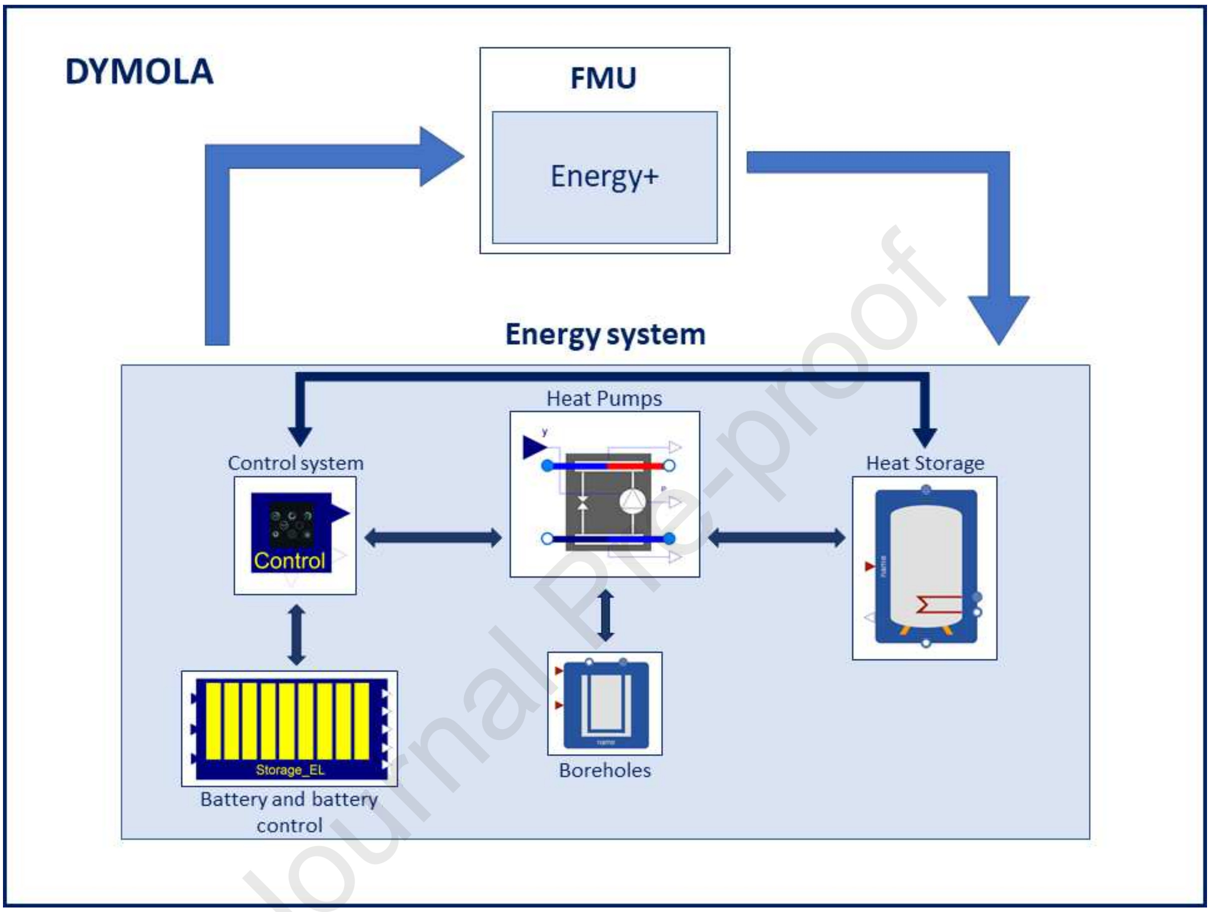


**Figure 10. Co-simulation model scheme**

As an explicit integration scheme sufficient number of steps needs to be used to maintain stability of the solution.

The simulation is dynamic, and the values are elaborated simultaneously with steps of 900 seconds (15 minutes). In each step all the following processes take place.

- The heat demand for SH and DHW (defined as the value of mass flow and return temperature of the water in the SH and DHW circuits) is sent by the FMU to the TESs (two TES are present, one for SH and one for DHW) defining the temperature and mass flow at the inlet of the heat exchanger at the top of the two TES.
- Temperature sensors are present at the outlet of the heat exchanger in each TES, the signals from these sensors are sent back to the FMU defining the temperature of the water that the two fictitious boilers send to SH and DHW circuits.
- HPs with their control system are also connected to the TESs. Depending on the temperature and the hour of the day the control system sends an on/off signal to the HPs keeping the TESs temperature within a range specified by the user. The same control system operates the pumps in the hydraulic systems between the boreholes and HPs and between HPs and TES.

- The FMU provides also the value of the PV energy production and the electricity consumption of the buildings. These two values, together with the electricity demand from the heat pumps are the input of the "battery and battery control" block. The control logic directly implemented into the battery control block manage the battery circuit and simulate different control strategies taking into account numerous constrains like the state of charge of the battery, the power required by the HP, the power supplied by the PV panels and the power demand of the buildings.

At this stage, in the control of the "Energy system", co-simulation shows all its usefulness, the number of parameters that is possible to control and the level of detail are one step ahead compared to a standard BPS tool, which on the other hand is still very useful when it comes to apply modification in terms of building envelope or occupant behaviour.

# 4 SIMULATED SCENARIOS AND RESULTS

## 4.1 Constrains

The case study present different constrains in terms of design and control options.

The design of the local energy centre that was heating the cluster of houses in this case study was already completed when the simulation work started. So, the parameters like number and power output of the heat pumps, number and depth of the boreholes, thermal and electric storage capacity were de facto fixed and difficult to change. Also, the contract with the electricity supplier was already in place and included a strong penalty for the use of electricity from the grid between 4 and 7 pm. The so-called transmission cost on each kWh is increases by a factor 10. The simulation tool has therefore a narrow range in which operate in terms of achieving optimisation of the energy system. Despite this, the results from the different simulated scenarios show that the even with this strong constrains the control strategy used to manage the energy flow is capable of provide consistent differences in terms of PV energy self-consumption, total energy acquired from the grid and energy bought in the 4-7pm hours.

## 4.2 DesignBuilder results

From the simulations using Design Builder the space heating demand in the 9 homes block before the refurbishment vary between 13943 $kWh_{th}$[4]/year and 8576 $kWh_{th}$/year, depending on the home position (mid terrace homes have lower SH demand) and between 11827 $kWh_{th}$/year and 9693 $kWh_{th}$/year in the bungalows, also here the end terrace home show higher heat demand.

The internal area of each home in the main block is 88 m², whereas each bungalow has an internal area of 47.5 m². Considering this the space heating energy demand can be expressed in terms of $kWh_{th}$/m²year, the resulting value vary between 158.5 $kWh_{th}$/m²year and 97.5 $kWh_{th}$/m²year for the apartments in the main block, with an average of 127.2 $kWh_{th}$/m²year. The bungalows heat demand goes from a maximum of 248.6 $kWh_{th}$/m²year in the end-terrace bungalow and a minimum of 203.7 $kWh_{th}$/m²year in the mid-terrace, the average heat demand for the bungalows is 231.7 $kWh_{th}$/m²year.

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[4] $kWh_{th}$ are thermal kWh

After the refurbishment the heat demand drops to an average of 5737 $kWh_{th}$/year in the terraced homes and 4406 $kWh_{th}$/year in the bungalows. In terms of $kWh_{th}/m^2$year the value is 55.14 $kWh_{th}/m^2$year for the flats in the block and 92.61 $kWh_{th}/m^2$year for the bungalows. As mentioned in 2.3.1 a new room was added to each of the flats in the block, increasing the internal surface to 104 m². The total reduction in heat demand is close to 50% in the block flats and 60% in the bungalows, but it is important to underline that this heat will now be supplied by an HP system.

## 4.3 Co-simulation results

### 4.3.1 Scenarios

In this research work, using the co-simulation tool, three distinct scenarios with different control schemes have been simulated to define the most efficient control strategy considering the pre-existent design and operative constrains.

- **Scenario 1 –** In this simulation both the heat pumps and building appliances have access to the battery circuit 24/7. The electricity produced by the PV plant is first used (direct self-consumption) to satisfy the total demand (HPs and appliances), the eventual surplus is stored in the battery and used when no PV power is available to integrate and reduce the energy bought from the grid. HPs control is set on OFF between 4-7pm, during this period the 10 homes rely only on the thermal storages to satisfy both space heating and domestic hot water demand.

- **Scenario 2 –** In this scenario the electricity demand for space heating has the priority between 00:00 and 16:00, in this time window the domestic appliances have no access to the battery circuit, the eventual PV power surplus not used by the HPs is send to the battery to be stored. In these hours if the HPs demand is satisfied and the battery is full then the PV energy can be used by the homes appliances to reduce the electricity bought from the grid (i.e. increase the self-consumption of PV energy). After 16:00 appliances have access to the battery circuit, to reduce the energy bought from the grid between 4 and 7pm. Like in Scenario 1 HPs are off between 4-7pm with heat storage providing space heating and DHW.

- **Scenario 3 –** Control strategy is equivalent to the one in Scenario 2, but, starting from day 105 (mid-April) and until day 273 (last day of September), appliances have full access to the battery circuit. The aim is by differentiating the energy used in different periods of the year to increase the amount of self-consumed energy during the summer period when the PV production is high. In this case, like in the previous two, the HPs are off between 4 and 7pm.

### 4.3.2 Co-simulation numerical results

The following charts show the energy details of the different scenarios, whereas Table 2 provides numeric data about the energy production and consumption:

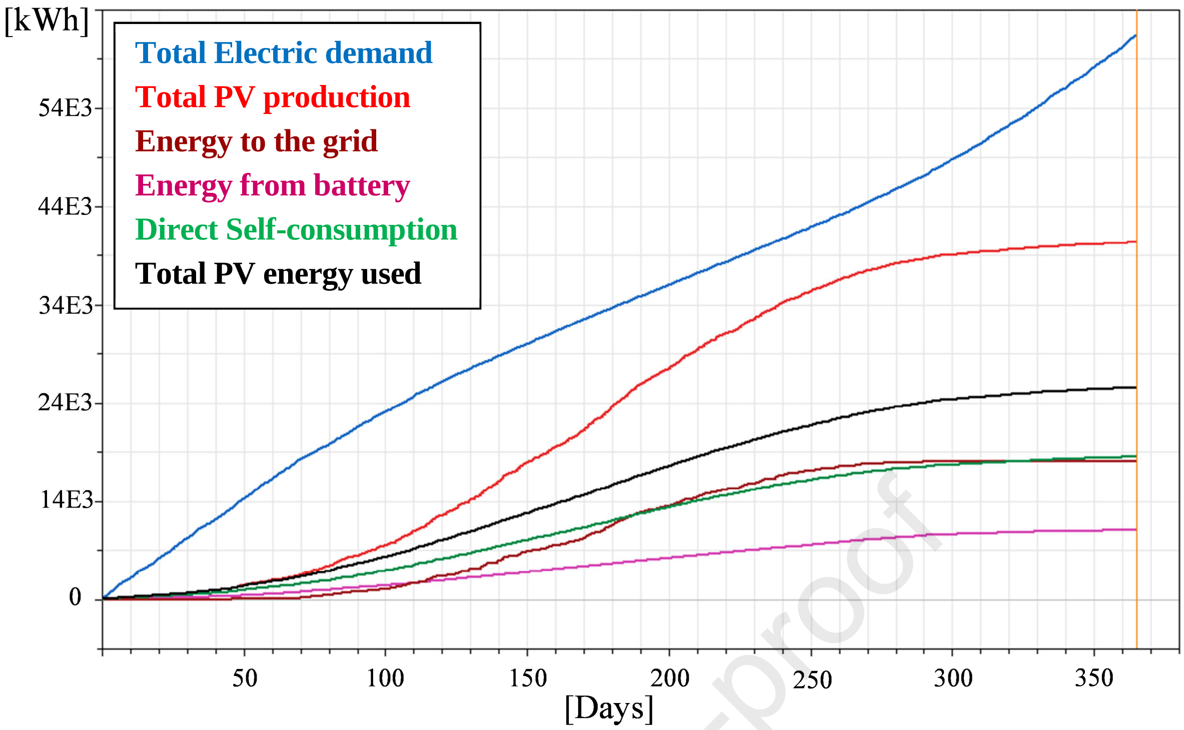

Figure 11. Scenario 1 Energy details

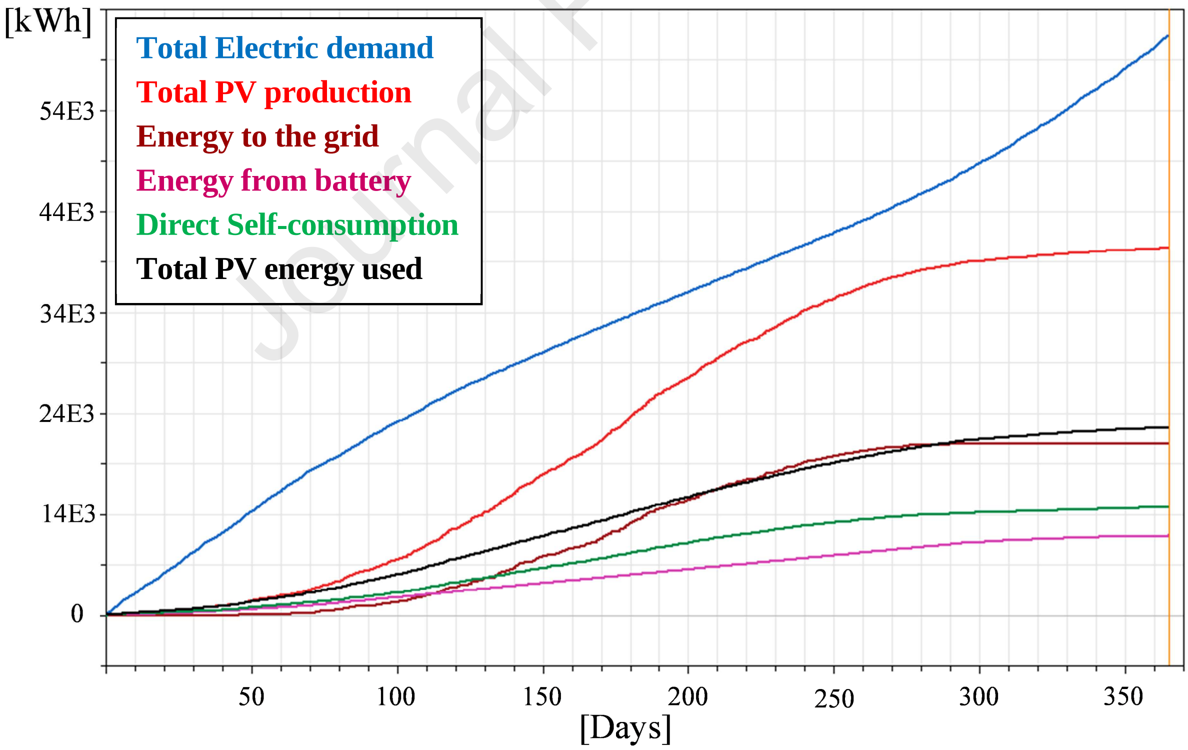

Figure 12. Scenario 2 Energy details

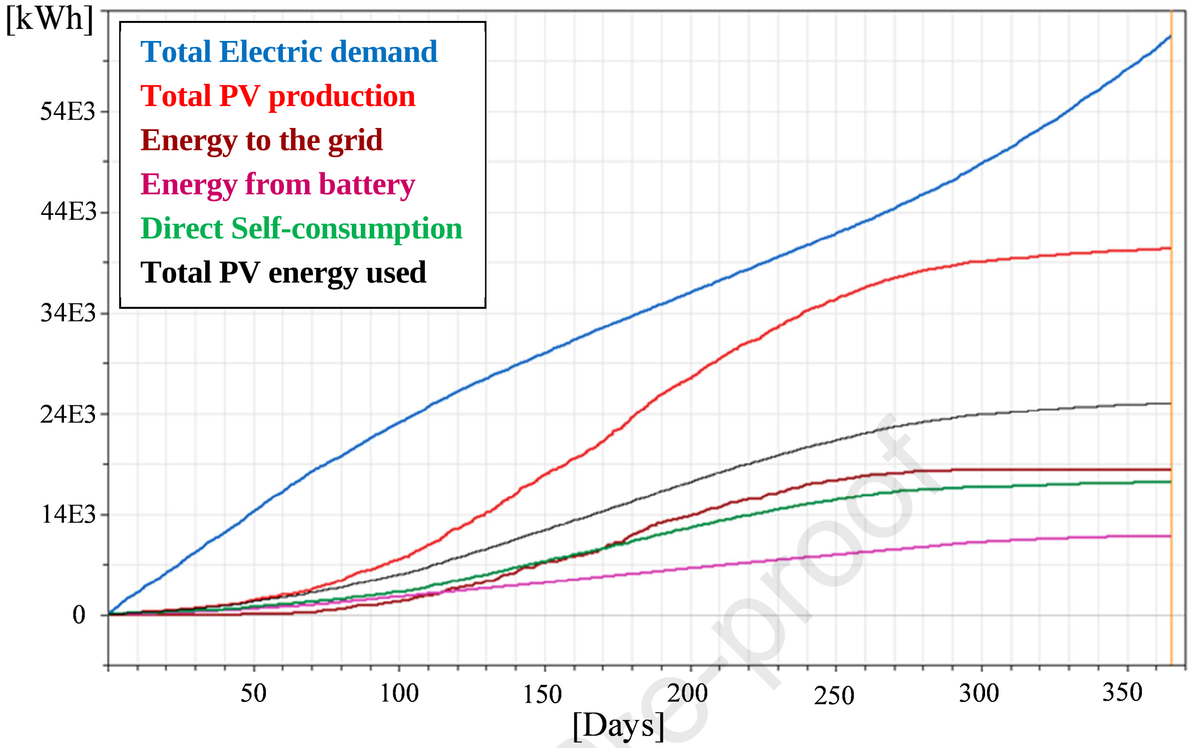

**Figure 13. Scenario 3 Energy details**

**Table 2. Energy utilization details for the three Scenarios**

| | SCENARIO 1 [kWh] | SCENARIO 2 [kWh] | SCENARIO 3 [kWh] |
|---|---|---|---|
| **Tot. Elec. Demand** | 57448 | 57448 | 57448 |
| **PV Production** | 36357 | 36357 | 36357 |
| **Total PV Used** | 21582 | 18569 | 21107 |
| **Direct Self-cons.** | 14549 | 10713 | 13267 |
| **Energy from battery** | 7033 | 7856 | 7840 |
| **Energy to the grid** | 14064 | 16991 | 14455 |
| **Share of PV used** | 59.4% | 51.1% | 58.1% |

Important, to define the behaviour of the system and define the most effective control scheme, is to compare the total amount of electricity bought between 16:00 and 19:00 when the price is at his maximum, these values are show in Figure 14 and Table 3.

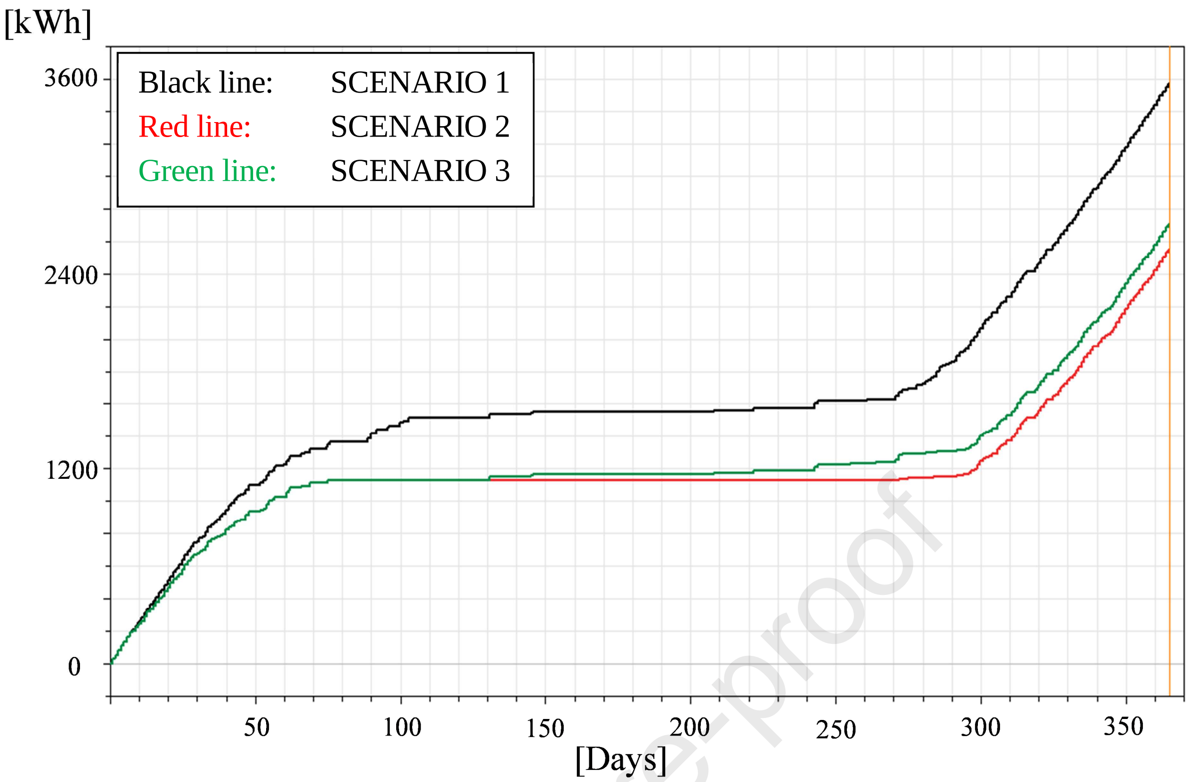

**Figure 14. Energy bought from the grid between 4 and 7pm**

**Table 3. Energy 4-7pm**

| | **SCENARIO 1 [kWh]** | **SCENARIO 2 [kWh]** | **SCENARIO 3 [kWh]** |
|---|---|---|---|
| **Energy bought from the grid between 4 and 7pm** | 3569 | 2543 | 2698 |

## 4.4 Results discussion

As shown in Figure 11, Figure 12, Figure 13 and Table 2 the energy consumption and the energy source change consistently accordingly to the different control scheme. Scenario 1 presents the best results in terms of total PV energy used, direct self-consumption and the lowest value in terms of PV energy send to the grid. On the other hand, Scenario 2 seems to offer the worst performances, with the lowest value in terms of total PV energy used and direct self-consumption. but the amount of energy sold to the grid is the highest of the 3 analysed cases. An exception is represented by the utilization of energy stored in the battery (i.e. a best use of the battery). Evaluating the first two scenarios it is clear that Scenario 1 directly self-consume about 4000 kWh/year more than Scenario 2 and that the difference in terms of total PV energy used is above 3000 kWh/year. In terms of percentage the share of PV energy self-consumed and not sent to the grid stands at 59% for Scenario 1 and just 51% for Scenario 2. Based on these data the control strategy in Scenario 1 seems to offer the best performance in terms of how the small district of 10 homes is capable to utilise the PV energy generated in the cluster. Scenario 3 offers values not very dissimilar from Scenario 1, where the share of self-used PV energy differs by just one percentage point, and the control strategy in Scenario 3 makes a better use of the battery.

At this point of the analysis it is important to consider also the amount of energy bought during the hours of peak price of electricity. In this case Scenario 1 performs in a much worst way compared to Scenario 2 and 3, with about 1000 kWh more consumed between 4-7pm. Scenario 2 and 3 present similar results with just 100 kWh difference. Doing a direct comparison between Scenario 1 and 2 appears clear that sacrificing just 400 kWh in one year, in terms of total PV energy used by the community, is possible to save around 1000 kWh in the hours in which the transmission cost increases by a factor 10. These peak price hours have the highest impact on the energy bill of the community.

After these evaluations is possible to state that the control scheme in Scenario 3 offers the better performances with an amount of PV energy self-consumption very close to the maximum shown in Scenario 1 but with a consistent reduction of the energy bought from the grid during the peak price time.

The model offers also the opportunity to analyse the behaviour of the different control strategies in terms of GHG emissions.

**Table 4. Energy utilization details pre-refurbishment and for the three Scenarios**

| Energy consumption | Pre-Refur. | SCENARIO 1 | SCENARIO 2 | SCENARIO 3 |
|---|---|---|---|---|
| **Gas for SH+DHW [$kWh_{th}$]** | 131850 | 0 | 0 | 0 |
| **Electricity for SH+DHW [$kWh_{el}$]** | 0 | 17747 | 17747 | 17747 |
| **Elec. for appliances and lights [$kWh_{el}$]** | 37819 | 39700 | 39700 | 39700 |
| **Total Elec. Consumption [$kWh_{el}$]** | 37819 | 57448 | 57448 | 57448 |
| **Total PV Self-consumption [$kWh_{el}$]** | 0 | 21582 | 18569 | 21107 |
| **Elec. from the grid (TOT-PV) [$kWh_{el}$]** | 37819 | 35866 | 38878 | 36341 |

**Table 5. Greenhouse gas emissions**

| CO2 Emissions [$kgCO_2e$] | Pre-Refurbishment | SCENARIO 1 | SCENARIO 2 | SCENARIO 3 |
|---|---|---|---|---|
| **Emissions from gas** | 26863 | 0 | 0 | 0 |
| **Emissions from Elec.** | 8817 | 8362 | 9064 | 8473 |
| **Total emissions** | 35680 | 8362 | 9064 | 8473 |
| **Emission Variation** | | -76.6% | -74.6% | -76.3% |

Table 4 shows the values for the energy consumption in the different scenarios, energy consumption is divided accordingly to utilization. The value "Elec. from the grid (TOT-PV)" represents the energy imported from grid calculated as the difference between the total electricity consumption and the PV energy self-consumed. To define the GHG emission before the refurbishment and in the three simulated scenarios the emission factor provided by the Department for Business, Energy & Industrial Strategy (BEIS) has been used. Greenhouse gas emissions are expressed in terms of “kilograms of carbon dioxide equivalent” as defined by BEIS, in this way is possible to consider not only the $CO_2$ emissions, but also the missions of other gasses (like $CH_4$) which also have a role in terms of greenhouse effect. Once the energy consumption has been broken down according to the energy source (or, in case of the electricity, energy vector) it is possible calculate the amount of GHG emitted. Before the retrofitting gas was used to provide SH and DHW, whereas after the entire energy demand of the buildings is satisfied with electricity provided by the PV plant and electric grid. This, combined with the reduction of energy demand achieved with the retrofit, allows to cut the GHG emission. In Table 5Table 5 is possible to see how the GHG reduction changes in the different scenarios, again control strategy plays an important role, scenario 1 indeed shows an emission reduction of 76.6%, 2 percentage points better than scenario 2. The difference between scenario 1 and 3 is, on the other hand, very small (0.3%) showing that with a similar benefit in terms of environmental impact is possible to reduce the electricity consumption during the peak price time.

**Table 6. Energy performance with different battery size**

| | SCENARIO 3 (36 kWh battery) [kWh] | SCENARIO 3 (72 kWh battery) [kWh] | Δ |
|---|---|---|---|
| **Tot. Elec. Demand** | 57448 | 57448 | |
| **PV Production** | 36357 | 36357 | |
| **Total PV Used** | 21107 | 25741 | 4634 |
| **Direct Self-cons.** | 13267 | 12975 | -292 |
| **Energy from battery** | 7840 | 12766 | 4926 |
| **Energy to the grid** | 14455 | 9340 | -5115 |
| **Energy from the grid** | 36341 | 31707 | -4634 |
| **Energy from the grid peak time** | 2698 | 2658 | -40 |
| | | | |
| **Share of PV used** | 58.1% | 70.8% | 13% |

A further analysis has been carried out to understand the effect of a bigger EES on the system. The 36 kWh battery of the case study has been replaced in the model with a 72kWh battery (doubling the size) looking for potential benefits. Table 6 highlights how an EES with twice the capacity of the original one would increase the share of the PV energy used by 13 points, reducing the annual import of electricity from the grid by more than 4600 kWh. These results do not justify the higher capital cost of a bigger battery, especially because the reduction in energy consumption during the peak time is only 40 kWh. As stated by the Energy Networks Association “there is a business model for electricity storage only if is the stored electric energy is used at times of higher price/cost periods. This allows users to benefit from the difference in the price of energy between peak and off-peak and avoid peak transmission and distribution costs. A number of potential business models for electricity storage exist that will become more attractive as costs continue to fall and changes to the regulatory regime occurs” [37]. This topic falls outside the perimeter of this paper, however the developed tool shows to be able of analysing complex multi-source hybrid energy systems with great accuracy, the possibility of optimising the EES size will be explored in future developments.

## 5 MODEL VALIDATION

The model has been validated comparing heat demand metered in the case study with the one obtained by the co-simulation model. Before presenting the data is necessary to point out some particularities of the case study and some modification that have proved to be necessary in order to calibrate the model. It must be considered, that the occupancy level considered in Design Builder for the various homes comes from the National Calculation Methodologies (NCMs), this means that the values are averaged and not representative of a particular case study, where a number of homes can be occupied by single, retired, elderly people and distort the expected energy consumption. To compensate this discrepancy and calibrate the model two homes have been modelled as if they are occupied by a single retired man. The values of the heat demand measured in this case study have been calculated as an averaged value not considering three homes that show completely unpredictable energy consumption. The particularity of the occupants' behaviour could be due to the previous circumstances in which residents used to live. For example, elderly people that spent many years in conditions of fuel poverty show the tendency to reduce the temperature settings in their home for "comfort" reasons (especially in the bedrooms) and in some occasions to switch off the heating leading to unpredictable results.

Analysing the heat demand (comprehensive of SH and DHW demand) from 10 homes in December (2018), January and February (2019) show a very close correlation between the metered data and the simulated one (Figure 15), with a difference between the two values of 0.3%, 2.25% and 2.13% in December, January and February respectively, these values stay within the allowable difference [38].

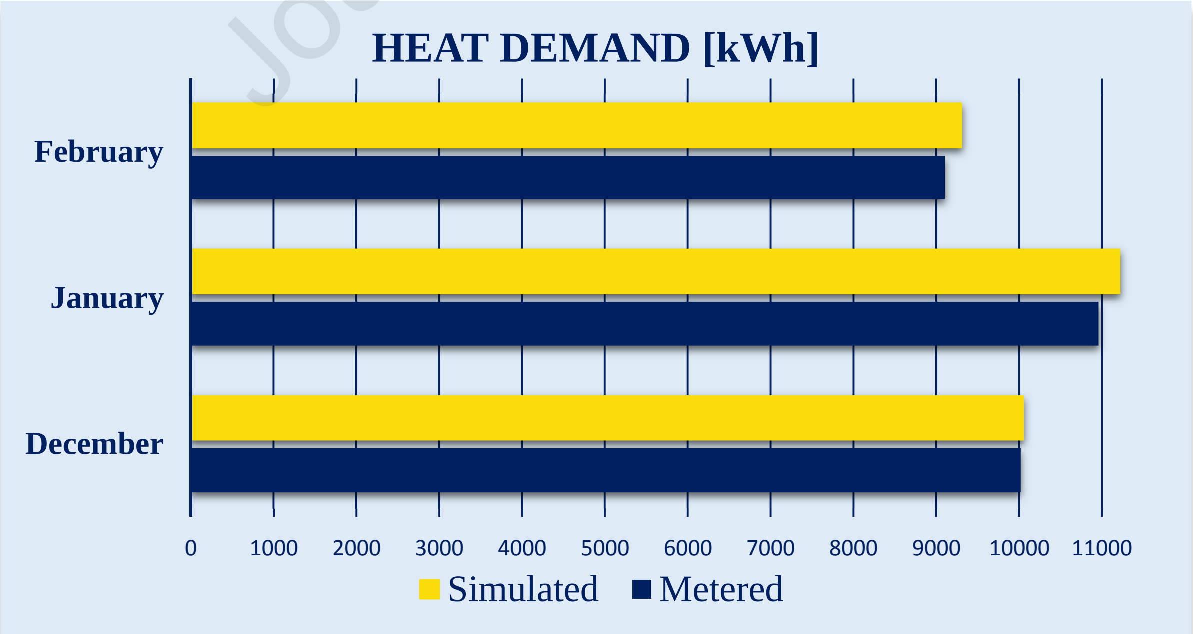

**Figure 15 Comparison between metered and simulated heat demand**

Analysing the results of the simulation accordingly to the methods suggested by ASHRAE-14 [39,40] is possible to calculate both the Normalized mean bias error (NMBE) and the Coefficient of variation of the root mean square error (CVRMSE), respectively calculated as:

$$NMBE = \sum^{n} \frac{(y_i - \hat{y}_i)}{(n-p) \cdot \bar{y}} \cdot 100 \tag{5}$$

And

$$\text{CVRMSE} = 100 \cdot \left[\sum (y_i - \hat{y}_i)^2 / (n-p)\right]^{\frac{1}{2}} \Big/ \bar{y} \tag{6}$$

Where:

n = number of data points
p = 1
$y_i$ = measured data
$\hat{y}_i$ = simulated data
$\bar{y}$ = arithmetic mean of the sample of n observations

Results from the calculation show that both NMBE and CVRMSE are well within the limits set by ASHRAE-14 (Table 7) confirming the validity of the model.

**Table 7.NMBE and CVRMSE values from the model and limits**

| | Calculated | Objective |
|---|---|---|
| **NMBE** | -1.59% | -5%<NMBE<5% |
| **CVRMSE** | 2.26% | <15% |

## 6 CONCLUSIONS AND FUTURE WORK

Heat networks have a very limited diffusion in the UK [41] due to historic development of gas networks. To eliminate fossil fuel and move to low carbon heat represent a major national challenge to the UK over the coming years. It will require major strengthening of the electricity grid. At present there is insufficient electricity generation to supply all electric domestic heat. The gas grid delivers more than twice the energy of the electricity grid. At the same time the sustainable “green” sources of electricity are volatile, seasonal and depends on environmental conditions. This means electricity need to be generated locally and stored in an appropriate way to maximise the economic efficiency. As part of the EU Horizon 2020 REMOURBAN project, in seven family houses and three bungalows a pilot deep retrofitting intervention, called 2050 Homes has been carried out. As part of the intervention an innovative Hybrid Energy system was developed where through local microgeneration renewable energy sources were utilised to meet the building’s energy demand. This new multi-element energy/heating system comprises a photovoltaic plant, two ground sourced heat pumps, a thermal energy storage and an electric energy storage. With this localised, scalable energy system, the heating of the houses is now achieved efficiently at low operating temperature to reduce energy losses. The paper illustrates the implementation of co-simulation tool as a holistic modelling environment for the evaluation of paraments of such complex hybrid energy system. The tool demonstrates to be suitable to implement and evaluate various control strategies in order to optimise the total energy used and consequentially the running cost. The present research work reveals that the utilization of BPS tool is not sufficient to properly simulate complex, multi-element hybrid energy system operating at small district level. The paper shows how by implementing an FMU block is possible to provide a two-way interaction between a BPS tool (Energy Plus) , which simulates the energy demand of the buildings and the specialised software (Dymola/Modelica) to do a detailed modelling of the energy system. Several different models have been developed using the co-simulation tool based on the two software platforms in order to assess the energy performances before and after the refurbishing, highlighting a significant reduction in energy consumption.

The co-simulation model is easily scalable suitable for bigger and more complex energy systems. The cluster of buildings that form the case study of this paper is undergoing a further development now with new enlarged energy centre feeding 39 homes, followed in the next couple of years by 5 new hybrid energy schemes feeding more than 250 residential homes in Nottingham. The co-simulation models will be updated to reflect the development of new, bigger and potentially more complex hybrid energy systems. The co-simulation tool has also shown the potentiality to be used in the design stage to provide indication about battery and thermal storage size, as well as further control schemes that might be suitable for the bigger and more complex energy systems. The future of residential heating is economy at scale – the introduction of decentralised hybrid heat local networks, integrating electrical and heat networks, supplying heat to between 10 to 100 houses, suitable for both urban and rural solutions.

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- Deep retrofitting intervention with full electric decentralised heating system.
- Complex multi-element energy supply systems require proper control strategy.
- EnergyPlus-Dymola co-simulation tool for detailed modelling and energy optimization.
- Scalable tool for community level energy assessment and optimization.

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: