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Energy Service Systems: Integrated Planning Case Studies

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***Abstract*-- A flexible methodology for planning of complex energy service systems with multiple energy carriers is presented. The methodology includes technical, economic and environmental aspects, and will enable public and corporate decision makers to carry out comprehensive analyses of energy supply systems with respect to investments, environmental impacts and consequences of different regulating regimes. The methodology is based on components with standard interface combined in a generic energy system model. The model is then mapped to a nodal network (graph) for overall system analysis and optimisation. In this paper two different case studies are presented where this methodology is used for integrated planning of local energy service systems including electricity, heat and gas.**

***Index Terms*-- Energy conversion - Energy resources - Energy services – Energy system - Planning - Modeling**

I. INTRODUCTION

New emerging technologies like small-scale co-generation, gas engines and fuel cells enable an increasing flexibility in energy service systems. This will yield new alternatives and better possibilities to design an optimal and sustainable energy system, but these technologies will also result in more complex systems to design, operate and maintain. It is of vital importance to keep an overall system perspective during all stages of planning and operation, where also geographic distance and topology have to be considered. This has created a need for new improved methodologies and tools for system planning and operation. The first part of this paper will present a systematic approach to meet the challenges of future integrated energy service systems. In the second part, two different case studies are used to demonstrate the usefulness of the proposed approach.

II. INTEGRATED ENERGY SERVICE SYSTEMS

In international literature one usually finds two different types of applied models or tools for planning of energy service systems: i) Models specially designed for a given area or utility that are not commercially available [1]-[3], and ii) large scale optimisation tools for regional or global system studies like MARKAL/TIMES and similar models [4]-[6].

In large scale energy system studies the energy system is typically represented with a “big boiler” type of modelling where resources are entered on one side and end use extracted on the other side. Inside the “boiler” various technologies are modelled with emissions and energy losses.

This approach is normally sufficient for system studies on a national or international level. However, in an improved analytical framework for local energy systems the boiler has to be “dismantled” to identify the different infrastructures inside. Some basic observations can then be made:

i. There are basically three different TYPES of technologies in an energy system [7]:
   - Conversion technologies that convert one energy carrier to another at a specific geographic location
   - Transport technologies that transport a given energy carrier over a defined geographic distance
   - Storage technologies that store a given energy carrier over time at a specific geographic location

ii. Some of the *energy resources* have to be converted to other forms of energy like electricity before they can be transported to the end users (hydro, wind, wave) while others are also *energy carriers* that can be transported down through the energy system towards the end users (gas, coal, biomass).

iii. Geography and topology are key elements in an improved optimisation approach. It is thus not only a question of *which* resources and which *amounts* to use, but also *where* in the system the necessary conversions should take place.

An end user (domestic, commercial or industrial) will generally require at least electricity and tap water heating. Depending on climate, the end user would also need air conditioning or space heating. In an urban area, the latter might be supplied from a district heating (DH) network. However, end users might want further types of energy like wood/biomass, gas or fuel oil. These energy sources also have to be transported to the house by some infrastructure(s). Thus at least three different energy infrastructures have to be considered in an overall system optimisation, some of them by cable or pipeline, some by road.

Today, energy carries like biomass or fossil fuels are used in boilers, furnaces or open fireplaces. A few years into the future, however, these energy carriers might be used in a micro-CHP unit at the end users property. This will create further challenges to all the involved infrastructures [8]:

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- When is the end user consuming electricity, and when is he generating and feeding back into the local grid?
- Who is responsible for accounting, control, security and quality of this connection?
- Is the end user also able to (allowed to) feed heat back into the district heating grid? How about heat storage capacity?
- Finally, if an end user with little or no technical competence installs a micro-CHP on his own property, who should be responsible for safe operation and maintenance of this unit?

Examples of situations with complex problems related to optimal co-ordination between different alternative energy carriers are: Development of a new suburb (including school, kindergarten, shopping center, medical center etc), design of new energy-efficient office buildings, or development of modern industry areas.

Thus, in an improved analytical framework for local energy service systems, an *integrated* approach must be used where all the different technologies and infrastructures can be optimised together.

III. OPTIMISATION

A. Problem formulation

The major objective of this research effort is to design a comprehensive optimisation tool for planning of energy service systems. The main task is to bring energy in such quantities and such forms that the needs of the end users are covered in the economically and environmentally best way possible. Specialists from different fields are involved in the development (Electrical and thermal engineering, Refrigeration/Air Conditioning etc) [9]. A major challenge is to handle different technologies at different geographical locations, connected by one or more energy distribution systems. To enable a comprehensive model of such complex network structures, power flow models and LP methods are developed from flow of electric current to more generic *flow of energy*.

The qualitative problem can be formulated as follows:

- Given a set of customers and customer needs within a defined geographic area/region,
- find the optimal energy service infrastructures to satisfy the customers' needs of the chosen period,
- subject to energy resources available within or at the system boundaries.

The methodology includes the following steps [8]:

1. Based on a library of available components, the user builds a model of the energy service system(s) with the alternative solutions to be optimised. Available energy resources are collected, processed, stored and transported in different forms and locations before being converted to desired end user energy like electricity and heat. Often a choice has to be made between large centralized CHP units feeding the electricity and district heating networks, or local mini-CHP installations in single buildings like offices, schools, health care centers etc. The model treats energy transport by pipeline and power line, as well as by road.
2. The user enters the necessary parameters for each component related to costs, lifetime, efficiency, emissions and relevant technical parameters specific to each component.
3. The connection to the network is made by a simple and unambiguous set of variables like energy flow, cost and emissions.
4. The model is then mapped to a generic network (graph) of nodes and branches.
5. The optimisation is made on this generic model graph, consisting only of nodes and branches where energy is flowing.

B. Environmental aspects

At present, environmental aspects are included in the model in a conventional way by adding a penalty to the object function of the format [10]:

$$penalty = \sum_{i \in I,\, j \in J} b_{ij} \cdot e_{ij} \tag{1}$$

where

$$e_i = \sum_{j \in J, k \in K, t \in T} a_{ijk} \cdot x_{jkt} \tag{2}$$

$$i \in I = \{CO_2, NO_x, SO_2, \ldots\}$$
$$j \in J = \{Emission\ sources\}$$
$$k \in K = \{gas, oil, electricity, \ldots\}$$

Future versions will include more generic environmental aspects by multi-criteria optimisation techniques.

C. Expansion planning

A major challenge in optimisation of complex energy systems is to combine the modelling demands of a variety of different energy processes in an unambiguous way. Adding the complexity and time span of the investment analysis creates an optimisation problem not easily solved using conventional methods. The optimization algorithm can be summarized as follows [10]:

1. Predefine a set of relevant expansion Projects (States) to be evaluated.
   - Each Project consists of one or more investment Objects, and each Object might be involved in one or more Projects
2. Minimize operating costs for each Year for each State
   - Each year is split at least in 4 Periods as shown in Fig. 1.
   - One or more representative days from each Period are optimized by time-series simulation
   - Infeasible States are identified and excluded

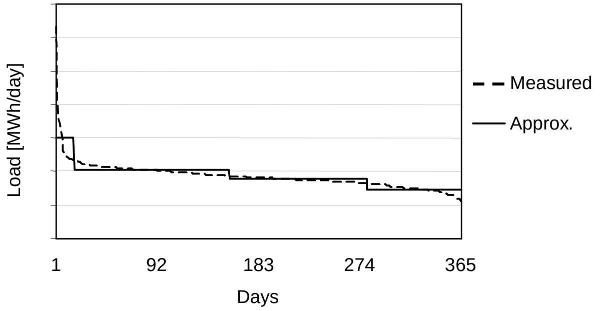

Fig. 1 Annual load segments

3. Establish matrix of optimal operating costs for State *s* in Period *w* of Year *t*:

$$C_{ts}^{ope} = \sum_{w \in Periods} \theta_w c_{tsw}^{ope} \quad \forall t, s \qquad (3)$$

where θ_w - length of Period *w*

4. Find best expansion plan by

$$\min\left\{ \sum_{t \in T} \delta_t \cdot \left(t^{step} \cdot c_t^{ope} + c_t^{inv} \right) - \delta_{t^{end}} \cdot \Phi \right\} \qquad (4)$$

where δ_t, $\delta_{t^{end}}$ - discounting factors

t^{step} - no. of years where c_t^{ope} is valid

c_t^{ope} - optimal operating cost for a given State and Year

c_t^{inv} - investment cost for a given State

Φ - rest value of investment at end of optimization period

This algorithm is shown in the flowchart of Fig. 2.

The design of the Graphical User Interface (GUI) is not yet specified, but some prototype developments have been made. Future integration with existing Geographic Information Systems (GIS) is also a possible alternative.

The usefulness of this methodology is demonstrated through case studies below.

IV. CASE STUDIES

Regular testing and evaluation of methodology and models with realistic data during the development phases is important. The funding partners of this project submit real-world cases to be used during the development of the tool. Currently, four different case studies are involved in the project:

- Waste fuelled CHP plant with DH network
- Gas engine CHP plant and DH network
- DH network in the city of Trondheim with multiple energy sources
- Bulk energy transport from western to eastern Norway incl. gas pipeline, LNG ships, HVDC or HVAC

The following sections show selected results from two of the case studies.

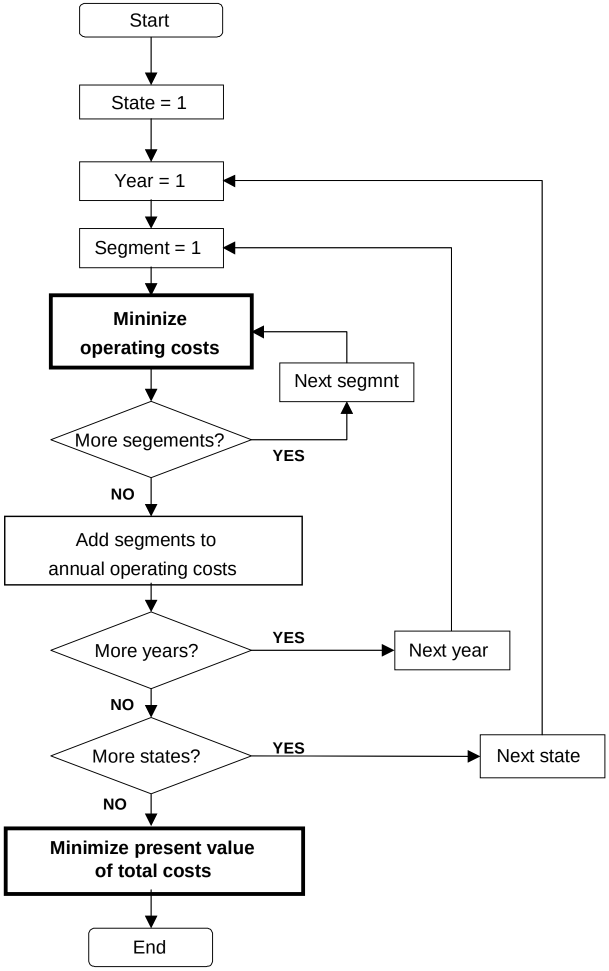

Fig. 2 Expansion planning flowchart [10]

A. Municipal waste plant project

In a municipality south of the city of Trondheim a waste-fuelled cogeneration (CHP) plant is planned to supply a local DH network with 17.1 GWh heat and 6.1 GWh electricity. The DH network will have a total length of approximately 2 km, with the major customers of municipal administration and office buildings, local industry, schools and health care institutions within a radius of 500 m from the plant [11].

The waste plant is based on the PYROARC process for gasification and pyrolysis treatment of municipal, industrial and hazardous waste [12]. The products leaving the process are fuel gas, leach resistant slag, molten metal and small amounts of secondary dust, which normally can be used for zinc and lead recovery. The produced fuel gas can be used in a conventional gas engine for heat and power generation, or in a gas boiler for heat generation only. Approx. 53% of the electricity generation is needed to run the waste destruction process itself.

The following scenarios are considered in the analysis [13]:

- Three gas engine capacities:
  - 100% of product gas, no waste storage
  - 80% of product gas, waste storage allowed
  - 50% of product gas, no waste storage
- Three alternatives for DH-grids:
  - Whole town

  - East of the river only
  - Whole town + extra heat load
- 6 different temperature levels

Fig. 3 shows the main system blocks of the model.

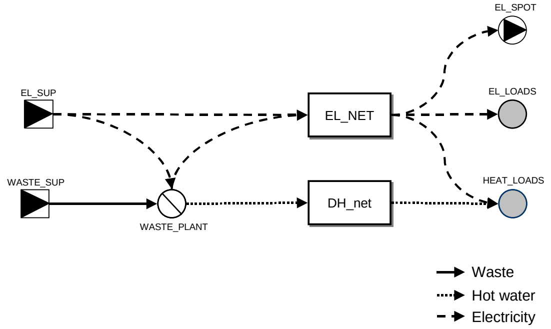

Fig. 3 Main system blocks

Included in the model is also a discrete transport component for transport of biomass or waste by car (or LNG/CNG by boat). A discrete component in the analysis makes it necessary to use Mixed Integer Programming (MIP), causing increased calculation time. This component is characterized by the parameters *Travel time*, *Capacity* and *Number of units*.

Fig. 4 shows a test run where two trucks with a 1-hour travel time are supplying the storage bin.

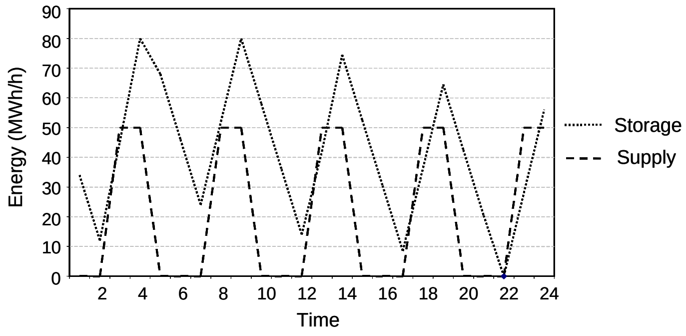

Fig. 4 Discrete model of waste supply

As the average ambient temperature rises, the demand for heat is reduced in the area. Since storage of hazardous waste fuel is not allowed in most scenarios the need to dump excess heat increases. Fig. 5 shows how the energy delivery from the unit gradually changes to less heat delivered and more heat dumped. In most of the periods the gas engine is running at rated load. Only on the coldest days is the plant running the boiler alone.

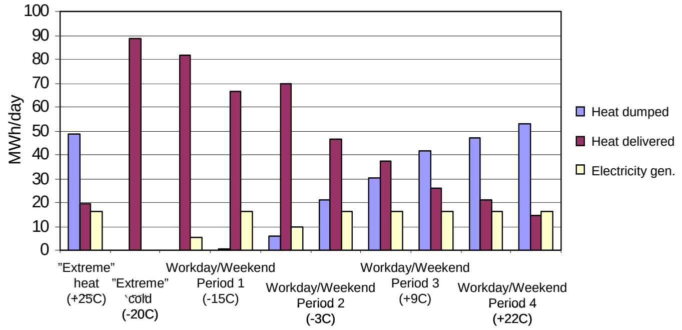

Fig. 5 Energy delivery from waste plant [13]

Dumping of large amounts of heat might be prohibited by the authorities, and the local utility thus wanted to promote new heat demanding industry into the area as base load. The result of such a heat load is shown in Fig. 6. As the demand for heat is increasing, the unit prefers to run in boiler mode instead of CHP mode. The unit then needs to import electricity to run the waste destruction instead of generating to the grid, and the utility suddenly has a load in their network instead of a local generator. This also influenced the electrical grid losses as shown in Fig. 7 causing increased operating costs.

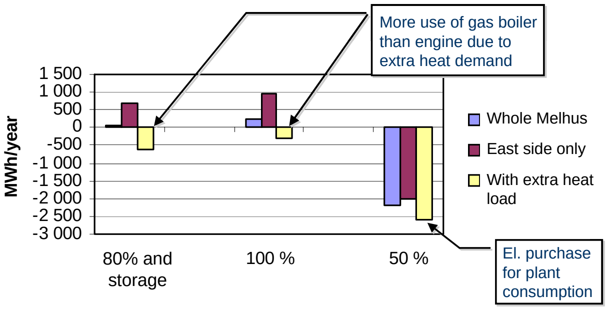

Fig. 6 Electricity generation from waste plant [13]

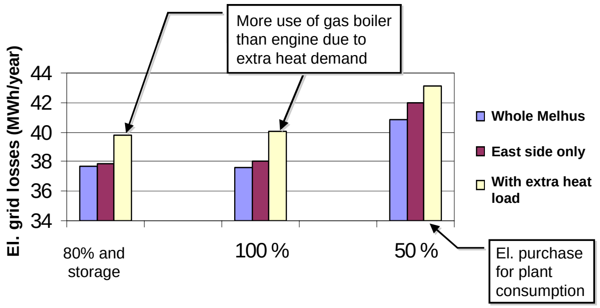

Fig. 7 Electrical grid losses [13]

Such a small DH-network is vulnerable for load profiles and variable consumption, and the must-run waste supply reduced the flexibility of the plant. The basic characteristics of such a plant makes it best suited as base load in a larger DH network. Currently, this plant is planned to be built in a more industrialised area with larger and more constant heat demand.

B. Suburb with gas-fired CHP engine

In the Hylkje area north of the city of Bergen there are plans to develop a major suburb with more than 2000 dwellings, shops and public services. The current radial electricity grid in the area is insufficient to cover the energy demand of the new suburb. There is a large marine gas engine factory in the area where compressed natural gas (CNG) will be available. The following alternatives of energy supply are considered [14]:

- Double electricity supply: New 132 kV line/cable into the area (Base case)
- 3.6 MW gas CHP at engine factory (some distance north of suburb) with DH grid
- 3.6 MW gas CHP at Hylkje substation (inside suburb) with local DH grid
- 5.0 MW gas CHP at Hylkje substation with local DH grid

Fig. 8 shows the main system blocks of this model.

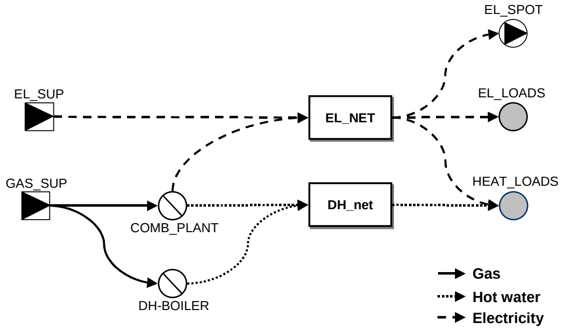

Fig. 8 System blocks for the Hylkje suburb [14]

Furthermore, the sensitivity of the results are tested with the following parameter variations:

- Spot price of electricity +15% (El+15)
- Gas price +50% (G+50)

Optimal operation of the different alternatives show that the base case with double electricity supply is most expensive in all cases, even when the gas price is increased by 50% (Fig. 9, 10).

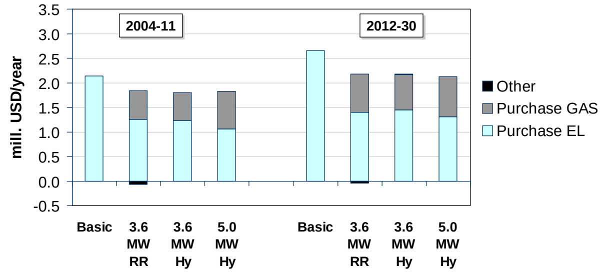

Fig. 9 Operating costs for base case [14]

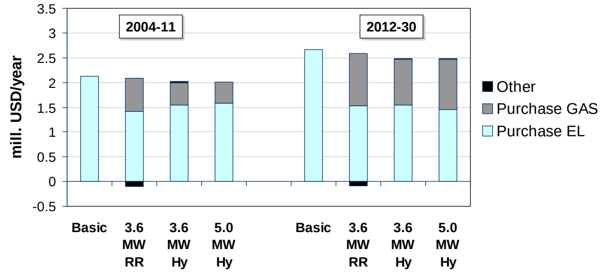

Fig. 10 Operating costs for scenario G+50 [14]

However, adding the investments in infrastructure the Net Present Value (NPV) is negative for nearly all DH alternatives compared to the base case of double electricity supply, as shown in Fig. 11. The only exceptions are the alternatives with increased electricity spot price and CHP unit inside the suburb. This would give minimum distance from the unit to the main heat load.

As the methodology includes hourly simulations of selected seasons with detailed technology and infrastructure models, a lot of further details can be extracted in addition to the economic evaluation:

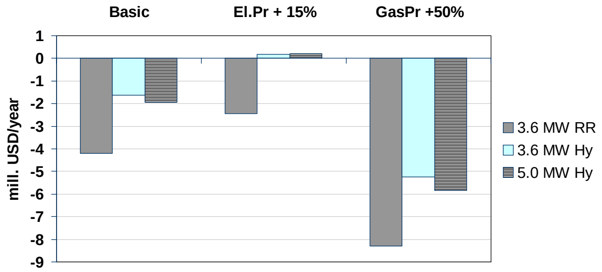

Fig. 11 NPV for different scenarios [14]

- The optimal operation of the CHP unit is sensitive to the energy prices (Fig. 12, 13):
  - At a high gas price the CHP unit is operated primarily to cover the heat load (G+50)
  - If the el price is high, on the other hand, the CHP unit operates at maximum load to generate electricity for sale and simply dumps surplus heat (El+15)
- If the gas price is 0.13 USD/Sm^3 (Base case) the CO_2 tax has to exceed 40 USD/ton to influence the operation of the CHP unit. However, if the gas price is increased to 0.20 USD/Sm^3 (G+50) a tax of 14 USD/ton is sufficient to make a major impact on the operating strategy of the unit (Fig. 14).

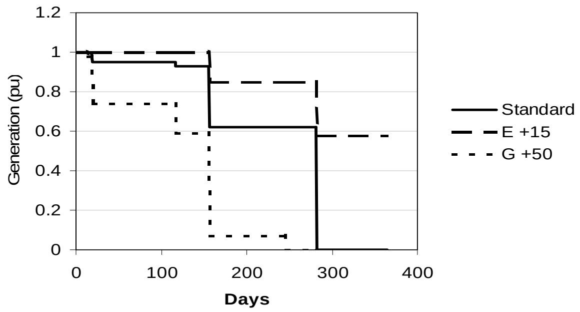

Fig. 12 Duration curves for gas engine [14]

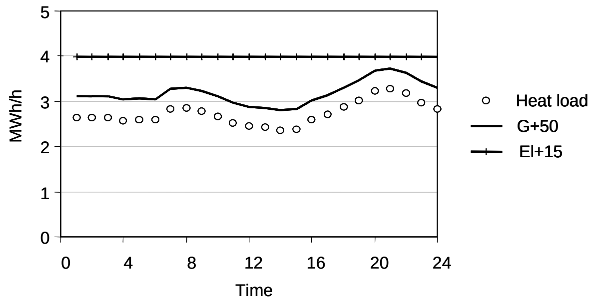

Fig. 13 Samples of heat generation [14]

Finally, as both the electricity and DH grids are modelled in detail also feasibility of solutions can be checked with respect to line capacity and tour- and return temperatures in the DH grid at peak load and low load hours.

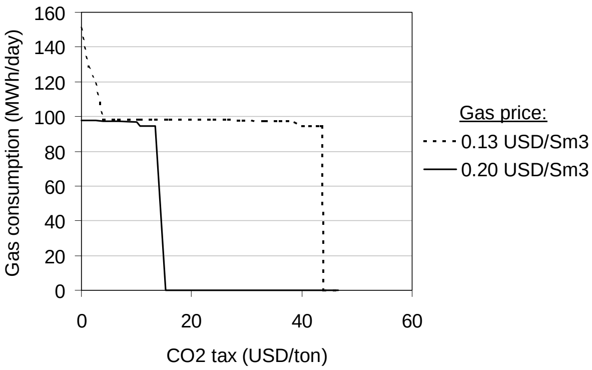

Fig. 14 Effect of CO2 taxes [14]

V. APPLICATIONS

The most relevant application of this tool is planning of local or municipal energy service systems, where a public or corporate decision maker wants to analyse the mutual influence between different energy carriers and infrastructures. The construction of new local power plants can be optimised with respect to size and location subject to economy and environmental constraints.

More importantly, the joint modelling of multiple energy carriers enables an evaluation of up-stream infrastructure for DER fuels like road transport of biomass and waste or capacity of existing gas networks. The optimal location of a new local plant can thus be found with respect to both upstream (fuels) and downstream (el/heat) infrastructures. The tool can also be used by energy companies to evaluate ”threats” from other DER suppliers in the same area.

Note that this model is a planning tool and not a design tool. More dedicated tools must be used for the detailed design of the system when the overall decisions are made.

VI. CONCLUSIONS

This paper has presented a new methodology for analysis of complex energy service systems with multiple energy carriers. The methodology is based on specific component modules with a standard interface combined in an energy system. The physical system model is mapped to a nodal network graph with generic energy flow. The variables currently represented in the graph are energy flow, cost, energy efficiency and environmental impact (emissions). The methodology will enable corporate decision makers to carry out comprehensive analyses of their energy service systems, while public decision makers will be able to do scenario studies of energy systems with respect to environmental impacts and consequences of different regulating regimes.

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VIII. BIOGRAPHIES

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