Integrated Energy Dispatch Approach Based on Energy Hub and DSM

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***Abstract*— Permanent increase of energy prices united with greater energy demand make the reduction of energy infrastructure operation costs a challenging task. Therefore, systematic application of energy management (EM) solutions became a necessity and the most viable approach for cutting down the energy costs. This paper proposes an EM solution that brings advancement of the state of the art related to the multi-carrier energy dispatch by optimizing the energy flows within a generic energy infrastructure. The proposed advancement is achieved through the enrichment of existing Energy Hub concept, leveraging on supply side optimization, with complementary optimization of demand side, known also as demand side management (DSM). Compelling simulation results, justifying the merging of these two concepts, were reported. The results show the potential for saving up to 25% of energy costs, depending on the use case scenario, comparing to a baseline scenario where no EM solution is applied. Considering that the proposed solution employs existing energy infrastructure, thus does not require expensive equipment retrofit, it makes it immediately applicable in both residential and commercial domain.**

I. INTRODUCTION

Current trends of increasing energy demand, present at both residential and industrial/commercial level, as well as constant rise of energy prices led to high energy related operation costs. This represents a great motive, apart from better saving of the environment, for introduction of energy conservation measures and cost reduction actions. Typically, this objective can be achieved either through introduction of energy efficient equipment (e.g. efficient boilers, pumps etc.), which represents a costly solution, or employment of an energy management (EM) solution aiming at optimization of energy flows upon existing equipment, requiring only additional ICT support. The objective of this paper is to propose such EM solution which might be integrated over existing Supervisory Control and Data Acquisition (SCADA) systems and considers energy dispatch optimization of complex multi-carrier energy infrastructures. The existing Energy Hub (EH) concept offers the modelling of energy flows from different energy carriers while satisfying the requested user demand [1]. 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 [2][3]. The latest research efforts even considered generalization of this concept by introducing renewable energy sources, which was first mentioned in [4]. However, considering that EH concept basically performs optimization of supply side, without affecting the desired energy demand, this paper proposes strengthening the EH concept with the introduction of additional, complementary, optimization of the demand side, which may create space for further energy cost savings in spite of all mentioned advantages of EH concept. This implies application 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. Therefore, 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 introduces basic features of the DSM approach, depicting its benefits as well as application limits varying case-by-case. Merging of the two concepts is elaborated in Section IV, where a complete evolution process is described in four sub-sections. Starting from the sub-section A, a baseline scenario, which represents the case in which no optimization is performed, is introduced. In this scenario the end use energy demand is satisfied directly from energy carrier which offers the highest conversion efficiency. The following is the sub-section B depicting the scenario where only DSM approach is applied. The corresponding optimization process is, therefore, performed only at the demand side through systematic modifications of requested loads with respect to given constraints corresponding to each energy carrier. Next is the sub-section C which elaborates the scenario where EH concept alone is involved. Contrary to the previous scenario, this one includes optimization of the supply side exploiting the conversion potential of particular entity. Finally, the sub-section D reveals the fourth scenario which merges the previous two and offers optimization of both supply and demand side. All four scenarios are simulated, using an example Hub configuration, and valuable simulation results are presented within Section V. Finally, the paper is concluded and the results are summarized in Section VI.

II. ENERGY HUB CONCEPT

As introduced, the existing EH concept models energy flows from different energy carriers aiming to satisfy the requested user demand by taking the advantage of the conversion potential of specific Hub. The overall concept is presented in Figure 1, depicting both basic Hub elements and its renewable energy extension, extensively elaborated in the following. The EH concept has originally foreseen only downstream energy flows going from inputs (left), i.e. energy supply infrastructures, towards the output (right), the energy end use, passing through the matrix of conversion and/or storage elements which enabled fulfilment of the loads from wide range of energy carriers. However, considering the addition of renewable energy sources, meaning that there is uncontrollable energy generation, it is also important to enable energy export, i.e. the upstream of energy, which can have strong economical and/or environmental benefits attached to it. This is done by means of "neighbourhood loads", which may represent a similar Hub like structure in its vicinity or another complex energy infrastructure comprised of wide range of energy carriers such as electricity (power grid), gas (gas network) and etc.

A Hub, from a mathematical perspective, is represented as a matrix which includes, in the most generic case, elements which enable conversion of all supply energy carriers into any of the load carriers. Moreover, in the case where storages are taken into account, each 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. Considering the illustration of Hub, 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. 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 ($\dot{\mathbf{E}}$), 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 the demand, loads (**L**), typically represented with electricity and heating/cooling loads. However, with the introduction of renewable energy sources and the neighbourhood concept, additional energy flows (vectors) should be defined as well. 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 added at the input. The output of the Hub, previously depicting the loads is now extended with neighbourhood loads (**N**), preserving the same distribution between electricity and heating/cooling loads, which allow the Hub to feed (export) the surplus 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 [2], is given in the following:

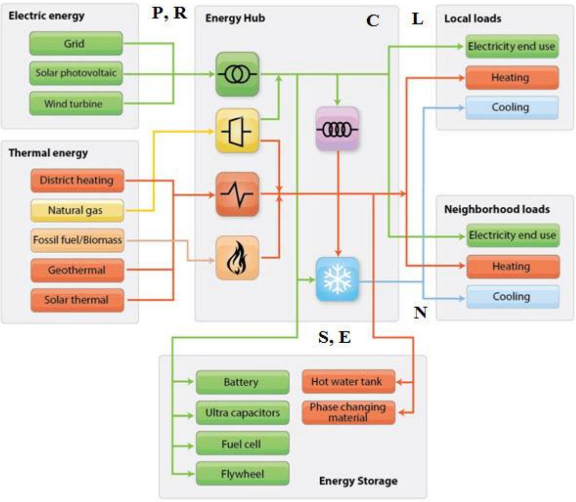

Figure 1. Energy Hub with renewable energy

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

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.

III. DEMAND SIDE MANAGEMENT

Considering the increasing trend of cutting down energy purchase costs a concept of demand side management (DSM), which aims at changing the energy end use, was introduced. Moreover, the DSM approach offers different mechanisms to alter energy consumption profile and/or improve end use equipment efficiency, in order to reduce operation costs of the consumed energy [5]. The DSM measures are most often undertaken by the end user, but can also be initiated by an energy provider itself. It usually includes increasing or decreasing the requested loads, shifting them from high to low tariff periods in case a variable tariff scheme is applied (e.g. moving loads towards off-peak periods such as during the nights, weekends) etc. Finally, the DSM concept encompasses a set of actions which may be divided in two main categories:

i. energy efficiency improvement and
ii. load management.

Starting with improvement of the energy efficiency, it implies delivering the same quality of service (satisfying the requested loads) for less energy. Therefore, these actions consider reduction of the energy consumption through utilization of energy efficient equipment (such as energy saving lighting devices, more efficient air conditioning units, circulation pumps etc). Hence, they are reducing the overall energy consumption and indirectly the demand peak which is one of the main targets of DSM. On the other hand, DSM is also applied through the load management upon which the methodology presented in this paper will be leveraged on.

The load management represents any intentional modification of the load profile aiming to reach a given objective. Usually, this objective considers reduction of the overall operation costs, taking the advantage of dynamic energy pricing schemes (peak and off-peak hours), but lately more and more ecological and environmental criteria, such as reduction of GHG footprint, are influencing the load management objectives. In order to reach a predefined objective, load management considers various actions ranging from shifting the load profile in time, changing its instantaneous levels or altering its cumulative sum. Considering the nature of energy production and supply processes, any occurrence of peaks (or sudden drops) in the load profile usually incurs additional costs (non-proportional to delivered energy) from the perspective of an energy provider. Having in mind that these costs are then forwarded towards the end user, a successful tackling of peaks encompassing control, curtailment and/or shifting of the load, may assume great savings in the operational costs. However, considering that it is rarely allowed to apply these actions over the entire load, which considers electricity, heating and cooling yielded by different critical building systems, such as air conditioning system, lighting system etc., it is first necessary to identify and appropriately categorise different types of loads.

With respect to the mentioned and considering the perspective of the DSM application, loads can be categorised according to the following breakdown [5]:

- critical load – should not be influenced (typically power supply of fundamental operation),
- curtailable load – could be reduced (the temperature set-point of the air conditioning system could be lowered during periods of high electricity price or if contracted peak consumption is being approached),
- reschedulable load – could be shifted (forwards or backwards) in time (pre-cooling of a building can be performed early in the morning before there is an actual cooling demand).

Having in mind the above listed categories, identification of the curtailable and reschedulable loads for each particular case is a prerequisite in order to select and apply suitable DSM measure.

When it comes to the implementation of DSM, various paradigms were used so far ranging from the manual analysis of load profiles and unit commitment allocation patterns towards the automatic load profile search leveraging on artificial intelligence (pattern search, GA, PSO etc.). For the purposes of this paper a GA based DSM implementation was hired to discover the optimal energy load profile over a given time window, described in detail in [6]. The selected approach takes into account building load forecast, applicable tariff scheme for each considered energy carrier (e.g. electrical energy, natural gas, fossil fuel etc) as well as set of constrains, depicting the modification limits coming from the nature of a load.

IV. EXTENDING ENERGY HUB WITH DSM

The aim of this section is to try to evaluate, and eventually justify, the merging of the EH concept with another, well known, concept of DSM. Although the EH concept alone can reduce the operation costs significantly, owing to the optimization of entering energy flows, corresponding energy conversion and status of storage systems, it was believed that additional optimization of energy end use may achieve even greater savings.

The hybrid concept can, therefore, be represented as a single Hub with additional DSM optimization engine which takes into account various load management techniques such as peak shaving, load shifting, valley filling etc. However, having in mind that the EH concept already takes into account the dynamic pricing for each energy carrier, it basically "moves" their consumption towards to the time intervals with lower energy prices. Therefore, initially there was a reasonable doubt if the introduction of DSM in the overall optimization will lead to the improvement of performance at all. Furthermore, another issue has been considered, i.e. if this hybrid solution will bring enough improvement that would justify the introduction of another optimization engine, which will certainly increase the computational efforts and extend the simulation process. However, this issue is highly dependent on the actual case and some figures for comparison will be presented in the following section.

In order to properly evaluate impact of both EH and DSM optimization, a baseline energy dispatch scenario was set-up, where no energy dispatch optimization was performed. This baseline scenario then gradually evolved passing through three characteristic steps, encompassing different energy dispatch optimization strategies, as following:

a. no EH, no DSM – baseline scenario in which there is no energy dispatch optimization;
b. No EH, DSM – scenario in which only DSM optimization was performed, thus representing the "demand side optimization";
c. EH, no DSM – scenario in which only Energy Hub optimization was performed, thus representing the "supply side optimization";
d. EH, DSM – scenario in which both Energy Hub and DSM optimization were performed, thus achieving both supply and demand side optimization;

Validating the proposed concept, at least theoretically, requires simulation of different optimization strategies which is presented in the following section.

V. SIMULATION AND VERIFICATION OF CONCEPT

The proposed hybrid concept was tested on the use case represented with a simple Hub with two supply energy carriers (P), two renewable energy sources (R) and the two loads (L) together with the corresponding conversion elements (C) and with no storage elements, as depicted in Figure 2. All four optimization strategies were simulated under the same conditions, i.e. the same energy pricing

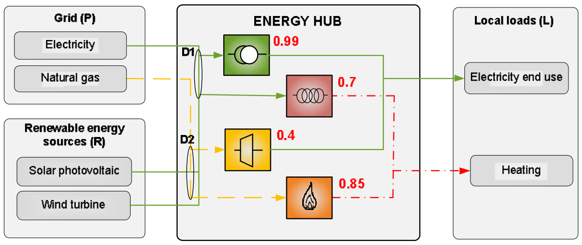

Figure 2. Use case scenario

scheme, see Figure 3, renewable energy contribution, see Figure 4, and finally the same requested energy demand, see Figure 5– a.2, during a twelve hours period during the day (06 – 17 h). Although some procedures, considered as part of DSM concept, suggest decrease or even increase of overall energy demand, in the scenarios where DSM optimization was performed (b. and d.) it was considered that the total energy demand per carrier remained the same as in other scenarios. In this way, different scenarios could be meaningfully compared and benchmarked. The simulation results are jointly depicted in Figure 5 representing the typical optimization output, which includes the time distribution of energy supply and demand. Each row represents the corresponding optimization strategy, whereas left column reveals the supply and right the demand profile.

A. No EH, No DSM

Comparing the supply and demand, an unusual mismatch between electricity demand and electricity supply can be noticed at the first sight. However, this difference comes from the fact that the renewable energy sources have significant contribution in the overall electricity supply. The same effect can be seen at Figure 6 where the time distribution of total energy dispatch costs is depicted. Namely, considering the peak energy production, coming mainly from the PV plant, the costs around the mid day are minimal. Furthermore, it should be emphasized that in this particular setting of the Hub, possibility of energy export (mainly renewable) was not taken into consideration. In spite of stimulating prices for energy export, described within a country's feed-in tariff scheme, the main objective of these simulations was to test different optimization procedures that leverage themselves mainly on the Hub's conversion capabilities as well as efficient demand management.

B. No EH, DSM

This scenario considers sole application of DSM procedures for the optimization strategy, and represents the first step towards the finally proposed solution. These procedures are usually implemented through heuristics derived from an actual energy bill analysis, performed by an energy manager at particular site, or some kind of systematic search for appropriate energy demand profile that will yield the minimum costs. It should be emphasized though that the level of freedom associated with this search is limited due to constraints related to initial demand profile. These constraints actually reflect the nature of particular demand profile, i.e. its breakdown to critical, curtailable and reschedulable loads. Therefore, before applying the proposed optimization a careful demand profile characterization should be performed and the corresponding constraints should be defined.

For the purpose of this example the following were adopted:

- Total load per energy carrier remained the same.
- Electricity load was allowed to vary within relative margins of ±3 p.u. with additional constraint of maximum absolute value of 10 p.u.
- Natural gas load was allowed to vary within relative margins of ±3 p.u. with no additional constraints for maximum absolute value.

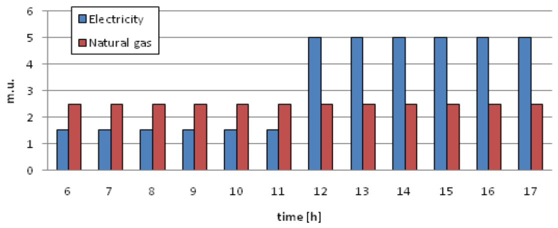

Figure 3. Variable energy pricing

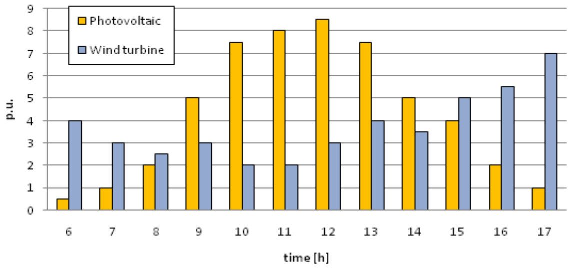

Figure 4. Renewable energy contribution

Finally, a Genetic Algorithm (GA) based approach was used for the "systematic search" for optimal energy demand profile, within given constraints. This generic optimization framework delivers very good results and offers rather high flexibility when it comes to the constraints for a given optimization problem. The GA was implemented by setting the total loads as a single individual of the population. This includes all carriers throughout the desired time frame. A set of these individuals represent a population which evolves, through generations (namely the iterations), to an optimal solution.

For the purpose of this example simulation the following GA parameters were adopted:

- 2 elite individuals
- 60% population crossover
- 40 % population mutation
- 100 individuals
- (each individual 24 values)
- 500 generations

The size of population, as well as number of generations, can be arbitrarily defined for each GA. They usually depend on the convergence nature of the actual optimization problem, i.e. the fitness function. Also, the two parameters suggesting the percentage of population for crossover and population can steer the optimization process towards either local or global optimal solution. On the other hand, the greatest impact on the duration of optimization process lies in the number of individuals as well as number of generations. Naturally, the higher these numbers are, the better will be the final solution. Nevertheless, a high number of individuals and/or generations cannot always be justifiable with the achieved results. Therefore it is a good practice to run the optimization for a large number of individuals for many generations and to observe the evolution of the solution. Usually, the solution tends to reach rather acceptable level after just a couple of generation and save the precious time and computational effort. Following the labelling considerations given in the baseline scenario, the simulation results are depicted in the second row of Figure

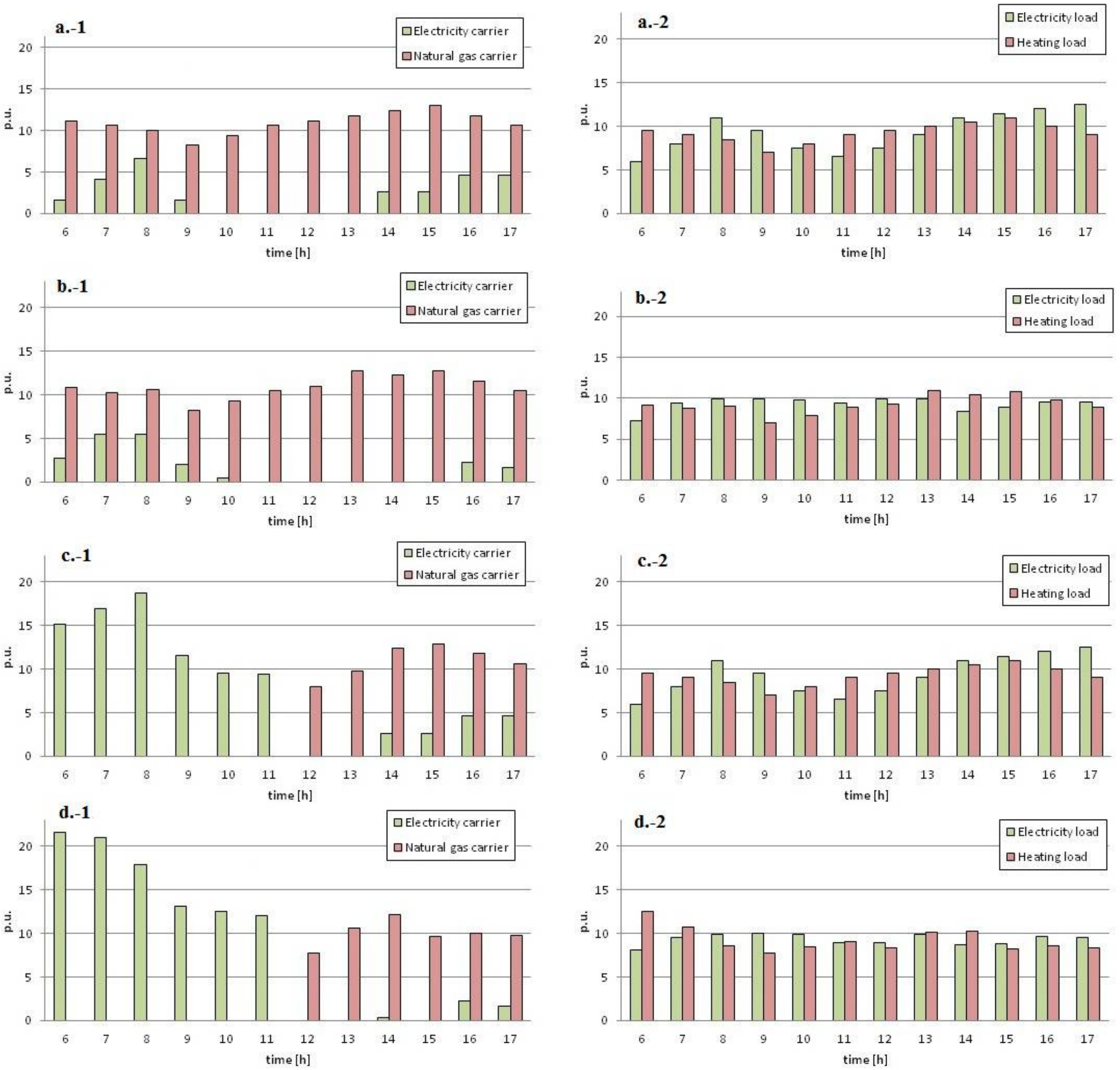

Figure 5. Energy supply (left-1) and demand (right-2) distribution:
a. No EH, No DSM; b. No EH, DSM; c. EH, No DSM; d. EH, DSM;

5 and Figure 6. It is obvious that the application of DSM resulted with the flattening of peaks in the demand profile as well as distribution of costs.

C. EH, no DSM

The third scenario leverages on the utilization of EH concept, meaning that optimization process is performed only at the supply side, while taking also into account different conversion possibilities and applying dynamic energy prices. Simulation results are presented in the third row of Figure 5 and Figure 6. Although not presented in the figures, part of simulation outputs also represents the set of dispatch factors, determined at each time step of the simulation. These dispatch factors are represented by a matrix, for each time step, suggesting the breakdown of each energy carrier for satisfaction of each load.

The results show radically increased usage of electricity in the first half of the day comparing to the baseline scenario. Considering that both electrical and thermal loads remained unchanged, this excess of electricity is actually used for satisfying the thermal loads instead of natural gas. This is the consequence of the difference between of purchase prices, in the corresponding time period, which makes the use of electricity more viable solution, even considering the lower conversion efficiency.

D. EH, DSM

Finally, the fourth scenario combines the previous two approaches by performing the optimization both at the supply and demand side, meaning that both profiles are found as the result of the optimization. For the optimization of supply side EH concept was utilized whereas for the demand side a previously mentioned GA algorithm, with the same definition of constraints, was hired. Among others, the most important constraint, saying that the total energy delivered per load remained constant before and after the optimization, was hired in order to make a reasonable comparison with previous cases. The results, depicted in the fourth row of Figure 5

TABLE 1.
SIMULATION RESULTS COMPARISON

Optimization	Costs (m.u.)	Savings (%)
a. No EH, No DSM	419.61	baseline
b. No EH, DSM	369.72	11.89
c. EH, No DSM	357.82	14.73
d. EH, DSM	317.92	24.23

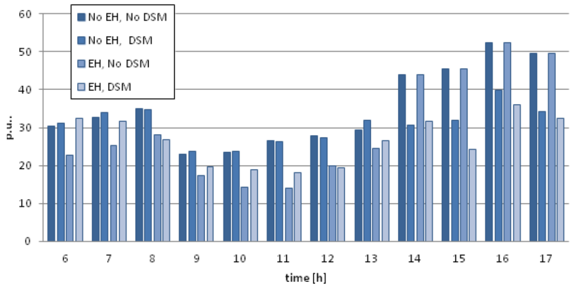

Figure 6. Comparison of total dispatch costs distribution

and Figure 6, show even without a detailed analysis how the demand profile is balanced contrary to the supply profile, which basically follows the curve of energy prices for each energy carrier, thus achieving the lowest energy dispatch costs.

Finally, the simulation results from all four scenarios are offered in Figure 6, where comparison of the time distribution of yielded operation costs is given for strategies in parallel, and Table 1, where the total energy dispatch costs are presented together with potential savings. It is immediately obvious that the joint optimization of both supply and demand side, proposed in this paper, is well justified. Moreover, the table suggests a decrease of dispatch costs up to 25%, for considered scenario. Although these values may greatly vary depending on many parameters such as energy price profile per carrier, the desired energy demand (load profile) and the Hub architecture, the benefits coming from this joint optimization approach are undoubted.

The above table also suggests the order of performance for different optimization strategies, which should be considered only conditionally. The first (a.) and last (b.) strategy yield the highest and lowest costs, respectively, regardless of the previously mentioned dynamic parameters. However, the relative order between the second (b.) and the third (c.) scenario depends heavily on these parameters.

VI. CONCLUSION

Need for an integrated optimization of multi-carrier energy systems is greater than ever, considering high operation costs and availability of energy supply in peak time periods. Concept named Energy Hub was considered as one of the solutions offering multi-carrier optimization as well as flexible modelling framework of the energy infrastructure. However, this concept is aiming to completely satisfy the end use energy demand, and thus leverages its optimization potential on better management of energy supply and conversion capacities of the system. This paper extends the proposed concept with complementary optimization of the demand side while offering higher saving potential. The presented simulation results show that integrated solution may produce savings of up to 25%, depending on the layout of the system, applicable energy pricing and the demand profile, comparing to the baseline case where no optimization is used. These savings, however, do not come without a compromise from the user side, which is required to comply with certain changes in the demand profile.

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REFERENCES

[1] P. Favre-Perrod, M. Geidl, B. Klöckl and G. Koeppel, “A Vision of Future Energy Networks”, presented at the IEEE PES Inaugural Conference and Exposition in Africa, Durban, South Africa, 2005.
[2] M. Geidl, **“**Integrated Modeling and Optimization of Multi-Carrier Energy Systems”, Ph.D. dissertation, ETH Diss. 17141, 2007.
[3] B. Klöckl, P. Stricker, and G. Koeppel, “On the properties of stochastic power sources in combination with local energy storage”, CIGRÉ Symposium on Power Systems with Dispersed Generation, Athens, Greece, 13-16 April, 2005.
[4] M. Schulze, L. Friedrich, and M. Gautschi, “Modeling and Optimization of Renewables: Applying the Energy Hub Approach”, IEEE conference, July 2008.
[5] Nörstebö V.S., Demiray T. H. et al., EPIC-HUB Deliverable D1.3 - Performance indicators, 2013.
[6] Nikola Tomašević, Marko Batić, Sanja Vraneš, “Genetic Algorithm based Energy Demand-Side Management“, in evaluation for ICIST 2014, Kopaonik 9.-12.3.2014, Belgrade, Serbia.