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An Optimization and Management Tool for Complex Multi-Generation Systems

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***Abstract*—Multi-generation systems where different energy vectors are interacting, should be controlled in an optimal way, minimizing their operational cost. This paper presents a web-based software tool for the management and optimization of such systems. The presented tool incorporates an optimization core, a graphical user interface, a module for the acquisition of field data and graphic reporting features. In this paper the different components of the tool are presented. The optimization tool is then applied to a real test case and the results are discussed.**

I. Introduction

Many industrial plants and civil or commercial centres rely on local power generation by means of multi-vector systems, which can provide steam, hot, low enthalpy heat, refrigerated water and electricity for the users needs. Such multi-generation systems can be quite complex in terms of energy inputs, interactions among the different energy vectors, and relation with external conditions, as for instance time variation of electrical energy price. In addition, the presence of energy storage modules can help the flexibility of the plant management but introduces new degrees of freedom in the control strategy.

As a consequence, it is not easy to set a commitment strategy for all the energy conversion blocks present in the system. A possible management strategy can be defined by searching for the production scheduling that minimises the operating cost, fulfilling, at the same time, all the user requests and technical constraints. Many software tools already exist for the simulation or optimisation of multi-generation systems [1].

The different tools are characterized by the different time frames considered in the optimization, monthly or weekly for operation optimization, years for planning optimization. Some tools are more suitable for building scale optimization, while others work on industrial plant, district or even regional or national scales.

This paper presents the optimization tool developed in the framework of the *EPSEM* project. The project focus was an operational optimization for industrial plants and for district heating which could also take into account renewable energy sources and which could also be fed by input data measured on the field.

In the following sections, the optimization core will be presented and the user interface will be described. Then the modules for measured data acquisition and for the results presentation will be presented. The tool is finally applied as an example to a simple test case.

II. The optimization core

The optimisation procedure implemented in the *EPSEM* tool is called *XEMS13* and finds the production profiles of all controllable power sources in order to minimise the management cost function subject to the fulfilling of balance equations and components constraints. Two categories of model equations are defined:

- balance equations;
- constitutive equations of the power production units and constraints.

The former equations ensure the energy balances for all the energy vectors, while the latter ones take into account the different operational conditions of each component as well as other operational constraints, e.g. management of ignition priority for Combined Heat and Power (CHP) blocks or Boilers. The objective function to be minimised, i.e. the overall operational costs of the system, and the balance equations are linear. Otherwise the constitutive equation and constraints in many cases are considered to be efficiently represented by approximated piecewise linear functions. Logical conditions, for instance the on/off statues of power blocks, can be represented by integer (0/1) variables. These conditions enable the use of an optimisation algorithm which can solve the problem in an efficient way.

The Mixed Integer Linear Programming (MILP) procedures can thus be properly used for the solution of this kind of optimisation problem, even in large scale ones, and

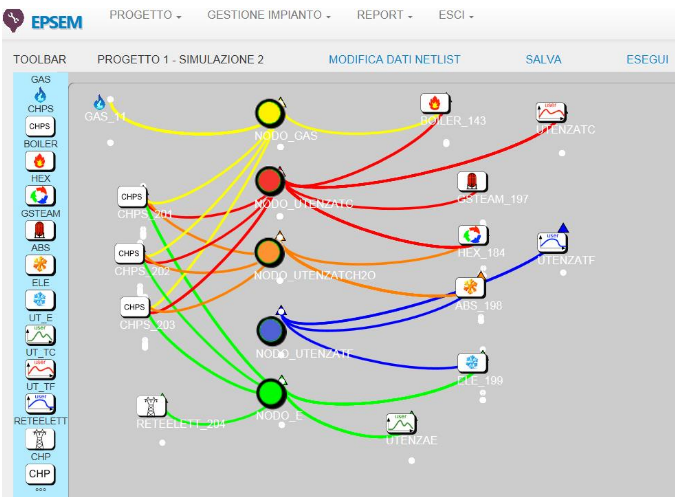

Fig. 1. Screen-shot of the user interface: colours refer to different energy vectors, circles represent balance nodes for each energy vector and power modules are shown as icons.

have already been applied in the specific field of energy and environmental management [2]–[4].

A relevant number of components are presently modelled so that complex interactions between many different sources and final users is possible. Furthermore, the optimisation problem can involve up to five energy vectors (electricity, steam, hot water, cold and low-enthalpy water) in order to exploit a wide number of heterogeneous system/plant configurations.

III. User Interface

A web user interface has been developed for the EPSEM tool with the goal of allowing users to create new system models from scratch, save them and view reports on the model behaviour.

The web portal, after logging in, allows users for drawing the structure of a multi-generation plant, via a user friendly drag-and-drop interface. In this way, it is possible to compose a system choosing from a set of available components, that are displayed in a toolbar. Each component can be connected with the others via a node, which characterizes the energy vector.

It is possible to customize the components through a custom data-entry form. After drawing the plant synoptic, the optimization procedure can be run. The final output of the optimization is given by a set of reports, presented in section V, which display, in graphical and alphanumerical way, the optimal production profiles of the various modules, the energy flows and the production shares of different sources.

The user interface is shown in Fig. 1. On the left of the screen there is the components toolbar. Each component can be dragged into the main workspace, and then further moved and customized. A consistency check is performed on each energy vector so that each component can only be connected other ones using the same energy vector (e.g. cold water outputs can be connected only to cold water inputs etc.).

The web portal has been implemented as a web SPA (Single Page Application). A SPA is a web application or web site that fits on a single web page with the goal of providing a more fluent user experience, similar to a desktop application. In a SPA, all the source code HTML, JavaScript, and CSS is retrieved with a single page load. SPAs focus on delivering better user experiences with significant client-side interactions using JavaScript, HTML5 and CSS. The information about components and plants is stored in a PostgreSQL database.

IV. Acquisition of Field Measured Data

The module for field data acquisition has been included in the project in order to achieve different goals:

- updating all the components operating curves, initially derived from data sheets, with actual values, so as to improve the accuracy of the optimization;
- comparing simulation results with real performances both to validate the simulation algorithms and the plant model, when operating in same conditions, and to evaluate the savings that could have been obtained if the plant had been operated in an optimized way.
- comparing the components data sheet operating curves with measured ones, to detect deviations and perform preventive maintenance.

In accordance with more diffused standards, the design of communication infrastructure connecting the supervisory system to the local control system of the plant has been based on Open Platform Communications (OPC) protocol. Today a wide range of OPC servers is available, covering almost all needs of interfacing communications between plant devices of different vendors and SCADA. To make the data/commands exchange from/to plant and SCADA easier, a general purpose OPC client has been developed as a layer between standard web services and OPC server. At the end of the chain, a tool, based on web services, periodically sends read requests to the OPC client and stores the responses into a database to make them available for further evaluations and usages. All the components of the communication infrastructure can be configured using information supplied as a by-product by the simulation model design tool.

V. Output and Reports

Smart results are the first step toward Energy Intelligence. The results of the optimization are saved in the database and managed for further analysis. The elaborated data can be exported and downloaded in both XML and excel format. The EPSEM results are displayed in web-based graphical reports. Also field measured parameters can be displayed in the graphical reports. This availability allows a simple comparison between measured and calculated data.

For every energy vector (electricity, steam, hot water, cold and low-enthalpy water) a balance report is generated. Each report presents the energy balance of that specific vector for each time step of the optimization. An example, for hot water, is presented in Fig. 2.

Also sankey diagrams can be generated (Fig. 3). Sankey diagrams are an efficient way of displaying the the total energy balance of the system and its conversion through the different vectors in the time window analysed.

Fig. 2. Example of node balance report.

In Fig. (3) all energy vectors exchanges among components in the energy nodes, losses and end-users request are present: on the horizontal line the energy flow is described from the primary sources: *gas* and *Gridp1* for natural gas and electrical networks, *env* for energy coming from the environment and processed by electrical chiller *EChi1*. The diagram shows also energy flows from primary sources to the conversion modules, e.g. *CHPS1*, *CHPS2* and *Abs1* and subsequently to the energy vectors, such as *ele* for electricity, *ste* for steam and *the* for hot water. In this way it is possible to follow all the energy transformations up to the end-users (U_e electrical, U_{tv} steam and U_c cooling users) and losses. On the vertical axis the magnitude of energy exchanges is represented allowing for an easy quantitative evaluation of different contributes.

Portability, scalability and usability in different contexts drove the choice of the libraries for report development. The first decision was the use of a JavaScript report generator. After a market survey the Google chart APIs [5] have been selected for their resilience and duration in time. The Sankey diagrams can also be generated with the free web-based tool Sankeymatic (like for the diagram of Fig. 3) [6].

VI. CASE STUDY

An example of possible application of EPSEM tool is presented in this section. The case study refers to a district heating network connected to a polygeneration system (Configuration 0) in North-West of Italy, fueled by natural gas, where an upgrade of the existing plant is considered.

The basic configuration is shown in Table I and the introduction of RES generation (Configuration 1) is foreseen according to the recent requirements of EU directive on energy efficiency in district heating (DH) networks. The RES contribution is represented by a two stage Heat Pump (HP): the first stage is a ground water heat pump, while the second stage is fed by the return water (low enthalpy water @40-45°C) used to cool down the intercooler of the two internal combustion engines (ICE). In addition, a Thermal Energy Storage (TES) system is also integrated to increase both the flexibility of the polygeneration system and the contribution of the cogeneration and RES to the heating demand. Table II summarises the technical characteristics of the new components and the heating load characteristics. The electricity demand profile of the plant is instead only related to the auxiliary requirements and to the pumping system of DH that usually are considered equal to the 5% of the heating profile.

TABLE I. DATA COMPONENTS OF CONFIGURATION 0

module	rated		
2 CHPs with ICE	$P_{en} = 2.004\ \mathrm{MW_e}$	$\eta_e = 0.440$	$\eta_t = 0.429$
2 Boilers	$B_{tn} = 11.2\ \mathrm{MW_{th}}$	$\eta_B = 0.92$	
1 Boiler	$B_{tn} = 5.3\ \mathrm{MW_{th}}$	$\eta_B = 0.92$	

TABLE II. DATA COMPONENTS OF CONFIGURATION 1

module	rated		
User	$U_{tpk} = 26\ \mathrm{MW_{th}}$		
2 CHPs with ICE	$P_{en} = 2.004\ \mathrm{MW_e}$	$\eta_e = 0.440$	$\eta_t = 0.429$
2 Boilers	$B_{tn} = 11.2\ \mathrm{MW_{th}}$	$\eta_B = 0.92$	
1 Boiler	$B_{tn} = 5.3\ \mathrm{MW_{th}}$	$\eta_B = 0.92$	
1 HP	$P_{tn} = 1.0\ \mathrm{MW_{th}}$	$COP_n = 3.0$	
Storage	$S_{tn} = 15.0\ \mathrm{MWh_{th}}$	$\eta_{St} = 0.5\ \%/\mathrm{h}$	

The EPSEM tool has been used to evaluate the operational cost of the new plant configuration by subdividing one year in 14 representative weeks. This analysis is commonly performed for district heating network located in the North of Italy where the heating season is between the October 15th and the April 15th. Hence two representative weeks are added to the conventional 12 weeks (one for each month of the year) in order to take into account the first half of October and the second half of April. Under these considerations, 14 simulations have been run by assuming the price of natural gas as shown in Table III and the price for the sold electricity as shown in Figure 5.

TABLE III. PRICES OF NATURAL GAS

Price	€/ Sm^3
C_d	0.354115
C_{nd}	0.362313

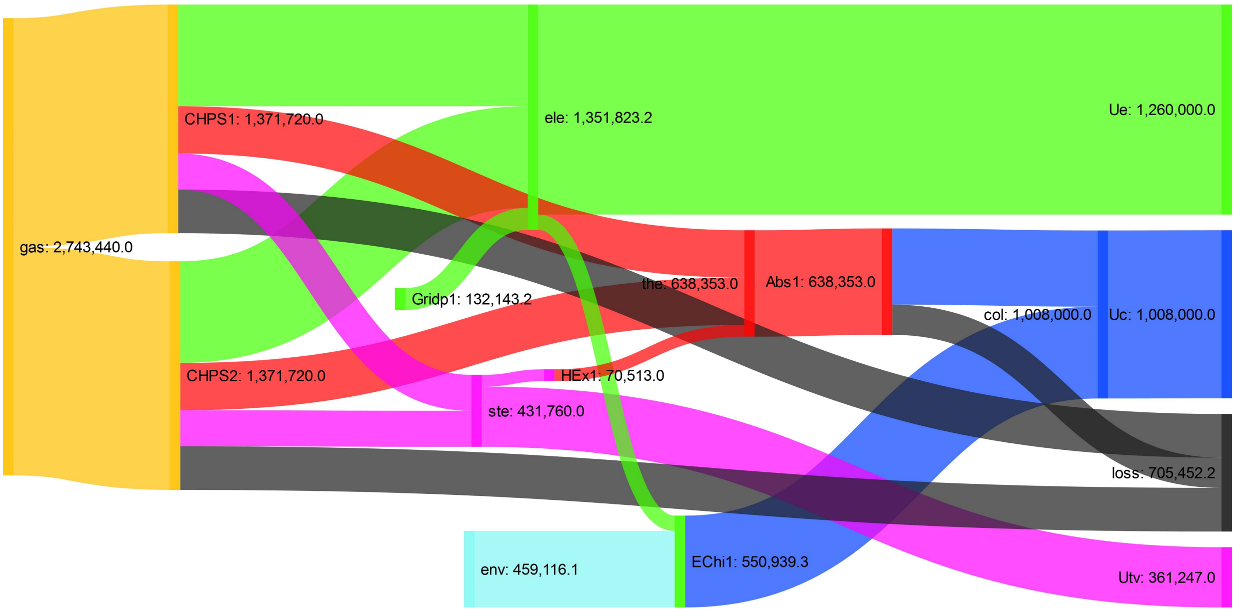

Fig. 3. Example of sankey report.

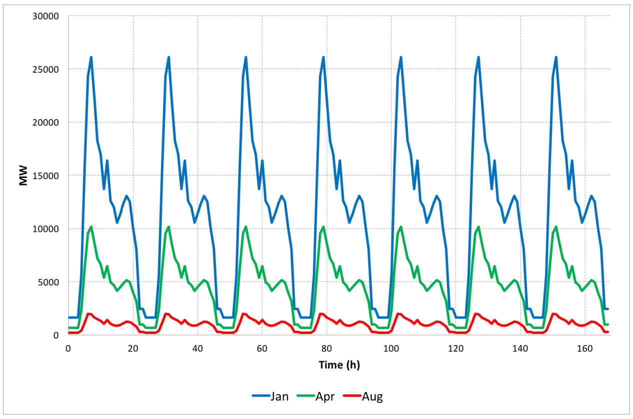

Fig. 4. Example of heating load profiles used for the case study.

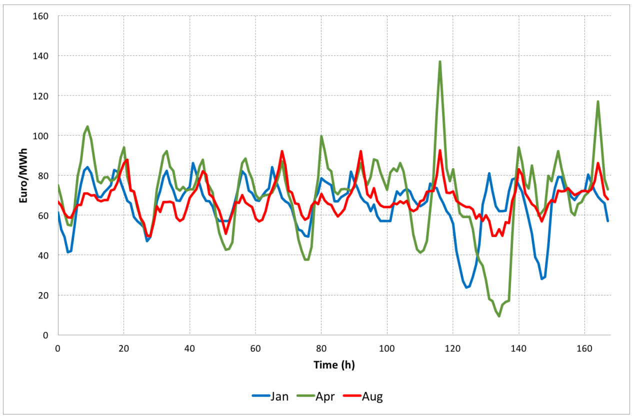

Fig. 5. Price of the electricity sold to the grid.

Results of EPSEM tool have been also finally used to evaluate the share of the different sources to the yearly demand and verify the requirements of EU directive on energy efficiency in district heating networks [7].

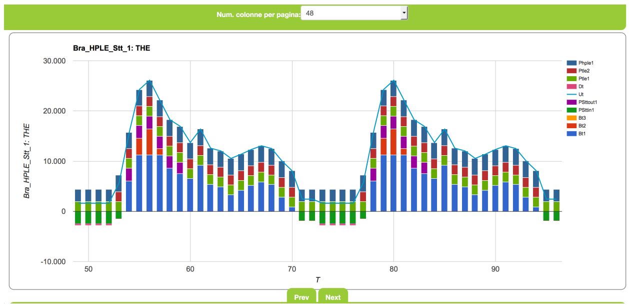

Fig. 6. Power profiles (hot water energy vector) of the components in week 1 for Configuration 1.

Figure 6, 7 and 8 show the production profiles of the components during different representative weeks. In all those figures is remarked how the contribution of two stage HP and the TES is strictly important to reduce the operation of the boilers and to increase the CHP operation. Most relevant impact can be observed during middle season (week 4) and summer season (week 9) where no contribution is required from the boilers and all the heating demand is covered by CHPs and HP by the crucial role of thermal energy storage usage. In particular, the optimised operation during middle season (see Figure 7) highlight that the CHPs and the HP can conveniently cover the heating demand and the storage is underused due to the still relevant heating demand. Otherwise, the interaction between CHPs and TES can be conveniently used during summer to produce hot water during evening and store part of the generation to satisfy the daylight demand (see Figure 8).

Similar results can be synthetically observed in the Sankey diagrams for the different weeks shown in Figure 9, 10 and 9 where also energy losses for the polygeneration system are highlighted. Consequently, the operational cost for Con-

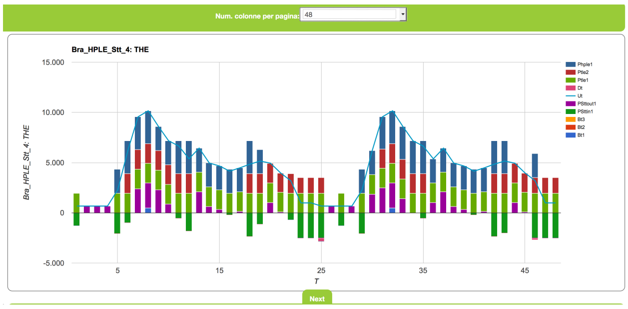

Fig. 7. Power profiles (hot water energy vector) of the components in week 4 for Configuration 1.

Fig. 8. Power profiles (hot water energy vector) of the components in week 9 for Configuration 1.

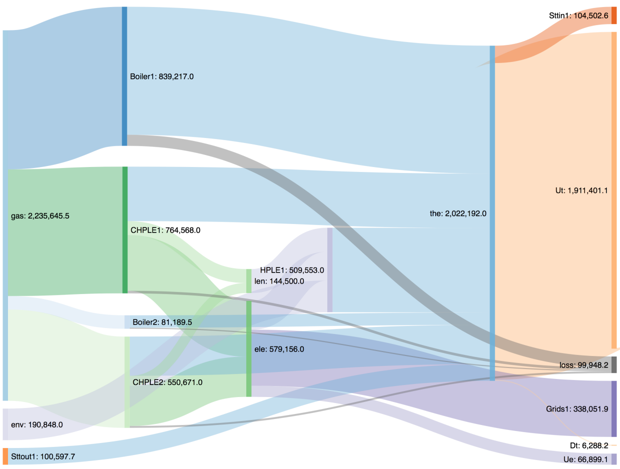

Fig. 9. Sankey diagram of week 1 for Configuration 1.

figuration 1 can be reduced of 19.5% with respect to the Configuration 0 obtaining the twofold advantage of reducing the economical cost and increasing the efficiency of the system.

Figure 12 shows the share of the different components to the yearly heating demand based on the weekly Sankey diagrams. The figure highlights as the TES and HP can significantly increase the RES contribution, that is related to HP operation, up to 28.57% and the operation of the Boiler 3 can be completely avoided. The sum of the contribution of RES and CHPs can thus reach 74% of the heating demand that is over the limits of 50% imposed by the EU Directive [7].

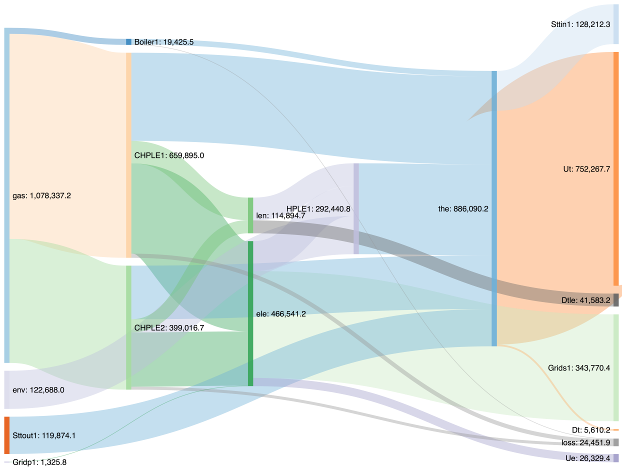

Fig. 10. Sankey diagram of week 4 for Configuration 1.

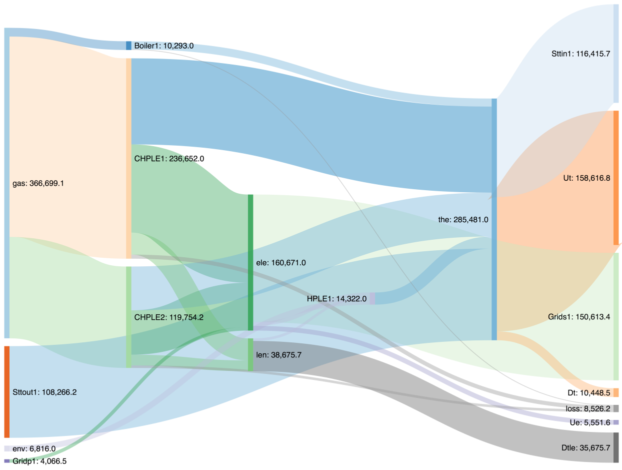

Fig. 11. Sankey diagram of week 9 for Configuration 1.

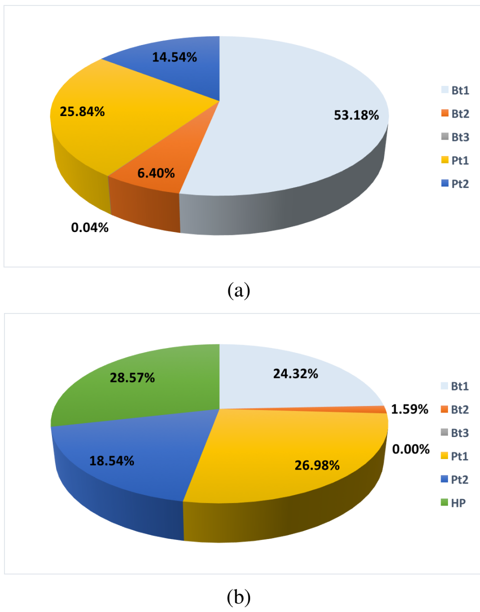

Fig. 12. Share of different components: (a) Config. 0; (b) Config. 1

VII. Conclusion

The EPSEM tool developed during the project is a user friendly interface created to replicate the topology and to take into account the technical characteristics of a polygeneration system. The tool can be used to define the optimal generation profiles for each components of the system in order to minimize the operational costs of a plant (based on the optimization procedure XEMS13) with different energy vectors and demands. Results can be analysed to evaluate economical and energy performance as well as other economical indicators for investment purpose.

An application of EPSEM tool has been presented for an industrial case study where the management of different production blocks and the availability of thermal storage enable the increase of the system efficiency. The economic and energy impacts of a polygeneration system with RES and TES have been evaluated in an existing district heating network in North-West of Italy. The results highlight as the tool allow to potentially reduce the operational costs of the new configuration and increase the RES usage to satisfy the heating demand.

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