A simple MILP optimization model for the economic and performance assessment of a solar photo-voltaic system to feed a university campus and a set of surrounding residential complexes

Stefano Casarin
stefano.casarin@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

November 2018

Abstract

The Instituto Superior Tcnico (IST) university has a campus located in the center of Lisbon and its electrical consumption represent a relevant share of the yearly budget. Being surrounded by plenty of residential complexes with available roof surface, there is a high potential for solar energy production. The goal of this work is to find an optimal configuration, i.e. the number and type of equipment, that IST should install on the roofs of the surrounding buildings so that both the campus and the residents can reduce their yearly electrical energy related costs. A MILP model is built to find the optimal configuration of the system: the campus is characterized by an electric consumption curve and two technologies photo-voltaic modules (PV) and solar-thermal collectors (ST) with thermal storage; four buildings are considered, each one characterized by an amount of available surface and an electric and a thermal load consumption profiles. The model has been run over four days, each representative of one season. Results show that the households thermal energy requirements are not significant enough to justify an investment in ST. In the base scenario all of the available surfaces are filled with PV modules. Finally a sensitivity analysis on the PV modules unitary cost shows that IST savings strongly decrease with the increase of this cost, while the residents are affected only as if the specific cost is high enough not to cover completely the available surfaces.
Keywords: MILP, optimization, renewable energy, solar energy, photo-voltaic, distributed generation

1. Introduction

Instituto Superior Tcnico (IST) is one of the most prominent academic institution in Portugal and boasts several partnerships with renowned universities all over the world, together with a prolific academic research activity. It has three campuses, the main one being the Alameda campus, situated in the center of Lisbon.

The Alameda campus was situated in the outskirts of Lisbon, but with the city's expansion in the first half of the XX century, it quickly became surrounded by multi-apartment buildings. The IST works all year long, with the exception of two weeks of the month of August, and requires a high amount of energy for didactic, administrative, and research activities. An internal energy audit revealed that the energy mix is composed for 81 % of electrical energy (EE), while 19 % is natural gas (NG). The energy consumption represents a relevant share of the yearly budget, and to this date it only relies on the connection to the electric grid and NG distribution network. The campus does not perform any self generation.

A way to reduce the energy-related costs and decrease the respective carbon footprint would be the integration of RES generators.

Due to the location in which the campus is situated, wind energy generators can not possibly be installed in an urban area. On the other hand, solar energy is a much more viable option: the campus is surrounded by residential buildings, whose roofs are not yet equipped with neither solar photovoltaic (PV) or thermal (ST) collectors: the produced energy therefore could be conveyed in low voltage thanks to the short distances.

The aim of this work is to assess the feasibility of a distributed generation (DG) network providing energy to IST campus and to those multi-apartment buildings that will host the energy conversion equipment, through a microgrid.

The reason for considering the ST technology is that in Portugal it is common to use EE for heating purposes: a ST system would reduce the renewable PV energy self-consumption allowing more EE to feed IST.

1.1. State of the art

The concept of *Energy Hub* can be defined as "an interface between consumers, producers, storage devices in different ways: directly or via conversion equipment, handling one or several carriers" [1]. Under this perspective, IST campus has the potential to become an EH with a careful design of the generators and their schedules.

Several approaches and optimization techniques have successfully been applied in both the design and the schedule operation of EH, polygeneration systems, distributed generation and microgrids [1–4]. The successful integration of energy from decentralized intermittent sources depends heavily on the optimisation of the energy systems [5].

In this work a MILP model has been developed to design a decentralized energy production network relying on solar energy. MILP has been chosen because such models have the advantage that – when convergence is attained – it is proven for the feasible solution to be optimal or close to optimal [6]. MILP is also being extensively used on energy hub models for being fast and reliable [7].

In the literature there are several softwares and languages to perform such analysis. Distributed Energy Resources - Customer Adoption Model (DER-CAM) is a powerful tool developed by the Berkeley Lab. It formulates problems as a MILP and finds globally optimal solutions for distributed energy resources investments, for either buildings or multi-energy microgrids. This tool has been thoroughly used to find the optimal design and configurations of DER systems [8, 9].

1.2. Objectives

The aim of this work is to assess the economic feasibility of the implementation of a decentralized renewable energy system. This translates into the search for the optimal configuration of the energy generation system i.e. the amount of installed PV modules, ST collectors and the size of the TS tank (if any), that will produce a reduction of the energy-related expenses for both the campus and the residential complexes.

If the conditions are favorable, IST and the owners of the apartments to which the rooftops belong will form a synergistic cooperative: the former will get the PV energy that is not self-consumed, while the latter receive free renewable energy by making available the unused roof surface.

The term USR is used to define a single residential complex, made of several apartments, each occupied by a family or a group of people.

The reason for considering the ST technology is that in Portugal it is common to use EE for heating purposes: a ST system would reduce the renewable PV energy self-consumption allowing more EE to

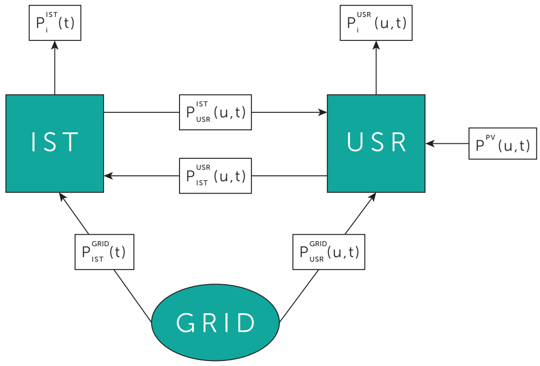


Figure 1: System representation.

feed IST.

As stated above, the following aspects will be considered:

- the amount and type of the energy conversion devices to be installed: IST, having a bigger purchase power than a regular household, can achieve a cheaper price per device than single families;
- the buildings fit to be selected for the partnership: each building is characterized by several parameters defining the surface availability and its quality (a north-facing rooftop is less valuable than a non-shaded south-facing roof), as well as a number of apartments that have an energy consumption profile;
- the economic conditions to which IST receives the EE from the USRs and vice-versa.

This work is structured as follows: section 2 describes the system under investigation and the methods employed for its characterization, namely the procedures to process raw data and obtain the energy consumption profiles of the campus and the residential complexes and formulates the optimization problem. Section 3 describes how the model is implemented, section 4 presents the results (including a sensitivity analysis) and reports the critical remarks. Finally in section 6 conclusions are drawn.

2. Methods

The system is modeled as a central consumption node (the campus) surrounded by residential complexes that can become generation nodes and that, if so, will connect to it radially.

Fig. 1 shows the possible interactions between IST, a generic USR, and the grid. As shown, there can be an energy flow between IST and the selected USR. The arrows represent the possible directions of the energy flows (defined as P). Superscripts and subscripts are to be read as “from-to”, respectively.

The IST campus has a peak EE consumption of 1 to 2 orders of magnitude greater than that of a single-family household: IST can be considered as a sink, therefore the extra EE that exceeds the requirements of a single household can always be accepted.

It can be hypothesized IST to be a fictitious storage system: with the exceeding EE produced by the over-sized PV modules, the USRs “charge” the campus which – when there is no solar energy production – can return the charged energy back to the respective USR. This is because IST has a different tariff regime than that of a common household, with lower prices per kWh. The IST-as-storage abstraction avoids a solution based on economic speculation: the price of energy the campus has access to – being a big consumer – is way lower than that of a private apartment, hence it could making profit just by selling at a higher price the energy it buys. This solution has not any added scientific value and would not have a positive impact on the grid system.

The system is modeled as a MILP problem: continuous variables are used for the energy and cash flows, and for the level of charge and volume of the thermal storage; integer variables are used for the amount of PV modules and ST collectors that will be installed; binary variables are used for the selection of the USR and to model the variable unitary cost of energy along the day.

2.1. Time horizon

The analysis is performed on a yearly basis, with 1 h resolution. With 8760 time steps to simulate a year, the computational effort (the solving time) would be too demanding. This is why it has been chosen to reduce the year to 4 representative design days, one for each season. This choice reduces greatly the complexity of the model without compromising the solution, since each day is simulated independently [10].

2.1.1 IST energy characterization

IST is characterized by an hourly electric energy demand. The “Campus Sustentável” project of IST [11] provided a file of hourly records of the campus electric demand. The measurements cover a time range from December 2015 to November 2017.

Figure 2 shows the steps performed for the data treatment: the raw data has been treated by removing the not-a-number (NaN) records. All the values that fall outside a $3\,\sigma$ (99.7 % confidence) interval are removed because considered outliers, which are unusual values whose existence is to led back to random malfunctions of the measurement instruments and are not related to the phenomena of interest.

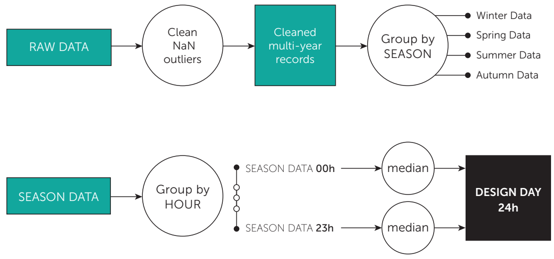


Figure 2: Representation of the procedure used to obtain the seasonal design days.

The records are grouped into seasons (winter, spring, summer, autumn), a division consistent with the environmental records as a matter of coldest, warmest and transition periods as shown in Fig. 3.

For each season, the records are again grouped by the hour of the day in which they were taken. For each of the 24 sets of each season, the median value is extracted: this value will be the value of the respective hour of the design day. The median has been preferred to the mean value due to its higher robustness and lower sensitivity on the extremes.

2.1.2 USR characterization

The city of Lisbon is made of thousands of buildings [12], for this reason it has been chosen to limit the number of USRs to four.

The four buildings have been picked following these criteria:

- vicinity from IST: lower distances mean lower losses, therefore the search for rooftops shall be focused on the surroundings of the campus;
- incident solar radiation: surfaces that receive large amounts of solar radiation over the year are more attractive than the others;
- representativity: the four buildings should not be unique, as the results from assessing a palace belonging to a family of constructions can be expected to be similar for the whole family.

Information regarding the amount of incident solar radiation on their respective roof as well as its surface extension was gathered from the “Solar Energy Potential” map [13].

Electric load Likewise for IST, the hourly electric energy demand for each USR was obtained from different sets of measurements. From a pool of dozens of household consumption records, three criteria have been applied to discard the unfit households: the location (only the households situated in Lisbon were considered), the period covered by the measurements (due to the discontinuities of the records, only those households for whom every month of the year was recorded at least once), and the diversity (in case two or more flats were found to be fit according to the previous criteria, and they were considered of the same kind. The same process shown in Fig. 2 to obtain seasonal design days has been adopted.

The measurements were performed on a set of electrical appliances. The files state that the monitored appliances were: 'washer', 'dishwasher', 'standby', 'fridge', 'rest'. This explains the relatively low peak energy consumptions, especially in winter, during the heating season. In fact, on a national scale, the use of EE for space heating is far greater than the natural gas [14]. Therefore, the electric consumption have been integrated with the energy consumption for space heating and domestic hot water (DHW)

Eventually an electric profile has been associated to each USR. The association is based on the following assumptions

- the electric profile is proportional to the number of inhabitants: a profile can be adapted to a greater or lower number of residents through a proportionality constant;
- in a building all the flats are equal in terms of geometry (type), occupancy (number of people), and routines;

Thermal load The thermal load is considered to be the result of two heating necessities: space heating (SH) and domestic hot water (DHW).

The daily space heating energy profile has been estimated with base on the weather data provided by IST Meteorological Service, the Portuguese regulations, and assumed U-values.

U-values Each building under examination belongs to the district of São Jorge de Arroios in Lisbon. The U-values were taken from Stavropoulos, in which for each district of Lisbon a statistical analysis was performed [12]. In this work, the minimum, mean, maximum, and std deviation values of the U-values for each district of Lisbon are provided. Since the difference between the mean and the maximum U-values is minimal, the latter have been chosen, for the analysis to be more conservative.

Additional assumptions were made: since all of the buildings taken into account are in between two more buildings, the side walls were considered to be adiabatic; the glazing area equal to $GAP = 35\,\%$ of the total wall area, the infiltration and ventilation rate as $IR = 1.25\,\mathrm{ACH}$ (air changes per hour), the height per floor as $h_f = 2.7\,\mathrm{m}$, and the available floor area as the 90 % of the roof surface[1]: $AFA = 0.9 \cdot S_{\mathrm{roof}}$.

The heating loss coefficient is then calculated as:

$$\begin{aligned} L = {} & (U_{\mathrm{ceiling}} + U_{\mathrm{floor}}) \cdot AFA + (1 - GAP) \cdot (UA)_{\mathrm{wall}} + GAP \cdot (UA)_{\mathrm{windows}} \\ & + AFA \cdot N_{\mathrm{floors}} \cdot h_f \cdot \widehat{\rho}_{\mathrm{air}} c_{p_{\mathrm{air}}} \cdot \frac{IR}{3600} (\mathrm{W\,K^{-1}}). \end{aligned} \tag{1}$$

Space heating load The approach used to determine the SH energy necessity is the one presented by Durmayaz et al. [15].

From 5-years of hourly weather records for the city of Lisbon, the daily mean temperatures where calculated for every day of each year. The values have been plotted and can be seen in 3. The daily temperature averages have been fitted with a 6 th-degree polynomial function. The beginning/end of the heating season has been identified for the days of the year in which the average temperature is below 15 °C. s of the year in which the average temperature is below 15 °C. The results is that the heating season ends on the 110 th and begins on the 313 th day, which corresponds to the 20 th of April and 9 th of November respectively.

With a similar procedure as the one shown in Fig. 2, a design-year has been extrapolated.

The energy load for space heating is assumed to be proportional to the sum of degree-hours for the heating season [15]. The amount of degree-hours for the heating season is:

$$DH_{\mathrm{season}} = \sum_{i=1}^{N} (T_{\mathrm{ind}} - \overline{T}_i) \quad \text{for } \overline{T}_i \le T_{\mathrm{ref}}, \tag{2}$$

where T_{ind} is the constantly adopted indoor design air temperature (20 °C according to the Portuguese regulation – REH), $\overline{T}_i$ is the i-th hourly mean temperature of the heating season, and T_{ref} is the base temperature for the beginning/end of the heating season, 15 °C.

[1] It is reasonable to assume that 10 % of the surface inside the building is made of common areas (stairs, corridors) that are not heated.

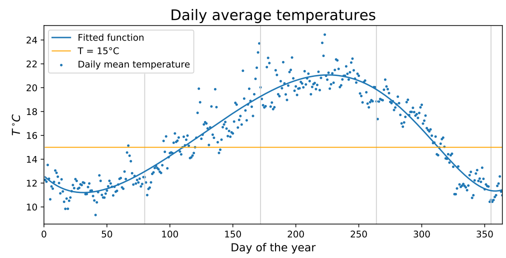


Figure 3: Yearly trend of the daily average temperatures. The vertical lines mark the ending of a season and the beginning of the next. Winter and summer cover the highest and lowest ranges of temperature levels respectively while spring and autumn cover the two transition periods.

The winter season is the only entirely included into the heating season, therefore the space heating load will only be present for the winter design day (also because its design day is the only one with a mean daily temperature below the 15 °C threshold).

The energy required for space heating for the winter design day is:

$$Q_{sh} = L \cdot DH_{\mathrm{dd}}. \tag{3}$$

Eventually, a normalized space heating profile has been applied to obtain the daily space heating energy consumption.

Domestic hot water load For the DHW energy consumption, the daily amount of energy has been calculated according to the REH [16]. The the municipal water feed temperature and the normalized profile for the DHW consumption were retrieved from Santos [17].

Eventually both thermal loads profile have been converted into electrical load (assuming such is performed through electrical resistance heaters).

2.2. Formulation of the optimization problem

A MILP description of a problem starts with the introduction of the parameters – that are known a priori and constant – and then the variables – whose optimum value will be found. A MILP optimization problem can be written in a general form as:

$$\begin{aligned} \min \quad & Z = f(\mathbf{x}(\mathbf{t})) \\ s.t. \quad & g(\mathbf{x}(\mathbf{t})) = 0 \\ & h(\mathbf{x}(\mathbf{t})) \leq 0, \end{aligned} \tag{4}$$

where Z is the objective function, $\mathbf{x}(\mathbf{t})$ the array of the decision variables, while $g(\mathbf{x}(\mathbf{t}))$ and $h(\mathbf{x}(\mathbf{t}))$ are respectively the equality and inequality constraints.

The objective function is the annual energy-related costs of IST, i.e. the costs had by purchasing energy from the grid, plus the actualized yearly cost of investment in solar equipment (if any is performed) and minus the revenues made by selling energy to the USRs:

$$Z = C_{inv+O\&M} + C_{el,grid} - Rev_{usr}^{ist}, \tag{5}$$

where $C_{inv+O\&M}(u)$ is the overall investment and operation and maintenance cost (expressed as a percentage of the former) for each USR, $C_{el,grid}$ are the costs from the purchase of EE from the grid and Rev_{usr}^{ist} are the revenues from the sale of EE to the USRs.

The costs in (5) are:

$$C_{inv+O\&M} = \sum_u (C_{pv}^{inv}(u) + C_{st}^{inv}(u)) \cdot (1 + 0.05) \tag{6}$$

$$C_{el,grid} = \sum_t P_{usr}^{grid}(u,t) \cdot \hat{c}_{el}^{ist}(t) \tag{7}$$

$$Rev_{usr}^{ist} = \sum_u \sum_t P_{usr}^{ist}(u,t) \cdot \hat{c}_{el}^{usr}(t). \tag{8}$$

The term $(1+0.05)$ in (6) represents the overall cost of the investment and the O&M costs, which for the solar technology, has been imposed 5 % [10].

2.2.1 Constraints

Energy balances There are three energy balances: two electrical (for IST and for each USR) and one thermal (only for USR). In fact the possibility to develop a district heating network is not contemplated in this work.

IST EE balance:

$$\begin{gathered} \hat{P}_L^{ist}(t) + \sum_u P_{usr}^{ist}(u,t) - \hat{\eta}_{el,t} \cdot \sum P_{ist}^{usr}(u,t) - \\ P_{ist}^{grid}(t) = 0. \end{gathered} \tag{9}$$

USR EE balance:

$$\begin{gathered} P_L^{usr}(u,t) + P_{ist}^{usr}(u,t) - \hat{\eta}_{el,t} \cdot P_{usr}^{ist}(u,t) \\ - P_{pv}(u,t) - P_{usr}^{grid}(u,t) = 0, \end{gathered} \tag{10}$$

where:

$$P_L^{usr}(u,t) = \hat{P}_{el}^{usr}(u,t) \cdot \alpha(u) + \frac{Q_{eh}(u,t)}{\hat{\eta}_{el,c}} \tag{11}$$

$$P_{pv}(u,t) = \hat{p}_{pv}(u,t) \cdot \sigma(u). \tag{12}$$

USR th. en balance:

$$\begin{gathered} Q_L^{usr}(u,t) \cdot \alpha(u) - Q^{st}(u,t) - Q^{eh}(u,t) \\ - Q_{disch}^{ts}(u,t) + Q_{ch}^{ts}(u,t) + Q^{diss}(u,t) = 0 \end{gathered} \tag{13}$$

where:

$$Q_L^{usr}(u,t) = \widehat{Q}_L^{sh}(u,t) + \widehat{Q}_L^{dhw}(u,t) \quad (14)$$

$$Q^{st}(u,t) = \widehat{q}_{st}(u,t) \cdot \chi(u) \cdot \widehat{A}_{coll}. \quad (15)$$

The binary variable $\alpha(u)$ appears in (11) and (13) serves to set the USR's demand equal to zero when it is not selected to form the cooperative ($\alpha(u) = 0$).

Energy flows management

$$P_{ist}^{usr}(u,t) \leq P_{pv}(u,t) \quad (16)$$

$$P_{usr}^{ist}(u,t) \leq \left(\widehat{P}_{el}^{usr} + \frac{\widehat{Q}_L^{sh} + \widehat{Q}_L^{dhw}}{\widehat{\eta}_{el,c}} \right)_{(u,t)} \cdot \alpha(u) \quad (17)$$

$$Q^{eh}(u,t) \leq Q_L^{usr}(u,t) \cdot \alpha(u) \quad (18)$$

$$Q^{diss}(u,t) \leq Q^{st}(u,t). \quad (19)$$

Constraint (16) is necessary to exclude the possibility that the USR sends EE to IST by purchasing it from the grid, similarly (17) is necessary so that IST does not send energy to a USR that has not been selected (because in the simulation all the USR start with a certain energy credit form IST): when the USR is not selected, there are shall not be any with IST. The energy consumption of the auxiliary heater when the USR is not selected is set to zero by (18), and the dissipated energy is null if there is not renewable solar thermal energy production by (19) .

Roof surface management

$$\sigma(u) \cdot \widehat{A}_{mod} + \chi(u) \cdot \widehat{A}_{coll} \leq \widehat{S}(u) \quad (20)$$

$$\sigma(u) \cdot \frac{\widehat{A}_{mod}}{\widehat{S}(u)} \leq \alpha(u) \quad (21)$$

$$\chi(u) \cdot \frac{\widehat{A}_{coll}}{\widehat{S}(u)} \leq \varepsilon(u) \quad (22)$$

$$\varepsilon(u) \leq \alpha(u) \quad (23)$$

Constraint (20) states that the overall surface covered in modules and collectors has to be lower or equal to the available amount. If a USR is not selected then the amount of modules is null thanks to (21), but if the roof is selected priority can be given to the PV rather than to the ST thanks to (22) and (23).

IST as storage Each USR begins the day with an initial energy credit (level of charge) of 100 kWh: this allows IST to send electrical energy to the USRs during the whole night, and not just until midnight.

$$LVL(u,t) = LVL(u,t-1) + \widehat{\eta}_{el,t} \cdot P_{ist}^{usr}(u,t) - P_{usr}^{ist}(u,t) \quad (24)$$

$$LVL(u,0) \leq LVL(u,23) \quad (25)$$

$$P_{usr}^{ist}(u,t) \leq \widehat{M} \cdot s_{el}(u,t) \quad (26)$$

$$P_{ist}^{usr}(u,t) \leq \widehat{M} \cdot (1 - s_{el}(u,t)) \quad (27)$$

Since IST is modeled as a sink, it is capable to accept all the energy that exceeds the consumption of the respective USR. If the campus should behave like a storage device, it would release up to the amount of energy it was charged with. When there is no production IST can purchase energy from the grid and sell it to the respective USR, until all the stored energy for the day is returned. This behavior is modeled by (24). Equation (25) is a consequence of IST being a fictitious storage: the energy conservation law does not apply, and the campus should not release more energy than received. The last two constraints – (26) and (27) – mandate that the energy can not be flowing in both senses at the same time.

Thermal storage

$$LVL_{ts}(u,t) = LVL_{ts}(u,t-1) \quad (28)$$

$$+ \frac{3600\,\mathrm{s\,h^{-1}}}{\widehat{\rho}_w \cdot \widehat{c}_{p,w} \cdot (T_h - T_c)} \cdot \left(\widehat{\eta}_{ts} \cdot Q_{disch}^{ts}(u,t) - \frac{1}{\widehat{\eta}_{ts}} \cdot Q_{ch}^{ts}(u,t)\right) \quad (29)$$

$$LVL_{ts}(u,0) = lvl_{ts}(u,23) \quad (30)$$

$$V_{ts}(u,t) = V_{ts}(u,t-1) + \frac{3600\,\mathrm{s\,h^{-1}}}{\widehat{\rho}_w \cdot \widehat{c}_{p,w} \cdot (T_h - T_c)} \cdot \sum_t (\widehat{\eta}_{ts} \cdot Q_{disch}^{ts}(u,t) - \frac{1}{\widehat{\eta}_{ts}} \cdot Q_{ch}^{ts}(u,t) \quad (31)$$

$$Q_{disch}^{ts}(u,t) \leq \widehat{M} \cdot s_{th}(u,t) \quad (32)$$

$$Q_{ch}^{ts}(u,t) \leq \widehat{M} \cdot (1 - s_{th}(u,t)) \quad (33)$$

The TS is modeled with the same underlying ideas as the *IST as storage*. The main differences are the round-trip efficiencies for the TS, and the volume of the storage tank, whose sizing is a result of the optimization process.

Economical constraints The following constraint imposes that – for the solution to be feasible – the USR has to save money compared to the case in which there is no intervention, and it purchases all of the energy from the grid:

$$\sum_t (P_{usr}^{grid}(u,t) \cdot \widehat{c}_{el}^{usr}(t)) \leq \sum_t (P_L^{usr}(u,t) \cdot \widehat{c}_{el}^{usr}(t)) \quad (34)$$

The optimization model was implemented in Python and solved using the MIP solver of GUROBI.

3. Implementation

The model is tested on four design days representative of one year: each design day is simulated independently, the resulting value of the objective function is multiplied by the number of days in the season and eventually the four results are summed.

The simulations are performed in two step:

1st step Each season is simulated independently. This will lead to a solution in which the decision variables change according to the season. This is the optimal solution, but the number of installed equipment can not change along the year: it is not viable in practical terms;

2nd step Each season is simulated again, with the decision variables fixed as parameters with the values obtained by the previous simulation: this equals to design the system according to a season in particular.

Four solutions are obtained, where the minimum of them is the optimal solution. The simulations were performed on a machine with a Intel Core i7-3517U 1.90 GHz quad core processor. The solving time of each simulation is lower than 1 s.

4. Results

The first step simulation results in every USR to associate with IST. The ST system, as well as the TS, are never part of the optimal solution: the focus is entirely on the electrical energy production.

Base scenario

The reference situation for the calculation of the savings is the case of no-intervention: IST and the USRs are connected to the grid and from it they purchase all the energy they need. In this scenario:

- IST spends 1 684 246.44 € $year^{-1}$;
- USR_1 spends 6581.048 € $year^{-1}$;
- USR_2 spends 4181.554 € $year^{-1}$;
- USR_3 spends 4991.068 € $year^{-1}$;
- USR_4 spends 13 942.419 € $year^{-1}$.

4.1. First step solution

The number of PV modules ($\sigma(u)$) part of the optimal solution are presented in Tab. 1. With this configuration it is found that IST's yearly saves the 0.312 % of yearly energy-related costs, while the USRs between the 8 and the 28 %. USR_2 has a lower monetary saving because the building surface has an azimuth angle tilted 60 East: the peak power production is shifted before noon: this results in starting the self-consumption of renewable energy before the beginning of the least favorable tariff phase (which starts at 08:00).

	USR_1	USR_2	USR_3	USR_4
σ_{winter}	42	1	1	54
σ_{spring}	42	59	35	85
σ_{summer}	42	59	35	85
σ_{autumn}	29	8	1	85
Savings (%)	28.30	8.71	23.46	27.48

Table 1: Results of the 1st step simulation: number of PV modules to be installed and yearly savings on the energy-related costs.

4.2. Second step solution

After running the simulation for the three cases (winter, spring-summer, autumn), the optimal configuration is the spring-summer one: all the available surface is covered with PV modules.

The total installed capacity is 64.09 kWp, for an initial investment of 128 180 €. By implementing this solution, the yearly savings in the cost of energy will be:

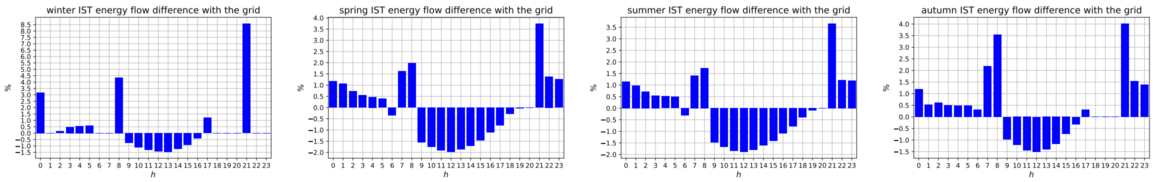
- for IST: 0.276 %
- for USR_1: 28.351 %
- for USR_2: 24.472 %
- for USR_3: 28.78 %
- for USR_4: 27.522 %

The energy purchased by IST from the grid decreases during the PV production time, while it increases in correspondence of the peak electricity demand from the USRs, as shown in Fig. 4.

In autumn and winter, when the sunset occurs before the end of the most expensive tariff phase, the variation of energy purchased is null: IST waits for the most expensive phase to finish before feeding back the USRs with the energy it has accumulated.

Analyzing the performance of IST as a storage system, USR_2 is the best one: its electricity demand profile is not very different than that of USR_3, but the amount of stored energy profile is remarkably different. This is due to the different and opposite azimuth angle of the surfaces: USR_2's peak PV energy production can cover the morning peak (completely in spring and summer, partially in autumn), on the other hand USR_3's surface orientation does not provide benefits in regards to the evening peak (at 20:00).

IST being a fictitious storage system has the advantage that it does not constrained by the law of

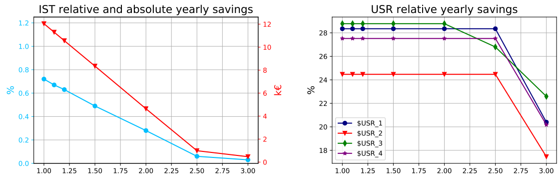


(a) Winter. (b) Spring. (c) Summer. (d) Autumn.

Figure 4: IST percentage variation of the energy purchased from the grid for each design day.

$\widehat{c}_{pv}$	Savings [%]				
[€/Wp]	IST	USR_1	USR_2	USR_3	USR_4
3.0	0.028	20.39	17.45	22.59	20.18
2.5	0.059	28.35	24.47	26.79	27.52
2.0	0.276	28.35	24.47	28.78	27.52
1.5	0.496	28.35	24.47	28.78	27.52
1.2	0.627	28.35	24.47	28.78	27.52
1.1	0.671	28.35	24.47	28.78	27.52
1.0	0.715	28.35	24.47	28.78	27.52

Table 2: Percentual savings obtained with the optimal solutions in the sensitivity analysis.



(a) IST. (b) USRs.

Figure 5: Yearly savings for IST and USRs as a function of the specific costs of the PV equipment

conservation of energy: the campus can receive unlimited amounts of energy and release as much as it is convenient to. In this framework, on IST's perspective, the most attractive partners would be those that make the level of charge increase from the beginning to the end of the day. USR_2 is the most attractive of the set in this regards: it is the only one that gives a positive contribution to the daily energy stored by IST for three seasons out of four (whereas the others manage to do so only in spring and summer, the most favorables. These results suggest that, for such electricity consumption profiles and tariffs, USRs with East-oriented surfaces are preferable for IST.

4.3. Sensitivity analysis

A sensitivity analysis has been performed by varying the price per PV module. The same has been done for the ST and TS systems, but these equipment are not part of the optimal solution even with a price of 200 € per collector and 500 € m^{-3} respectively. The thermal energy requirements do not justify the investment in ST under the model's assumptions.

The prices under analysis have been taken from [18]. In addition to that two more cases has been examined: those in which the specific costs are 2.5 and 3 € Wp^{-1}, for which the optimal configuration of PV modules are (42,59,31,85) and (20,11,17,42) respectively.

The sensitivity analysis presented in Tab. 2 shows that the price per watt-peak of a PV module affects principally the yearly savings of the campus, while those of the USRs remain unaffected when the number of modules installed do not change. In the model the investment costs are entirely on IST, therefore USRs' savings are affected only when the cost per unit module is high enough that it is not convenient to exploit completely the available surface. The savings for IST are inversely proportional to the unitary cost of the PV modules, whereas for the USRs they are proportional to the available surfaces they can offer (assuming it being fully covered in PV modules). These results are shown in Fig. 5.

5. Critical remarks

The system under analysis has been modeled under several simplifications and assumptions.

The design day technique is very useful, reducing the complexity of the simulations (solving time), but it comes with the drawback of neglecting the positive and negative peaks in energy consumption, production, and environmental conditions. Moreover, the design days are simulated independently: further studies should focus on the consequential simulation of time periods of at least a week long, to appreciate the variations from day to day and from weekdays to weekends.

Thermal loads are obtained from an approximation of the geometry of the residential complexes, procedure that can be performed with publicly available data and no need to access technical maps, but its accuracy on the amount of electrical and thermal energy used is insufficient for the actual design of the systems.

The advantages of the ST systems depend on both the correct characterization of the thermal loads and the accuracy of their description in the model. In this study they have been modeled so that the specific useful energy produced would be a parameter: a more accurate description could be done with multiple iterations of the MILP simulation or even non-linear modeling techniques.

Further assessments should include the possibility to install micro and/or mini CHP or CHCP systems in IST for the self production of electric, heating and cooling energy: these equipment would work for many hours per year at rated load since IST base electricity consumption is about 800 kW, and also the energy spent for HVAC during the day might justify cogenerative or trigenerative solutions.

IST makes profit by purchasing energy from the grid at night and selling it to the USRs at the same price they would normally buy it: this condition might not be acceptable for the grid management company, thus possibly undermining the feasibility of the project.

The last remark is that it has been assumed that the behavior of the residents does not change after the intervention: with the possibility of self-consuming the free renewable energy during the day, the electrical energy usage might increase. To avoid a decrease in residential energy efficiency as a consequence of the increase in renewable energy generation, compensating mechanisms and conditions should be investigated.

6. Conclusions

This work presents an economic assessment of the design of a distributed PV system supplying with renewable electrical energy the residential complexes on which the equipment is installed, and the university campus that finances the project. Four typical buildings have been studied to characterize the greatest number of residential complexes present locally. The campus was described with an electric consumption profile based on measured data. The residential complexes' geometry and occupancy were estimated from publicly available data such as the number of floors, apartments per floor, and roof surface; according to these estimates an electric consumption profile obtained from measurements was associated to each apartment. Similarly, the thermal load for space heating was assumed with basis on common thermal properties of the buildings in the parish and environmental data, while that for domestic hot water was calculated proportionally to the number of inhabitants. Two candidate technologies for energy generation were considered: photo-voltaic modules and solar thermal collectors with thermal storage. Both have been modeled with basis on environmental data (hourly solar radiation and external temperature) and technological parameters. From all the aforementioned data, four design days have been generated, each representative of a season of the year.

A MILP model was made to find the optimal configuration of the project, the objective function being the yearly energy-related costs.

The results show that the photo-voltaic is the only viable technology whereas the solar thermal equipment are never part of the optimal solutions. All of the roof surface is covered in modules, for a total of 221 modules at 580 € each. IST, with an initial investment of 128 180 €, benefits from a reduction of the yearly energy expenses of 0.276 % which equals to a net profit of about 4684 € per year, about 70 k€ at the end of the modules' lifetime (15 years). The highest share of savings is for the USRs, each of which yearly saves between the 24.47 % and the 28.78 %, corresponding to 341.10 to 479.65 € per apartment.

With this intervention the energy consumption of both the campus and the residents is reduced when the cost of energy is at its highest. The campus also returns partially or completely the energy received when there is no renewable generation and the cost of energy is lower. The East-side surface orientation has shown to be preferable for it anticipates the renewable energy production covering the domestic peak load and allows the campus to receive more energy than the amount returned during the off-peak phase.

A sensitivity analysis on the unitary price of the technologies has been performed. The solar thermal technology is again never part of the optimal solutions, if the prices are lowered reasonably. The residential savings depend on the amount of installed modules, while the campus' depend on the specific cost of the technology. To higher specific prices correspond a decrease of the number of installed modules, hence a reduction in economical benefits for both parts; the least favorable examined scenario was with a unitary price of 3 € Wp^{-1}, and under this conditions the total number of installed modules is 90. The yearly profit for IST is 0.028 %, about 471 € year^{-1}. The USRs savings decrease too, but the minimum one is still 17.5 %. On the other hand, on the most favorable scenario, where the cost is 1 € Wp^{-1} the investment cost is only 64.09 k€ and the yearly profit for IST is 0.715 %, corresponding to 12.04 k€, the USRs savings being the same as in the base case.

The MILP model is simple and allows the assessment of many buildings one by one. The accuracy of the results can be enhanced with an improved characterization of the residential complexes and their energy flows, and an analysis based on extended real time periods. Smart procedures, conditions, and constraints should be investigated in future works to avoid the development of energy inefficient practices as a result of the availability of free renewable energy.

References

[1] M. Mohammadi, Y. Noorollahi, B. Mohammadi-ivatloo, and H. Yousefi, "Energy hub: From a model to a concept – a review," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 1512–1527, dec 2017. [Online]. Available: https://doi.org/10.1016/j.rser.2017.07.030

[2] A. Alarcon-Rodriguez, G. Ault, and S. Galloway, "Multi-objective planning of distributed energy resources: A review of the state-of-the-art," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 5, pp. 1353–1366, jun 2010. [Online]. Available: https://doi.org/10.1016/j.rser.2010.01.006

[3] G. Chicco and P. Mancarella, "Distributed multi-generation: A comprehensive view," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 3, pp. 535–551, apr 2009. [Online]. Available: https://doi.org/10.1016/j.rser.2007.11.014

[4] M. Sameti and F. Haghighat, "Optimization approaches in district heating and cooling thermal network," *Energy and Buildings*, vol. 140, pp. 121–130, apr 2017. [Online]. Available: https://doi.org/10.1016/j.enbuild.2017.01.062

[5] K. Orehounig, R. Evins, and V. Dorer, "Integration of decentralized energy systems in neighbourhoods using the energy hub approach," *Applied Energy*, vol. 154, pp. 277–289, sep 2015. [Online]. Available: https://doi.org/10.1016/j.apenergy.2015.04.114

[6] L. A. Wolsey, *Integer Programming*, 1st ed. Wiley, 1998.

[7] A. Omu, S. Hsieh, and K. Orehounig, "Mixed integer linear programming for the design of solar thermal energy systems with short-term storage," *Applied Energy*, vol. 180, pp. 313–326, oct 2016. [Online]. Available: https://doi.org/10.1016/j.apenergy.2016.07.055

[8] J. Jung and M. Villaran, "Optimal planning and design of hybrid renewable energy systems for microgrids," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 180–191, aug 2017. [Online]. Available: https://doi.org/10.1016/j.rser.2016.10.061

[9] J. H. Braslavsky, J. R. Wall, and L. J. Reedman, "Optimal distributed energy resources and the cost of reduced greenhouse gas emissions in a large retail shopping centre," *Applied Energy*, vol. 155, pp. 120–130, oct 2015. [Online]. Available: https://doi.org/10.1016/j.apenergy.2015.05.085

[10] P. Gabrielli, M. Gazzani, E. Martelli, and M. Mazzotti, "Optimal design of multi-energy systems with seasonal storage," *Applied Energy*, vol. 219, pp. 408–424, jun 2018. [Online]. Available: https://doi.org/10.1016/j.apenergy.2017.07.142

[11] Instituto Superior Tcnico, "Campus sustentável," http://sustentavel.unidades.tecnico.ulisboa.pt/, accessed: 2018-10-04.

[12] A. S. Stavropoulos, "Spatial analysis of heating and cooling energy needs in lisbon," Master's thesis, Instituto Superior Tcnico, 2013.

[13] Munícipia and Lisboa E-Nova, "Carta de potencial solar," http://80.251.174.200/lisboaenova/potencialsolar/, accessed: 2018-10-05.

[14] S. M. Magalhães and V. M. Leal, "Characterization of thermal performance and nominal heating gap of the residential building stock using the EPBD-derived databases: The case of portugal mainland," *Energy and Buildings*, vol. 70, pp. 167–179, feb 2014. [Online]. Available: https://doi.org/10.1016/j.enbuild.2013.11.054

[15] A. Durmayaz, M. Kadıolu, and Z. Şen, "An application of the degree-hours method to estimate the residential heating energy requirement and fuel consumption in istanbul," *Energy*, vol. 25, no. 12, pp. 1245–1256, dec 2000. [Online]. Available: https://doi.org/10.1016/s0360-5442(00)00040-2

[16] Diário da Républica, "Regulamento de Desempenho Energético dos Edifícios de Habitaão (REH), Decreto-Lei n.o 118/2013," *Diário da República - I Série - A*, pp. 46(2468–2513), 2013.

[17] A. D. S. Santos, "Avaliao de sistemas solares trmicos de produo de gua quente sanitria em edifcios de habitao multifamiliar," Master's thesis, Instituto Superior Tcnico, 2012.

[18] C. H. Villar, D. Neves, and C. A. Silva, "Solar PV self-consumption: An analysis of influencing indicators in the portuguese context," *Energy Strategy Reviews*, vol. 18, pp. 224–234, dec 2017. [Online]. Available: https://doi.org/10.1016/j.esr.2017.10.001