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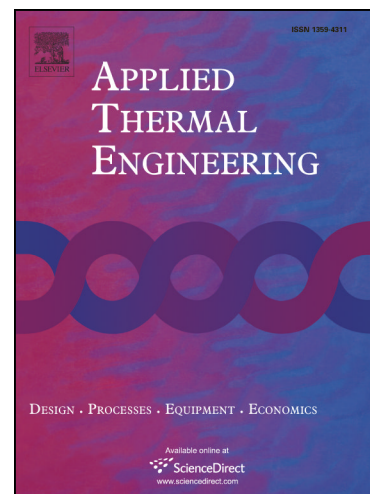
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Demand side management analysis of a supermarket integrated HVAC, refrigeration and water loop heat pump system

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Abstract

Supermarkets are intensive energy consumers because of a high electricity demand, mainly due to refrigeration utilities. Thus, in this work a supermarket integrated HVAC, refrigeration and water loop heat pump (WLHP) system was analyzed according to a demand side management approach, adopting a demand response strategy coupled with real-time pricing predictive rule based controls. The system was modeled with TRNSYS and several DR strategies were applied to both the space heating/cooling and the WLHP to determine the plant configuration with the most effective electricity cost saving. It was found that two setups guarantee the highest economic savings. The first consists of a predictive rule based control applied to the space heating/cooling only, which is basically inexpensive and allows an annual cost saving of 4.06% respect to the baseline configuration. The second, instead, combines predictive rule based controls applied to both the space heating/cooling and the WLHP auxiliary heater, and shows the best performance with the adoption of a 200 m³ water-based thermal energy storage. Respect to the baseline, this configuration provides an annual

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cost saving of 4.67%.

Keywords: Real-time pricing; Predictive rule based control; Thermal energy storage; Flexibility; Day-ahead market

1 1. Introduction

2 The European Renewable Energy Directive sets a target of at least 20% of
3 electricity produced from renewable sources by 2020 [1]. To date, one of the key
4 challenges to overcome the low predictability of renewable energies lies in the in-
5 crease of flexibility of energy networks. With a larger flexibility, energy systems
6 could improve their reliability and make the energy price more competitive.

7 A way to improve the flexibility of an energy system lies in the adoption of
8 demand side management [2]. DSM includes a set of policies able to influence
9 the customer's energy demand, changing the shape of the load and helping to
10 optimize the overall power system from generation to end use [3]. An important
11 DSM policy is referred to as demand response (DR) and consists of changes in
12 electricity use by end customers in response to variations of the electricity price
13 over time [4].

14 Given the more and more relevant energy consumption of the refrigeration
15 sector (17% of the overall electricity used worldwide [5, 6]), nowadays there
16 is a growing interest towards the adoption of DSM strategies by refrigeration
17 technologies. In literature, several works tried to apply DSM strategies to re-
18 frigeration applications. Referring to domestic refrigerators, Stadler et al. [7]
19 compared two types of control signals to use the thermal storage of a high
20 number of controllable refrigerators as balancing power. The authors showed
21 that the two control signals can be used for short term reserves with delivery
22 within 15 minutes, but they differ in possible shapes of the resulting load curves
23 and in the reaction time of the controlled system. In 2013, Niro et al. [8] pro-
24 posed a practical strategy for large-scale control of domestic refrigerators for
25 demand peak reduction in distribution systems. The results confirmed that the
26 strategy could contribute not only to reduce peak demand, but also to improve

27 losses and voltage profile of the power distribution systems. In the same year,
28 Kremers et al. [9] presented a multi-agent simulation model to analyze the pos-
29 sibilities of improving grid stability on island systems by local demand response
30 mechanisms. The authors found synchronization effects among the individual
31 refrigerators loads, having undesirable impacts on the system such as oscillations
32 of loads and frequency. Sossan et al. [10] showed the application of a stochastic
33 gray box model to identify electrical power consumption-to-temperature models
34 of a domestic freezer. The authors applied a model predictive control (MPC) to
35 shift the electricity consumption of the freezer, showing the ability of the MPC
36 to exploit the freezer as a demand side resource.

37 As regards supermarkets and commercial refrigeration systems, in 2012 Hov-
38 gaard et al. [11] proposed a MPC scheme for a supermarket that reduced op-
39 erating costs by utilizing the thermal storage capabilities of refrigerated goods.
40 The authors declared a cost reduction of 9% for a flat-rate fee scenario, and of
41 32% for a scenario with variable taxes. In another work [12], the same authors
42 considered the MPC of a commercial multi-zone refrigeration system used to
43 cool multiple areas/rooms. Through a sequential convex optimization method,
44 the simulations showed cost savings of 30% compared to a standard thermostat-
45 based control system. Shafiei et al. [13] showed a MPC at supervisory level for
46 refrigeration systems including distributed local controllers. The results showed
47 economic savings of 19% with a proportional-integrative control combined with
48 a specific algorithm, 28% using an energy-efficient scenario, and 36% using an
49 economic MPC scheme. Pedersen et al. [14] investigated control strategies for
50 the aggregation of a portfolio of supermarkets towards the electricity balancing
51 market. The large-scale simulation showed that the portfolio could be used for
52 upward regulation of 900 kW for a two-hour period.

53 In this work, instead, the application of DSM strategies to a water loop
54 heat pump (WLHP) system was analyzed. The WLHP system was introduced
55 some years ago to benefit from both distributed heating/cooling generation with
56 local control and lower condensing temperature for the refrigeration. The setup
57 consists of an hydraulic loop that can act simultaneously as sink/source for

58 several reversible water/water heat pumps. The most effective operation occurs
59 when the two operating modes are balanced, i.e. in the mid seasons or when
60 some zones require heating or cooling throughout all the year [15, 16, 17].

61 Thanks to its significant thermal capacity, a WLHP system could be used
62 as a thermal energy storage (TES) with the aim to change the timing of end-
63 use consumption from high-cost periods to low-cost periods, and to increase
64 consumption during off-peak periods. For this reason, the present work aims
65 to analyze the effects on the electricity demand and costs of a DSM strategy
66 implemented in a supermarket, where a WLHP system is integrated with the
67 refrigeration and the HVAC (Heating, Ventilation and Air Conditioning) sys-
68 tems. In this novel setup, for the first time the energy flexibility provided by
69 a water loop reservoir is analyzed. Furthermore, the energy flexibility provided
70 by the supermarket building with its HVAC system is also taken into account
71 and the thermal comfort level of the supermarket was investigated as well. The
72 DSM strategy consists of a DR program activated by real-time pricing (RTP).
73 Given that such strategy is intended also for existing systems, rule based con-
74 trols are considered. Specifically, the present work takes advantage of predictive
75 rule based controls [18], as their formulation is based on the prediction of the
76 electricity price. Respect to other control systems such as MPCs, predictive rule
77 based controls can be implemented inexpensively and they do not require sub-
78 stantial modifications of the setup under study. Additionally, their formulation
79 is almost independent of the energy system where they are applied, thus they
80 can be easily extended to different energy systems.

81 **2. Methods and case study**

82 The analysis aims at illustrating the DSM potential of a WLHP system
83 which provides heating and cooling in a supermarket building and which is cou-
84 pled with its refrigeration system for food conservation. A predictive rule based
85 control depending on RTP is implemented to exploit the energy flexibility pro-
86 vided by: i) the building thermal mass by varying the indoor air temperature

87 set-points; ii) the water loop energy storage by adjusting the temperature set-
88 points which regulate its operating conditions; iii) both the building and the
89 WLHP. Furthermore, the influence of the water storage volume of the plant
90 is taken into account. A real supermarket is considered and the DR strate-
91 gies above described are there implemented. The evaluations are performed by
92 means of a dynamic simulation tool in order to assess the final electricity energy
93 use and cost variations achievable in the DR context.

94 *2.1. Plant configuration*

95 The supermarket is located at the ground floor of a large modern shop-
96 ping mall. Its heating/cooling production plant configuration is depicted in
97 Figure 1. It can be conceptually divided into two sections: a water loop heat
98 pump (WLHP) system and a commercial refrigeration unit (CRU). The WLHP
99 includes several heat pumps (the hydrofluoroolefin R1234ze(E) was adopted as
100 low-GWP refrigerant) that provide climate control on the supermarket ther-
101 mal zones. The CRU, instead, consists of a CO₂ transcritical booster system,
102 comprising an additional high-pressure heat exchanger (HX) for heat recovery
103 purposes in favor of the WLHP.

104 In the heating operating mode, the water loop represents a heat source for
105 the water-to-water/air heat pumps. If the heat transferred from the CO₂ de-
106 superheating process to the water loop is not sufficient, an auxiliary heater based
107 on an air-to-water heat pump intervenes to maintain the water loop temperature
108 at a minimum set-point value. In the cooling season, the heat pumps operate
109 for air conditioning and a dry cooler on the water loop allows heat to be rejected
110 to the external, in order to keep the water temperature as low as possible.

111 The mass flow rate in the loop is constant and equal to around 150 t h⁻¹. A
112 water tank of 50 m³ is also provided as thermal energy storage, with the aim of
113 reducing the intervention of the auxiliary heater or the dry cooler.

114 *2.2. Supermarket building and heating, cooling and DHW demands*

115 The supermarket is divided into 4 different thermal zones, for a total of 12
116 areas: the food store (FDS), 7 common areas/hallways (CMA), 2 warehouses

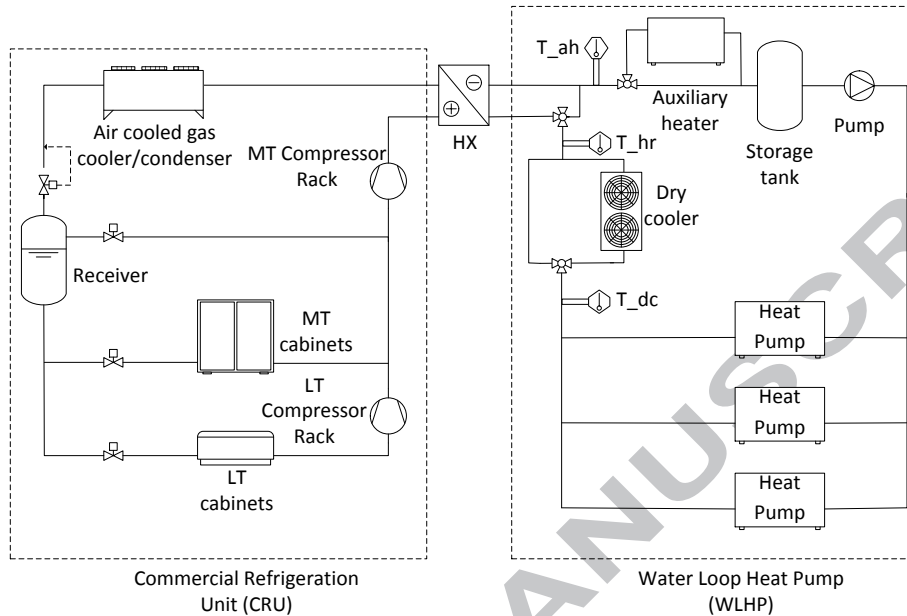


Figure 1: Supermarket heating/cooling production plant configuration.

117 (WRH) and 2 service areas (SVC). The food store consists of a 6352 m² vending
 118 area, while the remaining zones occupy an additional surface of 5411 m².

119 The supermarket is sited in Milan, Italy, a location with mild climate con-
 120 ditions. The monthly heating and cooling demands are detailed in Figure 2.
 121 The domestic hot water demand, instead, was estimated at a maximum value
 122 of 0.250 m³ h⁻¹ during the opening hours. Further details on the supermarket
 123 under study can be found in Polzot et al. [19].

124 2.3. Refrigeration demand

125 The refrigeration unit is divided into a medium (MT) and a low temperature
 126 (LT) section. The MT section is composed of refrigerated display cabinets for
 127 a total length of 208 m and 10 cold rooms, and has a capacity of 140 kW at
 128 an evaporating temperature of -8 °C. The LT section, instead, includes frozen
 129 food display cases for a total length of 86 m and 2 cold rooms, and has a power
 130 of 28 kW at an evaporating temperature of -35 °C.

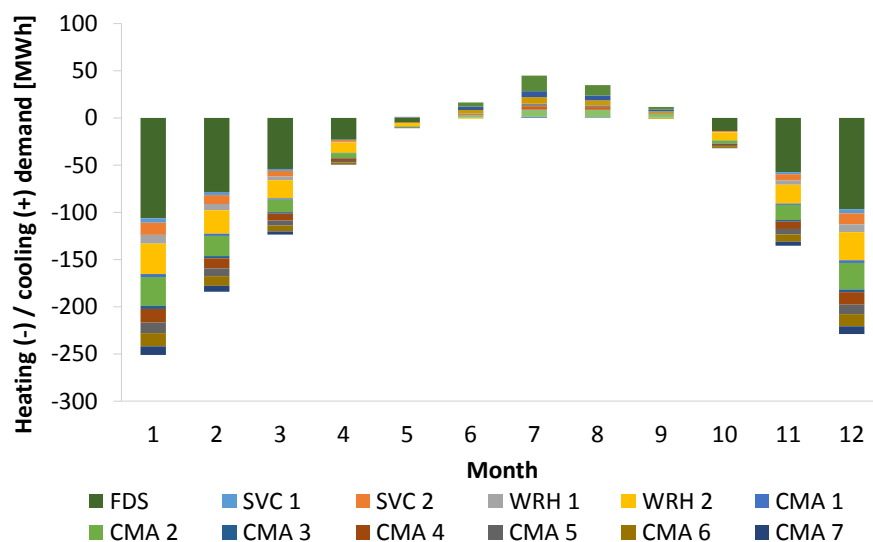


Figure 2: Heating (negative value) and cooling (positive value) demands of the supermarket thermal zones.

131 The monthly cooling load profile is depicted in Figure 3. Its evaluation is
 132 based on a detailed simulation of the refrigerated display cabinets/cold rooms
 133 and their interaction with the indoor ambient [20, 21].

134 3. System modeling

135 The commercial refrigeration unit, the HVAC system and the supermarket
 136 building were modeled in TRNSYS [22], adopting a time step of five minutes.
 137 The analysis was carried out for a full year (2017). The following sections
 138 describe the components of each system in detail.

139 3.1. Commercial refrigeration unit

140 For the CO₂ transcritical booster system with auxiliary compression, the
 141 global efficiencies of the compressors were defined as functions of the pressure
 142 ratio with BITZER Software [23]. The refrigerant thermodynamic properties,
 143 instead, were calculated through CoolProp libraries [24]. The values of the main

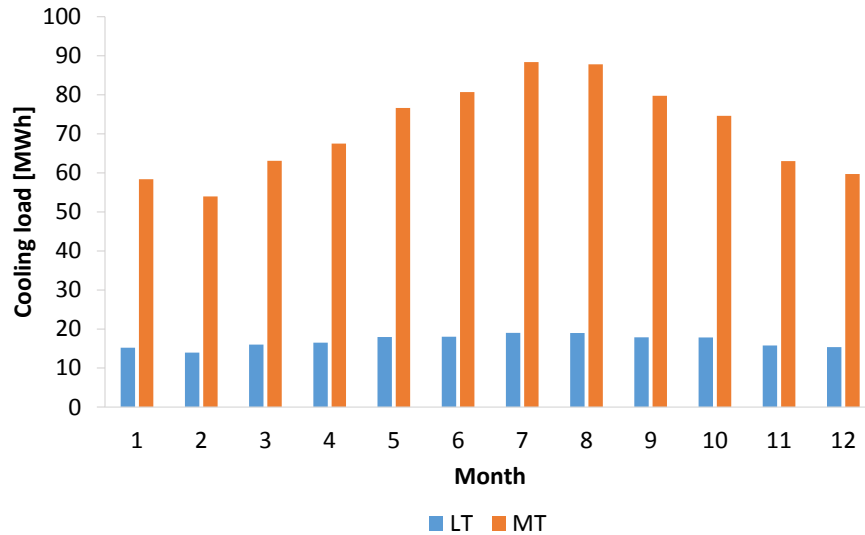


Figure 3: Cooling load of the LT and MT evaporators.

144 design parameters considered for the commercial refrigeration unit are provided
 145 in Table 1.

146 It should be noted that the CO₂ refrigeration system operational mode (sub-
 147 critical, transition or trans-critical) is a function of the ambient temperature,
 148 and its discharge and intermediate pressure at the liquid receiver are optimized
 149 to maximize the *COP* [19, 20].

150 3.2. HVAC system

151 The HVAC system of the supermarket comprises several heat pumps whose
 152 vapor compression cycles were implemented in TRNSYS linked to CoolProp
 153 libraries. The global efficiencies of the compressors were calculated as function
 154 of the pressure ratio by using Frascol Software [25]. The values of the main
 155 design parameters considered for the heat pumps are provided in Table 1. Heat
 156 pumps correlations for *COP* and *EER* were determined through a mathematical
 157 model simulating the R1234ze(E)-based thermodynamic cycle [19] at different
 158 operating conditions on the water loop (source side), while the temperature on
 159 the load side was kept constant at 45 °C in heating and at 7 °C in cooling.

Table 1: Main design parameters of the commercial refrigeration unit (CRU) and the heat pumps.

Quantity	Value
<i>CRU</i>	
MT evaporating temperature [°C]	-8
LT evaporating temperature [°C]	-35
Superheating at evaporators [K]	5
Approach temperature of the condenser/gas cooler [K]	3
Minimum condensing temperature [K]	8
Liquid receiver pressure (subcritical operation) [MPa]	3.8
Approach temperature of heat recovery [K]	5
<i>Heat pumps</i>	
Useful superheating [K]	4
Subcooling in heating mode [K]	3
Subcooling in cooling mode [K]	2
Approach temperature of the source/load HX [K]	5
Minimum condensing temperature (cooling mode) [°C]	25

160 *3.3. Supermarket building*

161 The model for the supermarket building derives from the outcomes of the EU
 162 CommONEnergy project [26]. The building was simulated using the TRNSYS
 163 multi-zone building Type 56. The climate conditions of the site were imported
 164 in the model of the building by means of Meteonorm weather files [27].

165 **4. Demand side management analysis**

166 The DSM strategy applied to the supermarket under study has the purpose
 167 to minimize the yearly electrical energy cost by shifting the electricity demand
 168 from peak hours to off-peak hours, using the energy flexibility provided by the
 169 WLHP circuit and by the building. It is assumed that the supermarket adheres
 170 to a demand response (DR) program based on real-time pricing (RTP) [28].

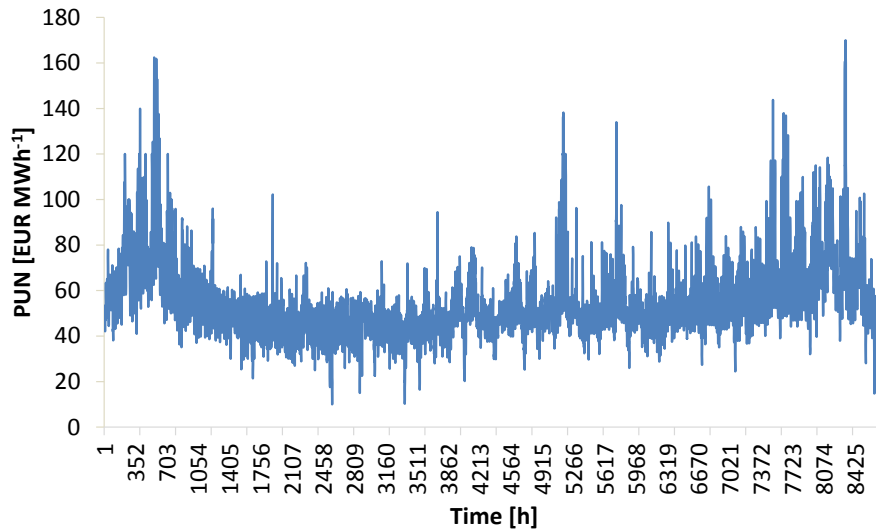


Figure 4: Trend of the Italian PUN in 2017.

171 Since the proposed supermarket is located in Italy, the Italian PUN (Prezzo
 172 Unico Nazionale, National Single Price) was considered as real-time price applied
 173 to the customer. The PUN is the electrical energy reference price observed on
 174 the Italian Power Exchange: it has a resolution of one hour, represents the price
 175 for electrical energy generation only (without taxes) and is based on a day-
 176 ahead market [29]. If the electricity price is well-defined 24 hours early, then
 177 there exists the possibility to implement a RTP predictive rule based control
 178 that tracks the PUN of 2017 (Figure 4).

179 As already mentioned, two different sections of the supermarket show the
 180 possibility to adopt a DR strategy: the heating/cooling of the thermal zones
 181 and the WLHP. In the former, the electrical load can be shifted by varying the
 182 set-points of the indoor air temperature. This strategy takes advantage of the
 183 thermal inertia of the building, but it is also influenced by the thermal capacity
 184 of the water loop. In the latter case, instead, the WLHP operation can be varied
 185 through the set-point temperatures of its main components (in particular, the
 186 auxiliary heater). In this case, the useful thermal inertia is the water circulating

187 in the hydraulic loop.

188 Following the Italian PUN 2017, both the strategies consist of predictive
189 rule based controls with daily parameters (daily minimum, maximum, and av-
190 erage PUN value) and a hourly resolution. Their specific implementation in
191 the supermarket heating/cooling and in the WLHP system are described in the
192 following sections. An initial configuration referred to as plant baseline is also
193 defined in order to provide a direct comparison between this “DSM off” case and
194 the “DSM on” cases.

195 4.1. Plant baseline

196 In its standard configuration without DR programs, the supermarket ther-
197 mal zones are subdivided into two groups. The first group includes the food
198 store (FDS) and the common areas/hallways (CMA), and is characterized by
199 a heating set-point temperature of 20 °C and a cooling set-point temperature
200 of 26 °C. The second group includes the supermarket warehouse (WRH) and
201 the service areas (SVC), and has a heating set-point temperature of 18 °C and a
202 cooling set-point temperature of 30 °C. We will refer to this specific supermarket
203 heating/cooling configuration as Build 0.

204 As concerns the WLHP, the heat recovery from the refrigeration unit and
205 the auxiliary devices of the water loop are activated according to the following
206 control strategy, which will be referred to as WLHP 0:

- 207 • in wintertime, when the water loop temperature drops below a heat re-
208 covery set-point temperature, $T_{hr} = 20\text{ °C}$, the heat recovery from the
209 refrigeration unit is activated;
- 210 • in wintertime, when the water loop temperature drops below a second
211 heating set-point temperature, $T_{ah} = 10\text{ °C}$, the auxiliary heater is acti-
212 vated;
- 213 • in summertime, when the water loop temperature rises to a cooling set-
214 point temperature, $T_{dc} = 20\text{ °C}$, the dry-cooler is activated to cool the
215 water loop.

Table 2: Yearly electricity consumption and cost of the baseline configuration (Build 0 + WLHP 0 + $V_{\text{tank}} = 50 \text{ m}^3$).

Quantity	Symbol	Value
Heat pumps [MWh]	E_{hp}	223.28
Dry cooler [MWh]	E_{dc}	10.58
Refrigeration unit [MWh]	E_{refr}	289.94
Auxiliary heater [MWh]	E_{ah}	217.57
Circulating pump [MWh]	E_{pump}	8.83
Total energy [MWh]	E_{tot}	750.20
Total cost [kEUR]	C_{tot}	45.63

216 Another important component of the WLHP circuit is the water tank. In
 217 fact, its volume directly influences the water loop thermal capacity and, as it will
 218 be seen in the following sections, represents a relevant parameter of the DSM
 219 analysis. In summary, the plant baseline is the system combining the configura-
 220 tions Build 0 and WLHP 0 with a water tank volume, V_{tank} , of 50 m^3 . Table 2
 221 reports the yearly electricity consumption and cost of the baseline configuration,
 222 subdivided among the main energy systems of the supermarket.

223 4.2. DR using energy flexibility from space heating and cooling

224 The set-points of the supermarket indoor air temperature can be modified
 225 in order to shift the electrical load of the heat pumps. In the present analysis,
 226 two cases were considered. In the first one (Build 1), the baseline set-points
 227 were allowed to vary by a maximum of $\pm 1 \text{ }^\circ\text{C}$, while in the second one (Build 2)
 228 the variation is equal to a maximum of $\pm 2 \text{ }^\circ\text{C}$. Higher variations were not con-
 229 sidered, in order to maintain the zones thermal comfort, as it will be discussed
 230 in the results.

231 The predictive rule based control that regulates the indoor ambient tem-
 232 perature is governed by the following hourly set-point equation, function of the

233 PUN:

$$234 \quad T_{\text{sp,DSM},i} = \begin{cases} T_{\text{sp},i} + \Delta T_{\text{sp}} \left(\frac{PUN_i - \overline{PUN}_i}{PUN_{\text{max},i} - \overline{PUN}_i} \right) & \text{if } PUN_i \geq \overline{PUN}_i \\ T_{\text{sp},i} + \Delta T_{\text{sp}} \left(\frac{PUN_i - \overline{PUN}_i}{\overline{PUN}_i - PUN_{\text{min},i}} \right) & \text{if } PUN_i < \overline{PUN}_i \end{cases} \quad (1)$$

235 where:

- 236 • i is the i -th hour of the year;
- 237 • $T_{\text{sp},i}$ is the hourly baseline heating/cooling set-point temperature, as defined in Section 4.1;
- 238
- 239 • ΔT_{sp} is equal to ± 1 or ± 2 °C according to the chosen case (Build 1 or 2)
- 240 and the HVAC mode (+ for cooling, – for heating);
- 241 • PUN_i is the hourly value of the PUN;
- 242 • \overline{PUN}_i is the average daily value of the PUN corresponding to i -th hour;
- 243 • $PUN_{\text{max},i}$ is the maximum daily value of the PUN corresponding to i -th
- 244 hour;
- 245 • $PUN_{\text{min},i}$ is the minimum daily value of the PUN corresponding to i -th
- 246 hour.

247 In order to simulate a realistic and simple control system, the set-point $T_{\text{sp,DSM},i}$
 248 does not assume continuous values but has a resolution of 1 °C. The predictive
 249 rule based control defined in Equation (1) has been designed to allow the heat
 250 pumps to absorb less energy when the hourly PUN is higher than the corresponding
 251 average daily PUN, and to consume more energy when the hourly
 252 PUN is lower than the corresponding average daily PUN. For example, Figure 5
 253 shows how the food store heating set-point varies between Build 0, 1 and 2.

254 4.3. DR using energy flexibility from WLHP

255 The WLHP operation is regulated by the set-point temperatures of the heat
 256 recovery exchanger, the auxiliary heater and the dry cooler. The heat recovery

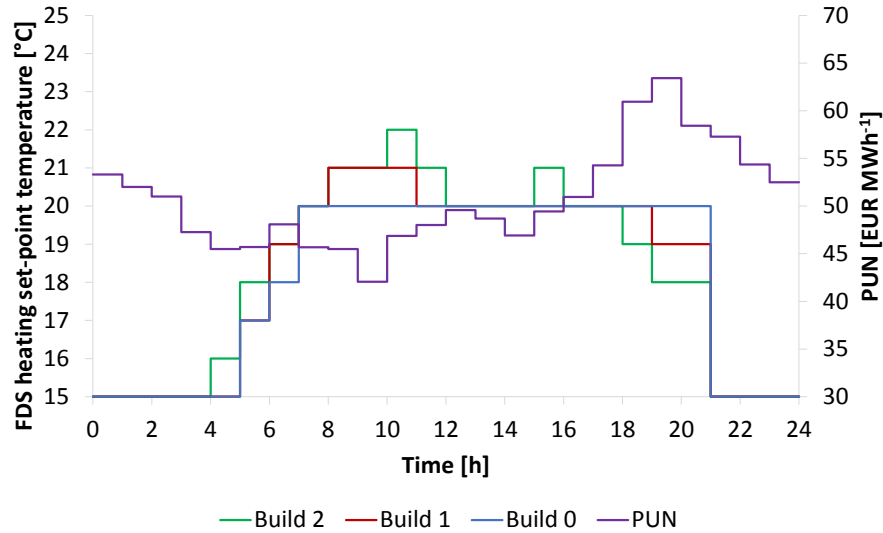


Figure 5: Heating set-point temperature of the food store (FDS) in Build 0, 1 and 2 during a typical day.

257 operation is optimized for the operational mode of the CO₂ refrigeration sys-
 258 tem (sub-critical, transition, trans-critical), thus this set-point was not modified
 259 according to a DR strategy. As regards the dry cooler, Table 2 shows that its
 260 electricity consumption is much lower than that of the auxiliary heater, thus a
 261 DR strategy applied to this component would not be so beneficial as it could
 262 be for the auxiliary heater.

263 The DR strategy in the WLHP was therefore limited to the auxiliary heater.
 264 In the same fashion of the space heating and cooling, a predictive rule based
 265 control described by Equation (1) was implemented in the simulation environ-
 266 ment. As the auxiliary heater is a heating device, ΔT_{sp} assumed a negative
 267 value and was allowed to vary of -1 , -2 and -3 °C. These three configurations
 268 will be referred to as WLHP 1, 2 and 3, respectively.

269 4.4. Economic analysis

270 As highlighted in Section 4.1, the volume of the water tank represents a
 271 relevant parameter of the analysis. Thus, it is important to quantify properly

272 the tank installation cost as a function of its storage volume. In literature, it is
273 reported that thermal energy storage devices with hot water as storage medium
274 have investment costs of 0.1-10 EUR kWh⁻¹ [30]. TES systems for sensible heat
275 are rather cheap because they consist basically of a simple tank for the storage
276 of water and the equipment to charge/discharge [31]. For the water tank of
277 the present study, we considered a specific cost of 50 EUR m⁻³, price that is
278 justified by the reduced amount and quality of thermal insulation required (the
279 water loop typically works in the range 10-30 °C). Since there are no strong scale
280 effects for water-based TES systems used in large installations [32], the chosen
281 specific cost was applied to all the volumes considered in this study. Taking into
282 account a depreciation period of 20 years, the annual specific cost of the water
283 tank would be 2.5 EUR m⁻³ y⁻¹.

284 It is also worth noting that the electricity cost associated to the baseline con-
285 figuration (Table 2) derives from a real-time pricing tariff based on the PUN.
286 Actually, typical non-household consumers such as the one under study usually
287 adopt time of use (e.g., high-low tariff schemes) or fixed price tariffs. Refer-
288 ring to the data provided by Eurostat for non-household consumers, in 2017
289 the average electricity price in Italy (excluding taxes and levies) was equal to
290 82.10 EUR MWh⁻¹ [33]. Taking into account a fixed tariff based on this price,
291 subtracted by a conservative -10% amount that accounts for the supplier's
292 markup, the electricity price would be 73.89 EUR MWh⁻¹. With this price,
293 the total electricity cost of the plant baseline would be 55.43 kEUR, cost that
294 is around 10 kEUR higher than that associated to the PUN-based real-time
295 pricing tariff.

296 5. Results of the analysis

297 The DR strategies defined in the previous section determine different varia-
298 tions in the annual electricity consumption and cost. In the following sections,
299 we will analyze the impact of each strategy (in the space heating/cooling or in
300 the WLHP), then we will see how the two strategies can be combined to provide

Table 3: Yearly electricity demand and cost variation of the main energy systems of the supermarket for different indoor temperature rule based controls (WLHP 0 and $V_{\text{tank}} = 50 \text{ m}^3$).

Quantity	Build 0	Build 1	Build 2
E_{hp} [MWh]	223.28	224.58	231.28
E_{dc} [MWh]	10.58	11.12	11.64
E_{refr} [MWh]	289.94	290.30	290.71
E_{ah} [MWh]	217.57	219.40	227.62
E_{pump} [MWh]	8.83	8.74	8.61
E_{tot} [MWh]	750.20	754.14	769.86
C_{tot} [kEUR]	45.63	44.35	43.77

301 an adequate operation of the supermarket energy plant.

302 5.1. Results of the space heating and cooling DR strategy

303 For the supermarket under study, the rule defined in Equation (1) determines
 304 an increase of the yearly electricity demand, both in Build 1 and 2. In Table 3
 305 it is possible to see what happens respect to the baseline Build 0, as defined
 306 in Section 4.1 ($V_{\text{tank}} = 50 \text{ m}^3$). Going from the baseline to Build 1, the yearly
 307 energy demand increases of 0.53%, while the increase is of 2.62% from the
 308 baseline to Build 2. The highest energy demand increase belongs to the auxiliary
 309 heater: from the baseline to Build 2, it is equal to 4.62%. This is a direct
 310 consequence of the increased demand of the heat pumps, which require hotter
 311 water in the winter season to satisfy the modified heating set-points.

312 Figure 6 shows how the daily electrical absorption of the heat pumps varies
 313 according to the different DR strategies defined by Equation (1). Respect to
 314 Build 1, Build 2 amplifies the effect of the predictive rule based control by
 315 following the PUN more closely.

316 It is interesting to analyze how the electricity demand varies when a larger
 317 flexibility is provided to the supermarket heating/cooling production by increas-

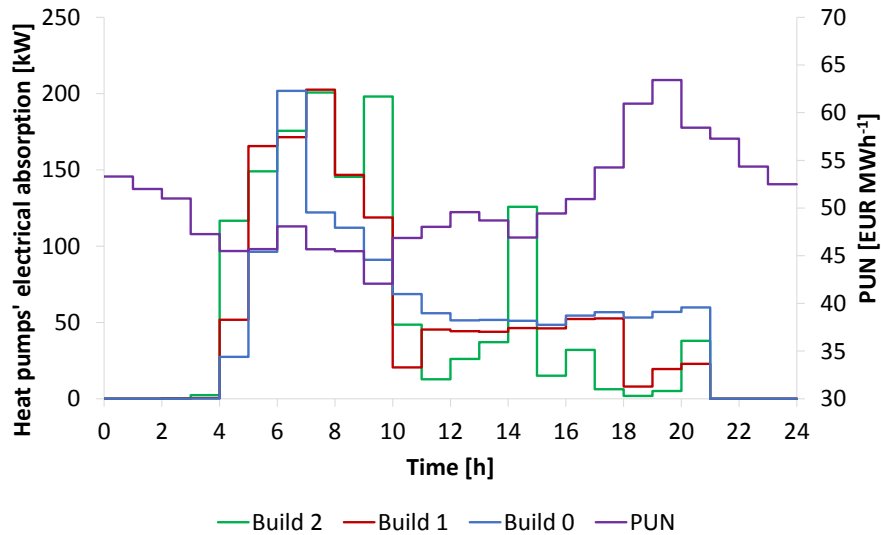


Figure 6: Electrical power absorbed by the heat pumps in a typical day (WLHP 0 and $V_{\text{tank}} = 50 \text{ m}^3$).

318 ing the water loop volume through a larger water tank. As depicted in Figure 7,
 319 the minimum overall energy demand lies approximately between 100 and 150 m^3
 320 for the different cases, while the consumption tends to increase for larger vol-
 321 umes. The increase is entirely due to the auxiliary heater, which has to heat a
 322 larger quantity of water.

323 Figure 7 also reports the trend of the yearly electricity cost for different
 324 DR strategies and water volumes. Focusing on the 50 m^3 case, it is possible
 325 to note that there is a cost saving in adopting a DR strategy. Going from the
 326 baseline to Build 1, the relative cost saving is equal to 2.79%, around 1273 EUR.
 327 Implementing the Build 2 DR strategy, there is a relative saving of 4.06%, for an
 328 amount of 1853 EUR. These savings require no modification of the supermarket
 329 plant configuration.

330 At this point, it is worth evaluating the possibility of an additional cost
 331 saving deriving from the use of larger water reservoirs. Although in Figure 7
 332 there seems to be an advantage in adopting tanks larger than 50 m^3 , such an

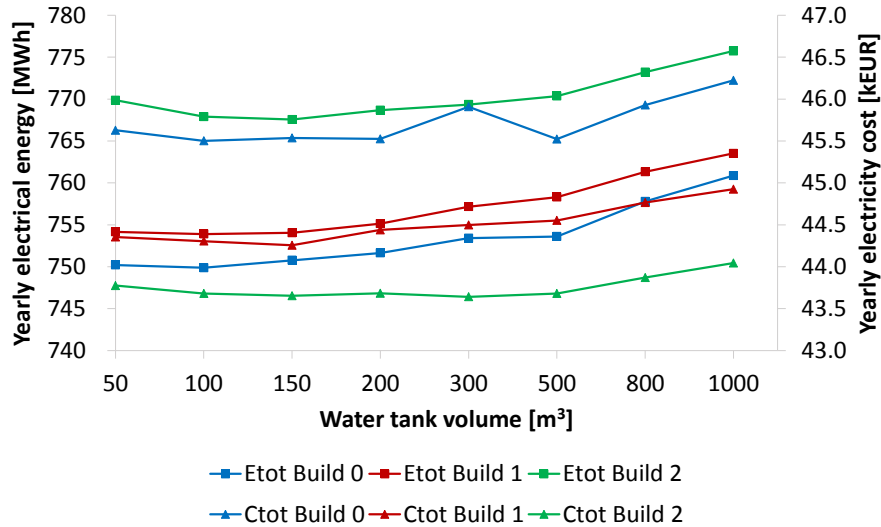


Figure 7: Yearly electricity demand and cost variations for different indoor temperature set-points and water tank volumes (WLHP 0).

333 investment would not justify the consequent small electricity cost saving. For
 334 instance, in Build 2 the substitution of a 50 m³ water tank with a 300 m³ one
 335 results in an additional annual saving of only 133 EUR, amount that is not able
 336 to compensate for the annual depreciation cost of a new water tank.

337 In conclusion, the DR strategy applied to the heat pumps seems to pro-
 338 vide a tangible energy cost saving. However, the modification of the space
 339 heating/cooling set-points clearly influences the thermal comfort quality of the
 340 supermarket thermal zones, therefore this aspect needs to be investigated care-
 341 fully. To this purpose, Figure 8 depicts how the predicted mean value, *PMV*,
 342 varies in the food store for Build 0, 1 and 2. In general, all the configurations
 343 guarantee an acceptable degree of thermal comfort, which clearly worsens when
 344 the temperature set-point variation is larger. Considering a working schedule of
 345 4380 hours in a year (12 hours every day), Build 0 is in the discomfort condition
 346 $|PMV| > 0.5$ for 40 hours of the cooling period, which correspond to a 0.91%
 347 of the total. Build 1 is in the discomfort condition for 78 hours (1.78%), while
 348 Build 2 shows a discomfort level of 124 hours (2.83%). In any case, the yearly

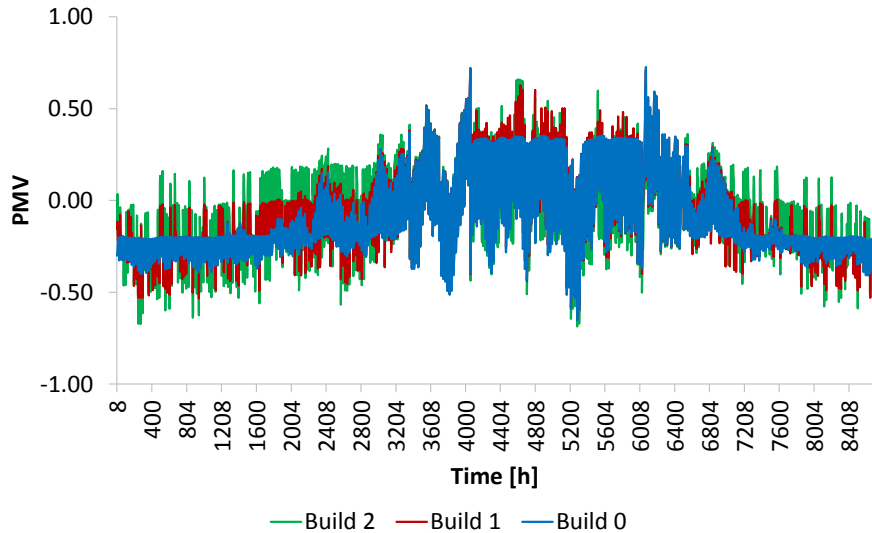


Figure 8: Yearly predicted mean value (PMV) of the food store (WLHP 0 and $V_{\text{tank}} = 50 \text{ m}^3$).

349 percentage discomfort level is well below 10%, value that is typically considered
 350 the maximum allowed discomfort level in a commercial activity.

351 5.2. Results of the WLHP DR strategy

352 The annual electricity consumption and cost for the DR strategies imple-
 353 mented in the auxiliary heater are provided in Table 4, that refers to the Build
 354 0 case with a 50 m^3 water tank volume. Under the energy point of view, it is
 355 possible to see that the adoption of any DR strategy (i.e., WLHP 1, 2 or 3) de-
 356 termines a slightly higher consumption (+0.30% for the WLHP 3 case), which
 357 is basically due to the auxiliary heater.

358 The hourly effect of the WLHP DR strategies is depicted in Figure 9, which
 359 shows the daily trend of the auxiliary heater electrical absorption for the dif-
 360 ferent WLHP set-point variations. A wider set-point is able to follow the PUN
 361 trend with greater accuracy.

362 Figure 10 shows how the electricity consumption and cost vary with the
 363 adoption of water tanks of variable size. Energy and cost have opposite trends,
 364 and it can be noted that there exists the possibility to obtain a considerable

Table 4: Yearly electricity demand and cost variation of the main energy systems of the supermarket for different auxiliary heater rule based controls (Build 0 and $V_{\text{tank}} = 50 \text{ m}^3$).

Quantity	WLHP 0	WLHP 1	WLHP 2	WLHP 3
E_{hp} [MWh]	223.28	223.33	223.06	222.52
E_{dc} [MWh]	10.58	10.60	10.59	10.61
E_{refr} [MWh]	289.94	289.94	289.94	289.94
E_{ah} [MWh]	217.57	217.72	218.47	220.58
E_{pump} [MWh]	8.83	8.82	8.82	8.81
E_{tot} [MWh]	750.20	750.41	750.88	752.46
C_{tot} [kEUR]	45.63	45.50	45.39	45.30

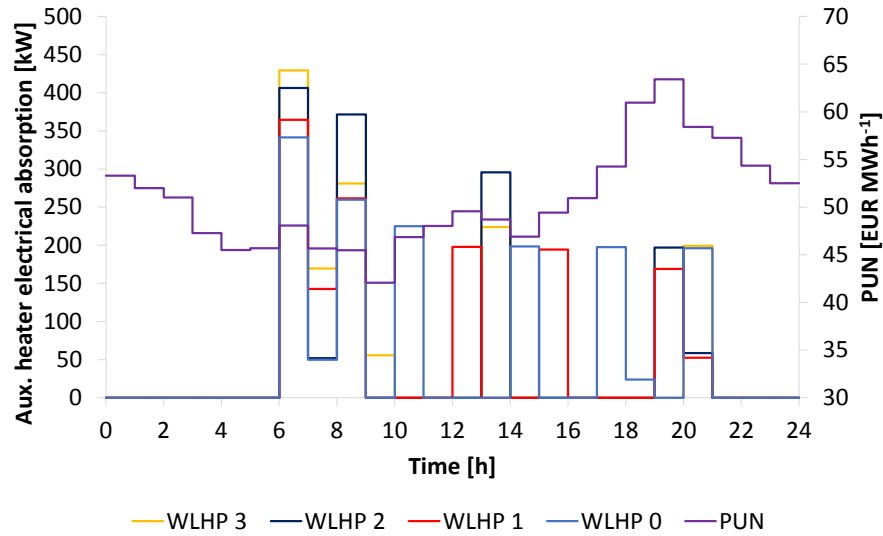


Figure 9: Electrical power absorbed by the auxiliary heater in a typical day (Build 0 and $V_{\text{tank}} = 50 \text{ m}^3$).

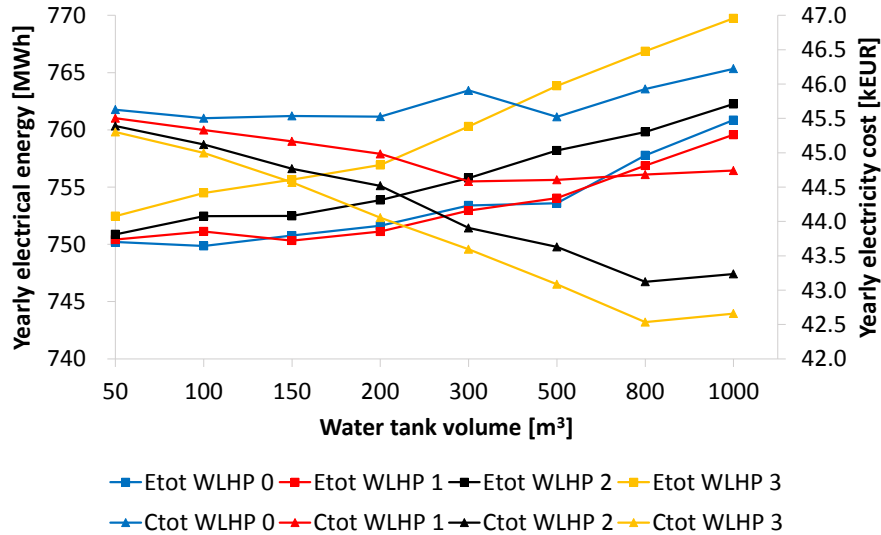


Figure 10: Yearly electricity demand and cost variations for different auxiliary heater set-points and water tank volumes (Build 0).

365 cost saving when a wide DR strategy is combined with a large water tank. In
 366 particular, the WLHP 3 rule seems to guarantee a promising result in terms of
 367 cost saving respect to the baseline (WLHP 0), showing a beneficial effect up to a
 368 volume of 800 m^3 , effect that is then neglected for larger tanks due to excessive
 369 thermal losses. Respect to the baseline case, the WLHP 3 case with a 800 m^3
 370 reservoir guarantees a cost saving of about 3092 EUR (-6.78%).

371 In conclusion, the WLHP DR strategy applied to the auxiliary heater shows
 372 a quantifiable cost saving, that is particularly sensible to the size of the water
 373 tank adopted. In this case, it is important to take into account the installation
 374 cost of the thermal energy storage. This aspect will be discussed in the following
 375 section.

376 5.3. Results of combined space heating/cooling and WLHP DR strategies

377 The DR strategy defined for the space heating/cooling and the auxiliary
 378 heater can be combined to verify if additional cost savings are feasible. Refer-
 379 ring again to the most favorable WLHP 3 case, Figure 11 depicts the electricity

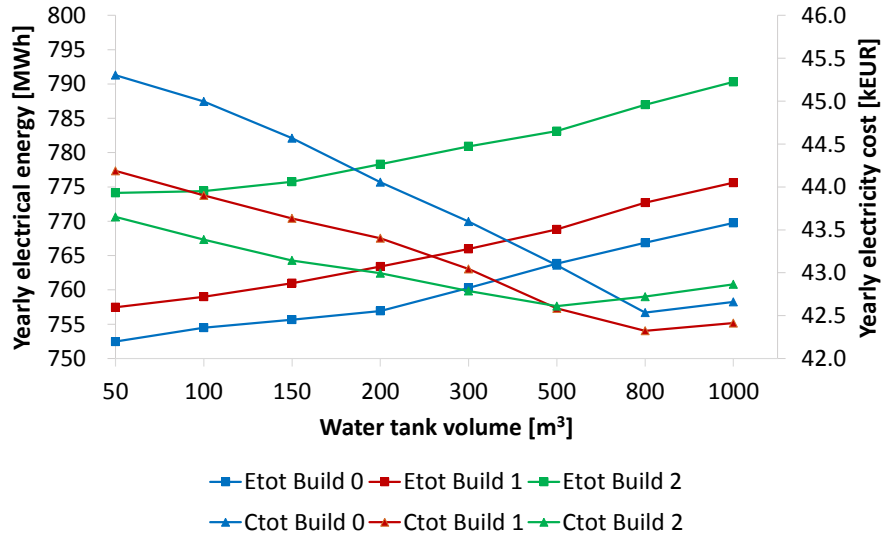


Figure 11: Yearly electricity consumption and cost vs. different water tank volumes (Build 0/1/2 + WLHP 3).

380 energy and cost trends when the WLHP 3 DR strategy is combined with the
 381 supermarket heating/cooling DR strategies (i.e., Build 1 and 2). While the
 382 energy trend increases with the water tank volume, the cost trend presents a
 383 minimum value. Specifically, Build 1 combined with the WLHP 3 rule guaran-
 384 tees a minimum yearly cost with a water volume of 800 m³, value that is 212
 385 EUR lower than the corresponding Build 0 case and more than 2000 EUR lower
 386 than the corresponding Build 1 + WLHP 0 case. As regards Build 2, the WLHP
 387 3 configuration shows a minimum electricity cost for a water volume of 500 m³;
 388 respect to the Build 0 case with the same water volume, the cost saving is of
 389 476 EUR, while respect to Build 2 + WLHP 0 the saving is equal to 1163 EUR.

390 In terms of total annual electricity cost, it is clear from Figure 11 that the
 391 best configuration is Build 1 + WLHP 3 with a water tank volume of 800 m³.
 392 Provided that its installation is not problematic in the plant under study, a water
 393 tank of this size has a considerable depreciation cost (2000 EUR y⁻¹) that does
 394 not justify its adoption. Combining the yearly electricity cost of the considered

395 configurations with the depreciation cost of water tanks larger than 50 m^3 , the
396 analysis revealed that the only setup able to provide an additional economic
397 convenience respect to the best 50 m^3 configuration (i.e., Build 2 + WLHP 3)
398 is the same Build 2 + WLHP 3 configuration with a 200 m^3 water tank. In
399 this case, in fact, it would be possible to save other 156 EUR respect to the
400 50 m^3 case, clearly considering the depreciation of the tank that is equal to 500
401 $\text{EUR}\cdot\text{y}^{-1}$.

402 In summary, the maximum electricity cost saving of the supermarket is
403 achieved for the configuration Build 2 + WLHP 3 with a water storage tank of
404 200 m^3 . Respect to the baseline, the selected configuration offers an electricity
405 cost saving of 2133 EUR (4.67%), amount that includes the 20-year depreciation
406 cost of the water tank. Another interesting configuration is Build 2 + WLHP
407 0 (discussed in Section 5.1), which requires no water storage tank larger than
408 50 m^3 and ensures a cost saving respect to the baseline of 1853 EUR (4.06%).
409 Configurations with only DR strategies applied to the auxiliary heater (Sec-
410 tion 5.2) are of no economic interest as they always require larger storage tanks
411 to be really effective, thus removing any cost saving in the short period. Finally,
412 supposing that the supermarket baseline does not adhere to a PUN-based RTP
413 electricity tariff but adopts a standard fixed tariff, the DR configuration Build 2
414 + WLHP 3 with a water tank of 200 m^3 would provide an annual cost saving of
415 11 938 EUR (-21.54%), while the DR configuration Build 2 + WLHP 0 would
416 guarantee an annual cost saving of 11 658 EUR (-21.03%). These cost savings
417 should represent a more realistic quantification of the amounts that could be
418 saved with an existing plant. Indeed in this paper a specific case study was
419 analyzed and thus the economic savings are strictly related to it. However, the
420 general conclusions about the effect of DR strategies applied to a WLHP system
421 can be easily extended to similar systems.

422 6. Conclusions

423 The DR analysis of the supermarket integrated HVAC, refrigeration and
424 WLHP system showed that two configurations are the most economically ef-
425 fective. The first configuration consists of a DR strategy applied to the space
426 heating/cooling, which allows to vary the internal air temperature set-points
427 up to 2 °C. Respect to the baseline, this setup ensures an annual cost saving
428 of 1853 EUR, does not worsen significantly the thermal comfort quality of the
429 thermal zones, and is basically inexpensive as it does not require a larger water
430 reservoir. The second configuration combines the predictive rule based controls
431 applied to the space heating/cooling and the WLHP auxiliary heater, device
432 installed in the water loop to integrate the heat from the CO₂ de-superheating
433 process. The flexibility of the auxiliary heater (± 3 °C) is given by the thermal
434 inertia of the water circulating in the hydraulic loop. In this case, the best eco-
435 nomic saving (2133 EUR y⁻¹) can be obtained with the installation of a 200 m³
436 water tank. Both the configurations guarantee an yearly electricity cost saving
437 of more than 4% respect to the baseline.

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442 Grid", Prot. 2015M8S2PA.

443 References

- 444 [1] European Union, Directive 2009/28/EC of the European Parliament and
445 of the Council of 23 April 2009 on the promotion of the use of energy
446 from renewable sources and amending and subsequently repealing Direc-
447 tives 2001/77/EC and 2003/30/EC, Official Journal of the European Union
448 5 (2009).

- 449 [2] P. D. Lund, J. Lindgren, J. Mikkola, J. Salpakari, Review of energy system
450 flexibility measures to enable high levels of variable renewable electricity,
451 *Renewable and Sustainable Energy Reviews* 45 (2015) 785–807.
- 452 [3] A. Faruqui, J. Chamberlin, Principles and practice of demand-side man-
453 agement, Palo Alto, CA: Electric Power Research Institute (1993).
- 454 [4] R. Aazami, K. Aflaki, M. R. Haghifam, A demand response based solution
455 for LMP management in power markets, *International Journal of Electrical
456 Power & Energy Systems* 33 (2011) 1125–1132.
- 457 [5] International Institute of Refrigeration, The role of refrigeration industry in
458 the global economy. 29th Inform, Note on Refrigeration Technology, Paris,
459 2015.
- 460 [6] A. Arteconi, F. Polonara, Demand side management in refrigeration appli-
461 cations, *International Journal of Heat and Technology* 35 (2017) S58–S63.
- 462 [7] M. Stadler, W. Krause, M. Sonnenschein, U. Vogel, Modelling and evalu-
463 ation of control schemes for enhancing load shift of electricity demand for
464 cooling devices, *Environmental Modelling & Software* 24 (2009) 285–295.
- 465 [8] G. Niro, D. Salles, M. V. Alcântara, L. C. da Silva, Large-scale control of
466 domestic refrigerators for demand peak reduction in distribution systems,
467 *Electric Power Systems Research* 100 (2013) 34–42.
- 468 [9] E. Kremers, J. Mari, O. Barambones, et al., Emergent synchronisation
469 properties of a refrigerator demand side management system, *Applied En-
470 ergy* 101 (2013) 709–717.
- 471 [10] F. Sossan, V. Lakshmanan, G. T. Costanzo, M. Marinelli, P. J. Douglass,
472 H. Bindner, Grey-box modelling of a household refrigeration unit using
473 time series data in application to demand side management, *Sustainable
474 Energy, Grids and Networks* 5 (2016) 1–12.

- 475 [11] T. G. Hovgaard, L. F. Larsen, K. Edlund, J. B. Jørgensen, Model pre-
476 dictive control technologies for efficient and flexible power consumption in
477 refrigeration systems, *Energy* 44 (2012) 105–116.
- 478 [12] T. G. Hovgaard, S. Boyd, L. F. Larsen, J. B. Jørgensen, Nonconvex model
479 predictive control for commercial refrigeration, *International Journal of*
480 *Control* 86 (2013) 1349–1366.
- 481 [13] S. E. Shafiei, J. Stoustrup, H. Rasmussen, A supervisory control approach
482 in economic MPC design for refrigeration systems, in: *Control Conference*
483 *(ECC), 2013 European, IEEE, 2013*, pp. 1565–1570.
- 484 [14] R. Pedersen, J. Schwensen, B. Biegel, J. Stoustrup, T. Green, Aggregation
485 and control of supermarket refrigeration systems in a smart grid, *IFAC*
486 *Proceedings Volumes* 47 (2014) 9942–9949.
- 487 [15] G. Cortella, O. Saro, Evaluation of energy savings by heat recovery from
488 refrigeration plants in supermarkets, in: *Proc. 1st IIR Conference on Sus-*
489 *tainability and the Cold Chain, Cambridge (UK), 2010*.
- 490 [16] A. Buonomano, F. Calise, A. Palombo, Buildings dynamic simulation:
491 Water loop heat pump systems analysis for european climates, *Applied*
492 *Energy* 91 (2012) 222–234.
- 493 [17] G. Cortella, P. D’Agaro, O. Saro, A. Polzot, Modelling integrated HVAC
494 and refrigeration systems in a supermarket, in: *Proc. 3rd IIR International*
495 *Conference on Sustainability and the Cold Chain, Twickenham, London*
496 *(UK), 2014*.
- 497 [18] D. Fischer, H. Madani, On heat pumps in smart grids: A review, *Renewable*
498 *and Sustainable Energy Reviews* 70 (2017) 342–357.
- 499 [19] A. Polzot, C. Dipasquale, P. D’Agaro, G. Cortella, Energy benefit assess-
500 ment of a water loop heat pump system integrated with a CO₂ commercial
501 refrigeration unit, *Energy Procedia* 123 (2017) 36–45.

- 502 [20] A. Polzot, P. D'Agaro, P. Gullo, G. Cortella, Modelling commercial re-
503 frigeration systems coupled with water storage to improve energy efficiency
504 and perform heat recovery, *International Journal of Refrigeration* 69 (2016)
505 313–323.
- 506 [21] A. Polzot, Energy benefit assessment of various refrigeration systems in-
507 tegrated with HVAC units in shopping malls, Ph.D. thesis, University of
508 Udine, Polytechnic Department of Engineering and Architecture, 2017.
- 509 [22] S. Klein, W. Beckman, J. Duffie, et al., TRNSYS 17: A Transient Sys-
510 tem Simulation Program. Mathematical reference, Solar Energy Labora-
511 tory, University of Wisconsin-Madison, 2010.
- 512 [23] BITZER, BITZER Software 6.4.4. 1464, 2016. URL: [https://www.
513 bitzer.de/websoftware](https://www.bitzer.de/websoftware).
- 514 [24] I. H. Bell, J. Wronski, S. Quoilin, V. Lemort, Pure and pseudo-pure fluid
515 thermophysical property evaluation and the open-source thermophysical
516 property library CoolProp, *Industrial & Engineering Chemistry Research*
517 53 (2014) 2498–2508.
- 518 [25] Frascold, FSS.3 (Frascold Selection Software), 2016. URL: [http://www.
519 frascold.it/en/](http://www.frascold.it/en/).
- 520 [26] European Union Seventh Framework Programme (FP7/2007-2013), Com-
521 mONEnergy: Converting eu shopping centres into beacons of energy effi-
522 ciency, 2013. URL: <http://www.commonenergyproject.eu>.
- 523 [27] J. Remund, S. Kunz, METEONORM: Global meteorological database for
524 solar energy and applied climatology, Meteotest, 1997.
- 525 [28] B. Shen, G. Ghatikar, Z. Lei, J. Li, G. Wikler, P. Martin, The role of
526 regulatory reforms, market changes, and technology development to make
527 demand response a viable resource in meeting energy challenges, *Applied
528 Energy* 130 (2014) 814–823.

- 529 [29] Gestore Mercati Energetici, Prezzo Unico Nazionale, 2018. URL: [http:](http://www.mercatoelettrico.org/)
530 [//www.mercatoelettrico.org/](http://www.mercatoelettrico.org/).
- 531 [30] L. Miró, J. Gasia, L. F. Cabeza, Thermal energy storage (TES) for in-
532 dustrial waste heat (IWH) recovery: A review, *Applied Energy* 179 (2016)
533 284–301.
- 534 [31] IEA-ETSAP, IRENA, Thermal energy storage: Technology brief E17, 2013.
- 535 [32] N. DeForest, G. Mendes, M. Stadler, W. Feng, J. Lai, C. Marnay, Optimal
536 deployment of thermal energy storage under diverse economic and climate
537 conditions, *Applied Energy* 119 (2014) 488–496.
- 538 [33] Eurostat, Electricity prices for non-household consumers, 2018. URL:
539 <https://ec.europa.eu/eurostat/web/energy/data/database>.

Highlights

1. Supermarkets are ideal candidate for demand side management (DSM) strategies
2. A supermarket integrated HVAC, refrigeration and water loop HP (WLHP) was analyzed
3. Demand response (DR) based on real-time pricing rule based controls was used
4. DR strategies were applied to the supermarket heating/cooling and the WLHP
5. Two setups guarantee the highest annual electricity cost savings (4.06% and 4.67%)