

An Energy Management System for Isolated Microgrids with Thermal Energy Resources

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Abstract—A novel Energy Management System (EMS) model for an isolated microgrid, integrating thermal energy resources, such as Combined Heat and Power (CHP) units, boilers, Heat Pumps (HPs), and Thermal Storage System (TSS), while considering thermal load models, is proposed in this paper. The developed EMS is tested and validated with a real testbed microgrid located in Bari, Italy, which supplies both electricity and heat to a building at the Politecnico di Bari. The proposed EMS aims to minimize the fuel cost and includes thermal comfort requirements and building models, along with suitable models for CHP units and hot water-based TSS, based on an optimization problem formulated as a Mixed Integer Linear Programming (MILP) problem, which is readily handled with commercial solvers, making the EMS fit for online applications. The proposed EMS is compared with an electrical-only EMS, i.e. a practical EMS that does not include thermal systems, with the simulations carried out for different winter days demonstrating the economic benefits of accounting for thermal system models in a microgrid EMS, resulting in significant savings in the daily fuel cost.

Index Terms—Combined heat and power, energy management system, microgrids, optimization, storage, thermal energy systems.

GLOSSARY AND NOMENCLATURE

Acronyms

ACHS	Additional Cost of Heat Supply
BESS	Battery Energy Storage System
CCHP	Combined Cooling, Heat and Power
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DER	Distributed Energy Resource
DG	Distributed Generation
DR	Demand Response
EMS	Energy Management System
ESS	Energy Storage System
FC	Fuel Cell
HP	Heat Pump
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MPC	Model Predictive Control
NHD	Net Heat Demand
OPF	Optimal Power Flow
PEV	Plug-in Electric Vehicle
PV	Photo-Voltaic

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RE	Reciprocating Engine
RES	Renewable Energy Source
SOC	State Of Charge
TSS	Thermal Storage System
UC	Unit Commitment
WT	Wind Turbine
<i>Sets</i>	
G	Generation units
H	Heat Pumps (HPs)
J	Boilers
N	Energy Storage Systems (ESSs)
S	Surfaces of building envelope
T	Time steps

Indices and superscripts

g	Generation units
h	HPs
j	Boilers
k	Time steps
min, max	Minimum and maximum limits
n	ESS units
s	Surfaces of building envelope

Parameters

α, β	Voltage exponent for active/reactive load model
Δt_k	Time interval between step k and step $k + 1$
η_j^B	Rated efficiency of boiler j
$\eta_n^{ch}, \eta_n^{dch}$	Charging/discharging efficiency of ESS unit n
η_g^R	Heat recovery system efficiency of Combined Heat and Power (CHP) unit g
η_g^T	Rated thermal efficiency of CHP unit g
η^X	Overall efficiency of the heating system not managed by the EMS
η^Y	Efficiency of hot water-based heating system
ψ_h^{HP}	Efficiency reduction coefficient of HP h
ρ^{air}	Air density [kg/m ³]
σ_s	Shadowing coefficient of building surface s
τ_s	Transmission coefficient of windows
θ_k^{ext}	External ambient temperature [K]
$\theta_h^{HP, out}$	Outlet temperature of HP h [K]
ξ_s	Amount of windows on building surface s
A^{TSS}	External surface of Thermal Storage System (TSS) [m ²]
a_g	Linear term of cost function g [€/kWh]
A_s	Area of building surface s [m ²]
b_g	Constant term of cost function g [€/h]
c_j^{fuel}	Cost of fuel of boiler j [€/fuel unit]

$c_g^{F,fuel}$	Cost of fuel of generation unit g [€/fuel unit]
C_{in}^{in}	Thermal capacity of building [kJ/K]
C_{LC}^{LC}	Load curtailment cost [€/kWh]
C_g^{sup}, C_g^{sdn}	Start-up/shut-down cost of generation unit g [€]
c_w^w, c_{air}^{air}	Water/air specific heat [kJ/(kgK)]
$c^{X,fuel}$	Cost of fuel of the heating system not managed by the EMS [€/fuel unit]
$h_j^{B,fuel}$	Heating value of fuel of boiler j [kWh/fuel unit]
$h_g^{F,fuel}$	Heating value of fuel of generation unit g [kWh/fuel unit]
$h^{X,fuel}$	Heating value of fuel of the heating system not managed by the EMS [kWh/fuel unit]
I_s	Solar irradiation on building surface s [kW/m ²]
m^{TSS}	Mass of water in the TSS [kg]
P_k^{PV}	Photo-Voltaic (PV) plant output [kW]
P_k^{WT}	Wind Turbines (WTs) output [kW]
Pd_k	Active power demand [kW]
Qd_k	Reactive power demand [kVar]
R^d	Reserve constraint coefficient for loads
R^{env}	Thermal resistance of building envelope [K/kW]
R^{PV}	Reserve constraint coefficient for PV plant
R_g^{up}, R_g^{dn}	Ramp-up and ramp-down rate of generation unit g [kW/h]
R^{WT}	Reserve constraint coefficient for WTs
T_g^{up}, T_g^{dn}	Min-up and min-down time of generation unit g [h]
U^{TSS}	Heat transmittance of TSS [kW/(m ² K)]
U_s	Heat transmittance of building surface s [kW/(m ² K)]
v_k^{rate}	Ventilation rate [1/h]
V_{ol}	Building volume [m ³]

Variables

ΔV_k	Deviation of voltage from rated value [p.u.]
θ_k^{in}	Indoor temperature [K]
θ_k^{TSS}	Water temperature of TSS [K]
$B_{n,k}$	Charge/discharge decision of ESS unit n (1=charge, 0=discharge)
$D_{g,k}$	Shut-down decision of generation unit g
$G_{g,k}^{on}, G_{g,k}^{off}$	ON/OFF time of generation unit g [h]
$P_{n,k}^{ch}, P_{n,k}^{dch}$	Charging/discharging power of ESS unit n [kW]
P_h^{HP}	Input active power of HP h [kW]
P_k^{LC}	Active load curtailed [kW]
$P_{g,k}$	Active power from generation unit g [kW]
$Q_{n,k}^{ESS}$	Reactive power from ESS unit n [kVar]
Q_h^{HP}	Input reactive power of HP h [kVar]
Q_k^{LC}	Reactive load curtailed [kVar]
$Q_{g,k}$	Reactive power from generation unit g [kVar]
$SOC_{n,k}$	State Of Charge (SOC) of ESS unit n [kWh]
$U_{g,k}$	Start-up decision of generation unit g
$W_{g,k}$	ON/OFF state of generation unit g (1=ON)
$\dot{Q}_{hs}$	Heating system output [kW]
$\dot{Q}^{TSS,in}$	Input power of TSS [kW]
$\dot{Q}_{g,k}^u$	Useful thermal power from CHP unit g [kW]
$\dot{Q}_{h,k}^{HP}$	Thermal power from HP h [kW]
$\dot{Q}_{j,k}^B$	Thermal power from boiler j [kW]
$\dot{Q}_k^{env}$	Heat transfer through building envelope [kW]

$\dot{Q}_k^{sun}$	Thermal solar power through windows [kW]
$\dot{Q}_k^{TL}$	Losses of TSS [kW]
$\dot{Q}_k^{TSS,out}$	Output power from TSS [kW]
$\dot{Q}_k^{vent}$	Heat transfer due to ventilation [kW]
$\dot{Q}_k$	Yield of hot water-based heating system [kW]

I. INTRODUCTION

ENERGY supply to an industrial process or a building usually involves different energy carriers (e.g. electricity, heat, hot water), due to the nature of energy demand. In this context, a microgrid can effectively integrate thermal energy resources and loads with electrical systems [1], [2], especially considering that some types of generation units, such as microturbines and diesel generators, yield significant waste heat. This heat can be recovered by means of proper heat exchangers and used for a variety of purposes, such as building heating, leading to a considerable increase in the overall system efficiency [3]. The combined generation of electricity and heat, which is referred to as Combined Heat and Power (CHP), has proven to be an economical and reliable way to reduce both fuel consumption and air pollution [3], [4]; furthermore, since some devices can provide cooling from heat absorption, their integration results in Combined Cooling, Heat and Power (CCHP). Increased flexibility can then be achieved by means of Thermal Storage System (TSS), since it allows time-decoupling between heat generation and consumption [4]. Thus, there exist several potential benefits from joint delivery of electricity and heat in multi-energy microgrids, which is a topical issue nowadays and the focus of this paper.

A microgrid relies on its Energy Management System (EMS) to provide a secure, reliable and economical operation in all operating conditions [1]. Consequently, the above-mentioned benefits can be obtained by developing suitable EMSs that integrate both electric and thermal energy systems, and account for practical operational aspects of multi-energy microgrids. Thus, in recent years, EMSs including thermal systems have been proposed by several researchers in, for example, [5]–[10]. Authors in [5] and [6] propose an EMS for a CHP-based microgrid, considering as objective the minimization of both operational cost and emissions. In [7], an EMS model in the context of a multi-factory industrial microgrid is developed, assuming that factories in the vicinity of each other cooperate to meet their thermal needs as a whole. An energy scheduling problem in a smart building composed of multiple smart homes and equipped with its own heat and power microgrid is proposed in [8]; minimum cost operation of both microgrid Distributed Energy Resources (DERs) and programmable household appliances is scheduled for next 24 h, under two different Demand Response (DR) schemes. A microgrid including CHP units, a power-only unit, a heat-only unit, Wind Turbines (WTs), a Fuel Cell (FC), a Battery Energy Storage System (BESS) and a heat buffer tank is considered in [9], using stochastic programming to calculate the optimal dispatch and evaluate the impact of DR strategies in both grid-connected and stand-alone mode. In [10], an energy dispatch strategy for a CCHP microgrid is proposed, focusing on demonstrating the benefits of integrating both heat

storage and ice storage tanks in the microgrid, considering both grid-connected and islanded operating mode.

None of the EMS formulations mentioned so far consider a model of the microgrid thermal demand, i.e. the thermal load is considered as an input to the EMS, which is assumed to be known in advance. However, in reality when both electricity and heat/cooling supplies are coupled, the thermal load depends on multiple factors, which need to be taken directly into account in the EMS model. For example, in a microgrid that provides heat for an industrial process in [7] or feeds the heating system of a building in [8], the main features of the industrial process and/or a thermal model of the building should be included in the EMS formulation as, for example, in [11]–[13]. Thus, in [11], an EMS model is proposed and applied to a residential energy hub featuring CCHP generation units, TSS, hot water storage, Photo-Voltaic (PV) plant, Plug-in Electric Vehicle (PEV), and shiftable and curtailable loads, and although this formulation allows to trace both indoor and hot water temperature patterns, it fails to capture the impact of solar irradiation on the building thermal dynamics, which is significant. In [12], the authors present an EMS for a grid-connected, single-house microgrid, formulating the optimization problem as a multi-objective problem that includes user satisfaction regarding smart appliances scheduling and thermal comfort levels, in addition to operating cost minimization, based on a thermal model of the house, with the relevant internal and external heat gains. A building thermal model is used also in [13], where a model predictive controller is designed to dynamically optimize the operation of a household PV-BESS-FC microgrid. In most papers, the thermal output of a CHP unit is considered as simply proportional to the electric output, where the rated thermal and electric efficiencies define the constant of proportionality; this assumption yields a linear mathematical model, but may lead to significant error whenever the unit does not operate close to its rated power. On the other hand, in [9], the relation between electric and thermal output is described by means of a feasible operating region, which is an appropriate model for extraction CHP units, mostly typical of large power plants. In [14]–[16] polynomial expressions are used for the electrical efficiency or heat to electric output ratio of a gas CHP unit and/or FCs. However, these models introduce non linearities, which complicate the online solution of the optimization problem. Thus, in [10], the nonlinear operating curves of CHP units are approximated through piecewise linearization, which allows the optimization problem to be formulated as a Mixed Integer Linear Programming (MILP) problem, that can be efficiently solved by commercial solvers. Furthermore, in most works, TSS is typically modelled adopting generic equations similar to those of BESS. However, in microgrids with thermal storage, specific models are needed depending on the technologies [12], [13], [17].

Finally, in several works the dispatch problem is solved assuming day-ahead forecasts for uncertain inputs, such as power generation from Renewable Energy Sources (RESs), electrical and/or thermal demand and market prices [5]–[8], [10], [12]. However, in practical microgrid operation, these inputs may significantly deviate from their forecasts, possibly

compromising the optimality and even the feasibility of the dispatch calculated by the EMS. Hence, a suitable technique must be used to tackle this issue, which in the current paper is done using a Model Predictive Control (MPC) approach, which has been shown to be an effective technique to deal with uncertainties in microgrid EMS (e.g. [18]), especially considering the online practical application and implementation of the proposed EMS.

From the literature review, it is clear that, although some work on microgrid EMS with thermal systems has been done, there is a need for the integration of thermal demand models and the representation of CHP units and TSS, while accounting for uncertainties in the inputs, in order to obtain reasonable and realistic online energy dispatch results. Thus, this paper presents a novel EMS for a real microgrid that integrates different kinds of thermal energy resources, specifically CHP facilities, boilers, HPs, and a water tank as TSS, for delivering both electricity and heat to an existing building, with the following main contributions to the current technical literature:

- Numerous papers consider the thermal load as a direct input to the EMS, assuming to be known in advance. However, in practice the thermal demand should be properly integrated into the microgrid EMS, as proposed in the paper, since this improves the model accuracy, thus reducing dispatching errors associated with inaccurate thermal load forecasting.
- The relation between electric and thermal outputs of CHP units is usually described either by a linear equation, i.e. constant electric efficiency, or by detailed modeling that introduces nonlinear constraints that complicate the online application of the EMS, where fast solution times are required. Thus, the proposed model is a compromise between these two models, in which linear constraints are used to represent the CHP, while properly representing variations on electric efficiency. This results in a Mixed Integer Linear (MIL) programming EMS model that can be readily handled by commercial solvers, and thus implementable in and applicable to practical microgrids.
- TSS is usually represented by generic equations that do not account for the energy storage technology, which is an issue addressed in the paper by more accurately modeling the water-tank based TSS system.
- Uncertainties in the inputs have often not been considered in prior works, with online implementation and applicability of the microgrid EMS usually not being investigated. Thus, the EMS model proposed in this paper considers uncertainties through an MPC approach.

The rest of the paper is organized as follows: In Section II, a review of the relevant background for the proposed EMS is presented. The proposed EMS model is then formulated in Section III, and in Section IV, relevant simulation results are shown for an actual microgrid, highlighting the benefits of including thermal systems in a microgrid EMS. Finally, the main conclusions and contributions of the paper are discussed in Section V.

II. BACKGROUND REVIEW

A. Microgrid EMS

An EMS can exhibit either a centralized or decentralized architecture [1]. In this paper, a centralized structure is considered, since it is more suitable for isolated microgrids that require a high level of coordination between DERs participating in control tasks. Although there exist numerous formulations of optimal EMS, the proposed EMS is based on the practical EMS described in [18] for balanced network conditions, since this model has been demonstrated to work properly for realistic microgrids. The model presented next does not account for thermal systems, and thus it is referred here to as the electrical-only EMS, which is chosen as the benchmark for the proposed EMS; its aim is to minimize the operating cost of the microgrid as follows:

$$\min z = \sum_{g \in G, k \in T} [(a_g P_{g,k} + b_g W_{g,k}) \Delta t_k + C_g^{\text{sup}} U_{g,k} + C_g^{\text{dn}} D_{g,k}] + \sum_{k \in T} (C^{LC} P_k^{LC} \Delta t_k) \quad (1)$$

where all variables, parameters, indices, and sets are defined in the Nomenclature section due to limited space. In (1), the first summation represents the linear operating costs of generating units, as well as their start-up and shut-down costs, and the second summation stands for the load curtailment costs, which are assumed to be large to represent customer inconvenience. Under the following constraints:

$$\sum_{g \in G} P_{g,k} + P_k^{PV} + P_k^{WT} + \sum_{n \in N} (P_{n,k}^{dch} - P_{n,k}^{ch}) = P_{d,k}(1 + \alpha \Delta V_k) - P_k^{LC} \quad \forall k \in T \quad (2)$$

$$\sum_{g \in G} Q_{g,k} + \sum_{n \in N} Q_{n,k}^{ESS} = Q_{d,k}(1 + \beta \Delta V_k) - Q_k^{LC} \quad \forall k \in T \quad (3)$$

$$\sum_{g \in G} (P_g^{\text{max}} W_{g,k} - P_{g,k}) + \sum_{n \in N} [P_n^{dch, \text{max}} (1 - B_{n,k}) - P_{n,k}^{dch}] \geq R^d [P_{d,k}(1 + \alpha \Delta V_k) - P_k^{LC}] + R^{PV} P_k^{PV} + R^{WT} P_k^{WT} \quad \forall k \in T \quad (4)$$

$$P_g^{\text{min}} W_{g,k} \leq P_{g,k} \leq P_g^{\text{max}} W_{g,k} \quad \forall g \in G, \forall k \in T \quad (5)$$

$$Q_g^{\text{min}} W_{g,k} \leq Q_{g,k} \leq Q_g^{\text{max}} W_{g,k} \quad \forall g \in G, \forall k \in T \quad (6)$$

$$P_{g,k} - P_{g,k-1} \leq R_g^{\text{up}} \Delta t_k + U_{g,k} P_g^{\text{min}} \quad \forall g \in G, \forall k \in T \quad (7)$$

$$P_{g,k-1} - P_{g,k} \leq R_g^{\text{dn}} \Delta t_k + D_{g,k} P_g^{\text{min}} \quad \forall g \in G, \forall k \in T \quad (8)$$

$$(G_{g,k-1}^{\text{on}} - T_g^{\text{up}}) (W_{g,k-1} - W_{g,k}) \geq 0 \quad \forall g \in G, \forall k \in T \quad (9)$$

$$(G_{g,k-1}^{\text{off}} - T_g^{\text{dn}}) (W_{g,k} - W_{g,k-1}) \geq 0 \quad \forall g \in G, \forall k \in T \quad (10)$$

$$U_{g,k} - D_{g,k} = W_{g,k} - W_{g,k-1} \quad \forall g \in G, \forall k \in T \quad (11)$$

$$U_{g,k} + D_{g,k} \leq 1 \quad \forall g \in G, \forall k \in T \quad (12)$$

$$SOC_{n,k+1} - SOC_{n,k} = \left(P_{n,k}^{ch} \eta_n^{ch} - \frac{P_{n,k}^{dch}}{\eta_n^{dch}} \right) \Delta t_k \quad \forall n \in N, \forall k \in T \quad (13)$$

$$SOC_n^{\text{min}} \leq SOC_{n,k} \leq SOC_n^{\text{max}} \quad \forall n \in N, \forall k \in T \quad (14)$$

$$0 \leq P_{n,k}^{ch} \leq B_{n,k} P_n^{ch, \text{max}} \quad \forall n \in T, \forall k \in T \quad (15)$$

$$0 \leq P_{n,k}^{dch} \leq (1 - B_{n,k}) P_n^{dch, \text{max}} \quad \forall n \in T, \forall k \in T \quad (16)$$

$$Q_n^{ESS, \text{min}} \leq Q_{n,k}^{ESS} \leq Q_n^{ESS, \text{max}} \quad \forall n \in N, \forall k \in T \quad (17)$$

$$\Delta V^{\text{min}} \leq \Delta V_k \leq \Delta V^{\text{max}} \quad \forall k \in T \quad (18)$$

where (2) and (3) represent, respectively, the active and reactive power balance constraints, and (4) guarantees that at each time step, the committed generation units and discharging BESSs provide the required spinning reserves, which is expressed as a linear combination of load and power generation from WTs and PV plant, according to [19]. Standard Unit Commitment (UC) constraints associated with thermal generators are represented by active (5) and reactive power (6) generation limits; ramp-up (7) and ramp-down (8) constraints representing how fast a generator can turn on or off, respectively; minimum-up (9) and minimum-down (10) time constraints corresponding to the minimum times a generator must remain on or off, respectively; and coordination constraints (11) and (12), which guarantee that a generator cannot be started up and shut down at the same time. Equations (13)-(17) correspond to BESS operation, namely energy balance and limits on charging/discharging power, reactive power, and SOC. The use of the binary variable $B_{n,k}$ in (15) and (16) allows to prevent simultaneous charging/discharging while keeping a linear formulation. Finally, (18) enforces the voltage upper and lower limits. It should be noted that the voltage dependence of load is represented, which is especially important for isolated microgrids, using the linearization proposed in [18]. Note that (9) and (10) are linearized in the solution process using the "Big M" method [20], thus resulting in an MILP problem.

B. Thermal Models

1) *CHP Unit*: For a fossil-fuelled CHP unit (e.g. micro-turbine), the relation between useful heat recovered from exhaust gas and electric power can be expressed as a nonlinear equation as follows [21]:

$$\dot{Q}^u = \frac{h^{F, \text{fuel}}}{c^{F, \text{fuel}}} Ch(P) \eta^T \eta^R \quad (19)$$

$$Ch(P) = \frac{c^{F, \text{fuel}} P}{h^{F, \text{fuel}} \eta^E(P)} \quad (20)$$

where $Ch(P)$ represents the hourly operating cost of the generation unit. In EMS problems, polynomial approximations, especially quadratic, are usually used to represent $Ch(P)$ (e.g. [18]). However, a linear expression is used here similar to (1), since it can be considered a good approximation for small units, as discussed in [22]. This has been confirmed for the generation units of the testbed microgrid considered in Section IV, where linear functions showed a close match between

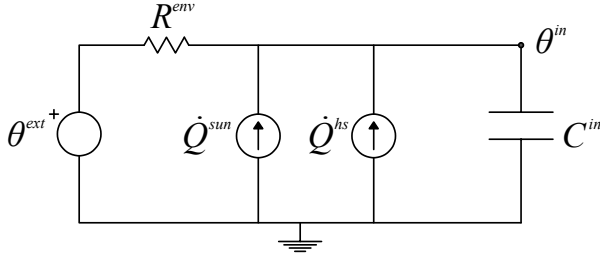


Fig. 1. Building thermal model.

measurements and the considered linear approximation. In this case (19) can be reformulated as:

$$\dot{Q}^u = \frac{h^{F,fuel}}{c^{F,fuel}} (aP + bW) \eta^T \eta^R \quad (21)$$

Nevertheless, depending on specific units' characteristics, and in order to keep a linear formulation, piecewise linear expressions could be used as well, as in [10].

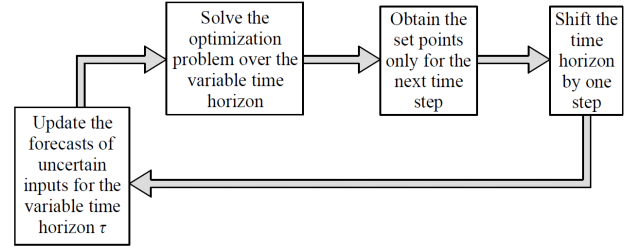
2) *Building*: Lumped resistance and capacitance (RC) models have been broadly employed to model thermal systems as, for example, in [21], [23], [24]. Some of these models, which account for all the heat transfer mechanisms, need a number of parameters in order to work properly, but some of those parameters may be difficult to measure/assess and/or are affected by large uncertainties. Furthermore, as highlighted in [23], a more complex model does not necessarily lead to significant enhancements in the representation of the building thermal dynamics. In [24], the whole house/single room is represented by a simple second-order model; namely, one differential equation for the indoor air temperature and the other for the walls inner temperature.

The simpler first-order model used in [21] and [25] considers the indoor air temperature dynamics and accounts for the main heat gains, such as conduction through the building envelope, solar irradiation, and heating system thermal power. Hence, a first-order model is also adopted here, which is a deterministic version of the simplest feasible model proposed in [23]. Thus, the equivalent circuit depicted in Fig. 1 is adopted as thermal model of a building, and the relevant dynamics are represented as follows:

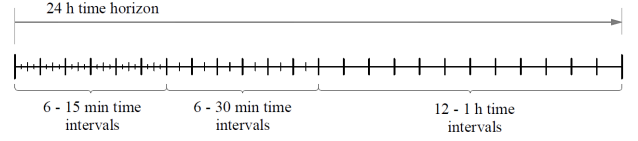
$$\begin{aligned} C^{in} \frac{d\theta^{in}}{dt} &= \dot{Q}^{hs} + \dot{Q}^{sun} - \dot{Q}^{env} \\ &= \dot{Q}^{hs} + \dot{Q}^{sun} - \frac{\theta^{in} - \theta^{ext}}{R^{env}} \end{aligned} \quad (22)$$

where the indoor temperature dynamics, defined by the capacitance C^{in} , depend on the heating system output $\dot{Q}^{hs}$, the thermal power due to solar irradiation that enters through the windows $\dot{Q}^{sun}$, and the heat transfer $\dot{Q}^{env}$ through the building envelope, which depends on the temperature difference and the thermal resistance R^{env} .

3) *TSS*: A closed-circuit water-based building heating system is considered here, neglecting water consumption and leakage. Moreover, a water tank is used as TSS, which is fed by some of the microgrid thermal units, as explained in detail



(a)



(b)

Fig. 2. MPC (a) process and (b) intervals.

in Section III. The following equation describes the hot water temperature dynamics in the TSS:

$$m^{TSS} c^w \frac{d\theta^{TSS}}{dt} = \dot{Q}^{TSS,in} - \dot{Q}^{TSS,out} - \dot{Q}^{TL} \quad (23)$$

where expressions for the thermal power input $\dot{Q}^{TSS,in}$ and output $\dot{Q}^{TSS,out}$ to/from the water tank depend in general on the water circuits that feed or are fed by the tank, respectively. Both (22) and (23) are discretized in the EMS model, with a time step in the order of minutes (see Section III), assuming that the water mass in the tank does not vary over time, which is reasonable due to the chosen time step duration, as discussed in [21].

C. MPC

In an EMSs with MPC approach, the optimization problem is solved at each time step over a chosen time horizon τ using up-to-date forecasts of uncertain inputs, in order to calculate the set points for the generation units accounting for the most likely value of those inputs, considering that the forecast accuracy improves when closer to the dispatch time t . Although uniform duration of time intervals can be used, the reduction of forecast accuracy over time makes it convenient to consider non-uniform intervals, with a duration that increases over the time horizon, as originally proposed in [26]. This yields a lower overall number of intervals in the time horizon and thus, compared to uniform-intervals, reduces computational burden, without a significant loss of accuracy in the optimization process. In this paper, a non-uniform resolution is used, as for example in [17] and [18], with each MPC iteration being composed of the following steps:

- At time t the forecast of uncertain inputs for the time horizon τ is updated.
- The optimization problem is solved between t and $t + \tau$, with a variable time step Δt_k .
- The solution of the problem provides the set points of controllable DERs only for the next time step, i.e. between t and $t + \Delta t_1$.

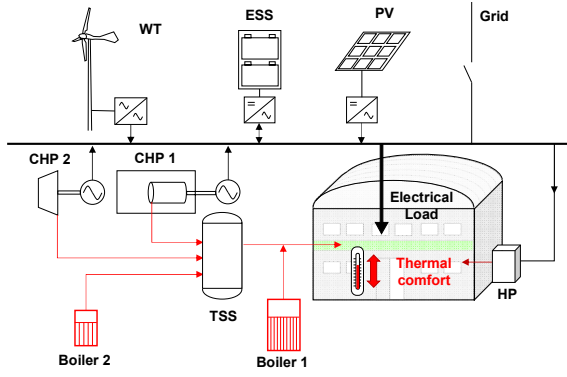


Fig. 3. PrInCE microgrid layout at the Politecnico di Bari [21].

- The time horizon is shifted forward by Δt_1 .

These steps are then repeated every Δt_1 . The MPC process and intervals are depicted in Fig. 2.

III. PROPOSED EMS

The microgrid considered here is intended to provide a building with both electricity and heat, and includes fossil-fuelled generation units, BESSs, PV and WTs as RES, and loads. Moreover, it is assumed that the generation units are CHP units, and boilers and HPs are available in order to meet the thermal demand of the building. The heating system is partly based on hot water, and a water tank is used as TSS, which is fed by the CHP units and some of the boilers. An illustrative example of such a system is the testbed microgrid built at the Electric Power System Laboratory of Politecnico di Bari, Italy, within the PrInCE (Innovative Processes of Energy Conversion) EU project [27]. The experimental facility is a three-phase, low-voltage network, which includes the following equipment: a natural-gas fuelled Reciprocating Engine (RE)-based CHP unit (CHP1); a gas microturbine in cogeneration layout (CHP2); an ESS based on nickel-sodium batteries; a 50-kW PV plant; a 60-kVA WT emulator; and two programmable loads with 150 kVA rated power each. The microgrid layout is shown in Fig. 3, including an air-to-water HP, two boilers, and a water tank as TSS. The microgrid is intended to supply electricity and heat to a former industrial warehouse, currently hosting some offices and laboratories. Water pipes and associated thermal losses are neglected, and occupants' thermal comfort is considered, allowing the indoor temperature to vary between imposed limits. Given these assumptions, the proposed EMS can be formulated as follows:

$$\begin{aligned} \min z = & \sum_{g \in G, k \in T} [(a_g P_{g,k} + b_g W_{g,k}) \Delta t_k + C_g^{\text{sup}} U_{g,k} \\ & + C_g^{\text{dn}} D_{g,k}] + \sum_{j \in J, k \in T} \left(\frac{c_j^{B, \text{fuel}} \dot{Q}_{j,k}^B \Delta t_k}{h_j^{B, \text{fuel}} \eta_j^B} \right) \\ & + \sum_{k \in T} (C_k^{LC} P_k^{LC} \Delta t_k) \end{aligned} \quad (24)$$

where, compared to (1), the first and the third summation terms are unchanged and refer now to CHP units, whereas

the second summation term represents the operating cost of boilers. Subject to power balance equations:

$$\begin{aligned} \sum_{g \in G} P_{g,k} + P_k^{PV} + P_k^{WT} + \sum_{n \in N} (P_{n,k}^{dch} - P_{n,k}^{ch}) \\ = P_{d,k} (1 + \alpha \Delta V_k) + \sum_{h \in H} P_{h,k}^{HP} - P_k^{LC} \quad \forall k \in T \end{aligned} \quad (25)$$

$$\begin{aligned} \sum_{g \in G} Q_{g,k} + \sum_{n \in N} Q_{n,k}^{ESS} = Q_{d,k} (1 + \beta \Delta V_k) \\ + \sum_{h \in H} Q_{h,k}^{HP} - Q_k^{LC} \quad \forall k \in T \end{aligned} \quad (26)$$

which compared to (2) and (3) also account for HPs. Moreover, (4)-(18) are used unchanged, and the following constraints, pertaining to heat supply, are added:

$$C^{in} \frac{(\theta_k^{in} - \theta_{k-1}^{in})}{3600 \Delta t_k} = \dot{Q}_k^Y + \sum_{h \in H} \dot{Q}_{h,k}^{HP} + \dot{Q}_k^{sun} - \dot{Q}_k^{env} - \dot{Q}_k^{vent} \quad \forall k \in T \quad (27)$$

$$\dot{Q}_k^Y = \eta^Y \left(\dot{Q}_k^{TSS, out} + \sum_{j \in J, j \notin TSS} \dot{Q}_{j,k}^B \right) \quad \forall k \in T \quad (28)$$

$$\begin{aligned} m^{TSS} c^w \frac{(\theta_k^{TSS} - \theta_{k-1}^{TSS})}{3600 \Delta t_k} = \sum_{g \in G} \dot{Q}_{g,k}^u + \sum_{j \in J, j \in TSS} \dot{Q}_{j,k}^B \\ - \dot{Q}_k^{TSS, out} - \dot{Q}_k^{TL} \quad \forall k \in T \end{aligned} \quad (29)$$

$$\dot{Q}_{h,k}^{HP} = \psi_h^{HP} \frac{\theta_h^{HP, out}}{\theta_h^{HP, out} - \theta_k^{ext}} P_{h,k}^{HP} \quad \forall h \in H, \forall k \in T \quad (30)$$

$$\dot{Q}_k^{sun} = \sum_{s \in S} \sigma_s I_s A_s \xi_s \tau_s \quad \forall k \in T \quad (31)$$

$$\dot{Q}_k^{env} = \sum_{s \in S} U_s A_s (\theta_k^{in} - \theta_k^{ext}) \quad \forall k \in T \quad (32)$$

$$\dot{Q}_k^{vent} = \frac{v_k^{rate} \rho^{air} Vol c^{air} (\theta_k^{in} - \theta_k^{ext})}{3600} \quad \forall k \in T \quad (33)$$

$$\dot{Q}_{g,k}^u = \frac{h_g^{F, fuel}}{c_g^{F, fuel}} (a_g P_{g,k} + b_g W_{g,k}) \eta_g^T \eta_g^R \quad \forall g \in G, \forall k \in T \quad (34)$$

$$\dot{Q}_k^{TL} = U^{TSS} A^{TSS} (\theta_k^{TSS} - \theta_k^{ext}) \quad \forall k \in T \quad (35)$$

$$\theta_k^{in, \min} \leq \theta_k^{in} \leq \theta_k^{in, \max} \quad \forall k \in T \quad (36)$$

$$\theta_k^{TSS, \min} \leq \theta_k^{TSS} \leq \theta_k^{TSS, \max} \quad \forall k \in T \quad (37)$$

$$0 \leq \dot{Q}_{j,k}^B \leq \dot{Q}_{j,k}^{B, \max} \quad \forall j \in J, \forall k \in T \quad (38)$$

$$0 \leq P_{h,k}^{HP} \leq P_{h,k}^{HP, \max} \quad \forall h \in H, \forall k \in T \quad (39)$$

$$0 \leq \dot{Q}_k^{TSS, out} \leq \dot{Q}_k^{TSS, out, \max} \quad \forall k \in T \quad (40)$$

where (27) and (29) represent, respectively, the thermal dynamics of indoor air and hot water in the TSS. These constraints are obtained through discretization from (22) and (23), respectively, using a backward difference method to approximate the time derivatives. The relevant heat gains and

heat transfer terms are defined by (28) and (30)-(35). Finally, (36)-(40) enforce the relevant operating limits. In (30), the HP input power is multiplied by the Coefficient Of Performance (COP), which depends on the HP outlet temperature and the outside ambient temperature through a heat sink [21].

Note that in the proposed optimization problem (24)-(40), a thermal demand model is now included, since the indoor air temperature dynamics are represented by considering a building thermal model in (27), plus min/max indoor temperature limits are also imposed in (36), which allows representing the occupants' thermal comfort. Furthermore, the CHP model in (34) now links electrical and thermal power generation, accounting for the variation of electrical efficiency with power output while maintaining linearity. Finally, the TSS is modeled based on the specific technology considered instead of a typical generic model, with the hot water temperature dynamics equation (29) accounting for charge/discharge of the thermal storage with constant water mass in the system.

For the EMS, PV plant and WT power outputs, outside ambient temperature, and electrical load are uncertain inputs; thus, forecasted values over the optimization time horizon T are assumed, and thus an MPC approach is applied to take into account the deviations from the forecast. Furthermore, an electrical load forecasting engine is assumed to provide a reasonable load forecast directly to the EMS, whereas the RES power generation is not treated as a direct input to the EMS, since it is assumed that a local weather forecasting service, which are now ubiquitous, provides the EMS with local solar irradiation, wind speed, and outside ambient temperature. Hence, the proposed EMS architecture includes a wind generator model and a PV generator model. Therefore, the wind speed at a reference height is converted into the actual speed at the turbine hub height, and then the WT power output is calculated from its power curve [28]. On the other hand, the output of a PV plant is evaluated from the ambient temperature and the total solar irradiation on the panels [28], [29], decomposing the total horizontal irradiation into direct, reflected and diffuse irradiation; subsequently, each of these terms is transformed into actual irradiation on the panels, accounting for the actual location and orientation, and considering the day of year [29]. Similar calculations are performed to evaluate the contribution due to solar irradiation (31) in the building thermal power balance (27).

The proposed EMS architecture is illustrated in Fig. 4. Thus, the EMS output consists of UC decisions and dispatch values in agreement with the operational constraints of dispatchable generation units, electric and thermal storage systems, active/reactive and thermal power balances, spinning reserves and thermal comfort requirements.

An MPC approach is used with a time horizon of 24 h, divided into 48 time intervals of non-uniform duration, as follows: the first 6 h are divided in 15 min intervals, the following 6 h in 30 min intervals, and the last 12 h in 1 hour intervals; consequently, the model is solved every 15 min. The proposed EMS model is an MILP problem, which has been coded in GAMS [30], and solved using the CPLEX solver [31], on an Intel® Xeon® 1.87 GHz 4-processor server.

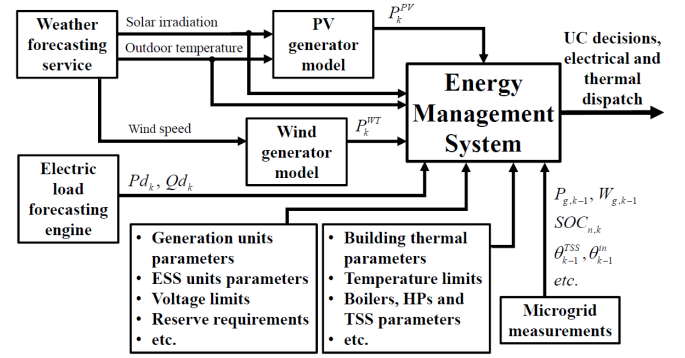


Fig. 4. Proposed EMS architecture.

TABLE I
CHP UNITS PARAMETERS

CHP unit n°	$P^{\min}$ [kW]	$P^{\max}$ [kW]	S^{inv} [kVA]	$\frac{a}{\text{kWh}}$ [€]	$\frac{b}{\text{h}}$ [€]	C^{sup} [€]	C^{sdn} [€]	$R^{\text{up}}, R^{\text{dn}}$ [kW/h]	$T^{\text{up}}, T^{\text{dn}}$ [min]	η^r	η^t
1	10	105	120	0.1415	3.589	1.875	0.625	140	30	0.56	0.75
2	7.5	30	30	0.1572	2.244	0.8438	0.2813	120	30	0.5	0.75

TABLE II
BESS PARAMETERS

$SOC^{\min}$ [%]	$SOC^{\max}$ [%]	$P^{\text{ch}, \max}$ [kW]	$P^{\text{dch}, \max}$ [kW]	$Q^{\text{ESS}, \min}$ [kVAr]	$Q^{\text{ESS}, \max}$ [kVAr]	S^{inv} [kVA]	η^{ch}	η^{dch}
20	90	57	63	-53	54	70	0.838	0.873

IV. RESULTS AND DISCUSSION

The proposed EMS is applied to the PrInCE testbed depicted in Fig. 3. The CHP units and the BESS parameters are shown, respectively, in Tables I and II, based on [21].

In order to validate the proposed EMS, simulations were carried out for different weather and load conditions in two study cases for two typical winter working days. Thus, the impact of integrating thermal energy resources and loads in the microgrid EMS is evaluated by comparing the dispatch results of the proposed EMS with those of the electrical-only EMS formulated in Section II. Outside temperature, solar irradiation and wind speed were obtained from a weather station located in the vicinity of the microgrid site [32], whereas the electric load profile was obtained from local historical measurements. A total of 24 h of operation of the microgrid are simulated, and in order to emulate the uncertain input forecasts, random normally distributed variations are used. The selected wind generator mimicked by the WT emulator is a horizontal axis wind turbine, with 30-kW rated power and 3.5, 11, and 26 m/s as cut-in, nominal, and cut-off speeds, respectively. Furthermore, a ventilation rate of 0.5 volume/h is considered only during working hours, i.e. from 7:00 a.m. to 8:00 p.m., and the limits on indoor minimum temperature are assumed to be 22°C during working hours and 15°C for the rest of the day, with a maximum of 24°C throughout the day. The temperature comfort limits are defined according to the intended use of

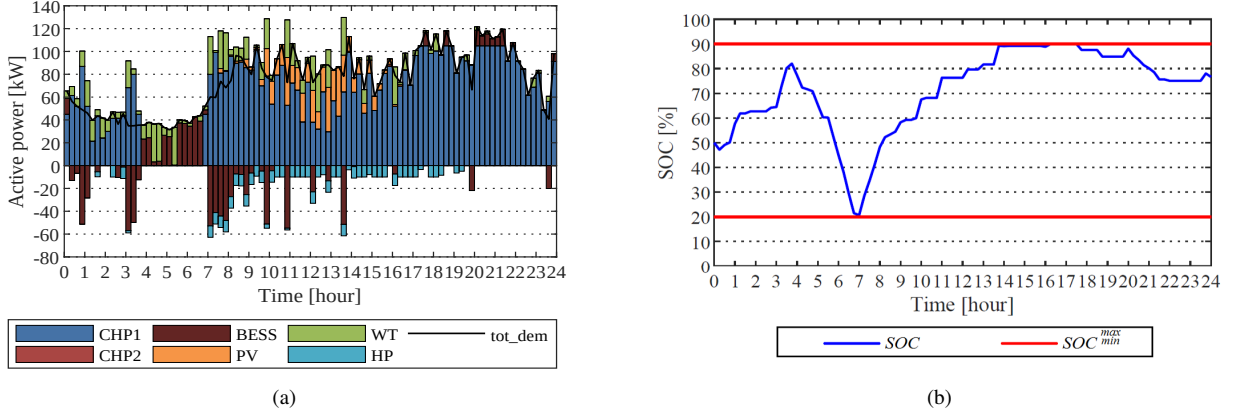


Fig. 5. Proposed EMS (a) dispatch results and (b) BESS SOC for Case 1.

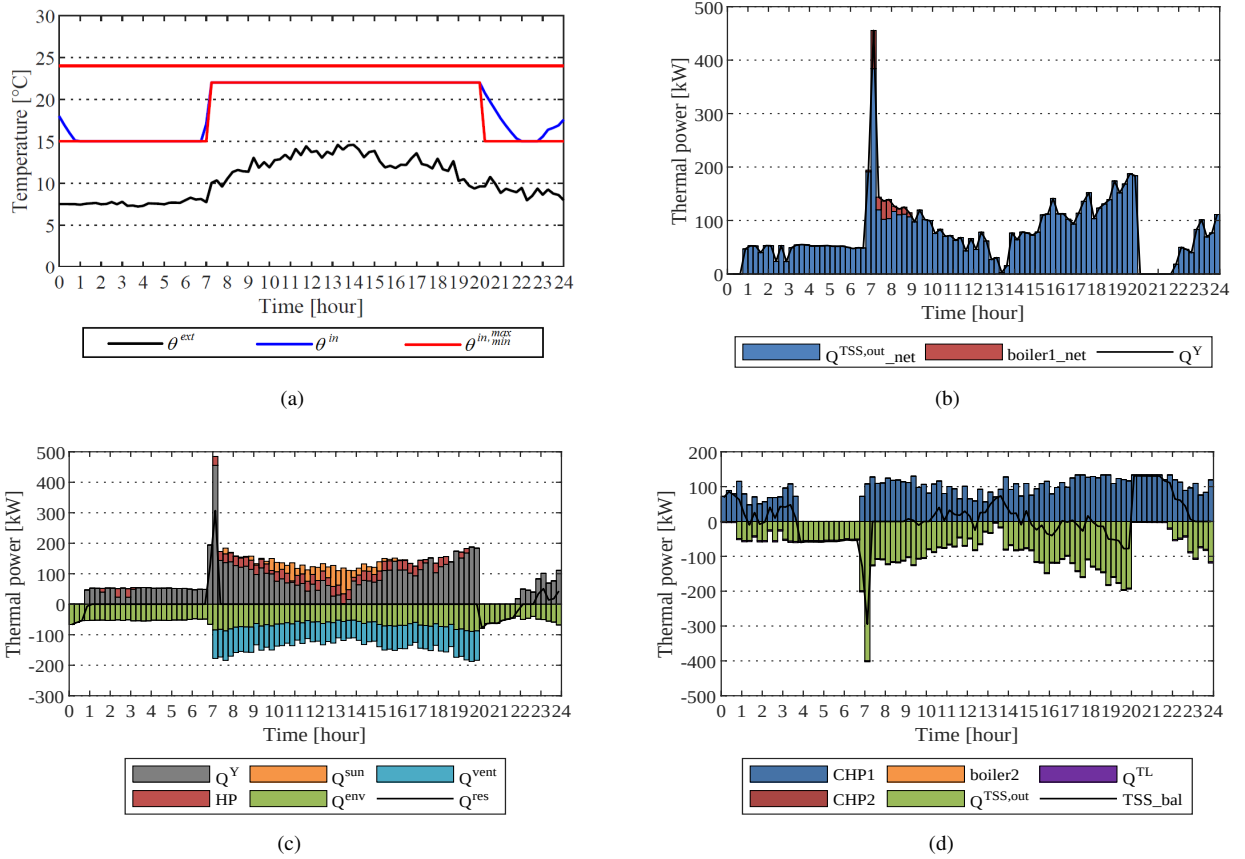


Fig. 6. Proposed EMS heat supply results for Case 1: (a) indoor and outdoor temperature, (b) hot water-based heating system power balance, (c) building thermal power balance, (d) TSS power balance.

the building, i.e. an office in the case study, which requires a higher maximum temperature and a smaller gap between minimum and maximum temperatures during working hours [21], [25].

For Case 1, the dispatch results and BESS SOC for the proposed EMS are shown in Fig. 5(a) and 5(b), respectively, where the BESS power is negative when charging and positive when discharging. Note that CHP1 is always committed, except for the time period between 3:45 and 6:45 a.m., in which the load is at its daily minimum and the BESS and WT

emulator are used to meet the demand. On the other hand, the significant output from RESs is mainly used to charge the BESS in the first hours and in the middle of the day, while during the evening and night, when the RES output is very small or null and the load reaches its peak values, the BESS discharges at load peaks (e.g. 8:00-9:30 p.m.), and charges when there is some load reduction (e.g. 7:45-8:00 p.m. and 11:30-11:45 p.m.). In all the simulations, the microgrid voltage is mostly at its lower limit, as expected in a stand-alone microgrid, since the load decreases with voltage.

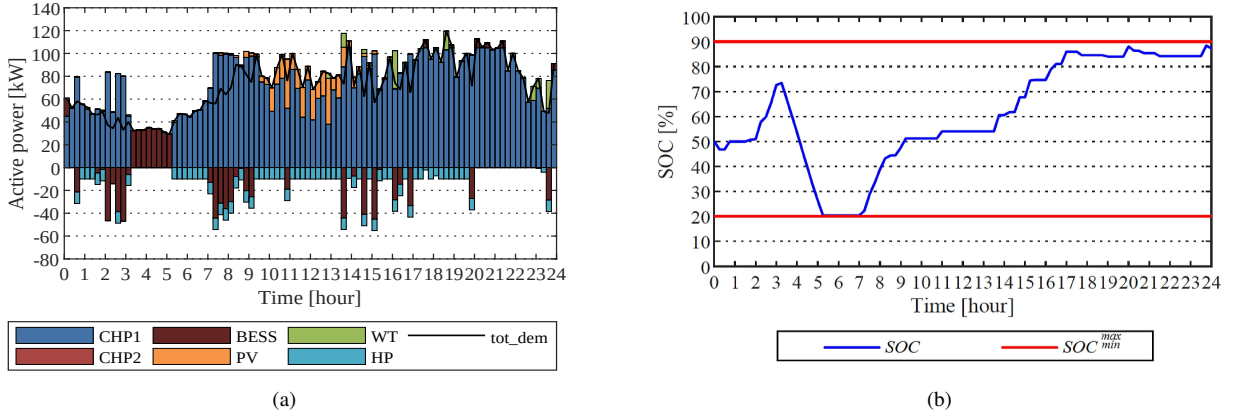


Fig. 7. Proposed EMS (a) dispatch results and (b) BESS SOC for Case 2.

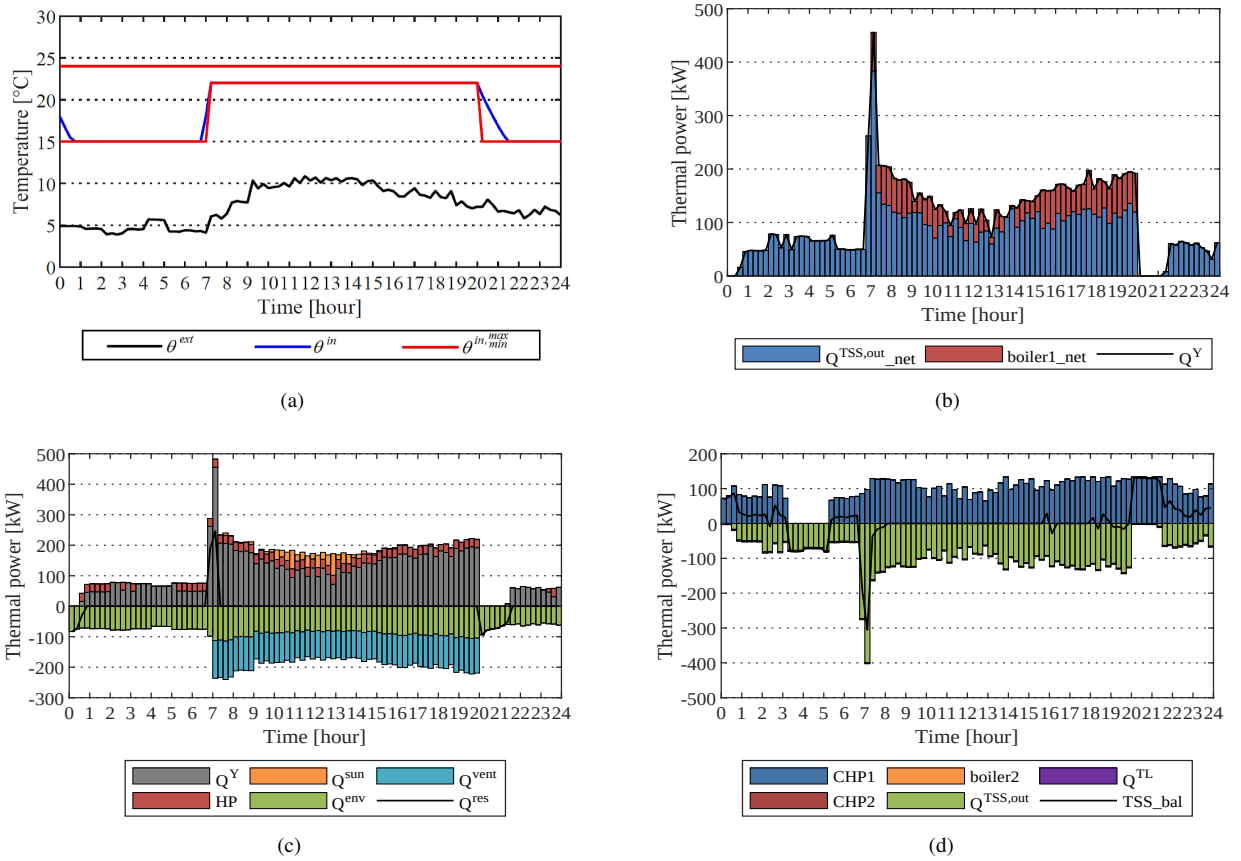


Fig. 8. Proposed EMS heat supply results for Case 2: (a) indoor and outdoor temperature, (b) hot water-based heating system power balance, (c) building thermal power balance, (d) TSS power balance.

With regard to heat supply, Fig. 6(a) represents the indoor temperature during the day. All simulations show that the EMS tends to keep the indoor temperature at its minimum limit, which is expected, since the objective is to minimize the fuel cost. When the lower temperature limit increases, the hot water-based heating system power output is increased as well, in order to attain the desired temperature, as it can be observed in Fig. 6(b), which illustrates the net power delivered by the hot water-based heating system, along with its components. Moreover, note a reduction in the heating system output in the

middle of the day, due to the contribution of solar radiation, as shown in Fig. 6(c), which illustrates the thermal balance of the building, where a positive residual demand (black curve) implies a rise in the indoor temperature, whereas a negative residual demand means a temperature decrease. An indoor temperature decrease is observed at night, when the lower temperature limit is reduced again; however, in the last hour of the day, the indoor temperature increases since the TSS is at its maximum charge. Finally, the TSS thermal balance is illustrated in Fig. 6(d), where the black curve represents the

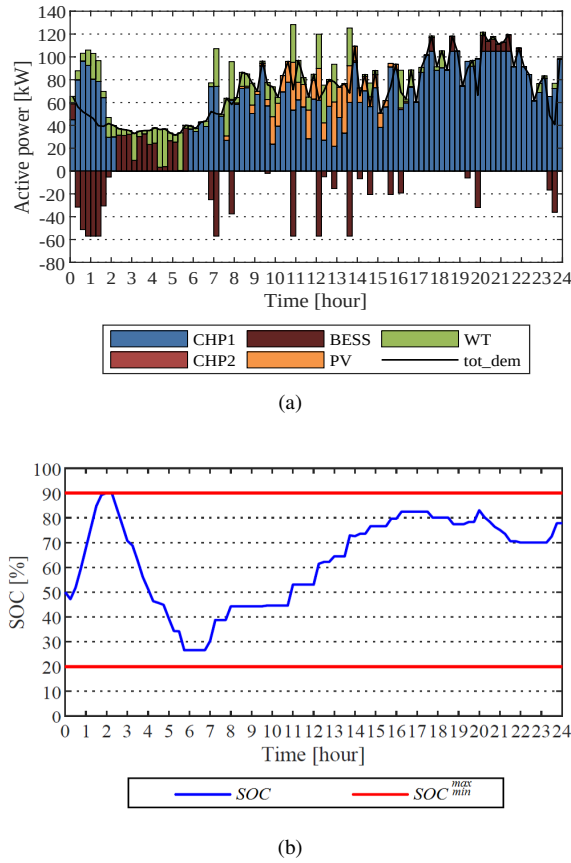


Fig. 9. Electrical-only EMS (a) dispatch results and (b) BESS SOC for Case 1.

power balance, meaning water temperature rise if positive, and temperature reduction if negative.

In Case 2, the electric load profile is similar to Case 1, but weather conditions are significantly different, with outdoor temperatures, wind speeds, and solar irradiation being considerably lower. The dispatch results of the proposed EMS for Case 2, which are shown in Fig. 7(a), generally resemble those of Case 1; however, in Case 2, higher dispatch levels of CHP1 can be observed, due to modest power production from both the PV plant and WT. The BESS charge/discharge in Fig. 7(b) shows similar overall trends to Case 1, despite variable charge rates in the middle of the day and moderate discharge at night. The thermal dispatch in this case corresponds to a colder day, as illustrated in Fig. 8(a), with Boiler1 being used significantly more than in Case 1, as shown in Fig. 8(b). The residual thermal demand pattern, accounting for indoor temperature variations, and the relevant heat gains can be observed in Fig. 8(c). Finally, as shown in Fig. 8(d) and similarly to Case 1, the TSS charges early in the morning, goes through a fast discharge when the indoor temperature lower limit increases, and finally charges at night; however, in this case, the hot water temperature does not reach its maximum value at night and hence no indoor temperature rise is observed (Fig. 8 (a)).

The electric dispatch results of the electrical-only EMS are depicted in Fig. 9(a) for Case 1 only, since no major differences can be found in Case 2. Overall, notice some similar dispatch patterns such as CHP1 not being committed in early

TABLE III
DAILY COSTS FOR THE PROPOSED EMS

Case n°	Optimum total cost [€]	Total electricity consumption [kWh]	Average electricity cost [€/kWh]	CHP units [€]	Boilers [€]	Net heat demand [kWh]
1	300.52	1879.17	0.1588	298.39	2.13	2225.44
2	348.41	1824.51	0.1774	323.75	24.66	3090.64

TABLE IV
DAILY COSTS FOR THE ELECTRICAL-ONLY EMS

Case n°	Total cost [€]	Optimum electricity cost [€]	Total electricity consumption [kWh]	Average electricity cost [€/kWh]	Additional cost of heat supply [€]
1	424.58 (+41.3%)	281.21	1770.43	0.1588	143.37
2	496.46 (+42.5%)	297.35	1650.60	0.1801	199.11

morning, and similar charge/discharge decisions for BESS, with some differences in the depth of each charge/discharge cycle as shown in Fig. 9(b). However, more significant differences can be seen in the operating costs. Hence, the costs for the proposed EMS and the electrical-only EMS are shown, respectively, in Tables III and IV. In Table III, the minimum cost obtained from the optimization is divided between CHP units and boilers, since the operating cost of boilers is not related to electricity delivery. Hence, the operating cost of CHP units, i.e. electricity delivery cost, is compared to the minimum cost obtained from the electrical-only EMS, with the former being larger than the latter. On the other hand, note that in the proposed EMS the overall electricity consumption is larger, due to the additional electric load represented by the HP (Fig. 5(a)); thus, the average daily electricity cost in Tables III and IV does not show significant differences between the proposed EMS and the electrical-only EMS.

The Net Heat Demand (NHD), which is reported in the last column of Table III, represents the heat supplied with the proposed EMS; whereas the Additional Cost of Heat Supply (ACHS) in Table IV is the cost associated with the thermal systems, which are not considered in the electrical-only EMS, and corresponds to the same NHD obtained with the proposed EMS. This cost is calculated assuming that the whole heat demand is covered by a centralized, natural-gas fuelled system not managed by the EMS, with 90% overall efficiency, as follows:

$$ACHS = \frac{c^{X,fuel} NHD}{h^{X,fuel} \eta^X} \quad (41)$$

Thus, the sum of the optimum electricity cost and the ACHS in Table IV yields the total cost. This results in a considerable increase in the total cost of over 40% compared to the proposed EMS. Therefore, the integration of thermal systems in a microgrid EMS is proven to be beneficial.

All simulations required a running time between 10 and 15 minutes for the whole 24 hour of operation of the microgrid, i.e. 96 MPC runs of the model, according to the chosen time

step, as explained in Section II. Hence, the average time of each MPC is less than 10 s, which is considerably less than the time step between two consecutive EMS runs, thus making the proposed model certainly applicable online. Note that, in the CPLEX solver, for both the EMS models, which are MILP problems, the maximum absolute relative gap was set to 1%.

V. CONCLUSION

In this paper, a novel EMS model for an isolated microgrid, integrating different thermal energy resources, has been proposed. Occupants' thermal comfort was represented by including a thermal model of the building in the optimization problem, and suitable models were used for CHP units and hot water-based TSS. The proposed EMS was tested on a real testbed microgrid located at the Politecnico di Bari, Bari, Italy, for different winter days, showing that, without significant variations in the average daily electricity cost, the integration of thermal systems in the EMS resulted in a significant reduction in the overall costs, i.e. for both electricity and heat supply. Therefore, the integration of thermal systems in a microgrid EMS is shown to be beneficial.

Future work will focus on the integration of the proposed EMS in the microgrid control system and its consequent experimental validation. Moreover, other aspects could be investigated, such as cooling and/or hot water supply.

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