**Optimization Model Concept Diagram**



Immagine che contiene schermata, testo, quadrato, Software multimediale

Descrizione generata automaticamente

Figure 1: EXAMPLE OF System configuration

**Nomenclature**

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| **Decision Variables** | |
|  | Installed area of PV (m2) |
|  | Cooling rate provided by absorption chiller (dependent variable) (kW) |
|  | Total annual energy cost (€) |
|  | Total annualized investments cost (€) |
|  | Total annual O&M cost (€) |
|  | Total annual cost (€) |
|  | Capacity of battery (kWh) |
|  | Maximum ramp-down rate of CHP NG ICE (dependent variable) (kW) |
|  | Maximum charging power of battery (dependent variable) (kW) |
|  | Charging power for battery (kW) |
|  | Maximum discharging power of battery (dependent variable) (kW) |
|  | Discharging power for battery (kW) |
|  | Power provided by CHP FC (kW) |
|  | Power provided by CHP NG ICE (kW) |
|  | Maximum load of CHP NG ICE (dependent variable) (kW) |
|  | Minimum part load of CHP NG ICE (dependent variable) (kW) |
|  | Power required by the electrolyser (dependent variable) (kW) |
|  | Maximum part load of EZ (dependent variable) (kW) |
|  | Minimum part load of EZ (dependent variable) (kW) |
|  | Power required by the heat pump (dependent variable) (kW) |
|  | Grid power (kW) |
|  | Power provided by PV (kW) |
|  | Share of power from PV allocated for usage in the EZ (kW) |
|  | Total annual CO2 emission related to gas consumption (kgCO2) |
|  | Total annual CO2 emission related to grid power consumption (kgCO2) |
|  | Total annual CO2 emissions (kgCO2) |
|  | Gas volumetric flow rate consumed by CHP NG ICE (dependent variable) (Nm3/h) |
|  | H2 charging for H2 storage (m3/h) |
|  | H2 discharging for H2 storage (m3/h) |
|  | H2 stored in H2 storage (m3) |
|  | Maximum H2 charging for H2 storage (dependent variable) (m3) |
|  | Maximum H2 discharging for H2 storage (dependent variable) (m3) |
|  | Discharging heat rate from TES (kW) |
|  | Charging heat rate to TES (kW) |
|  | Heat rate provided by CHP NG ICE (dependent variable) (kW) |
|  | Heat rate provided by the heat pump (kW) |
|  | Heat rate provided by natural gas boiler (kW) |
|  | Thermal energy stored in TES (kWh) |
|  | Maximum SOC battery (dependent variable) |
|  | Minimum SOC battery (dependent variable) |
|  | Designed size of the technology(kW – kWh) |
|  | Maximum ramp-up rate of CHP NG ICE (dependent variable) (kW) |
|  | Binary variable for usage of battery for charging process |
|  | Binary variable for usage of battery for discharging process |
|  | On/off status of CHP NG ICE |
|  | On/off status of EZ |
|  | Binary variable for usage of H2 storage for charging process |
|  | Binary variable for usage of H2 storage for discharging process |
|  | Binary variable for the choice of technology |
|  | Efficiency of heating pipeline (dependent variable) |
| *c* | Constant in *Fobj* (kgCO2/€) |
|  | Objective function of the multi-objective optimization problem |
|  | Volumetric flow rate of hydrogen (m3/h) |
|  | Battery SOC |
|  | Weight value in *Fobj* |
| **Parameters** | |
|  | Maximum area for PV installation (m2) |
|  | Carbon intensity of natural gas (kgCO2/Nm3) |
|  | Carbon intensity of power grid (kgCO2/kWh) |
|  | COP of heat pump in heating mode |
|  | Capital recovery factor |
|  | Specific capital cost (€/kW)–(€/kWh)–(€/m2) |
|  | Time-varying power demand of mEH (kW) |
|  | Time-varying heat rate demand of mEH (kW) |
|  | Hourly solar irradiance (kW/m2) |
|  | Lower heat value of natural gas (kWh/Nm3) |
|  | Specific O&M cost (€/kWh) |
|  | Natural gas price (€/Nm3) |
|  | Time-varying unit price of grid power (€/kWh) |
|  | Generation level (kW) – (kWh) |
|  | Maximum size of technology in the market (kW) |
|  | Minimum size of technology in the market (kW) |
|  | Distance between mEH *j* and user *u* (m) |
|  | Efficiency of charging process for battery |
|  | Efficiency of discharging process for battery |
|  | Efficiency of H2 storage |
|  | Electric efficiency of PV |
|  | Electric efficiency of CHP FC |
|  | Electric efficiency of CHP NG ICE |
|  | Electric efficiency of EZ |
|  | Thermal efficiency of CHP NG ICE |
|  | TES storage loss fraction |
| *Dt* | Length of the time interval (1 hour) |
| *Ni* | Lifetime (years) |
| *r* | Interest rate |
|  | Lower heat value of hydrogen (kWh/m3) |
|  | Parameter representing the thermal loss per meter in heating pipeline |
| **Subscripts/Superscripts** | |
| *d* | Index of representative season day |
| *HM* | Heating mode |
| *hr* | Index of hour in representative season day |
| *i* | Index of technology |
| *j* | Index of powerplant |
| *pipe* | Heating pipeline |
| *SC* | Space cooling purposes |
| *ST* | Solar thermal |
| *tech* | Technology |
| *Th* | Thermal purposes |

### Operational analysis phase

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| **Optimisation problem** |
| **Description of the considered optimisation problem** |
| With regards to the functionality of the operation optimization of multi-carrier energy systems with multi-objective tool, it obtains (through a scenario-generation approach or forecasting tools as input) the optimal expected hourly operation strategies of the technologies in the multi-carrier systems by minimizing the weighted sum of total net daily costs and CO2 emissions. Therefore, by adopting a multi-objective framework, the tool determines the optimal operation scheduling of the multi-energy system in the following modes:  Based on the system design, technologies, and their characteristics in the planning phase, the optimisation problem for the operational analysis phase allows for the dispatch of the multi-carrier by pursuing multiple objectives when analysing the various operational scenarios or day-ahead dispatch. More specifically, the “Operational analysis” toolbox involves two tools: Operation optimization of multi-carrier energy systems with multi-objective approach and optimal management of EVs in multi-carrier energy systems with multi-objective approach tool.  With regards to the functionality of the operation optimization of multi-carrier energy systems with multi-objective tool, it obtains (through a scenario-generation approach or forecasting tools as input) the optimal expected hourly operation strategies of the technologies in the multi-carrier systems by minimizing the weighted sum of total net daily costs and CO2 emissions. Therefore, by adopting a multi-objective framework, the tool determines the optimal operation scheduling of the system in the following a **Deterministic approach**:  In this case, the optimization problem is deterministic and uses as input data for RES generation, users’ loads, and energy prices the day-ahead forecasted data as specified below:   * 1. Day-ahead solar irradiance profiles and wind velocity (daily profiles with 1 hour as a time step)   2. Day-ahead energy demand profiles (electricity, heating and cooling) (daily profiles with 1 hour as a time step)   3. Day-ahead energy market prices (electricity, gas) (daily profiles for electricity with 1 hour as a time step).   The other input data that are common for both approaches are indicated below:   * Information in terms of installed technologies and energy flows among technologies within each mEH and among mEHs * Technical data of energy technologies * Carbon intensity of input energy carriers.   The optimisation problem below is formulated for the operation optimization of multi-carrier energy systems with multi-objective tool in relation to the stochastic approach. It must be mentioned that this problem can be easily adapted to the deterministic approach, by not considering the dependence of variables on scenarios. |
| **Formulation of the optimisation problem** |
| **Energy carriers involved** |
| Gas, hydrogen, electricity, heating, cooling, mobility. |
| **Energy technologies involved** |
| * CHP with different types of prime movers:   + Internal combustion engine   + Micro-gas turbine   + Fuel cell * Electrolyser * Natural gas boilers * Wind energy (Soria)   + *Wind speed (offers sizing) or wind power profile (negative load)?* * Solar PV   + *Irradiance or Power profile?* * Solar thermal   + *Thermal power (provided by Raffaele for Soria and Portici)(negative thermal load)  or Irradiance?*   + *Rankine cycle turbine ???--> electricity* * Reversible heat pump * Absorption chiller * Battery * Hydro pumped energy storage   + Options: *b) could be modelled as a battery* * Supercapacitor   + *Options: a) could be ignored /eliminated b) could be modelled as a battery* * Thermal storage for heating and cooling   + *Using a phase-change material?* * Hydrogen storage   PEVs (only for Optimal management of EVs in multi-carrier energy systems with multi-objective approach tool) |
| **Objective function(s) of optimisation problem** |
| The proposed tool allows to find the optimal expected operation strategies of the system while considering short- and long-term objectives.  **Economic objective function**  The short-term objective is the economic objective to minimize, representing the total net daily energy costs to minimize:  (27)  It is the sum of the total cost of gas calculated by multiplying the gas price (a parameter) by the total amount of gas consumed by the CHPs and boilers in energy system, and the total cost of buying grid power calculated by multiplying the time-varying unit price of grid power (a parameter) and the total amount of electricity taken from the grid, minus the profit for selling electricity from CHPs and PVs in the system.  **Environmental objective function**  The environmental objective is to minimize the total annual CO2 emissions, consisting of the sum of the following functions:  (29)  (30)  (31)  In Eq. (30), the total CO2 emission associated with the gas consumed by the CHPs and auxiliary boilers in the energy system depends on the carbon intensity (CI) of gas, whereas in Eq. (31), the total CO2 emission associated with the grid power depends on the carbon intensity of the power grid, which the energy system is connected to. |
| **Optimisation method used to solve the formulated problem** |
| **W**ith the economic and environmental objectives formulated above, the operation optimization problem has two types of objective function to be minimized. To solve this multi-objective optimization problem, the weighted-sum method is used to have a single objective function formulated as:  (32)  where *c* is a constant scaling factor to keep the two objectives at the same order of magnitude, and *ω* is the weight for the economic objective function varying in the range of 0-1. When *ω* = 1, it is to find the solution that minimizes the total daily energy cost of the whole ILEC, and when *ω* = 0, it is to find the solution that minimizes the total daily environmental impact of energy system. When varying the weight *ω* in the range of [0, 1], the Pareto front between economic and environmental objectives can be found.  The problem formulated for both tools is linear and involves both discrete and continuous variables. To solve the problem efficiently, branch-and-cut, which is powerful for MILP problems, is used. |
| **Formulation of system balances equation for energy carriers involved** |
| 1. **System balance constraints**   ***Power balance***  In the energy system the electrical demand and the power required by the heat pumps (either in the heating or cooling mode) and electrolysers installed in the associated system, must be met by the sum of the electricity provided by the CHPs and the electricity provided by PV together with the battery and the power grid:  (33)  where , and represent the power provided by CHPs in the following CHP electricity balance constraints:  (34)  (35)  (36)  (37)    *Power balance (valid for optimal management of EVs in energy systems (if we want consider them)*  (38)  Eqs. (34-37) are valid also for this tool.    ***Thermal energy balance***  In the energy system the thermal demand must be met by the total thermal energy provided by the CHPs, boilers, heat pumps, and the thermal storage installed:    (39)  where , and are the heating rates provided by CHPs, which are involved in the following CHP thermal balance constraints,  (40)  (41)  (42)  The thermal balance for the cooling demand can be formulated similarly. |
| **Temporal resolution** |
| Hourly resolution |
| **Time horizon** |
| 1 Day |

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| **Input data connection**   * Describe where the input data were derived and provide connection link |
| ***Energy demand of users***  *The hourly energy rate demand for electricity, thermal energy (including the demand of domestic hot water and space heating), and space cooling of energy system is given for four representative season days, as shown in Figure 1, Figure 2, Figure 3, and Figure 4. Based on the climatic characteristics of the zone, and when it is possible to turn on the heating systems in the relative climatic zone (from October 22 to April 7), to compute the annual energy requirements of the 4 micro-energy hubs, the year is assumed to be composed of 90 days in the cold season (December – February), 92 days in the cold mid-season (October 22 – November 30, and March 1 – April 7), 91 days in the hot mid-season (April 8 – May 31, and September 1 – October 21), and 92 days in the hot season (June – August).*  *Immagine che contiene testo, linea, schermata, Diagramma  Descrizione generata automaticamente*  Figure 1. Hourly mean energy rate demand for U1- hospital: (a) a representative cold season day; (b) a representative cold mid-season day; (c) a representative hot mid-season day; and (d) a representative hot season day  Immagine che contiene testo, diagramma, linea, Carattere  Descrizione generata automaticamente  Figure 2. Hourly mean energy rate demand for U2 (offices): (a) a representative cold season day; (b) a representative cold mid-season day; (c) a representative hot mid-season day; and (d) a representative hot season day  Immagine che contiene testo, diagramma, Diagramma, linea  Descrizione generata automaticamente  Figure 3. Hourly mean energy rate demand for U3(1 hotel): (a) a representative cold season day; (b) a representative cold mid-season day; (c) a representative hot mid-season day; and (d) a representative hot season day  *Immagine che contiene testo, Diagramma, linea, diagramma  Descrizione generata automaticamente*  Figure 4. Hourly mean energy rate demand for U4 (residential units): (a) a representative cold season day; (b) a representative cold mid-season day; (c) a representative hot mid-season day; and (d) a representative hot season day  ***Solar energy availability***  Information about solar energy is taken from the meteorological data in South Italy. The hourly solar irradiance for each representative season day is evaluated as the average of the hourly mean values of the solar irradiance in the corresponding hour of all days in the relative season and is shown in Figure 5.  Immagine che contiene testo, Diagramma, linea, diagramma  Descrizione generata automaticamente  Figure 5. Average hourly solar irradiance profiles for the four representative season days  ***Prices and energy factors of primary energy carriers***  Energy prices are chosen according to the Italian market. The hourly electricity price for each representative season day is evaluated as the average of the hourly mean values of the electricity price in the corresponding hour of all days in the relative season and is shown in Figure 5.  The unit prices of natural gas are reported in Table 1  *Immagine che contiene testo, Diagramma, linea, schermata  Descrizione generata automaticamente*  Figure 6. Average hourly electricity price profiles for the four representative season days  Table 1. Unit prices of natural gas for the four representative season days   |  |  | | --- | --- | | Representative cold season day | 0.2302 (€/Nm3) | | Representative cold-mid season day | 0.1185 (€/Nm3) | | Representative hot-mid season day | 0.164 (€/Nm3) | | Representative hot season day | 0.1986 (€/Nm3) |   Technical and economic information of energy devices and other inputs  The technical and economic information of energy devices in the 4 mEHs, derived from [1], are reported in , whereas Figure 7 and Figure 8 report the specific capitals costs and efficiencies vs. sizes of CHP with gas-fired internal combustion engine and CHP with gas-fired micro-turbines, and the specific capital cost vs. size of single-stage absorption chillers, respectively.  Table 2. Technical and economic information of energy devices for the 4 mEHs   |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | *Energy device* | *Size range (kW - kWh)* | *Specific capital cost* | *O&M costs*  *(€/kWh)* | *Efficiency* | | *Lifetime* | |  | *Maximum area for RES installation (m2)* |  |  | *Electrical* | *Thermal* |  | | *Wind Power* | *Fixed size negative load* | *2500 €/kWp* | *0.012* | *(direct power curve like a negative load)* |  |  | | ***Solar PV*** |  | *2000 €/kWp* | *0.010* | *0.14* |  | *30* | | *mEH1* |  |  |  |  |  |  | | *mEH2* |  |  |  |  |  |  | | *mEH3* |  |  |  |  |  |  | | *mEH4* |  |  |  |  |  |  | | ***Solar thermal*** |  | *200 €/m2* | *0.0057* |  | *0.6* | *15* | | *mEH1* |  |  |  |  |  |  | | *mEH2* |  |  |  |  |  |  | | *mEH3* |  |  |  |  |  |  | | *mEH4* |  |  |  |  |  |  | | ***Battery*** | *-* | *350 €/kWh* | *0.005* | *= 0.9* |  | *5* | | ***Pumped hydro Storage*** |  | *200 €/kWh* | *?0.002* | *? 0.75* |  | *? More than 80 years* | | ***Rankine Cycle turbine*** | *Fixed value (500kW)* | *2000 €/kWh* | *0.005* | 0.4 | 0.38 | *15* | | ***Thermal storage*** | *-* | *20 €/kWh* | *0.0012* |  | *φTES = 0.05* | *20* | | ***H2 storage*** | *0 - 10,000 kWh* | *25 €/kWh* | *0.001* | *=0.071* |  | *10* | | ***CHP NG ICE*** | *20-5000* | *840 – 1495 €/kW* | *0.008 – 0.023* | *0.28 – 0.41* | *0.40 – 0.68* | *20* | | ***CHP NG MTG*** | *30-300* | *1630 – 2492€/kW* | *0.011 – 0.019* | *0.26 – 0.32* | *0.44 – 0.52* | *20* | | ***CHP fuel cell*** | *0 - 100* | *1800 – 2492 €/kW* | *0.05* | *0.55* | *0.35* | *10* | | ***Electrolyser*** | *20 - 1000* | *1000 €/kW* | *0.027* | *0.5* |  | *10* | | ***NG Boiler*** | *10-2000* | *100 €/kW* | *0.0014* |  | *0.9* | *15* | | ***Reversible heat pump*** | *10-5000* | *460 €/kW* | *0.0025* |  | *COPSH=3.5*  *COPSC=3.0* | *20* | | ***Absorption chiller*** | *10-5000* | *203 - 510 €/kW* | *0.0020* |  | *COP=0.8* | *20* |   *Immagine che contiene testo, diagramma, numero, Carattere  Descrizione generata automaticamente*  Figure 7. Specific capitals costs and efficiencies vs. sizes of: (a) CHP with gas-fired internal combustion engine and (b) CHP with gas-fired micro-turbines [1]  *Immagine che contiene testo, schermata, Carattere, linea  Descrizione generata automaticamente*  Figure 8. Specific capital cost vs. size of single-stage absorption chillers [1]  The other inputs are relative to the average emission factor for grid electricity, and the emission factor for natural gas, fixed to 0.354 kg CO2/kWh, and 0.202 kg CO2/kWh, respectively. |
| *Baseline configuration description EXAMPLE of residential users :*  *In this section, it is presented the hypothetical traditional power and thermal supply system for the energy system considered. This power and thermal supply system has been characterized by specific features and assumptions utilized as a reference point for subsequent analyses. The key parameters and assumptions for this system’s power and thermal supply system are as follows:*  *Electrical Energy: The electrical energy required by the EH is sourced directly from the grid. Moreover, for the analysis, it has been assumed an average emission factor of 0.354 kg CO2/kWh for grid electricity, which is indicative of typical emissions associated with Italian electricity generation.*  *Thermal Energy: Thermal energy for heating purposes is provided by a conventional boiler supplied by Natural gas, boasting an efficiency rating of 0.85, which represents an average efficiency of such systems. To calculate the energy content of the natural gas used in the boiler, it has been considered a Lower Heating Value (LHV) of 9.8 kWh/Nm3 for methane (natural gas). Additionally, the emission factor for natural gas combustion has been considered equal to 1.98 kg CO2/Nm3.*  Cooling Energy: *Cooling energy is furnished by an electric chiller with a coefficient of performance (COP) set at a value of 3, representing the average efficiency level for such equipment.*    *This reference system plays a pivotal role the analysis, serving as a baseline for subsequent calculations of electrical and thermal energy consumption, energy costs, and carbon dioxide (CO2) emissions*  *Tables 3, 4, 5, 6, 7 and 8 present data of the system related to:*   * *Electrical energy demand for a representative day in each season (*kWh/day) * *Natural gas demand for a representative day in each season (*Nm3/day) * *Primary energy consumption a representative day in each season (*kW/day) * *Total emissions for a representative day in each season (*kg CO2/day) * *Associated energy electricity costs for a representative day in each season (*€/day) * *Associated NG costs for a representative day in each season (*€/day)   *for this “conventional” system. This comprehensive data will enable to assess the relative advantages and environmental impacts of the optimized Energy Hub configurations compared to this reference system.*  Table 3 *Electrical energy demand for a representative day in each season*   |  |  |  | | --- | --- | --- | | Electricity demand cold season day | 19315,49 | kWh/day | | Electricity demand cold-mid season day | 18840 | kWh/day | | Electricity demand hot-mid season day | 18840 | kWh/day | | Electricity demand hot season day | 28716,03 | kWh/day |     Table 4 Natual gas demand for a representative day in each season   |  |  |  | | --- | --- | --- | | NG demand cold season day | 5158,13 | Nm3/day | | NG demand cold-mid season day | 1032,45 | Nm3/day | | NG demand hot-mid season day | 1032,45 | Nm3/day | | NG demand hot season day | 1032,45 | Nm3/day |   Table 5 Primary energy consumption a representative day in each season   |  |  |  | | --- | --- | --- | | Primary energy consumption representative cold season day | 97092,96 | kW/day | | Primary energy consumption Representative cold-mid season day | 55515,54 | kW/day | | Primary energy consumption hot-mid season day | 55515,54 | kW/day | | Primary energy consumption hot season day | 79313,21 | kW/day |   Table 6 Total emissions for a representative day in each season   |  |  |  | | --- | --- | --- | | Emission cold season day | 17050,76 | kg CO2/day | | Emission cold-mid season day | 8713,59 | kg CO2/day | | Emission hot-mid season day | 8713,59 | kg CO2/day | | Emission hot season day | 12304,32 | kg CO2/day |   Table 7 Associated energy electricity costs for a representative day in each season   |  |  |  | | --- | --- | --- | | Electricity costs for cold season day | 1339,191 | €/day | | Electricity costs for cold-mid season day | 976,5087 | €/day | | Electricity costs for cold-mid season day | 967,315 | €/day | | Electricity costs for hot season day | 1527,227 | €/day |   Table 8 Associated NG costs for a representative day in each season   |  |  |  | | --- | --- | --- | | NG costs for cold season day | 1187,41 | €/day | | NG costs for cold-mid season day | 205,04 | €/day | | NG costs for hot-mid season day | 122,33 | €/day | | NG costs for hot season day | 168,83 | €/day | |