



Title	Mapping the energy flexibility potential of single buildings equipped with optimally-controlled heat pump, gas boilers and thermal storage
Authors(s)	D'Ettorre, Francesco, De Rosa, Mattia, Conti, Paolo, Testi, Daniele, Finn, Donal
Publication date	2019-10
Publication information	D'Ettorre, Francesco, Mattia De Rosa, Paolo Conti, Daniele Testi, and Donal Finn. "Mapping the Energy Flexibility Potential of Single Buildings Equipped with Optimally-Controlled Heat Pump, Gas Boilers and Thermal Storage." Elsevier, October 2019. https://doi.org/10.1016/j.scs.2019.101689 .
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/11536
Publisher's statement	This is the author's version of a work that was accepted for publication in Sustainable Cities and Society. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Sustainable Cities and Society (50, (2019)) https://doi.org/10.1016/j.scs.2019.101689
Publisher's version (DOI)	10.1016/j.scs.2019.101689

Downloaded 2026-05-02 00:29:36

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

Mapping the energy flexibility potential of single buildings equipped with optimally-controlled heat pump, gas boilers and thermal storage

Francesco D’Ettorre^{a,b,c}, Mattia De Rosa^{b,c,*}, Paolo Conti^a, Daniele Testi^a, Donal P. Finn^{b,c}

^a*BETTER (Building Energy Technique and Technology Research Group), Department of Energy, Systems, Territory and Constructions Engineering (DESTEC), University of Pisa. Italy*

^b*School of Mechanical and Materials Engineering. University College Dublin. Belfield, Dublin 4. Ireland*

^c*UCD Energy Institute. University College Dublin. Belfield, Dublin 4. Ireland*

Abstract

The present paper assesses the capability of a cost-optimal control strategy to activate demand response actions in a building equipped with an air-source heat pump coupled with a water thermal storage system. Commencing with a reference scenario where no demand response actions are considered, the electricity consumption pattern and the operational cost are evaluated. Several demand response scenarios are next considered by adapting consumption patterns by reduction of baseline heat pump power consumption. The difference between the operational cost evaluated under a specific demand response program and the benchmark cost are used to assess the marginal cost that should be considered to provide incentives to promote user participation in demand response programs. The results illustrate the effectiveness of thermal energy storage for reducing the total system operational cost and its seasonal primary energy consumption, both with and without demand response actions. The application of the proposed methodology over the whole heating season, allows performance maps to be created that can be used either by the grid-operator or end-user to identify the best demand response action to be implemented on any particular day. These maps represent useful decision tools to assess and optimise the flexibility potential while meeting end-user needs.

Keywords: energy flexibility, building, smart grids, thermal storage, heat pump, model predictive control

1. Introduction and state of the art

2 One of the main objectives of the EU’s energy policies is the reduction of greenhouse gas
3 emissions by 80-95% by 2050 [1]. This decarbonisation process requires policies promoting

*corresponding author

Email address: `mattia.derosa@ucd.ie` (Mattia De Rosa)

4 investment in new low-carbon technologies, energy efficiency measures, renewable energies
5 and grid infrastructure. Reaching high penetration of Renewable Energy Sources (RES)
6 is widely recognised as one of the first steps towards the development of new energy sys-
7 tems capable of meeting EU targets, while increasing competitiveness and supply security.
8 Notwithstanding, the experiences from countries with high shares of RES - such as Denmark,
9 where renewable electricity generation accounts for approximately two thirds of the overall
10 production [2] - have highlighted challenges related to the technical integration of RES into
11 the existing power system network.

12 Since the power grid requires a continuous match between power supply and demand, the
13 intrinsic stochastic nature of renewable sources makes this balance challenging [3]. Moreover,
14 even if the traditional power system is capable of coping with uncertainty in both demand
15 and supply power profiles, the flexibility offered by the supply-side might not be sufficient
16 compared to the flexibility required for high penetration of RES. Therefore, in order to
17 increase the RES share, and to use energy more effectively, energy system flexibility needs
18 to be improved. Alongside traditional measures, i.e., supply-side regulation and power grid
19 upgrades, new flexibility sources can be obtained by enabling the active participation of the
20 demand-side in the power system operational procedures.

21 Generally, the term *demand side management* (DSM) refers to the modification of end
22 user demand by implementing strategies capable of reducing end user energy consumption,
23 harnessing demand efficiencies, improved control and optimisation as well as incorporating
24 RES measures. Among these solutions [4], demand response (DR) strategies are gaining
25 increased attention as promising techniques for the emerging smart grid by providing better
26 integration and exploitation of renewable energy sources, through the management of end
27 user generation and consumption patterns. DR has been shown to be a promising proposi-
28 tion [5] and is based on adapting user demand profiles to grid requirements, by increasing,
29 reducing, or shifting the amount of energy consumed, according to external signals coming
30 from the grid operator (e.g., electricity prices). DR programs can be classified either as (for
31 an exhaustive description of the different DR programs, refer to [6]):

- 32 • Incentive-Based Programs (IBP): consumers receive incentive payments in return for
33 the load-reduction provided over a given period. Programs belonging to this category
34 can be classified as Direct Load Control, Curtailable Load and Demand Bidding.
- 35 • Price-Based Programs (PBP): consumers voluntarily schedule their consumption pro-
36 files according to economic signals, such as electricity tariffs. PBP can be classified
37 according to dynamic pricing rates, i.e., time-of-use tariff, critical peak and real-time
38 pricing.

39 This classification leads to another interesting aspect related to the type of DR followed
40 by the *prosumer*, which can be either active or passive depending on the type of program
41 adopted. Typically, IBPs lead to active DR actions, since prosumers change their consump-
42 tion patterns (DR) following specific requests from the grid. These DR actions can drive
43 the system to sub-optimal working conditions (either from a technical and economic point
44 of view), leading to higher operational costs and consequently to positive marginal costs of

45 the flexibility provided. Hence, incentives are needed to promote the involvement of the
46 consumers in these kind of programs. On the other hand, PBP encompasses passive DR
47 behaviour, since consumers adapt their consumption profiles to the electricity price patterns,
48 with the aim of minimising operational costs. Even if the tariff structure leads the consumers
49 to decrease their consumption during peak hours, providing an indirect service to the grid
50 (i.e., passive), no active interactions between these actors are in place. End-user ability to
51 control the demand in response to electrical grid requirements strictly depends on their type
52 and size. Industrial consumers can play a more significant role due to the magnitude of their
53 energy and power demands. Moreover, they are often readily equipped with the facilities
54 required to implement energy management and DR measures, even if their potential has not
55 yet been fully and thoroughly exploited [7, 8].

56 Besides industrial users, residential and commercial end-users are potential providers of
57 demand response, since the building sector accounts for about 40% of the primary energy
58 consumption worldwide [9]. In Europe, heating and cooling loads in residential and com-
59 mercial buildings account for almost 50% of the total final energy demand, being responsible
60 for about 36% of all GHGs emissions [10]. Consequently, the decarbonisation of the heating
61 sector must be addressed to successfully complete the transition towards a more sustainable,
62 secure and affordable energy future. To this aim, the EU has developed several directives
63 aimed at improving the energy performance of buildings. Among these, the Energy Perfor-
64 mance of Building Directive (EPBD) [11] and the Energy Efficiency Directive (EED) [12] are
65 the main legislative instruments established to promote long-term strategies for mobilising
66 efforts aimed at implementing energy efficiency measures and at fostering active participa-
67 tion of end-users in the energy market. Moreover, the EPBD directive was recently updated
68 (EPBD Directive 2018/844/EU [13]) by introducing instruments to support the use of smart
69 technologies and technical building systems through the establishment of a Smart Readiness
70 Indicator (SRI). This indicator will allow for the rating of the smart readiness of buildings,
71 i.e., the capability of buildings (or building units) to adapt their operation to the needs of
72 occupants and to signals from the grid (energy flexibility) [14].

73 Among the different technologies available for implementing demand response actions,
74 the use of advanced control strategies for the management of electric heat pumps and thermal
75 energy storage is one promising solution [15–21]. In this context, defining the flexibility
76 potential is not a straightforward process due to the absence of common accepted definitions,
77 quantification methodologies and standardised assessment procedures [22–24].

78 Stafford [25] defined the flexibility potential of two hybrid heat pump/gas boiler systems
79 as the percentage of the building load which can be shifted from the heat pump to the gas
80 boiler in response to grid requirements (switching off the heat pump for approximately 1
81 hour at periods of peak consumption). The results showed that the load share between the
82 two generators can be shifted towards the gas boiler with only a modest increase in the
83 overall energy consumption. A methodology to assess the resulting energy penalty using the
84 heat pump thermal output as a predictor of system energy consumption was outlined, but
85 economic assessment was not considered.

86 Similarly, Oldewurtel et al. [26] developed a methodology to quantify the energy shifting
87 potential of different buildings by using a model predictive control (MPC) and predefined

88 price signals. The flexibility potential was characterised by means of an efficiency parameter
89 defined as the ratio between the maximum power shift and the resulting additional energy
90 consumption of the system, while there was no explicit mention of resulting additional costs.
91 An analogous methodology was presented by De Coninck et al. [27], who defined the building
92 flexibility as the maximum positive (and negative) deviations from a reference cost-optimal
93 consumption pattern available during a given time period of the day. An existing office
94 building equipped with electrically-driven air source heat pumps and gas boilers were used
95 as a case study: three optimal control problems were solved to determine a cost-optimal
96 baseline for the consumer, and then the maximum positive and negative flexibility over the
97 DR action interval (from one to three hours) was examined while maintaining the building
98 indoor temperature within the comfort boundaries.

99 Ali et al. [28] proposed a hierarchical two-stage optimisation framework for a residential
100 building: at first, a cost-optimal consumption profile is defined on the basis of the hourly
101 prices of the day-ahead market; then, a second stage is set up where incentives are provided
102 to customers if they either increase or reduce their hourly consumption patterns. Adopt-
103 ing similar assumptions, Bianchini et al. [29] considered a DR strategy based on external
104 price-volume signals sent by an aggregator to the building energy management system. A
105 model predictive control strategy was adopted to minimise the energy cost, while a heuristic
106 algorithm based on problem decomposition was developed to reduce the computational cost.

107 Although the above mentioned works outline the lack of a commonly adopted method-
108 ology, it is worth mentioning the work of IEA Annex 67 in establishing standardised and
109 harmonised procedures to characterise energy flexibility of individual buildings and building
110 clusters [30]. To this end, the IEA EBC Annex 67 has identified initially the dimensions of
111 energy flexibility, namely capacity, duration and cost. Then, the energy flexibility potential
112 is evaluated by determining the capability of buildings and systems to change associated
113 energy demand profiles, with respect to a reference scenario, according to external penalty
114 signals (e.g., energy prices, carbon dioxide emissions, RES exploitation, etc.), acting as ad-
115 ditional boundary conditions [31]. Once the dynamic response of a building (or cluster of
116 buildings) to the penalty signal is identified, each flexibility dimension is then assessed by
117 evaluating its deviation from the reference value (e.g., the relative amount of saved carbon
118 dioxide emissions).

119 While many authors have focused on the optimal control of integrated hybrid systems to
120 implement DSM [32–35], quantitative technical, economic and environmental assessments of
121 the energy flexibility associated with hybrid systems (gas boiler/heat pump/thermal stor-
122 age) are still scarce. Research efforts are still required in order to address the research
123 needs in terms of data, modelling approaches and assessment methodologies, as highlighted
124 by Kreuder and Spataru [36]. Moreover, developing such methodologies is paramount for
125 establishing policies and business opportunities leading towards a more rational and sus-
126 tainable use of energy in cities. Compounding this research gap, is the lack of common
127 definitions and standardised procedures to determine the *flexibility cost*, as well as the pro-
128 vision of exhaustive and comprehensive generalisations capable to extending information at
129 larger scale and to establish appropriate policy and legislation frameworks [37]. In this con-
130 text, the techno-economic and environmental assessment of the flexibility potential offered

131 by hybrid heat pump-gas boiler generators has to date been rarely investigated. Therefore,
132 the present paper focuses on:

- 133 • proposing a set of comprehensive indicators capable of assessing the performance of
134 DR programs and to identify DR actions which fit a specific user requirements,
- 135 • presenting a methodology to develop a control algorithm for hybrid heat pump, in this
136 case boiler systems aimed at minimising the daily operational costs and enabling the
137 implementation of DR programs,
- 138 • investigating and assessing different DR programs from a techno-economic and envi-
139 ronmental point of view, by creating performance decision-making maps for end-users,
140 building managers and grid network operators.

141 To this purpose, an optimal control problem (OCP) is solved to determine the control
142 strategy of the thermal generators and the storage tank, to meet the load at minimum
143 cost. In addition, the impact of a price-based DR program is investigated in terms of
144 consumption patterns and daily operational costs. Different scenarios in terms of requested
145 flexibility from the grid under IBPs are investigated to determine associated operational
146 costs. Since any deviation from the optimal control strategy obtained by solving the OCP
147 will result in sub-optimal operation, leading to higher operating costs, the difference between
148 the new operational costs and the benchmark cost relating to the PBP is used to assess the
149 minimum pay-out that should be adopted in an IBP scenario to promote the involvement
150 of the consumer in this kind of program.

151 The following structure is adopted in the paper: Section 2 describes the methodology
152 used to assess the cost associated with different DR actions, the system modelling and the
153 optimal control problem formulation. Section 3 presents a description of the case study
154 analysed and Section 4 discusses the results obtained. Finally, Section 5 summarises the
155 main findings of the work.

156 **2. Methodology**

157 *2.1. System overview and modelling*

158 A building equipped with a hybrid generator composed of an electrically-driven air-
159 source heat pump, coupled with a gas boiler, was assumed as a case study, as outlined in
160 Figure 2. The generators are considered to be operating in parallel: when the heat pump
161 cannot meet the required thermal output, the boiler supplies the residual load demand. Both
162 generators are controlled by a model predictive control (MPC) strategy. Unlike traditional
163 controller, model predictive control is an advanced method of control which, compared
164 to more traditional controller, is capable to evaluate the best control actions (\mathbf{u}) to be
165 implemented not only on the basis of the current state of the system, but also based on
166 information (predictions) about future disturbances (\mathbf{w}) that can affect the behaviour of the
167 system. At each time-step t , the control action is evaluated solving an open loop optimal
168 control problem, whose aim is to minimise over a finite prediction horizon τ a specific

169 objective function J (e.g. total cost or CO_2 emissions). Once the OCP is solved, the
 170 controller implements the optimal control trajectory (\mathbf{u}_{opt}) over the control horizon only,
 171 i.e., a 1 hour time step. A schematic view of the MPC procedure is given in Figure ??.

```

for  $t = 1$  to  $\mathcal{H}$  do // e.g., for each hour of the heating season
  STAGE 1: Get information about future events
  Forecast disturbances over the prediction horizon  $\tau$ : // e.g. external
  temperatures or electricity prices;

   $\mathbf{w}_j = [w_j^{t|t}, w_j^{t|t+1}, \dots, w_j^{t|t+i}, \dots, w_j^{t|t+\tau-1}] \forall j \in [1, \mathcal{N}]$ 
  with  $w_j^{t|t+i}$  the value of the  $j$ -th disturbance at time steps  $t + i$  as predicted at
  time step  $t$  and  $\mathcal{N}$  the number of disturbances.

  STAGE 2: Solve the open loop optimal control problem
  Identify the control sequence  $\mathbf{u}_{opt}$  that minimise the objective function  $J$  over the
  considered horizon  $\tau$ :

   $\mathbf{u}_{opt} = \underset{\mathbf{u}}{\operatorname{argmin}} J(\mathbf{u}, \mathbf{w}) = \underset{\mathbf{u}}{\operatorname{argmin}} \sum_{l=0}^{\tau-1} f(\mathbf{u}^{t|t+l}, \mathbf{w}^{t|t+l})$ 
  where:
   $\mathbf{w}^{t|t+l} = [w_1^{t|t+l}, w_2^{t|t+l}, \dots, w_j^{t|t+l}, \dots, w_{\mathcal{N}}^{t|t+l}]$ 
   $\mathbf{u}^{t|t+l} = [u_1^{t|t+l}, u_2^{t|t+l}, \dots, u_k^{t|t+l}, \dots, u_{\mathcal{M}}^{t|t+l}]$  //  $\mathcal{M}$  number of control variables;
  output: Optimal trajectories
   $\mathbf{u}_{opt,k} = [u_k^{t|t}, u_k^{t|t+1}, \dots, u_k^{t|t+i}, \dots, u_k^{t|t+\tau-1}] \forall k \in [1, \mathcal{M}]$ 

  STAGE 3: Implementation
  Once the optimal control trajectories are known then only their first elements are
  implemented by the controller by setting:
   $\mathbf{u} = [\mathbf{u}_{opt,1}^{t|t}, \mathbf{u}_{opt,2}^{t|t}, \dots, \mathbf{u}_{opt,k}^{t|t}, \dots, \mathbf{u}_{opt,\mathcal{M}}^{t|t}]$ 
  then move to the next time step.
end

```

Figure 1: MPC algorithm

172 Two different system configurations are considered: the first one (Figure 2a) consists of
 173 the hybrid generator only, whereas the second one (Figure 2b) includes also a space heating
 174 water tank connected in series to the heat pump to decouple the energy generation and
 175 distribution. The TES is considered for space heating only. Although combining a TES
 176 with an existing DHW tank can be considered as a further option, the adoption of two
 177 separated tanks is generally preferable, as shown in [18, 38–40]. First, space heating tanks
 178 are characterised by higher capacities, due to the higher energy demand required for heating
 179 than for DHW [18]. Moreover, DHW demand is intrinsically stochastic, since it follows
 180 consumer needs, and it needs to meet specific quality standards for health reasons (i.e., by

181 performing anti-legionella cycles). All these aspects make the use of space thermal energy
 182 storage (TES) tanks more suitable for implementing DR measures.

183 The boiler is considered connected directly to the thermal load in both the configurations.
 184 The performance of different kinds of electrically-driven heat pump units can show different
 185 behaviour depending on the unit control strategy [41]: during part-load operations, an on-
 186 off unit modulates its capacity by varying its sequence of on-off cycles, while a modulating
 187 unit can work continuously by reducing its thermal power and, consequently, the energy
 188 delivered. Therefore, when the part-load factor is reduced, the coefficient of performance
 189 (COP) decreases for on-off units, while for modulating units it remains constant until a
 190 minimum part-load factor is achieved [42].

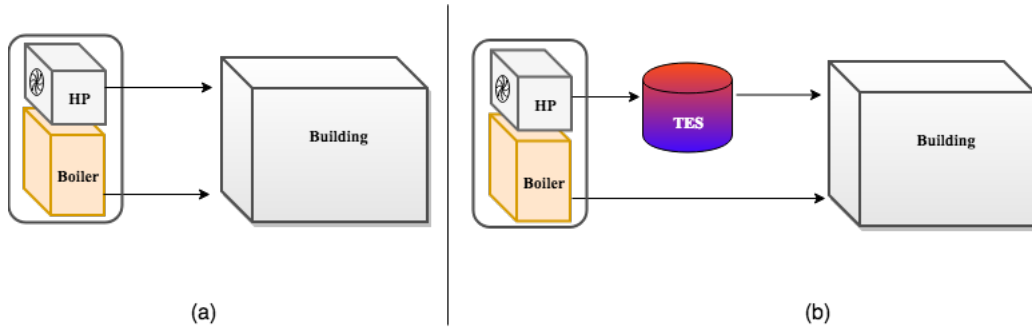


Figure 2: Schematic of the heating system (a) without and (b) with TES.

191 Generally, the coefficient of performance of a heat pump at full load conditions (COP_{FL})
 192 can be evaluated by means of the so-called second law efficiency η^{II} , as shown in Eq. 1:

$$COP_{FL} = \eta^{II} \cdot COP_{Carnot} = \eta^{II} \cdot \frac{T_H + 273.15}{T_H - T_L} \quad (1)$$

193 where COP_{Carnot} is the coefficient of performance of a Carnot cycle operating between a high
 194 temperature (T_H) and a low temperature (T_L) reservoirs – i.e., the condenser and evaporator
 195 temperatures. To take into account the variation of the heat pump performance with the
 196 load-factor, a part-load correction factor (f_{PL}) is introduced according the standards EN
 197 14825 [43] and UNI/TS 11300-4 [44]:

$$f_{PL} = \frac{CR}{(1 - C_c) + C_c CR} \quad (2)$$

199 The term C_c in Eq. 2 represents the degradation coefficient, assumed to be equal to 0.9, as
 200 suggested in [43, 44], while CR is the heat pump part-load ratio, defined as the ratio between
 201 the delivered thermal power ($\dot{Q}_{HP,th}$) and the heat pump maximum power ($\dot{Q}_{HP,th}^{max}$), as shown
 202 in Eq. 3.
 203

$$CR = \frac{\dot{Q}_{HP,th}}{\dot{Q}_{HP,th}^{max}} \quad (3)$$

204

205 The COP over all of the operative range can be expressed as shown in Eq. 4.

$$COP = \eta^{II} \cdot COP_{Carnot}(T_L, T_H) \cdot f_{PL}(CR) \quad (4)$$

206

207 Moreover, the heat pump can operate only if the external temperature is higher than a
 208 cut-off value ($T_{ext} > T_{cut-off}$), otherwise it is switched-off. Furthermore, in order to avoid
 209 comfort constraint violations, the gas boiler is designed to deliver all of the thermal power
 210 required by the load at any time, at a constant efficiency η_B over all operative ranges. The
 211 thermal energy storage is modelled as a perfectly mixed water tank, the temperature T_{TES}
 212 of which varies according the following energy balance:

$$V_{TES} \rho_w c_w \frac{dT_{TES}(t)}{dt} = \dot{Q}_{HP,th}(t) - \dot{Q}_{TES,th}(t) - \dot{Q}_{TES,loss}(t) \quad (5)$$

213

214 with V_{TES} the volume of the storage tank and ρ_w and c_w the density and the specific heat
 215 capacity of water, respectively, while $\dot{Q}_{TES,th}$ is the power delivered by the storage to the
 216 load. When optimising a heating/cooling system coupled with a TES, the most common
 217 approach is to model the storage energy content as a single state, i.e., perfectly mixed [45–
 218 47]. This assumption allows to simplify the optimal control problem formulation, which
 219 otherwise would result in a non-convex optimisation problem. Moreover, incorporating
 220 buoyancy or mixing would result in transient model behaviour and, consequently, unsuitable
 221 for gradient based optimization methods, as outlined in Beaten et al. [48]. Furthermore,
 222 the assumption of perfect mixing represents a conservative hypothesis, since neglecting the
 223 spatial distribution of the temperature profile in the tank leads to a lower exploitation of
 224 the TES, since the storage is not used to its full extent, as it has been shown in [48].

225 The storage losses ($\dot{Q}_{TES,loss}$) are evaluated as shown in Eq. 6, where UA_{TES} is the
 226 overall heat transfer coefficient, considered proportional to the size of the tank [49], while
 227 $\Delta T(t)$ is the difference between the storage temperature and its surrounding temperature.

$$\dot{Q}_{TES,loss}(t) = UA_{TES} \cdot \Delta T(t) \quad (6)$$

228 Finally, Eq. 7 is used to determine the useful stored energy a state of charge (SoC)
 229 parameter, in which T_{em} and T_{TES}^{max} are the constant temperature required by the emission
 230 system and the maximum storage temperature, respectively.

$$SoC = \frac{T_{TES} - T_{em}}{T_{TES}^{max} - T_{em}} \quad (7)$$

231 2.2. OCP and implementation of DR program

232 2.2.1. Baseline OCP

233 In order to define a baseline case to assess the impact of the applied active demand
 234 response measures, a scenario with no DR measures is considered. In this scenario, the

235 hybrid generator is controlled by an MPC strategy aimed at satisfying the load demand
 236 while minimising the operative-cost of the system, according to the hourly profile of the
 237 electricity tariff from the day-ahead market. To this end, an open-loop OCP is solved at
 238 each time-step over a chosen prediction horizon τ . Once the optimal control profiles are
 239 obtained, only the first action of the computed control sequence is implemented to get a
 240 new system state before the optimisation process is repeated. Since the OCP is aimed at
 241 minimising the operational costs for heating, the objective function J is defined as the cost
 242 over the horizon τ (C_τ), as shown in Eq. 8.

$$J = C_\tau = \int_0^\tau \left[p_{el}(t) \frac{\dot{Q}_{HP,th}(t)}{COP(t)} + p_{gas} \frac{\dot{Q}_{B,th}(t)}{\eta_B} \right] dt \quad (8)$$

243 $\dot{Q}_{HP,th}$ and $\dot{Q}_{B,th}$ in Eq. 8 are the thermal power delivered by the heat pump and the
 244 boiler, respectively, while p_{el} and p_{gas} denote the electricity and gas tariffs, respectively.
 245 The thermal dynamics of the storage tank are considered as a state constraint expressed
 246 by the energy balance shown in Eq. 5. Several constraints must be applied to the operative
 247 ranges of the generators and the thermal energy storage. Regarding the generators, the
 248 following expressions are used:
 249

$$\dot{Q}_{HP,th}^{min} \leq \dot{Q}_{HP,th}(t) \leq \dot{Q}_{HP,th}^{max} \quad \forall t \in [0, \tau] \quad (9)$$

$$\dot{Q}_{B,th}^{min} \leq \dot{Q}_{B,th}(t) \leq \dot{Q}_{B,th}^{max} \quad \forall t \in [0, \tau] \quad (10)$$

250
 251 Moreover, information about the minimum temperature required by the building emitter
 252 system must be provided, since it affects the amount of useful stored energy. For this reason,
 253 and considering that the storage temperature (T_{TES}) varies during the day depending on the
 254 different charging and discharging phases (and heat losses), the storage is considered capable
 255 of delivering energy to the load only if its temperature is above the minimum temperature
 256 required by the emitter system. Considering $\dot{Q}_{S,th}$ as the power delivered by the storage
 257 tank to the building, this condition can be introduced as follows:

$$\begin{cases} \dot{Q}_{TES,th}(t) \geq 0, & \text{if } T_{TES}(t) \geq T_{em} \\ \dot{Q}_{TES,th}(t) = 0, & \text{otherwise} \end{cases} \quad \forall t \in [0, \tau] \quad (11)$$

258
 259 Further constraints on the operative range of the storage tank temperature are introduced
 260 by means of the following inequalities:

$$T_{TES}^{min} \leq T_{TES}(t) \leq T_{TES}^{max} \quad \forall t \in [0, \tau] \quad (12)$$

261
 262 In order to ensure the fulfilment of the building thermal demand at any time, the following
 263 constraint is added:

$$\dot{Q}_{TES,th}(t) + \dot{Q}_{B,th}(t) = \dot{Q}_{L,th}(t) \quad \forall t \in [0, \tau] \quad (13)$$

264 The implementation of the above methodology in a real control application requires the
 265 use of forecasting models for estimating future weather and market price profiles, which may
 266 affect the solution of the optimisation problem described above. As for instance, Felten and
 267 Weber [50] analysed the impact of forecast errors on estimating the flexibility potential of
 268 an air-source heat pump, coupled with a thermal heat storage and controlled by a MPC
 269 strategy. The results estimated differences of heat pump energy consumption and operation
 270 costs were below 5% when compared to the ideal case of a perfect foresight. Moreover, the
 271 authors showed that the effect of this error has to be considered as relevant when large
 272 storage are installed (i.e., $TES > 1 \text{ m}^3$). However, since the present work performs an *ex-*
 273 *post* analysis, in which historical weather and market price data are used as external signals,
 274 the assumption of a perfect forecast is considered.

275 2.2.2. DR strategy

Once the baseline OCP is solved, several active DR measures are implemented to adapt
 the user demand profiles to possible grid requirements. Indeed, depending on the specific
 circumstances - e.g. mismatch between power supply and demand - the amount of energy
 consumed can be increased (positive flexibility) or reduced (negative flexibility) by modifying
 the baseline heat pump electrical load profile ($P_{HP,el}^{ref}$). In view of this, the hourly electricity
 price is assumed to be an external signal driving the DR request from the grid end a threshold
 cost function has been introduced to simulate the activation of this condition which is, by
 definition, a discrete variable: DR request on or off [5, 51]. When the price is above the
 threshold value (p_{el}^{thld}), a DR action is activated, and the reference heat pump electrical
 power is reduced to a fraction (α) of its value, as shown in Figure 3. It is important to
 state that the identification of a methodology aimed at defining such a threshold price still
 represents a research gap, as highlighted by [5]. While fixed values over the whole year are
 widely adopted, as in [5], Rodriguez et al. [51] demonstrated that using dynamic thresholds,
 calculated on a daily basis and capable of capturing the daily price variations, represents a
 better alternative. Therefore, in the present work, the threshold price is evaluated by using
 the formulation adopted in [5] (Eq. 14), which is computed on a daily basis. The terms
 $\mu_{p_{el}}$ and $\sigma_{p_{el}}$ are the mean and the standard deviation of the daily electricity price profile,
 respectively.

$$p_{el}^{thld} = \mu_{p_{el}} + \sigma_{p_{el}} \quad (14)$$

276 Moreover, it is important to highlight that the adoption of a threshold value as a trig-
 277 gering signal for the activation of a DR action, does not affect the possibility to have an
 278 appropriate heat pump response. Arising from its predictive capability, the controller can
 279 schedule the heat pump operation taking into account any future DR requests, while eval-
 280 uating its impact on the considered objective function, namely the operational costs of the
 281 system. In the present analysis, a maximum duration of the demand response action of two
 282 hours is considered [16]. Therefore, the baseline consumption profile is modified in a new
 283 target profile ($P_{HP,el}^{target}$) and a new OCP can be formulated by adding a flexibility constraint

284 (Eq. 15) aimed at equalling the heat pump consumption profile with the target profile,
 285 during those hours in which the DR action is active ($\delta = 1$).

$$\int_0^\tau \left[\frac{\dot{Q}_{HP,th}(t)}{COP(t)} - P_{HP,el}^{target}(t) \right]^2 dt = 0 \quad (15)$$

$$P_{HP,el}^{target}(t) = \alpha \cdot \delta(t) \cdot P_{HP,el}^{ref}(t) \quad (16)$$

286

287 The term δ in Eq. 16 is a binary variable equal to unity only when the DR is active:

$$\delta(t) = \begin{cases} 1 & \text{if } p_{el}(t) \geq p_{el}^{thld} \\ 0 & \text{otherwise} \end{cases} \quad (17)$$

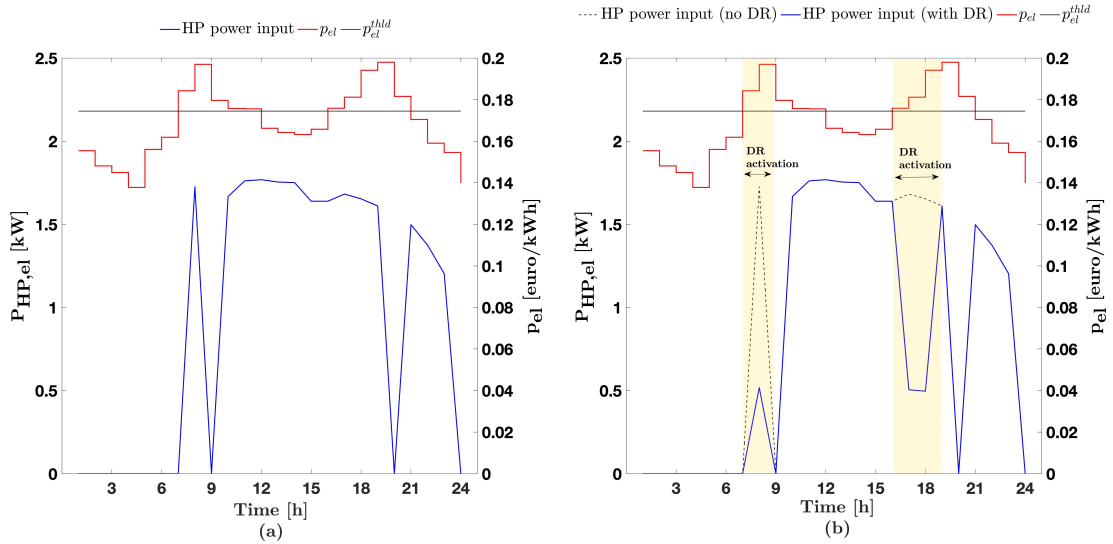


Figure 3: Demand Response measure.

288 2.2.3. Flexibility indicators

289 The impact of the applied demand response measures is assessed by comparing the daily
 290 costs resulting from the solution of the new OCPs and the reference costs. The cost-deviation
 291 from the baseline case can be defined as follows:

$$\delta C_{Flex} = C_{Daily}^\alpha - C_{Daily}^{ref} \quad (18)$$

292

293 while the marginal or specific cost can be defined as the ratio between cost-deviation (Eq.
 294 18) and reduction in the heat pump electrical energy consumption due DR (δE_{DR}) as:

$$c = \frac{\delta C_{Flex}}{\delta E_{DR}} \quad (19)$$

295
 296 An environmental indicator is also defined as the variation of the primary energy consump-
 297 tion caused by the DR actions (δPE):

$$\delta PE = PE_{DR} - PE^{ref} \quad (20)$$

298 3. Case Study

299 Since the current research investigates DR programs at the generator level (no DR actions
 300 at building level, e.g. changes in the internal temperature set point, are considered), the
 301 building is considered a boundary condition of the optimisation problem. To this end,
 302 a synthetic building thermal demand profile ($\dot{Q}_{L,th}$) is evaluated according to the Energy
 303 Signature method [52]. This method evaluates the building load demand as a linear function
 304 of the temperature difference between the indoor air and the external air, whose slope and
 305 intercept are indexes of the overall heat transfer coefficient and the maximum building
 306 thermal load, respectively.

307 Considering the internal air thermostatically controlled, the thermal load reaches the
 308 design value ($\dot{Q}_{L,th}^{max}$) when the external temperature reaches the design outdoor temperature
 309 (T_{ext}^{des}), while it becomes zero at the switch-off temperature (T_{ext}^{off}), where building gains and
 310 losses are balanced and the heating system is turned off (see Eq. 21).

$$\dot{Q}_{L,th} = \dot{Q}_{L,th}^{max} \cdot \left(1 - \frac{T_{ext} - T_{ext}^{des}}{T_{ext}^{off} - T_{ext}^{des}} \right) \quad (21)$$

311 The building is assumed to be located in North-Eastern Italy, in the city of Trieste,
 312 within the Italian climatic zone E [53]. The maximum required heating load of the buildin
 313 is 6 kW at a design temperature of $T_{ext}^{des} = -1.1$ °C and a room temperature of 20 °C, while
 314 it becomes equal to zero when the external temperature is $T_{ext}^{off} = 20$ °C. The resulting
 315 thermal load profile obtained is shown in Figure 3a. The hourly profile of the external
 316 temperature (Figure 3b) was taken from the Italian Thermo-Technical Committee [54].

317 The COP of the HP is evaluated as described in Section 2.1 (Eq. 1 and Eq. 4) consid-
 318 ering the temperature of the storage tank as T_H and the external temperature as T_L . The
 319 heat pump cut-off temperature is set equal to $T_{cut-off} = 0$ °C [55], while a low tempera-
 320 ture heating emitter system with a constant emitter supply temperature (T_{em}) of 45 °C is
 321 considered [19, 42].

322 The storage tank, assumed to be located in a utility room with a constant temperature
 323 equal to °C, is sized such that the maximum heat load of the year can be supplied to the
 324 building for 2 hours [56]. Considering the allowed temperature difference in the storage
 325 $\Delta T_{TES} = 20$ °C and the specific heat capacity of water, this leads to a storage size of 0.086
 326 m³ per kW nominal heat load, which for a maximum building heating demand of 6 kW
 327 corresponds to a storage size of around 0.5 m³.

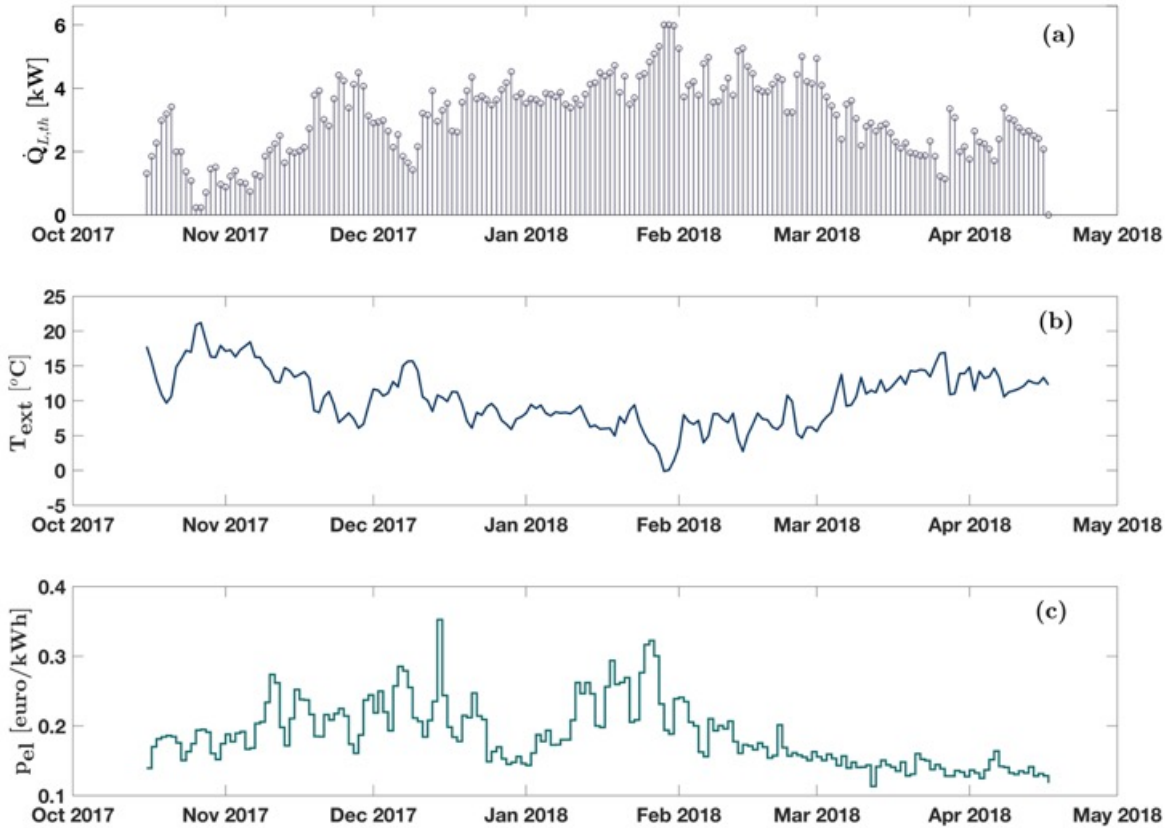


Figure 4: Hourly Profiles during the heating season: (a) Building heating demand; (b) External temperature; (c) Electricity prices.

328 Several demand response strategies are considered according to the procedure described
 329 in Section 2.2, on the basis of hourly values of the electricity prices extracted from the Italian
 330 Electricity Market Operator (EMO) database with regard of the year 2017 (Figure 3c) [57].
 331 The threshold value for the activation of the DR action is determined in accordance with
 332 Eq. 14, while different DR measures are investigated by varying the term α , in the range
 333 $[0.3,1]$. Finally, the natural gas price is considered constant and equal to 0.08 €/kWh . All
 334 the simulations were performed over the heating season, which goes from the 15th October
 335 to the 15th April according to D.P.R n.412/1993 [53]. Table 1 summarise the characteristics
 336 of the building load demand and of the heating and emission systems.

337 The continuous form of the two OCPs, as described in Section 2.2, is converted into a
 338 non-linear programming problem (NLP) by using a direct collocation technique, with three
 339 collocation points for each simulation time step, which is set equal to 1 hour [58]. The
 340 resulting NLP is solved over a discretised prediction horizon of 24 hours using the CasADI
 341 interface to IPOPT with Python [59].

Parameter	Units	Value
Annual energy consumption	kWh	7740
Peak load demand $\dot{Q}_{L,th}^{max}$	kW	6
Design external temperature T_{ext}^{des}	$^{\circ}C$	-1.1
Shut-off temperature T_{ext}^{off}	$^{\circ}C$	20
Emitter temperature set-point T_{em}	$^{\circ}C$	45
Heat pump size	kW	4
Boiler efficiency	-	0.96
TES size	m^3	0.5/0.75
U_{TES}	W/m^2K	0.5

Table 1: Characteristics of the building and its heating system.

342 4. Results and discussion

343 Section 4.1 gives a flexibility assessment based on different hybrid system configurations.
344 In particular, the impact of a TES on control strategy and resulting seasonal costs and energy
345 consumption is compared to a configuration with no TES. In section 4.2, a characterisation
346 of energy flexibility potential and associated marginal costs is presented with regard to the
347 configuration with TES for different DR actions.

348 4.1. Impact of TES

349 Table 2 presents the results based on the methodology described in Section 2 and includes
350 the baseline OCP problem with an implemented PBP for the configuration without TES
351 and with TES. It can be observed a cost-saving and a reduction in seasonal primary energy
352 consumption up to 8% and 13.5%, respectively, for the configuration with TES compared
353 to that without a storage tank. Both results are due to the capability of the controller to
354 exploit periods when low electricity tariffs apply. This can be observed by analysing in detail
355 the daily operation of generators in both cases (see Figure 5).

Configuration	Boiler share [%]	HP share [%]	PE [kWh]	Tot. Cost [€]
no TES	49.5	50.5	7423	590
TES (0.5 m^3)	24.5	75.5	6444	541

Table 2: Seasonal load share, primary energy (PE) consumption and total cost for the configuration without and with TES under a PBP.

356 Figure 5 shows the daily operation of the generators (Figure 5a and 5b) over the first week
357 of February (chosen as being representative of typical winter conditions) for both analysed
358 configurations. In addition, the net energy balance of the TES is presented in Figure 5c. On
359 the basis of Eq. 5, positive energy represents the charging phase of the tank (input greater
360 than output), while negative energy the discharging phase.

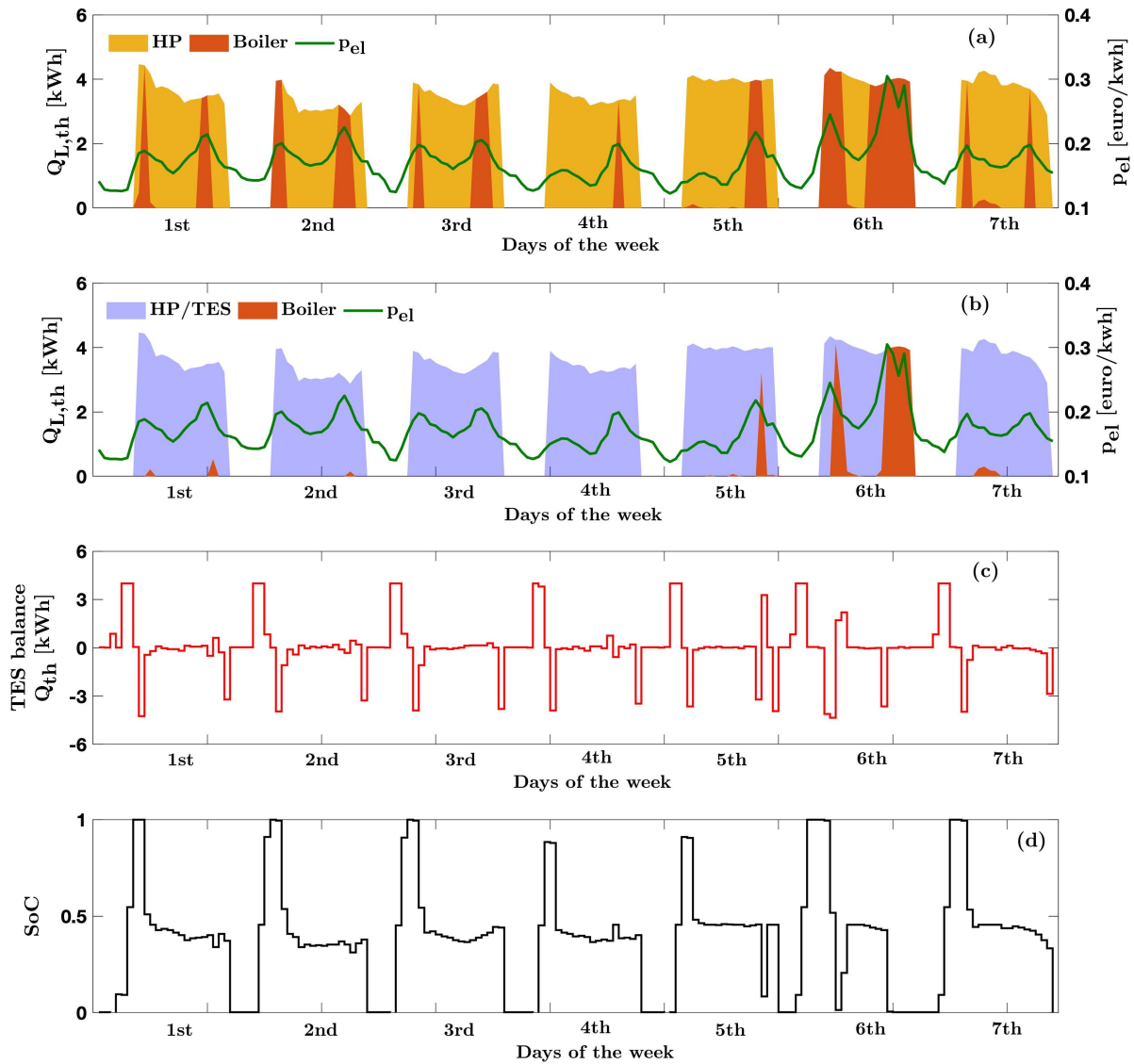


Figure 5: Hourly profile between February 1st and 7th: (a) Load share between heat pump and boiler (configuration without TES); (b) Load share between heat pump/TES and boiler (configuration with TES); (c) Charging and discharging phases of TES; (d) State of charge (SoC) of TES.

361 Figure 5d, represent the evolution of the state of charge of TES over the considered
 362 period. It can be noted that without TES, the controller operates the heat pump for most
 363 of the time, while the gas boiler enters into production only during hours during which
 364 the electricity price reaches high values. On the other hand, if a TES is introduced, this
 365 behaviour is limited only to the 5th and 6th day of the week. This can be explained by
 366 comparing the thermal energy delivered by the boiler for the configuration without TES and
 367 its relationship with the maximum storage capacity (equal to 8 kWh). For this case, the

368 thermal energy delivered by the boiler during days 1 to 4 is lower than the storage capacity
 369 and, consequently, the load shift operated by the controller to pre-charge the storage unit by
 370 running the HP during off-peak periods is enough to avoid the activation of the gas boiler
 371 during those hours when the HP is less cost-effective. On the other hand, for days 5 and 6,
 372 the TES is not capable of storing all the energy required to avoid the boiler entering into
 373 production.

To better understand the logic followed by the controller, Figures 6 and 7 examine in more detail the results obtained for day 2. In the configuration without TES, the control strategy prioritises the most cost-effective generator for each time step. In particular, it can be noted that the controller operates the HP only when its COP is higher than a threshold value (COP_{eq}), calculated on the basis of electricity and gas prices and the efficiency of the gas boiler:

$$COP_{eq}(t) = p_{el}(t)/p_{gas} \cdot \eta_B \quad (22)$$

374 The COP of economic equivalence is an important metric representing the COP at which
 375 the HP is economically equivalent to the gas boiler. Since the controller tends to minimise
 376 the operative cost of the system, the HP will operate only if $COP > COP_{eq}$, otherwise the
 377 controller will favour the boiler. Moreover, in the configuration without TES, the system is
 378 incapable of exploiting periods when low electricity tariffs apply (4 am - 6 am, Figure 6),
 379 since generation and demand cannot be decoupled and the balance between them must be
 380 met at every moment.

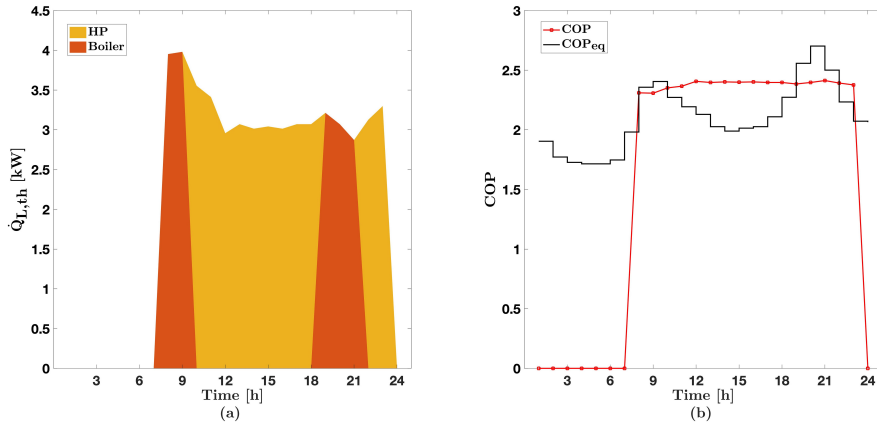


Figure 6: Configuration without TES: Load share between the generators and evolution of COP and COP_{eq} (Day 2).

381 On the other hand, when a TES is installed, the controller can exploit the available
 382 flexibility, thereby taking advantage of lower tariffs (see Figures 7a-7b). Consequently, load-
 383 shifting can be observed since the HP is operated to charge the storage tank during the
 384 night, when the load demand is zero and the electricity price is lower, reducing the load-
 385 share covered by the gas boiler from 33% to 0.3% compared to the configuration without
 386 TES. The same behaviour is found for the other days, as per Table 3, which reports the load
 387 share between the generators and TES during the considered week.

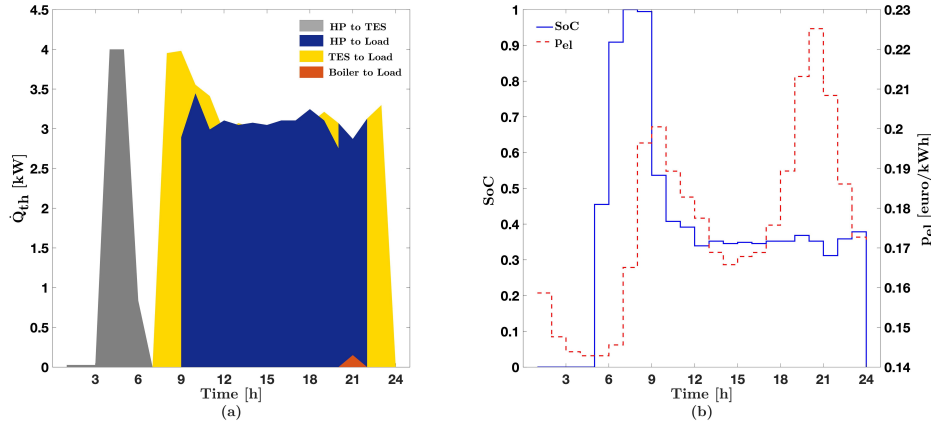


Figure 7: Configuration with TES (Day2): (a) Load share between generators and TES (b) TES State of charge (SoC) and electricity price evolution.

388 Finally, it can be observed that, even if the TES allows the most cost-effective load-
 389 shifting strategy, the overall energy consumption of the system slightly increases because of
 390 the TES thermal losses.

	Boiler [kWh]		HP _{th} [kWh]		HP _{el} [kWh]		TES [kWh]		Demand [kWh]
	No TES	TES 0.5m ³	No TES	TES 0.5m ³	No TES	TES 0.5m ³	No TES	TES 0.5m ³	
Day 1	12	0.7	46.6	57.8	19.9	23.1	–	56.9	58.6
Day 2	17	0.6	34.6	52	14.5	20.2	–	51.1	51.7
Day 3	14.3	0	42.2	56.7	17.9	22.3	–	56.5	56.5
Day 4	3.4	0	51.5	55.7	21.8	21.7	–	54.9	54.9
Day 5	12.2	4	51.6	60.6	22.4	24.7	–	59.8	63.8
Day 6	48.5	27	15.9	38.3	6.9	15.6	–	37.4	64.4
Day 7	8.4	0.9	53.6	60	22.7	24.3	–	60.1	61

Table 3: Energy share between generators and TES for each day of the week for configurations without TES and with TES.

391

392 4.2. Impact of DR programmes

393 The present section analyses the impact on the daily operational cost of different active
 394 DR measures, based on the reduction of the daily energy consumption according to specific
 395 requests from the grid. To this purpose, the operative (marginal) costs resulting from the
 396 variations of the electrical consumption from the baseline identified in the previous section
 397 must be determined. All results are based on the solution of the OCP under PBP conditions.
 398 Hence, the marginal costs for the provided flexibility are assessed as the ratio of the difference
 399 between the new costs and the baseline cost (see Eq. 18) and the reduction in the electrical
 400 energy consumption during the DR actions (Eq. 19). At first, a power reduction of the

401 heat pump electric load profile due to the DR equal to 50% and 70% of the reference value
402 ($\alpha = 0.5$ and $\alpha = 0.3$) are considered. Then, a sensitivity analysis on α is carried out by
403 varying its value within the range 0.3 – 1.

404 Figure 8 refers to the 2nd day of the week considered in previous sections, and it shows
405 the optimal control strategy related to the baseline case, without DR (Figure 8a), and those
406 with DR program implemented (Figures 8b and 8c). The results show an increase in gas
407 boiler usage during the hours in which the DR action is active (at 9am and between 6 pm –
408 7 pm). At the same time, changes in the use of the storage tank and, consequently, of the
409 heat pump before the DR event are observed. Examining the profile of the state of charge
410 (SoC) of the storage tank, it can be noted that a load-shift occurs just before the start of
411 the DR action: the controller anticipates the DR action by charging the TES and reuse this
412 energy later when the DR action is activated.

413 Compared to the baseline case (Figure 8a), Figures 8b and Figure 8c show that when
414 the DR is introduced, the HP operates at its maximum power between 4 pm – 5 pm. In this
415 way, a fraction of the thermal energy (34% and 25% for $\alpha = 0.5$ and $\alpha = 0.3$, respectively)
416 can be shifted to the period when the HP has to reduce its power consumption due to the
417 limit imposed by the DR request. It is interesting to note that the same behaviour is not
418 observed for the first DR of the day (at 9 am): in this case, the evolution of the SoC in
419 the baseline case indicates that the storage tank capacity is already at its maximum value
420 ($SoC = 1$) before the start of the DR action. Consequently, the heat pump cannot be
421 operated to anticipate the DR action and, consequently, no modifications in the charging
422 profile occur.

423 Generally, an energy flexibility event may be followed by a rebound effect. For instance,
424 a DR action aimed at reducing the internal temperature set point is typically followed by
425 a rebound effect due to the energy required to restore the previous temperature set point.
426 However, in the present case study, it is possible to maintain the heat supply as well during
427 the DR event arising from the presence of the TES and the gas boiler, as highlighted in
428 [60]. As a consequence, no rebound effects follow the DR measures, but they result in a
429 higher usage of the heat pump, to charge the TES before that the DR action takes place.
430 It should be pointed out that at the end of the day both the HP operation and the state of
431 charge of the storage are almost the same independently of the applied DR action ($\alpha = 0.5$
432 or $\alpha = 0.3$). Therefore, each day can be considered as independent by the previous one in
433 terms of DR planning.

434 Table 4 and Figure 9 assess the effectiveness of the TES in shifting the accumulated
435 energy that must be transferred from the boiler to the heat pump arising from the DR
436 event. Results are presented for a comparative analysis between TES systems with $0.5 m^3$
437 and $0.75 m^3$ storage capabilities. For the analysis, different DR actions are considered by
438 varying the value of the parameter α within the range 0.3 – 1. Referring to Table 4, it can
439 be noted that the load share covered by the boiler decreases as the available storage capacity
440 increases, since the controller is able to exploit the more cost-effective heat pump. Moreover,
441 the load fraction which can be shifted ahead during the day by using the HP before the DR
442 activation depends on the forecast capability as well as on the storage capacity (higher
443 storage capacities lead to higher load shifts and vice-versa). Nevertheless, a saturation of

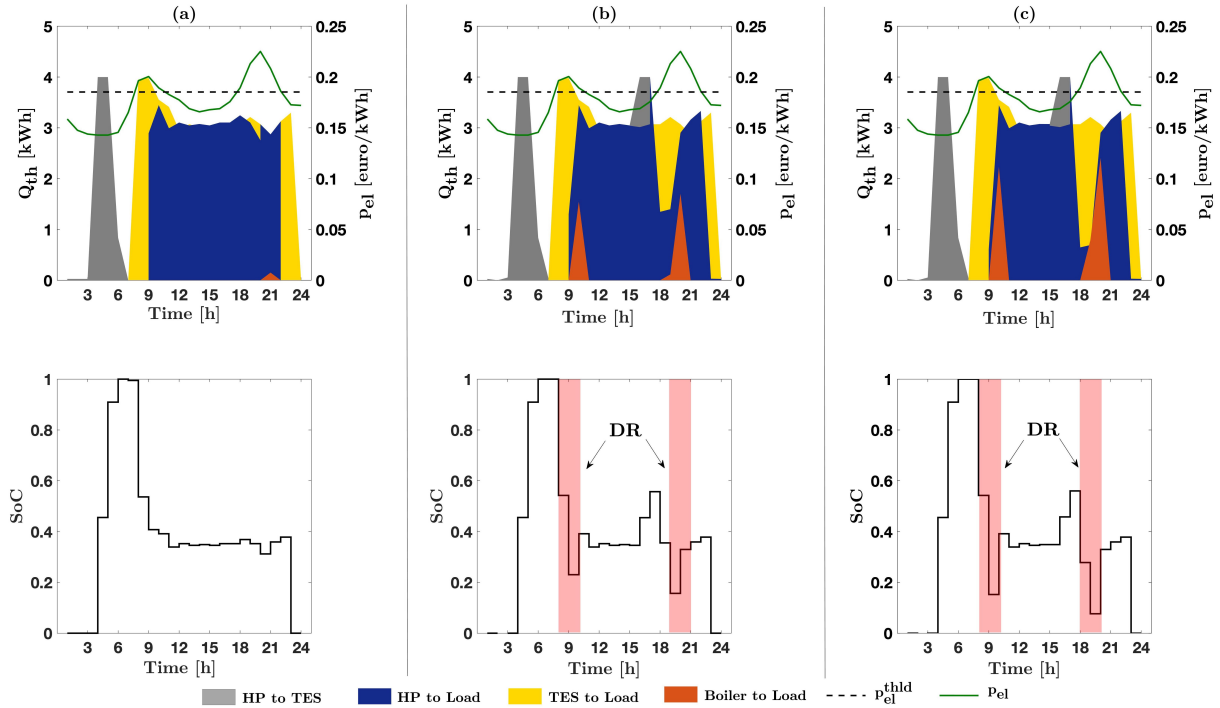


Figure 8: Load share between Boiler and TES and evolution of TES SoC (Day 2): (a) $\alpha = 1$ (no active DR); (b) $\alpha = 0.5$; (c) $\alpha = 0.3$;

444 the load-fraction covered by the storage would be expected to occur, if further limitations
 445 on the heat pump operation are considered (e.g., when DR occurs over a longer period or
 446 for lower α).

447 The daily cost-deviation and the specific cost of the flexibility provided are reported
 448 in Figure 9a. If no TES are installed, the cost-deviation results are proportional to the
 449 reduction of the HP electricity consumption. Therefore, the related specific costs remain
 450 constant for all α considered. On the other hand, both configurations with TES installed
 451 showed a non-linear behaviour of cost-deviation curves. In particular, the cost-deviation
 452 increases slowly, as outlined by the values of the related specific costs. This positive effect,
 453 is due to the load shift that the controller is capable to operate before the activation of

	no TES		TES 0.5 m ³		TES 0.75 m ³	
	Boiler [%]	HP-TES [%]	Boiler [%]	HP-TES [%]	Boiler [%]	HP-TES [%]
$\alpha = 0.3$	37	63	10	90	3.4	96.6
$\alpha = 0.5$	35.6	64.4	6.5	93.5	2.6	97.4
$\alpha = 1$	33	67	0	100	0	100

Table 4: Load share between the HP/TES and the gas boiler.

454 the DR, limiting as consequence the use of the less cost-effective gas boiler. It should be
 455 also noted in Figure 9a that the higher values of the cost-deviation (δC_{Flex}) with regard the
 456 configuration with $0.5m^3$ water tank are due to the higher energy reduction performed during
 457 the DR (see Figure 9b), and not to a lower efficiency of the process or the TES. In fact, the
 458 specific costs decrease as a storage capacity is introduced, highlighting the cost-effectiveness
 459 of TES for DR programs.

460 Finally, it is interesting to note that the configuration with $0.75 m^3$ storage presents
 461 the same specific costs when a fraction equal to 10% and 20%, respectively, of the baseline
 462 electrical energy consumption is reduced as a consequence of DR. Analysing the operation of
 463 the generators, compared to the baseline case, it can be noted that the reduction of thermal
 464 energy due to DR (0.68 kWh and 1.35 kWh for $\alpha = 0.9$ and $\alpha = 0.8$, respectively), is equal
 465 to the energy shifted by operating the HP to pre-charge the storage tank before the DR
 466 request. No variations in the boiler operation are observed, which does not provide any
 467 contribution, as in the baseline case (see Table 4 with TES = $0.75 m^3$ and $\alpha = 1$). This
 468 means that the load demand which cannot be met due to DR limitations can be completely
 469 shifted in time, pre-charging the storage tank before the DR request and avoiding in this
 470 way to increase the gas boiler production to fulfil the load demand, and consequently the
 471 associated specific cost.

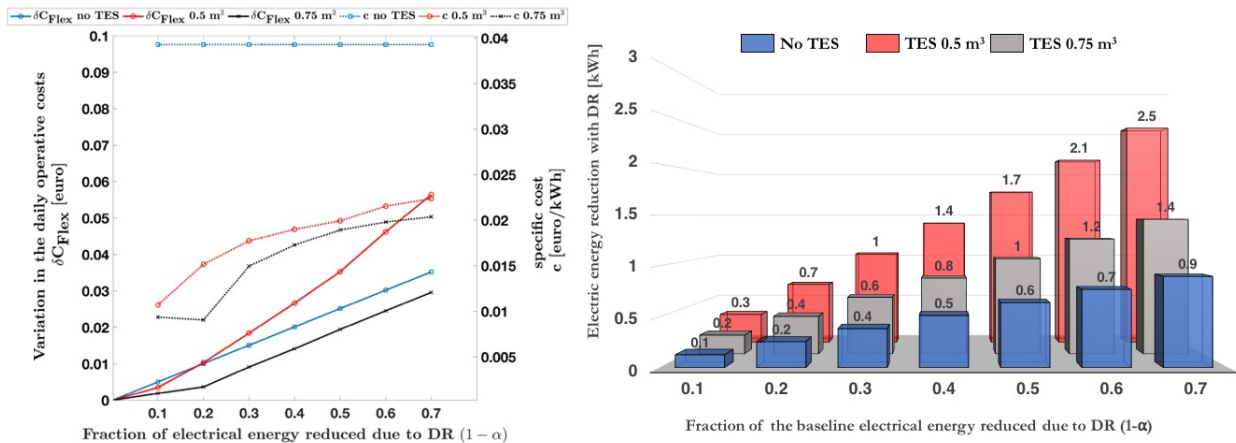


Figure 9: (a) Daily cost and specific costs under different active demand response measures; (b) electrical energy reduced as consequence of DR (Day 2).

4.3. Seasonal assessment of the provided flexibility

472 Applying the proposed methodology over the whole heating season makes possible to
 473 derive maps for each performance indicator (Figures 10a–10c), capable to characterise the
 474 energy flexibility offered by the building following demand-response requests from the the
 475 grid. To detect those days in which the DR request takes place, Figure 10d shows the
 476 evolution over the whole heating season of a DR signal, equal to 1 if one or more DR request
 477 take place and zero otherwise.
 478

479 Results show that the heating season is characterised by two periods of high-demand
 480 of flexibility ($\delta = 1$): one across the months of December and January and another one in
 481 March (see Figure 10d). It can also be observed that these periods are those in which the
 482 highest levels of flexibility are provided (δE_{DR}), while low or nil flexibility can be offered
 483 at both the beginning and the end of the heating season. Indeed, being these periods
 484 characterised by high external temperatures, which lead to a low heating demand, the heat
 485 pump power consumption turns out to be low, thus, reducing its power modulation capacity
 486 and, consequently, the available flexibility. Moreover, these periods are characterised by a
 487 low request of flexibility from the grid, as it shown by the value of the DR signal which is
 488 constantly zero across the end of October and the beginning of November. The maximum
 489 flexibility potential is achieved in March, when the building can offer a reduction of the
 490 energy consumption up to 4.5 kWh , with a cost deviation and an increase in the primary
 491 energy consumption of 0.15 € and 3.5 kWh , respectively.

492 It is important to mention that these maps can be used either by the end-user or by a
 493 grid-operator to identify day by day the best DR action to be implemented in accordance
 494 with their needs. For instance, an end-user might be interested in identifying the DR action
 495 that minimises its cost while preserving the comfort constraint within the building, while
 496 a grid-operator might be interested also in those DR actions that minimise the flexibility
 497 costs as well as other environmental indicators, such as the primary energy consumption or
 498 the total CO_2 emission associated with them.

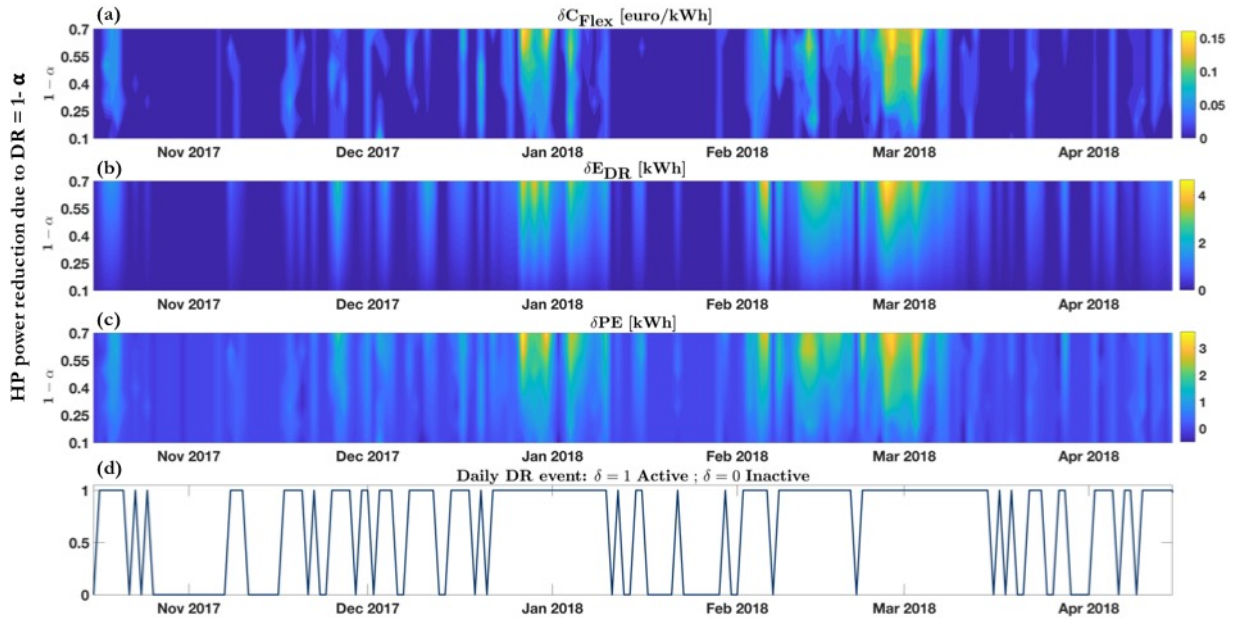


Figure 10: (a-c) Performance maps over the whole heating season and (d) evolution of the DR request.

499 5. Conclusions

500 The present work investigated the flexibility potential associated with a building equipped
501 with an optimally controlled hybrid generator (an electrically driven air source heat pump
502 and a gas boiler) under different demand response measures. The impact of thermal energy
503 storage coupled with the heating system and the control strategy of the heat pump unit
504 were also analysed. The main findings can be summarised as follows:

- 505 • Impact of the TES: the comparison between the two-studied configurations (without
506 and with TES) demonstrated the cost-effectiveness of installing the TES. The storage
507 tank enables the controller to operate the heat pump by taking advantage of periods
508 during which low electricity tariffs apply, leading to a more cost-effective operation of
509 the heating system. Moreover, this leads not only to a cost-saving up to 8% but also
510 to a reduction of primary energy consumption (and consequently of CO_2 emissions)
511 up to 13% compared to the configuration without TES. Moreover, the TES allows the
512 controller to operate load-shifting throughout the day, thereby limiting the use of the
513 boiler during periods when the COP is lower than the COP of economic equivalence.
514 Critically, the storage capacity and the heat pump size are interdependent: the HP
515 size affects the time needed to charge the storage and consequently the ability to take
516 advantage of the favourable operating periods during the day. On the other hand, the
517 storage capacity limits the amount of energy that can be shifted. The optimal sizing
518 strategy based on these two perspectives should be further investigated.
- 519 • Impact of DR programs: the TES allows the controller to operate load-shifting through-
520 out the day, thereby limiting the use of the boiler to meet the load demand that cannot
521 be met by the HP due to the limitations imposed by the DR programme. In this way,
522 a reduction in the specific cost associated with different DR actions between 45% and
523 75% is observed for the configuration with 0.5 m^3 TES and between 50% and 78%
524 for that with 0.75 m^3 TES. Moreover, the shape of the specific cost curve is affected
525 by the amount of thermal energy that can be shifted by pre-charging the TES before
526 the DR request. If the shifted energy equals the total thermal energy required by the
527 load during the hours where DR is active, the specific cost will remain nearly constant,
528 otherwise it will start to increase proportionally to the fraction of thermal load that
529 cannot be shifted.
- 530 • Achievable flexibility: the results showed that the energy flexibility is strictly depen-
531 dent on the storage capacity and operations which, in turn, are affected by the gener-
532 ator sizing. Further analysis should be carried out to investigate the effects of these
533 parameters on the available flexibility and its marginal cost, as well as to fully char-
534 acterise the functional relationship between the parameters affecting the cost-curves.
- 535 • Performance indicators: the proposed methodology allows the assessment of the energy
536 flexibility potential through its main dimensions by mapping three flexibility indica-
537 tors: cost-deviation, modulation capacity and efficiency. Those maps can be easily

538 used to identify day by day the best DR action to be implemented and, therefore, they
539 represent useful tools for both building manager and grid-operators.

540 Attempting to further generalise the presented results, additional simulations with different
541 storage capacities and prediction horizon lengths could be performed, providing convenient
542 and useful dimensionless correlations for costs and savings, as a function of the provided
543 flexibility by DR actions.

544

545 **Nomenclature**

546 **Acronyms**

547 B Boiler

548 DR Demand–Response

549 DSM Demand–Side Management

550 EMO Electricity Market Operator

551 HP Heat Pump

552 ICP Incentive–Based Programs

553 MPC Model Predictive Control

554 NLP Non–Linear Programming

555 nZEB nearly Zero Energy Building

556 OCP Optimal Control Problem

557 PBP Price–Based Programs

558 RES Renewable Energy Systems

559 SoC State of Charge

560 TES Thermal Energy Storage

561 **Greek letters**

562 α Percentage of reduction of the electrical power due demand-response action [%]

563 δ Binary variable

564 μ_{el} Mean daily electricity price [$\text{€}/kWh$]

565 σ_{el} Standard deviation of the daily electricity price profile

566 τ Prediction horizon [s]

567 ε Error in the forecast of the external temperature [$^{\circ}C$]

568 **Symbols**

569 δC_{Flex} Daily flexibility cost–deviation [€]

570 δE_{DR} Variation of the Heat Pump energy consumption due to demand-response [kWh]

571 δPE Variation of the Primary Energy consumption due to demand-response [kWh]

572 ΔT Temperature difference between the storage tank and the surrounding environment
573 [$^{\circ}C$]

574 $\dot{Q}_{B,th}$ Boiler thermal output [kW]

575 $\dot{Q}_{HP,th}$ Heat Pump thermal output [kW]

576 $\dot{Q}_{L,th}$ Load demand [kW]

577 $\dot{Q}_{TES,loss}$ Storage losses [kW]

578 $\dot{Q}_{TES,th}$ Storage heat rate [kW]

579 η^{II} Heat Pump second-law efficiency

580 η_B Boiler efficiency

581 \mathcal{H} Hours in the heating season

582 ρ_w Water density [kg/m^3]

583 \tilde{T} External temperature forecast

584 c Specific cost [€/kWh]

585 C_c Degradation coefficient

586 C_{Daily}^{α} Daily cost with demand-response [€]

587 C_{Daily}^{ref} Daily reference cost without demand-response [€]

588 c_w Specific heat of water [kJ/kgK]

589 COP Heat Pump coefficient of performance

590 COP_{eq} Heat Pump coefficient of performance of economic equivalence

591	CR	Heat Pump part-load ratio
592	f_{PL}	Part-load correction factor
593	p_{el}	Electricity Price [$\text{€}/kWh$]
594	p_{gas}	Gas Price [$\text{€}/kWh$]
595	$P_{HP,el}$	Heat Pump electric power [kW]
596	PE	Primary Energy [kWh]
597	t	Time [s]
598	$T_{cut-off}$	Heat Pump cut-off temperature [$^{\circ}C$]
599	T_{em}	Emission system temperature [$^{\circ}C$]
600	T_{ext}	External temperature [$^{\circ}C$]
601	T_{ext}^{des}	Design external temperature [$^{\circ}C$]
602	T_{ext}^{off}	External temperature at which the heating system is turned-off [$^{\circ}C$]
603	T_H	Condenser temperature [$^{\circ}C$]
604	T_L	Evaporator temperature [$^{\circ}C$]
605	T_{TES}	Storage temperature [$^{\circ}C$]
606	UA_{TES}	Storage overall heat transfer coefficient [kW/K]
607	V_{TES}	Storage Volume [m^3]
608	Subscripts	
609	B	Boiler
610	DR	Scenario with demand-response
611	FL	Full-load
612	HP	Heat Pump
613	PL	Partial-load
614	TES	Thermal Energy Storage
615	Superscripts	
616	max	Maximum

617 *min* Minimum

618 *ref* Reference scenario

619 *thld* Threshold

620 References

- 621 [1] European commission, 2050 energy strategy, online report, [https://ec.europa.eu/energy/en/topics/energy-](https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy)
622 [strategy-and-energy-union/2050-energy-strategy](https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy), [last accessed: 06/10/2018].
- 623 [2] US Energy Information Administration, International energy statistics, 4 March 2018.
- 624 [3] A. S. Brouwer, M. Van Den Broek, A. Seebregts, A. Faaij, Impacts of large-scale intermittent renewable
625 energy sources on electricity systems, and how these can be modeled, *Renewable and Sustainable Energy*
626 *Reviews* 33 (2014) 443–466.
- 627 [4] L. Gelazanskas, K. A. Gamage, Demand side management in smart grid: A review and proposals for
628 future direction, *Sustainable Cities and Society* 11 (2014) 22 – 30.
- 629 [5] L. Schibuola, M. Scarpa, C. Tambani, Demand response management by means of heat pumps con-
630 trolled via real time pricing, *Energy and Buildings* 90 (2015) 15–28.
- 631 [6] M. H. Albadi, E. F. El-Saadany, A summary of demand response in electricity markets, *Electric power*
632 *systems research* 78 (2008) 1989–1996.
- 633 [7] M. Starke, D. Letto, N. Alkadi, R. George, B. Johnson, K. Dowling, S. Khan, Demand-side response
634 from industrial loads, in: 2013 NSTI Nanotechnology Conference and Expo, volume 2, p. 46.
- 635 [8] M. H. Shoreh, P. Siano, M. Shafie-khah, V. Loia, J. P. Catalão, A survey of industrial applications of
636 demand response, *Electric Power Systems Research* 141 (2016) 31–49.
- 637 [9] M. Carragher, M. De Rosa, A. Kathirgamanathan, D. P. Finn, Investment analysis of gas-turbine com-
638 bined heat and power systems for commercial buildings under different climatic and market scenarios,
639 *Energy Conversion and Management* 183 (2019) 35 – 49.
- 640 [10] Heat Roadmap Europe 2050, Online report, [https://heatroadmap.eu/wp-](https://heatroadmap.eu/wp-content/uploads/2018/09/3.1-Profile-of-the-heating-and-cooling-demand-in-the-base-year-in-the-14-MSs-in-the-EU28-2.pdf)
641 [content/uploads/2018/09/3.1-Profile-of-the-heating-and-cooling-demand-in-the-base-year-in-the-](https://heatroadmap.eu/wp-content/uploads/2018/09/3.1-Profile-of-the-heating-and-cooling-demand-in-the-base-year-in-the-14-MSs-in-the-EU28-2.pdf)
642 [14-MSs-in-the-EU28-2.pdf](https://heatroadmap.eu/wp-content/uploads/2018/09/3.1-Profile-of-the-heating-and-cooling-demand-in-the-base-year-in-the-14-MSs-in-the-EU28-2.pdf), [last accessed: 31/05/2019].
- 643 [11] European Union, Directive 2010/31/eu of the european parliament and of the council 19 may 2010 on
644 the energy performance of buildings (recast), 2010. In *Official Journal of the European Union*.
- 645 [12] European Union, Directive 2012/27/eu of the european parliament and of the council of 25 october
646 2012 on energy efficiency, amending directives 2009/125/ec and 2010/30/eu and repealing directives
647 2004/8/ec and 2006/32/ec, 2012. In *Official Journal of the European Union*.
- 648 [13] European Union, Directive (eu) 2018/844 of the european parliament and of the council of 30 may 2018
649 amending directive 2010/31/eu on the energy performance of buildings and directive 2012/27/eu on
650 energy efficiency, 2010. In *Official Journal of the European Union*.
- 651 [14] Smart Readiness Indicator for Buildings, <https://smartreadinessindicator.eu>, [last accessed:
652 05/04/2019].
- 653 [15] M. Miara, D. Günther, Z. L. Leitner, J. Wapler, Simulation of an air-to-water heat pump system to
654 evaluate the impact of demand-side-management measures on efficiency and load-shifting potential,
655 *Energy technology* 2 (2014) 90–99.
- 656 [16] F. D’Ettorre, M. De Rosa, P. Conti, E. Schito, D. Testi, D. P. Finn, Economic assessment of flexibility
657 offered by an optimally controlled hybrid heat pump generator: a case study for residential building,
658 *Energy Procedia* 148 (2018) 1222–1229.
- 659 [17] K. Hedegaard, O. Balyk, Energy system investment model incorporating heat pumps with thermal
660 storage in buildings and buffer tanks, *Energy* 63 (2013) 356–365.
- 661 [18] D. Fischer, T. Wolf, J. Wapler, R. Hollinger, H. Madani, Model-based flexibility assessment of a
662 residential heat pump pool, *Energy* 118 (2017) 853–864.

- 663 [19] A. Arteconi, N. J. Hewitt, F. Polonara, Domestic demand-side management (dsm): Role of heat pumps
664 and thermal energy storage (tes) systems, *Applied thermal engineering* 51 (2013) 155–165.
- 665 [20] F. Ruiz-Calvo, M. De Rosa, P. Monzó, C. Montagud, J. M. Corberán, Coupling short-term (b2g model)
666 and long-term (g-function) models for ground source heat exchanger simulation in trnsys. application
667 in a real installation, *Applied Thermal Engineering* 102 (2016) 720–732.
- 668 [21] D. Dominković, P. Gianniou, M. Münster, A. Heller, C. Rode, Utilizing thermal building mass for
669 storage in district heating systems: Combined building level simulations and system level optimization,
670 *Energy* 153 (2018) 949–966.
- 671 [22] C. Finck, R. Li, R. Kramer, W. Zeiler, Quantifying demand flexibility of power-to-heat and thermal
672 energy storage in the control of building heating systems, *Applied Energy* 209 (2018) 409–425.
- 673 [23] G. Reynders, R. A. Lopes, A. Marszal-Pomianowska, D. Aelenei, J. Martins, D. Saelens, Energy flexible
674 buildings: An evaluation of definitions and quantification methodologies applied to thermal storage,
675 *Energy and Buildings* (2018).
- 676 [24] J. Clauß, C. Finck, P. Vogler-Finck, P. Beagon, Control strategies for building energy systems to unlock
677 demand side flexibility—a review, in: *IBPSA Building Simulation 2017*, San Francisco, 7-9 August 2017,
678 IBPSA.
- 679 [25] A. Stafford, An exploration of load-shifting potential in real in-situ heat-pump/gas-boiler hybrid sys-
680 tems, *Building Services Engineering Research and Technology* 38 (2017) 450–460.
- 681 [26] F. Oldewurtel, D. Sturzenegger, G. Andersson, M. Morari, R. S. Smith, Towards a standardized
682 building assessment for demand response, in: *Decision and Control (CDC)*, 2013 IEEE 52nd Annual
683 Conference on, IEEE, pp. 7083–7088.
- 684 [27] R. De Coninck, L. Helsen, Quantification of flexibility in buildings by cost curves—methodology and
685 application, *Applied Energy* 162 (2016) 653–665.
- 686 [28] M. Ali, A. Alahäivälä, F. Malik, M. Humayun, A. Safdarian, M. Lehtonen, A market-oriented hierar-
687 chical framework for residential demand response, *International Journal of Electrical Power & Energy*
688 *Systems* 69 (2015) 257–263.
- 689 [29] G. Bianchini, M. Casini, A. Vicino, D. Zarrilli, Demand-response in building heating systems: A model
690 predictive control approach, *Applied Energy* 168 (2016) 159–170.
- 691 [30] S. Ö. Jensen, H. Madsen, R. Lopes, R. G. Junker, D. Aelenei, R. Li, S. Metzger, K. B. Lindberg, A. J.
692 Marszal, M. Kummert, et al., Annex 67: Energy flexible buildings—energy flexibility as a key asset in
693 a smart building future (2017).
- 694 [31] R. G. Junker, A. G. Azar, R. A. Lopes, K. B. Lindberg, G. Reynders, R. Relan, H. Madsen, Charac-
695 terizing the energy flexibility of buildings and districts, *Applied Energy* 225 (2018) 175 – 182.
- 696 [32] R. Renaldi, A. Kiprakis, D. Friedrich, An optimisation framework for thermal energy storage integration
697 in a residential heat pump heating system, *Applied Energy* 186 (2017) 520 – 529. *Sustainable Thermal*
698 *Energy Management (SusTEM2015)*.
- 699 [33] Pallonetto, F., Oxizidis, S., Duignan, R., Neu, O. and Finn, D., “Demand response optimisation of
700 all-electric residential buildings in a dynamic grid environment: Irish case study”, 13th Conference
701 of the International Building Performance Simulation Association, BS 2013; Chambery; France (2013)
702 1616–1623.
- 703 [34] F. Pallonetto, M. De Rosa, F. Milano, D. P. Finn, Demand response algorithms for smart-grid ready
704 residential buildings using machine learning models, *Applied Energy* 239 (2019) 1265 – 1282.
- 705 [35] F. Pallonetto, S. Oxizidis, F. Milano, D. Finn, The effect of time-of-use tariffs on the demand response
706 flexibility of an all-electric smart-grid-ready dwelling, *Energy and Buildings* 128 (2016) 56 – 67.
- 707 [36] L. Kreuder, C. Spataru, Assessing demand response with heat pumps for efficient grid operation in
708 smart grids, *Sustainable Cities and Society* 19 (2015) 136 – 143.
- 709 [37] K. Aduda, T. Labeodan, W. Zeiler, G. Boxem, Y. Zhao, Demand side flexibility: Potentials and
710 building performance implications, *Sustainable Cities and Society* 22 (2016) 146 – 163.
- 711 [38] D. Patteeuw, L. Helsen, Combined design and control optimization of residential heating systems in a
712 smart-grid context, *Energy and Buildings* 133 (2016) 640–657.
- 713 [39] D. Fischer, T. R. Toral, K. B. Lindberg, B. Wille-Haussmann, H. Madani, Investigation of thermal

- 714 storage operation strategies with heat pumps in german multi family houses, *Energy Procedia* 58 (2014)
715 137–144.
- 716 [40] B. Baeten, F. Rogiers, L. Helsen, Reduction of heat pump induced peak electricity use and required
717 generation capacity through thermal energy storage and demand response, *Applied Energy* 195 (2017)
718 184–195.
- 719 [41] M. Dongellini, C. Naldi, G. L. Morini, Seasonal performance evaluation of electric air-to-water heat
720 pump systems, *Applied Thermal Engineering* 90 (2015) 1072–1081.
- 721 [42] G. Bagarella, R. Lazzarin, M. Noro, Sizing strategy of on–off and modulating heat pump systems based
722 on annual energy analysis, *International journal of refrigeration* 65 (2016) 183–193.
- 723 [43] European Committee for Standardisation, Standard en 14825: 2013, air conditioners, liquid chilling
724 packages and heat pumps, with electrically driven compressors, for space heating and cooling e testing
725 and rating at part load conditions and calculation of seasonal performance, 2013.
- 726 [44] Italian Committee for Standardisation, Standard uni ts 11300 part 4: 2012, energy performance of
727 buildings e part 4: Renewable energy and other generation systems for space heating and domestic hot
728 water production, 2012.
- 729 [45] G. P. Henze, C. Felsmann, G. Knabe, Evaluation of optimal control for active and passive building
730 thermal storage, *International Journal of Thermal Sciences* 43(2) (2004) 173–183.
- 731 [46] S. F. Fux, M. J. Benz, L. Guzzella, Economic and environmental aspects of the component sizing for
732 a stand-alone building energy system: A case study, *Renewable Energy* 55 (2013) 438–447.
- 733 [47] D’Ettorre, F., Conti, P., Schito, E. and Testi, D., Model predictive control of a hybrid heat pump
734 system and impact of the prediction horizon on cost-saving potential and optimal storage capacity,
735 *Applied Thermal Engineering* 148 (2019) 524 – 535.
- 736 [48] B. Baeten, F. Rogiers, D. Patteeuw, L. Helsen, Comparison of optimal control formulations for stratified
737 sensible thermal energy storage in space heating applications, *The 13th International Conference on*
738 *Energy Storage* (2015).
- 739 [49] S. Kalaiselvam, R. Parameshwaran, *Thermal energy storage technologies for sustainability: systems*
740 *design, assessment and applications*, Elsevier, 2014.
- 741 [50] B. Felten, C. Weber, The value(s) of flexible heat pumps assessment of technical and economic
742 conditions, *Applied Energy* 228 (2018) 12921319.
- 743 [51] L. R. Rodríguez, J. S. Ramos, S. Á. Domínguez, U. Eicker, Contributions of heat pumps to demand
744 response: A case study of a plus-energy dwelling, *Applied Energy* 214 (2018) 191–204.
- 745 [52] European Committee for Standardisation, Standard en 15603: 2008, energy performance of buildings
746 e overall energy use and definition of energy ratings, 2008.
- 747 [53] *Gazzetta Ufficiale della Repubblica Italiana*, Decree of the president of the italian republic no. 412,
748 26/08/93 and subsequent modifications, 1993.
- 749 [54] Comitato Termotecnico Italiano, Documentation available at <https://www.cti2000.it> (in italian), [Last
750 accessed: 07/10/2018].
- 751 [55] G. Bagarella, R. Lazzarin, M. Noro, Annual simulation, energy and economic analysis of hybrid heat
752 pump systems for residential buildings, *Applied Thermal Engineering* 99 (2016) 485–494.
- 753 [56] D. Fischer, K. B. Lindberg, H. Madani, C. Wittwer, Impact of pv and variable prices on optimal system
754 sizing for heat pumps and thermal storage, *Energy and Buildings* 128 (2016) 723733.
- 755 [57] Gestore Mercati Energetici, Online database. www.mercatoelettrico.org/it/statistiche/me/datisintesi.aspx
756 (in italian), [last accessed: 07/10/2018].
- 757 [58] M. Kelly, An introduction to trajectory optimization: How to do your own direct collocation, *SIAM*
758 *Review* 59 (2017) 849–904.
- 759 [59] J. A. E. Andersson, J. Gillis, G. Horn, J. B. Rawlings, M. Diehl, Casadi: a software framework for
760 nonlinear optimization and optimal control, *Mathematical Programming Computation* (2018).
- 761 [60] L. Zhang, N. Good, P. Mancarella, Building-to-grid flexibility: Modelling and assessment metrics for
762 residential demand response from heat pump aggregations, *Applied Energy* 233 (2019) 709–723.