Software Module for Integrated Energy Dispatch Optimization

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Abstract — **Continuous increase of global energy demand combined with the lack of conventional energy sources resulted in rise of operational costs for energy infrastructures. This calls for systematic and comprehensive Energy Management (EM) approaches that are able to take the advantage of increasingly used Renewable Energy Sources (RES) as well as to provide for more efficient operation of existing multi-carrier energy infrastructures. The presented work focuses on the development of an extensive, flexible and modular simulation tool for the analysis and optimisation of such energy systems based on extended Energy Hub concept. The tool was developed as a software module which allows for both energy planning and operation scenarios within multi-carrier environment. The prototype of the analysis and optimisation tool was first developed in MATLAB® and subsequently a corresponding software module was implemented in Java® environment. Technical details and challenges associated with the implementation of software module were elaborated in detail after which the applicability of developed software is highlighted and finally an example of use-case is given.**

I. Introduction

The trends of global energy conservation seek for energy savings through various means such as inclusion of Renewable Energy Sources (RES) as well as better utilization of conventional energy sources through improved efficiency of ongoing energy intensive processes. Apart from environmental aspects, these energy saving activities are also coupled with high economical impact since any savings in energy can be easily associated with tangible monetary repercussions. In order to reconcile these two there is a need for a comprehensive Energy Management (EM) solution that will be able to economically evaluate integration of RES in long term as well as to provide efficient operation of existing infrastructures on daily basis. The first objective requires careful consideration of various hybrid energy infrastructures in order to successfully tackle the stochastic nature of RES and provide continuous power supply to the end user. On the other hand the second objective entails satisfaction of the user demand in the most efficient and hence the most economic way.

This paper therefore especially focuses on the development of an EM software tool used partly for long term economical appraisal related to small-scale hybrid renewable energy systems, suitable for supplying the residential users with clean but also reliable source of energy and partly as an energy dispatch module that will be able to integrate on existing Building Management Systems (BMS) and conduct smart energy management strategies.

A. State of the Art

An exhaustive research of the state of the art in the area of RET simulators and optimizers with the similar objective was performed and the most prominent were recognized. Starting with the NREL [1], a computer model called HOMER [2] was developed, which deals with evaluation of design options for large-scale off-grid and grid-connected power systems for remote, stand-alone, and distributed generation applications. HOMER is presently available as fully commercial tool. Another tool called REopt [3] serving as an energy planning platform that offers concurrent, multiple technology integration and optimization capabilities to help clients evaluate potential savings and energy performance objectives was developed in the same laboratory. Following is the Hybrid2 [4] software package, developed in RERL [5], representing a tool performing long term performance and economic analysis on a wide variety of hybrid power systems. Furthermore, software for clean energy project analysis, called RETScreen [6] was developed with objective to provide for a decision support tool for RET deployment. Finally, a RET simulation and optimization software called iHOGA [7], based on utilization of genetic algorithms, was also analyzed.

However, none of the aforementioned applications provides a light-weight, web-enabled and easy to integrate tool serving both for energy planning decision support as well as optimal operation of existing energy infrastructures.

B. Selected approach

The objective of this paper is to elaborate on the software module built on the extended Energy Hub (EH) concept described in [8] and [9]. This concept takes the advantage of existing Supervisory Control and Data Acquisition (SCADA) systems and additional metering, if necessary, to provide energy dispatch optimization of complex multi-carrier energy infrastructures. The original EH concept offers modelling of energy flows from different energy carriers while satisfying the requested user demand [10]. The concept leverages on the conversion potential of a specific, constrained, domain referred as Hub which serves as a point of coupling between existing energy supply infrastructures and energy end use. The Hub basically represents a set of energy converters and/or storages which is responsible for delivering required energy by taking into consideration different conversion and/or storage options while meeting a desired optimization criterion. So far, many aspects of the EH have been thoroughly elaborated, thus emphasizing optimization potential of the concept owing to its flexible modelling framework, diverse technologies and wide range of energy carriers [11][12]. The latest research efforts even considered generalization of this concept by introducing renewable energy sources, which was first mentioned in [13]. However, considering that EH concept basically performs optimization of supply side, without affecting the desired energy demand, the concept has been further improved by including additional, complementary, optimization of the demand side, which proved to create space for further energy cost savings. This implied utilization of the well-known concept of demand side management (DSM), which consists of various techniques for modifying the energy end use profile, i.e. the demand side. However, it should be emphasized that any further savings, compared to EH approach, require certain level of compromise from the user (changing the time schedules of equipment, reducing the demand etc.). Nevertheless, this is perfectly aligned with current trends in energy supply as more and more energy providers offer significant economic benefits if, in return, the end user complies with some energy end use constraints (reducing loads in peak hours, improving power factor etc.).

The remainder of the paper starts with the Section II describing the existing EH concept and its modelling framework. The Section III briefly elaborates on the modelling and development aspects of the optimization engine prototype. The actual software module is elaborated in Section IV, where all technical details are revealed. Finally, the paper is concluded and the impact of the developed software is discussed in Section V.

II. Energy Dispatch Optimization Concept

As introduced in previous sub-section, the selected approach for development of energy dispatch optimization framework is based on integrated optimization of both supply and demand side of so called energy Hub. Hence, a mathematical representation and theoretical basis for optimization of such a Hub are given in the following.

From the modelling perspective, Hub is represented as a matrix which includes, in the most generic case, elements which enable conversion of various supply energy carriers to satisfy different load types. Furthermore, since physical Hub may also take into account different types of storages, each energy carrier is associated with its storage unit which acts as energy buffer at the cost of storage efficiency, and the corresponding storage matrix is considered as well. This is depicted in the Hub's conceptual schemata shown in Figure 1. As depicted, the power input comprising of conventional (P) energy sources, such as electricity power grid, natural gas, district heating, fossil fuels etc., is supplied to the Hub. Apart from the power input (P), a vector comprising of all local energy production (R), such as photovoltaic, wind turbines for electricity and/or solar thermal and geothermal for thermal energy, is also considered as Hub's input. The input power is then transformed using the conversion elements (C), allowing for conversion from electrical towards thermal energy and vice versa, and/or energy storages ($\dot{E}$), such as batteries, ultra capacitors, fuel cells for electricity or boilers and phase changing materials for thermal energy, while taking into account the storage efficiencies depicted with coupling matrix (S). Passing through the Hub, depicted by the conversion and/or storage matrix, power from the supply side is fed to

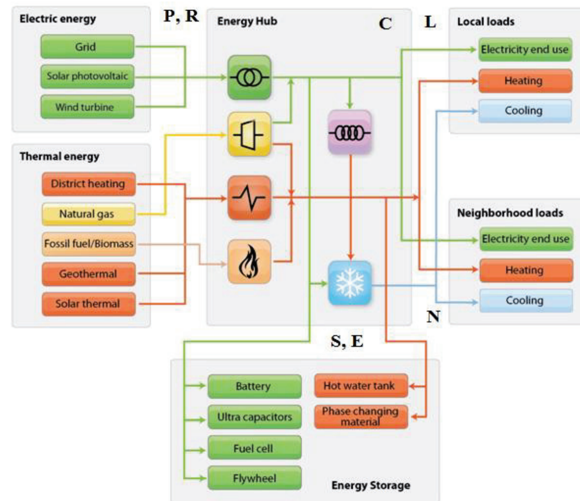

Figure 1. Energy Hub concept

the demand, loads (L), typically represented with electricity and heating/cooling loads. The output of the Hub is also complemented with the vector depicting neighbourhood loads (N), while preserving the same distribution between electricity and heating/cooling loads, which allow the Hub to feed the surplus (export) of energy towards the neighbourhood, which is considered to be another similar entity or a piece of power infrastructure. Finally, the complete Energy Hub model equation, defined in [11], is given in the following:

$$(L+N)=C(P+R)-S\dot{E}=\begin{bmatrix} C & -S \end{bmatrix}\begin{bmatrix} P+R \\ \dot{E} \end{bmatrix}$$

Considering the flexibility and generality of such modelling approach, a Hub concept can be applied to an entity ranging from single residence up to an entire city or country. Once all the matrices and vector parameters are defined, according to described model, an optimization problem is hence formulated and a corresponding solver was applied. Based on the research efforts related to the development of integrated energy dispatch optimization concept, described in more detail in [14], the following are key features of the actual software module prototype as well as mature application.

III. Optimization Engine Prototype Development

A prototype of the software module for the analysis and optimisation of multi-carrier energy systems described as Hubs has been implemented in MathWorks®/MATLAB® environment based on the defined mathematical model. Given the formulation of the Hub, the optimization problem depicting energy dispatch, may be represented as Linear Program (LP). Although there is an abundance of solvers dealing with that kind of optimisation problem, it was decided that IBM® ILOG® CPLEX® Optimizer should be used as it is one of the industry standards. It requires the following input data:

- *f*: vector for the definition of the objective function
- *Aineq*: matrix for inequality constraints
- *bineq*: vector for inequality constraints
- *Aeq*: matrix for equality constraints

- *beq*: vector for equality constraints

The major functionality of the developed MATLAB code is to define the system data in matrix and vector form and translate this information into the input matrices and vectors required by the employed solver. This process can be efficiently performed by exploiting the powerful matrix and vector manipulation routines of the MATLAB engine. The implemented MATLAB code has the following major functional sections.

1) **Data Input**: The energy hub model of the physical system is defined by defining the model matrices, i.e. the input storage matrix *Sqin*, input dispatch matrix *Fin*, conversion matrix *C*, output dispatch matrix *Fout*, output storage matrix *Sqout* as described in Section 2. At a second stage other parameters needed for the formulation of the optimisation problem (such as load data, price data, etc.) are defined as time series or read in from corresponding files.

2) **Solution:** After the matrix and vector parameters defining the optimisation problem have been formulated the solver routine is called to execute the optimisation.

3) **Result Processing:** If an optimal solution has been found by the optimisation function, the optimisation results are processed for display purposes.

IV. Optimization Engine as Software Application

A. Technology considerations

After the development of integrated energy dispatch optimization engine prototype in MATLAB environment, together with CPLEX Optimizer, the objective was proceed with its development within such environment that would enable integration of the developed software module with existing BMS. Having this in mind and considering that majority of the BMS components are mainly developed under the object oriented paradigm, the choice was made to opt for Java™ framework. More precisely, the development of business logic components was done using Java programming language whereas the corresponding Web technologies were used to enable remote access to the engine. However, considering the developed MATLAB prototype, there were two alternatives for integration within Java environment:

- To generate Java classes out of the MATLAB source code using the MATLAB Builder™ JA - Then Java classes can be integrated into Java applications and deployed royalty-free to desktop computers or web servers that do not have MATLAB installed using the MATLAB Compiler Runtime (MCR) that is provided with MATLAB Compiler™.
- Or, to develop native Java application from scratch offering the same functionalities as developed prototype.

Naturally, both approaches have their advantages and disadvantages, as explained in the following.

The first one takes the advantage of the implemented source code and does not require in-depth knowledge of the underlying algorithms. However, it requires additional pre- and post- processing of the information stored in the generated Java classes. Also, considering the fact that MATLAB prototype is using external optimizer (CPLEX), which is dependent on the programming environment, it would be necessary to break the MATLAB source into two parts, i.e. the one before the call of CPLEX functions and the other one after, to provide for corresponding CPLEX library for Java. However, using CPLEX in JAVA environment is quite different than in MATLAB, where it is required only to replace the call towards native MATLAB functions with call towards CPLEX functions using the same arguments. This means that even if the MATLAB source was used, although wrapped in object oriented paradigm, access towards CPLEX would have to be completely changed in Java environment. Using CPLEX in Java environment is, however, a bit more complex and requires utilization of a specialized Application Program Interface (API). This allows Java application to call CPLEX directly, through the JNI (Java Native Interface). The Java interface is built on top of ILOG Concert Technology for Java and supplies a rich functionality allowing you to use Java objects to build an optimization model. This concept is depicted in Figure 2. However, this would require additional coding to adapt both inputs and outputs coming from the MATALB code, in order to be able to run CPLEX optimization engine within Java environment.

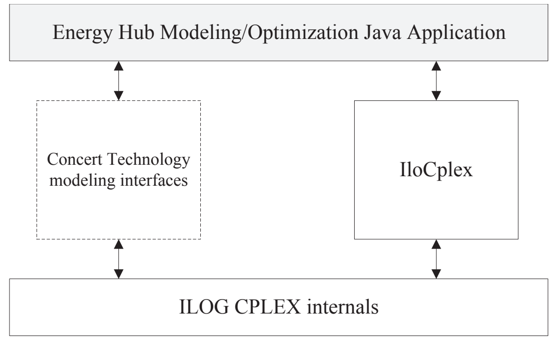

Figure 2. ILOG Concert Technology for Java (taken from http://www.cs.cornell.edu/)

On the other hand, the second approach of pure Java application requires in-depth knowledge of underlying algorithms in order to perform semantic translation, unlike in the previous case where it was possible to perform translation solely on the syntax level. However, since the use of CPLEX API for Java is inevitable in any case, developing application in pure Java is more favoured approach for many reasons. It represents a more streamlined approach with many advantages when it comes to the model scalability, easy maintenance of the code and, the most importantly, shorter execution times. Therefore, the rest of this section aims at providing an insight to the implementation of optimization engine as pure Java application.

B. Java application development

The optimization engine is basically a Java application based on Java Enterprise Edition 7 (Java EE 7). For the development and implementation of this application an Integrated Development Environment (Eclipse Java EE IDE - Juno Service Release 2) was utilized. Furthermore, having in mind that one of the main objectives was also to enable remote access to the optimization engine results, further developments were conducted in the direction of developing an online tool easily accessible at any time or place from a web browser. This suggested use of a thin

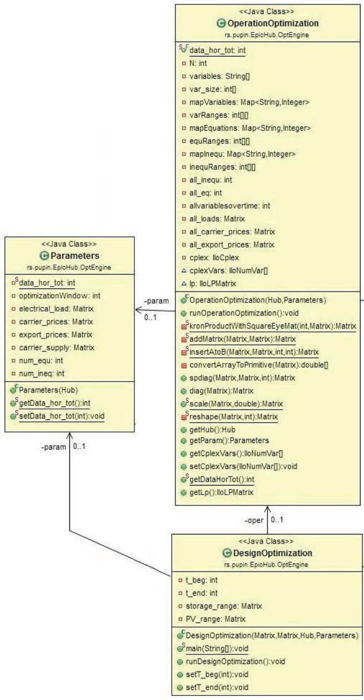

Figure 4. Comparison of total dispatch costs distribution

client and three-tier software system architecture, which has proven to be an immensely useful for the enterprise application development. Therefore, an Application Server (Apache/Tomcat 7.0) was employed as well.

As regards external components (apart from Java System Library) that are necessary for engine implementation, they are as following:

1) CPLEX API – represents a library which contains CPLEX Concert Technology for Java, thus offering API that includes modelling facilities to allow the programmer to embed CPLEX optimizer in Java application. Therefore, it provides a set of interfaces and classes that enable typical CPLEX features such as creating a model, solving the model, querying results after solving, and handling error conditions.

2) CPLEX core engine– represents implementation of CPLEX optimizer in a dynamic linked library which is needed to be able to run Java applications that use CPLEX. In other words, this represents a light weight approach where there is no need for the installation of the overall ILOG CPLEX Optimization Studio for running CPLEX applications.

3) Matrix manipulation – represents an open source, pure Java library that provides Linear Algebra primitives (matrices and vectors) and algorithms. Given the fact that the overall mathematical modelling and representation of Energy Hub is done using matrices use of Linear Algebra library was imperative.

The first two components were employed based on the previous decision to use CPLEX for solving our LP and MILP problems. Although there are other, open source solver solutions, the CPLEX was picked owing to its unprecedented performance and availability through Academic Licence. The last component, La4J, was selected based on a search for Java library for Linear

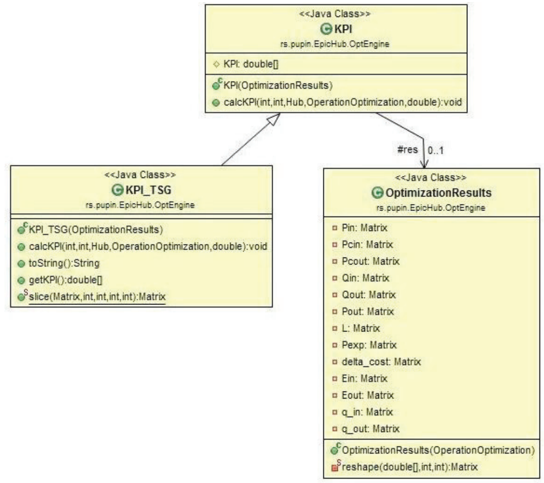

Figure 3. Comparison of total dispatch costs distribution

Algebra that provides manipulation with extremely large matrices. This implies utilization of concept of sparse matrices which enables viable manipulation of matrices with over 100k rows and columns. La4J was picked out of the group of several libraries that were tested such as: Commons_math, Colt, Ojalgo, JBlas, EjML, MtJ, Jeigen/Eigen and La4J.

When it comes to the implementation of the optimization engine as Java application, it was done using 7 classes as depicted in the corresponding UML diagrams in Figure 4 and Figure 3. The first one depicts classes that were used for actual optimization whereas the second one represents classes responsible for post-processing of the optimization results and calculation of corresponding Key Performance Indicators (KPIs) used for evaluation of different alternatives. Hence, Figure 4 depicts classes that implement the following key features:

- Hub operation optimization – implements the energy dispatch optimization of a particular Hub configuration. It uses the mathematical representation of Hub and corresponding parameters to model its behaviour over a given time span as LP problem. Furthermore, in order to be able to run the CPLEX optimizer, modelling was performed using the previously mentioned API and the corresponding interfaces as in following:
  - IloNumVar – modelling variables
  - IloRange – ranged constraints
  - IloObjective – optimization objective
  - IloNumExpr – expression using variables.
- Hub design optimization – features design optimization as multiple concentric loops going over different combinations of corresponding energy asset alternatives (namely different energy sources and storages) which are then used to run corresponding energy dispatch optimization.
- Hub modelling – models the topology of Energy Hub by defining corresponding matrices and necessary parameters. One of features of developed software module is ability to generate artificial data for various time variable input parameters (production from renewables, energy pricing and load profiles) which enables testing of

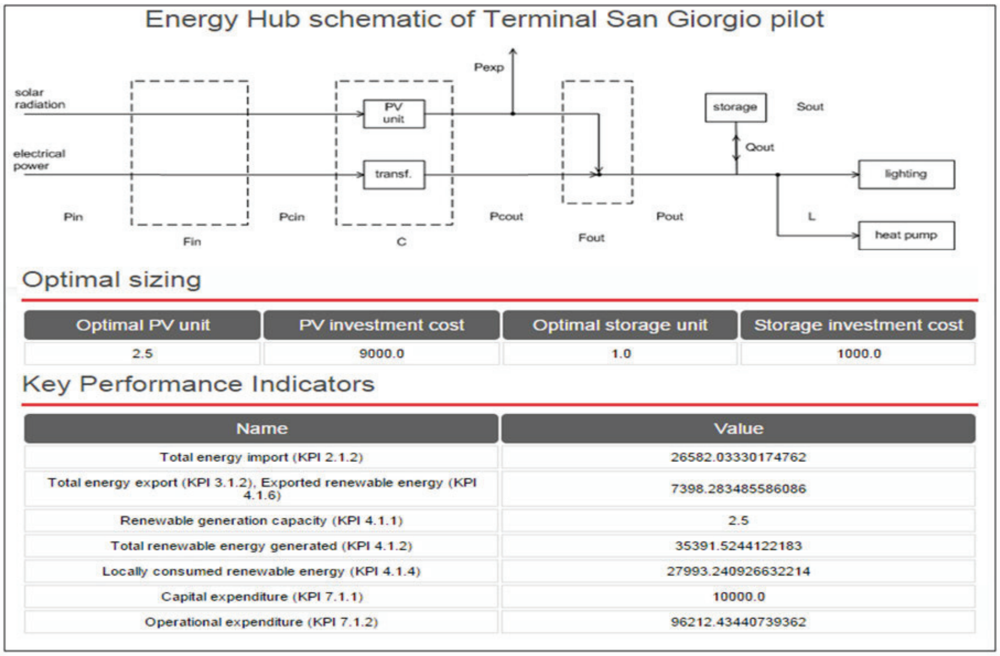

Figure 5. Example result from the optimization software module

the module itself but also provides opportunity to conduct sensitivity analysis of the proposed design solution.

V. Conclusion

This paper presents the work performed to conceptually develop and implement a software module for the analysis, simulation and energy dispatch optimisation of multi-carrier hub systems. The employed mathematical formalisation of the system equations allows for a modular approach which can be exploited at the software development stage to provide a tool that is efficient and flexible in its capability to model systems of different sizes and complexity. Furthermore, the presented tool enables the full numerical computation of analytical results starting from the physical data and parameters describing the pilot and will form a key part of the functionalities featured in the overall energy management platform. Starting from the prototype developed in MATLAB environment, the tool has finally grown to a high maturity level as Java application, suitable for integration with existing energy management software. Figure 5 contains a piece of user interface of web instance of the software module which is used to asses different sizing options for a given pilot. The figure is depicting a use case of the Terminal San Giorgio, part of the Genoa harbour, along with the recommendations for the optimal retrofit of energy infrastructure. Given the meteorological conditions of the terminal as well as its daily demand, a choice was made to opt for the installation of both PV panels and corresponding storage units. Also, a list of the key performance indicators for the suggested configuration is given enabling easier benchmarking with non preferred options. Further work will be focused on the development of REST-full services that will offer these results over machine readable interface and allow for easier integration with EM systems.

Acknowledgment

The research presented in this paper is partly financed by the European Union (FP7 EPIC-HUB project, Pr. No: 600067), and partly by the Ministry of Science and Technological Development of Republic of Serbia (SOFIA project, Pr. No: TR-32010).

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