

# Economic dispatch of a bioclimatic office building considering thermal energy, electricity and water demands

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**Abstract.** Energy and other resources management in production systems is a common topic in recent literature as many environmental and economic issues are related to the efficient use of their devices. In this sense, conversion and storage models based on input-output balances are helpful to determine the combination of resources that allow to operate a plant with the lowest possible cost. This paper is aimed at analyzing the optimal flows of resources that would meet the demands of a bioclimatic building, taking into account the characteristics of its facilities, which includes both photovoltaic modules and solar collectors to produce self-consumption electric and thermal energy. The simulation results for two different days of 2018 have been included. They verify the validity of the proposed model, which could be extended for carrying out analyses on similar buildings, modelled as an energy hub, in order to assess its optimality and proposing management policies.

**Key words.** Energy hubs, multi-energy systems, self-consumption, solar modules, optimization.

## 1. Introduction

Energy consumption in residential and commercial buildings represents over the 40% of the total energy consumption in developed countries and near the same amount of CO<sub>2</sub> emissions [1], [2], which are the main responsible for the greenhouse effects and global warming. Renewable energies can reduce the global CO<sub>2</sub> emissions and, at the same time, allow the governments to fulfill their global agreements about climate change, providing clean, cheap and durable energy sources. However, because of the intermittent and stochastic nature of those related to weather conditions, they cannot be used to produce power uninterruptedly and often require storage systems and combining multiple energy vectors to implement flexible and efficient management strategies.

An energy hub (EH) is considered as a unit where the production, conversion, storage and consumption of different energy carriers takes place, representing an interface between different energy infrastructures and/or loads [3]. Some authors consider it a promising option for energy management of Multi-Energy Systems (MES) [4], and its ins and outs have been scrutinized in several reviews on the concept itself [5], optimal management [6], uncertainty [7]

or comprehensive approaches [8]. Particularly, it is possible to find several works in literature that address the management of MES in buildings using the EH concept, either with just control purposes (meeting the heating, cooling and electricity demands) [9], [10] or to design a new facility [11], [12].

In this work, the economic dispatch of a real bioclimatic building is presented where not only energy (thermal energy and electricity) is modelled and managed but also water demand, which produces a shiftable load in form of electricity. This task is done by exploiting the EH concept and formulating a linear input-output model for conversion and storage processes. The real building is the CIESOL research center [13], a bioclimatic building which can be considered a MES since it has both conventional energy sources and renewable ones.

The rest of the paper is organized as follows: Section 2 is devoted to present and describe the CIESOL building and its equipment, whereas Section 3 presents the model proposed for the CIESOL building. The main results from this work are presented and discussed in Section 4 and the conclusions deduced from them are summarized in Section 5.

## 2. Scope of the work

The work presented in this paper has selected the CIESOL research center (<http://www.ciesol.es>) as a reference building, see Fig. 1. It is placed inside the Campus of the University of Almería (South-East of Spain) under typical desert Mediterranean climatic conditions. This building occupies a surface of 1072 m<sup>2</sup> divided into two floors and, as it was built following bioclimatic criteria, it has several passive and active approaches.

The most representative passive strategies adopted at CIESOL building are the setback of windows which faces South and East, the use of different types of enclosures as a function of the orientation and the shadowing of the rooftop through the installation of both a photovoltaic field and a solar collector field.



Fig. 1. CIESOL building components

In addition, this building has also some active strategies as a solar cooling installation, automated windows and blinds and a renewable energy based microgrid. The solar cooling installation is formed by an absorption machine, a refrigeration tower, hot and cold-water storage tanks, a boiler and the solar collectors field used to shadow the rooftop.

Furthermore, the building is equipped with an extensive network of sensors distributed throughout the building. It is worthy to mention the existence of five characteristic rooms completely monitored by means of indoor air temperature, relative humidity, plane radiant temperature and CO<sub>2</sub> concentration sensors among others. Besides, the building has also a meteorological station located in the rooftop which provides measures as outdoor temperature and relative humidity, solar radiation, etc. A complete description of the building and all its components can be found in [13].

### 3. Energy hub modeling

The model set up for simulations, and the economic dispatch problem, are based on the general approach presented previously by some of the authors of this work in [14], which has been adapted for the structure of the CIESOL building, see Fig. 2.

#### A. Problem formulation

The energy hub counts with electricity ( $I_1$ ) and water ( $I_5$ ) from the public utility grids, solar radiation ( $I_2$  and  $I_3$ ), and propane ( $I_4$ ) as inputs. Also, the following loads can be identified: electricity ( $O_1$  and  $O_5$ ), heating ( $O_3$ ) and cooling ( $O_2$ ) power, and water ( $O_4$ ) as outputs. Note the difference between  $O_1$  and  $O_5$ , which are examples of shiftable and non-shiftable loads, respectively: the first one considers the demand owing to most electric devices and equipment, whereas the second one represents the demand of the pump system. Thus,  $O_5$  is only an actual consumption if the impulsion pump is activated ( $\delta_{D,7}$ ) for maintaining the

required pressure on the water flow (which is assumed to happen any time a tap is opened, or the storage tank is charged). Furthermore, each device is numbered in order to establish the equations of the system as in [14].

The conversion and storage processes are expressed through equations (1) and (2), respectively. These are matrixial expressions where  $O$ ,  $M$ ,  $Q_c$ ,  $Q_d$ , and  $S$  are vectors whose size depend on the number of outputs (see Fig. 2),  $\delta_O$  is the identity matrix with the element (5,5) substituted by  $\delta_{D,7}$ , and the remaining matrixes express losses in conversion ( $C$ ), charging ( $C_c$ ), discharging ( $C_d$ ) and storing ( $C_s$ ) operations.

$$\delta_O(k)O(k) + M(k) = C(k)P(k) - Q_c(k) + Q_d(k) \quad (1)$$

$$S(k+1) = C_s(k)S(k) + C_c(k)Q_c(k) - C_d(k)Q_d(k) \quad (2)$$

It must be remarked that  $P$  is a vector that depends on the system's structure and allows a linear formulation of the problem. In order to represent all the resources flows, it contains as many variable as possible paths between the inputs and the outputs (readers are referred to [14] for clarification), so that equation (3) relates input vector  $I$  (whose variables split into the different paths) with vector  $P$ .

$$I(k) = C_i P(k) \quad (3)$$

Similarly, the flows through each device can be obtained in form of a vector  $D$  by suitably defining a matrix  $C_D$  that relates them with vector  $P$ , as in (4).

$$D(k) = C_D(k)P(k) \quad (4)$$

In addition, the physical limits of the flows through either conversion or storage devices, the storage and selling capacity, and the availability of input resources are expressed as in equations (5) to (10),

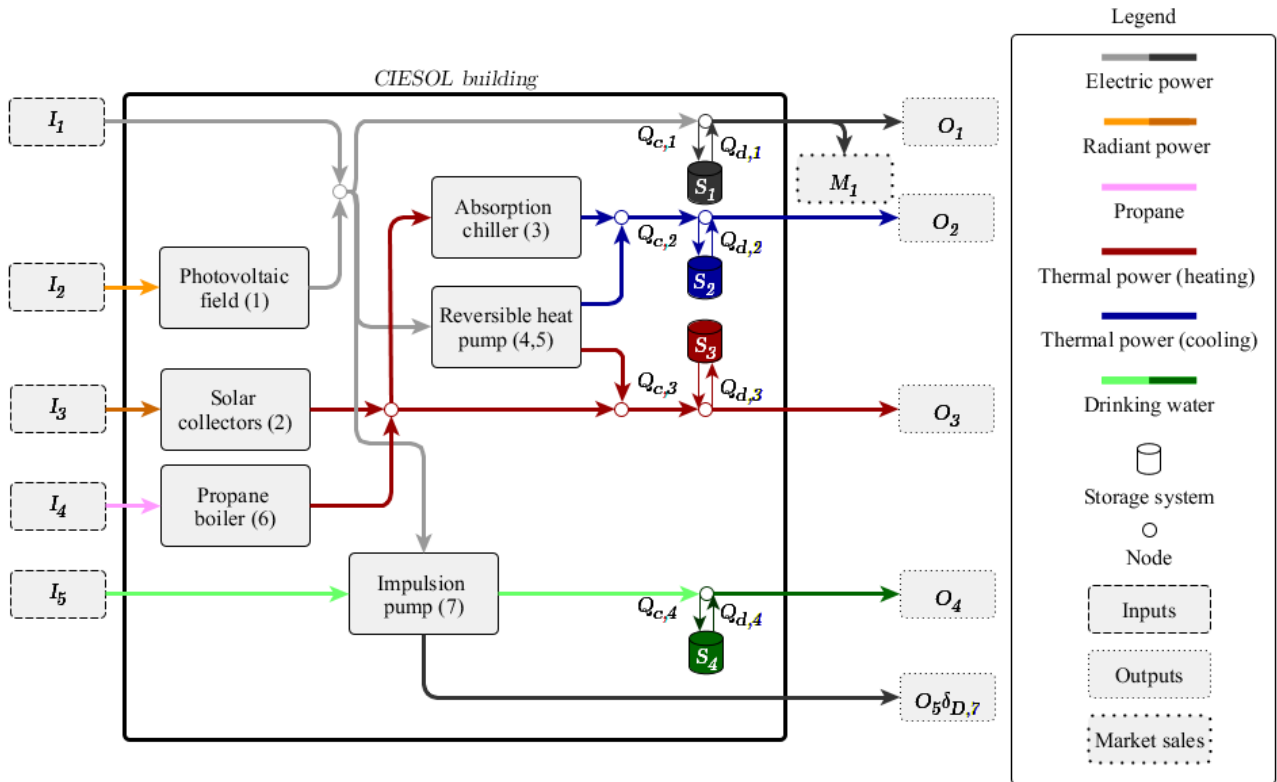


Fig. 2. Conceptual input-output model of the building based on [14]

$$\delta_c(k)Q_c^{\min}(k) \leq Q_c(k) \leq Q_c^{\max}(k)\delta_c(k) \quad (5)$$

$$\delta_d(k)Q_d^{\min}(k) \leq Q_d(k) \leq Q_d^{\max}(k)\delta_d(k) \quad (6)$$

$$\delta_D(k)D^{\min}(k) \leq D(k) \leq D^{\max}(k)\delta_D(k) \quad (7)$$

$$S^{\min}(k) \leq S(k) \leq S^{\max}(k) \quad (8)$$

$$\delta_M(k)M^{\min}(k) \leq M(k) \leq M^{\max}(k)\delta_M(k) \quad (9)$$

$$\delta_I(k)I^{\min}(k) \leq I(k) \leq I^{\max}(k)\delta_I(k) \quad (10)$$

At this point, one should note that  $\delta$  is employed to design diagonal matrixes whose elements are the binary variables that determine the state on/off of both devices and market sales or input flows.

On the other hand, equations (11) to (13) are required for avoiding simultaneous processes as selling and purchasing electricity (11), charging and discharging the same storage device  $o$  (12), with  $o \in \{1, 2, 3, 4\}$ , and generating both heat and cool with the reversible heat pump (13).

$$\delta_{I,1}(k) + \delta_{M,1}(k) \leq 1 \quad (11)$$

$$\delta_{c,o}(k) + \delta_{d,o}(k) \leq 1 \quad (12)$$

$$\delta_{D,4}(k) + \delta_{D,5}(k) \leq 1 \quad (13)$$

The optimization problem is then defined by means of equation (14) that includes the economic cost of acquiring resources  $(c(k))$  and the revenues from selling  $(s(k))$ .

$$\begin{aligned} \min \sum_{k=1}^{24} (c(k)I(k) - s(k)M(k)) \\ \text{s.t. the above restrictions} \end{aligned} \quad (14)$$

### B. Simulation scenarios

Two typical clear days of autumn (September 29<sup>th</sup>, 2018) and winter (February 3<sup>rd</sup>, 2018) were selected because of the significant availability of solar radiation (see Fig. 3) as well as thermal necessities. Regarding the cost and selling vectors, the price of 1,694 €/kg was considered for propane, and 0,547 €/m<sup>3</sup> for water, whereas electricity purchases and sales are subject, respectively, to the local supply company tariff (0,0892 €/kWh from 0:00 h to 8:00 h, 0,2044 €/kWh from 18:00 h to 22:00 h and 0,1127 €/kWh the rest of the day) and to the hourly price fixed in the electricity market (plus the generation fee and IVPEE) [14], shown in Fig. 3.

Besides, the conversion coefficients and operation limits of the seven devices (the reversible heat pump is virtually divided into two different components) and the four storage systems are collected in Table I and Table II, respectively. The flow is referred to each device input for conversion processes, and the minimum charge and discharge flows are set to zero for each storage system. Solar production limits and conversion are calculated hourly depending on weather conditions (see Fig. 3), and by considering the isotropic sky model together with the equivalent circuit for a photovoltaic generator [15] or the model previously developed for the solar collector field [16]. For more information on this regard readers are also referred to [14].

Table I. - Devices characterization

Device number	Minimum flow	Maximum flow	Conversion efficiency
3	0 kW	100 kW	0.7 kWh/ kWh
4	0 kW	26.5 kW	2.9 kWh/ kWh
5	0 kW	26.5 kW	3.1 kWh/ kWh
6	4 kg/h	6.8 kg/h	11.54 kWh/kg
7	0 m <sup>3</sup> /h	1 m <sup>3</sup> /h	1

Table II. - Storage systems characterization

System number	Charge (efficiency)	Discharge (efficiency)	Capacity (degradation)
1	3 kW ( $\eta = 0,7$ )	3 kW ( $\eta = 0,8$ )	11 kWh ( $\eta = 0,02$ )
2	20,9 kW ( $\eta = 0,9$ )	20,9 kW ( $\eta = 0,9$ )	29 kWh ( $\eta = 0,06$ )
3	125.4 kW ( $\eta = 0,9$ )	125.4 kW ( $\eta = 0,9$ )	174.2 kWh ( $\eta = 0,06$ )
4	0.01 m <sup>3</sup> /h ( $\eta = 1$ )	0.01 m <sup>3</sup> /h ( $\eta = 1$ )	0.09 m <sup>3</sup> ( $\eta = 0$ )

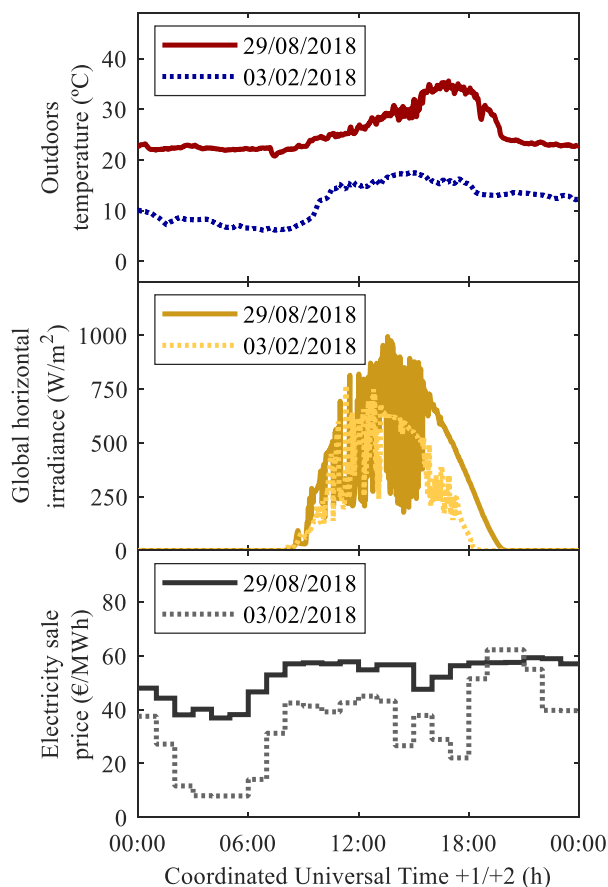


Fig. 3. Weather conditions and pricing for each scenario

## 4. Results

The problem addressed is solved by running MATLAB® solver *intlinprog* on an Intel® Core™ i7-6700K CPU, taking less than one second to solve each dispatch, which means that the model would be still suitable if the computational burden increased as a result of diminishing the sampling time or employing a rolling horizon strategy. Considering the information presented in Fig. 3, heating power demand was neglected in autumn because of the weather conditions (outdoor temperature from 21 °C to 35 °C) and so was cooling power in winter (outdoor temperature from 6 °C to 18 °C). Results are shown in Fig. 4 and Fig. 5, employing colors according to each kind of resource as in Fig. 2, and summarized in Table III, in terms of accumulated flows during the day, that is, amounts of energy, volume or mass.

Table III. – Resources dispatch summary (accumulated)

	Sep. 29 <sup>th</sup> , 2018		Feb. 3 <sup>rd</sup> , 2018	
Var.	Amount	Cost	Amount	Cost
$I_1$	1,7 MWh	201,12 €	1,8 MWh	217,93 €
$I_2$	365 kWh	0 €	308 kWh	0 €
$I_3$	169 kWh	0 €	656 kWh	0 €
$I_4$	0 kg	0 €	0 kg	0 €
$I_5$	2,10 m <sup>3</sup>	1,15€	2,45 m <sup>3</sup>	1,34 €
$O_1$	1,6 MWh	-	1,7 MWh	-
$O_2$	64,4 kWh	-	0 kWh	-
$O_3$	0 kWh	-	309 kWh	-
$O_4$	2,10 m <sup>3</sup>	-	2,45 m <sup>3</sup>	-
$O_5$	72 kWh	-	72 kWh	-
Total		202.27 €		219,27 €

Regarding Fig. 4 and Fig. 5, both contain the hourly demand profiles for each output, plotted in thick line, and the market sales profile ( $M$ ), stacked over the latter one in thin line; scaled to the left axis and expressed in terms of power or flow. The dashed line, which is scaled to the right axis, represent the evolution of the storage systems, corresponding to each output ( $S$ ), in terms of energy, mass or volume. In each plot, the right axis upper limit corresponds to the storage maximum capacity. Colored stacked bars (scaled to the left axis) indicate inputs flows ( $I$ ) that meet the demand profile; therefore, when they are over the demand and sales profiles, the storage systems are charged (so the dashed line has a positive slope) whereas they are discharged when under them. Because of the degradation assumed in certain energetic stored resources, in some cases the storage profile has a negative slope, similar to a discharge, even when the demand and sales profiles are strictly met.



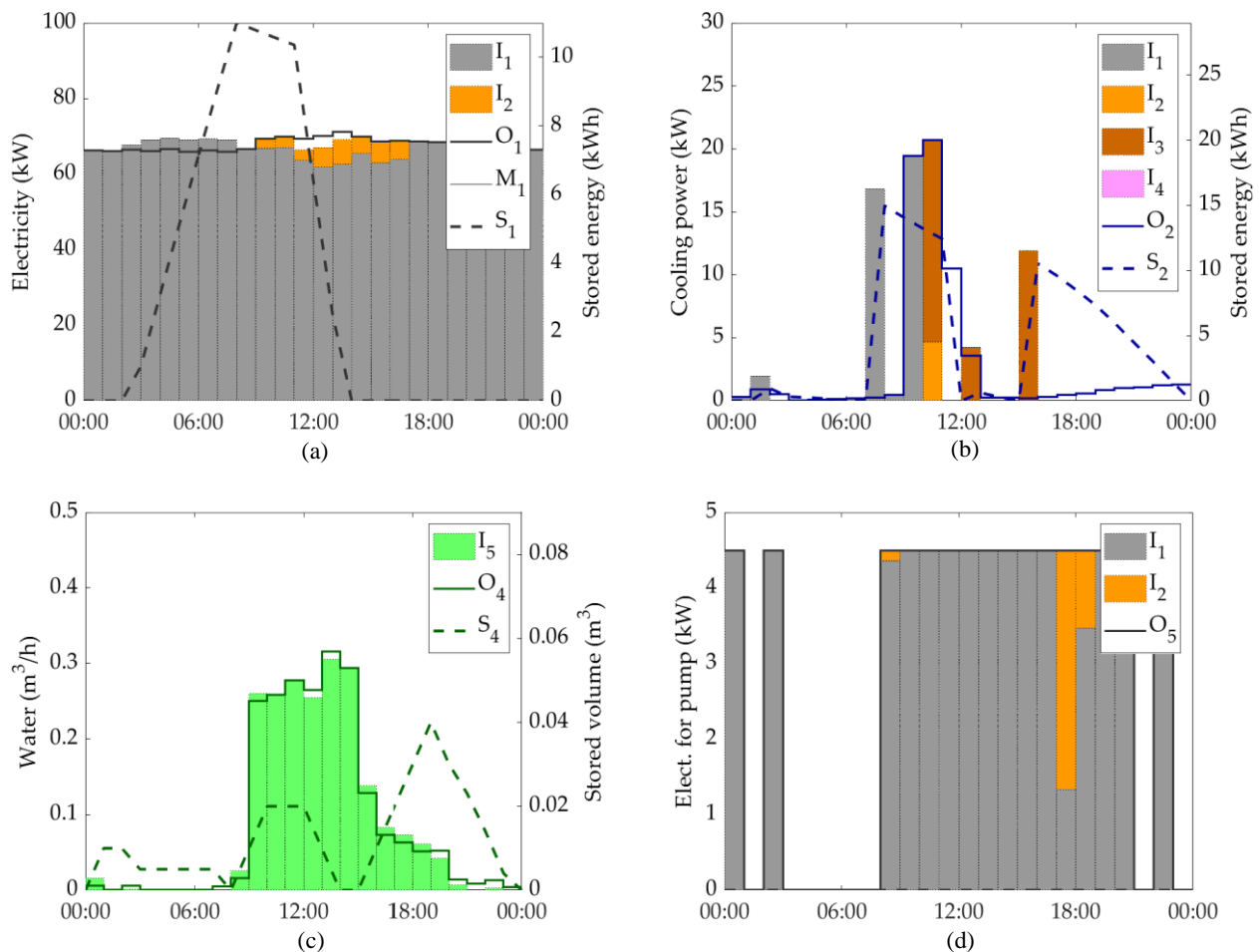


Fig. 4. Optimal economic dispatch of the resources (Coordinated Universal Time +2, September 29<sup>th</sup>, 2018)

Note that both water (Figs. 4(c) and 5(c)) and thermal (Figs. 4(b) and 5(b)) demands are concentrated during the mid-hours of the day due to working schedules, but electricity (Figs. 4(a) and 5(a)) demand remain nearly immutable during the whole period because of the equipment that operate in the building constantly. Thermal and electric demands are met, when possible, by means of solar resources since they are freely available in contrast to purchasing propane and/or electricity. However, the size of the photovoltaic field is not enough to provide the required amount of power by the building, so it is self-consumed instead of sold and most of the energy needed is acquired via the public utility grid. Also, there exists correspondence between Figs. 4(c) and 4(d) and Figs. 5(c) and 5(d) as the impulsion pump is activated at any time water is provided from the public grid. Because the water storage system flow is physically limited, the amount of water charged during a sample periods tends to be as high as possible: in order to take advantage of the electricity that would be spend anyway to feed the pump.

The storage system management is closely related to both the price of the resources and the equipment characteristics. See, for example, Figs. 4(a) and 5(a), where owing to the lower price before 8 a.m. the batteries are filled early in the morning and discharged after. In the case of water (Figs. 4(c) and 5(c)), because the irrigation pump will be needed during the mid-period of the day, it is preferable not to use it even if the electricity price is low unless there is some water demand (as at 00:00 both days).

## 5. Conclusion

Considering the optimization-based framework presented in this work, the basis for carrying out further analyses on similar buildings, modelled as an energy hub and validated in a case study, have been set up. These could include assessing necessities such as increasing the storage systems' capacity or adding different conversion technologies. Both constitute design problems that can be solved employing a multi-level approach [12] in which a genetic algorithm generates different structures of energy hub based on the presented model. In that sense, add new components is not an issue since the formulation does not need to be substantially modified because of the use of matricial notation.

Besides, the problem could be integrated into a receding horizon strategy aimed at managing shiftable loads while updating the predictions (weather, electricity price...). That would constitute a control approach in which uncertainty is taken into account and could involve using the dispatch results as inputs for lower-level control loops.

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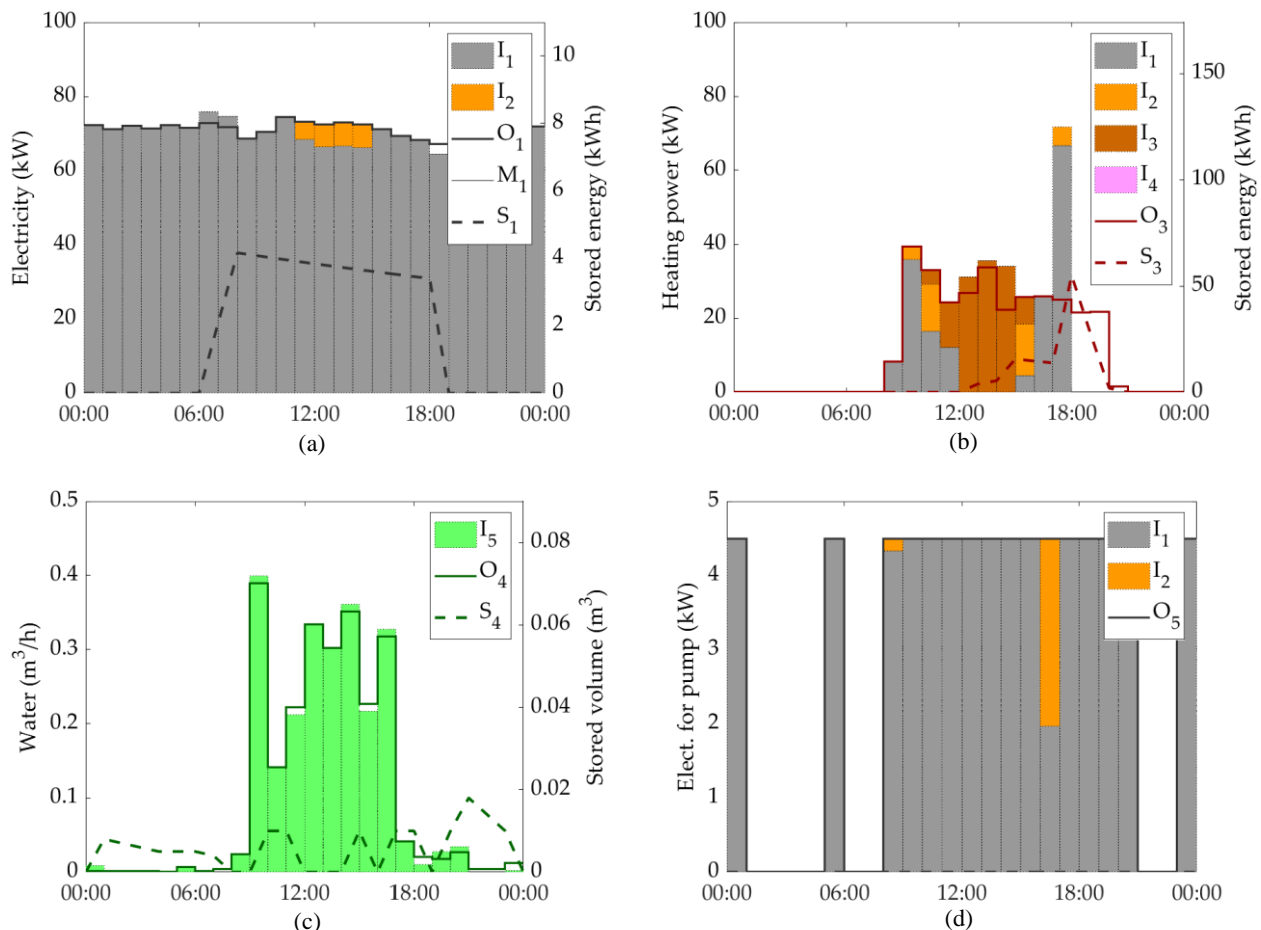


Fig. 5. Optimal economic dispatch of the resources (Coordinated Universal Time +1, February 3<sup>rd</sup>, 2018)

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