MULTI-ENERGY SYSTEMS IN SMALL SETTLEMENTS: METHODOLOGY AND CASE STUDY FOR ELECTRICITY AND HEAT SUPPLY

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ABSTRACT

This paper presents a methodology and a tool for pre-feasibility studies to optimally design an energy supply system with multiple energy carriers for a site. The tool is based on mixed-integer linear programming (MILP) and it optimally determines the type and the size of energy conversion technologies such that the resulting design satisfies the demand for heating, hot water and electricity in hourly resolution. Thermal and electrical storage as well as demand response are also taken into account. It is noted that the objective of the optimization is twofold: life-cycle cost and CO2 emissions. Thus, a set of Pareto solutions are provided, where each solution represents a different optimal combination of energy conversion and storage technologies, allowing the user to select the best combination according to her/his preference. The methodology is tested on a greenfield settlement in the proximity of Baden in Switzerland.

Index Terms — multi-energy optimization, energy hub, multi-energy planning

INTRODUCTION

The energy strategy 2020 of the European Commission guides towards sustainable, environmentally friendly and energy efficient solutions for heat and electricity supply [European Commission, 2015]. Simultaneously, these technological solutions shall have a solid economic feasibility in order to find application in practice. There are different solutions available for heat and/or electricity generation. Typically each technology is associated with a certain trade-off, e.g. it is relatively easy and cheap to install but expensive to operate, while others imply high investment costs, while being environmentally friendly. Inherently, once various energy conversion technologies are combined to cover energy demand in several forms, an overall increase in efficiency is expected. A widely-known and adopted example of such synergy is exploited in combined heat and power production plant, which is not the focus of this work.

The objective of this paper is to suggest a methodology well-suited for the quantitative pre-feasibility assessment of technological solutions for power and heat supply of a site. “OptiHub”, a MILP-based tool, is developed using GAMS as modelling language and CPLEX as the optimization solver. The types and capacities of energy conversion and storage technologies are optimally determined by OptiHub. Each solution in the Pareto set contains different devices and is associated with different Net Present Cost (NPC) and emission level. The tool allows the user to make the final decision according to her/his preference, which can be based on, for example, minimizing the investment cost or minimizing the CO2 emissions. Illustrative examples on a settlement near Baden in Switzerland are presented.

Literature review

In [Geidl et al., 2007] authors determine the optimal configuration and properties of the energy conversion devices with multiple inputs and outputs. Aspects of economic dispatch for systems with multiple energy carriers are addressed in [Geidl, 2007; Ramirez-Elizondo and Paap, 2015]. Other publications addressed questions of load management in residential setting [Brahman et al., 2015; Rastegar et al., 2015], design [Fazlollahi et al., 2015] and operating strategy of integrated district energy systems [Evins et al., 2014; Orehounig et al., 2014, 2015; Parisio et al., 2012] as well as energy management in multi-energy networks in presence of interconnected energy hubs [Geidl, 2007; Scala et al., 2014]. An energy hub is considered as a unit where multiple energy carriers are converted and stored. In [Mancarella, 2014], the reader can find an overview of several modelling approaches and an analysis of the tools using these modelling frameworks.

Contributions

The approach and the assumptions are as follows:

- Each energy technology is treated as an individual system with a single input and a single or multiple outputs.
- The augmented e-constraint method is utilized in order to generate the Pareto optimal solutions
- The minimization of both the costs and the CO_2 emissions is targeted. The multi-objective solutions determine the Pareto frontier.
- The concept of a flexible demand is included through the assumption that energy demand responds to changes in prices.

Review of selected commercial and academic tools

Table 1 provides an overview of the relevant commercial and academic tools, and how they compare to OptiHub.

METHODOLOGY & IMPLEMENTATION

Problem formulation

The problem of optimal (in terms of NPC over life-time) energy supply with minimal emissions can be solved by combining various energy sources, installing conversion

Table 1. An overview of commercial and academic tools for multi-energy optimization

	HOMER	OSeMOSYS	TIMES	EnergyPlan	ETEM	OSMOSE	OptiHub
Planning optimization	Yes	Yes	Yes	No	Yes	Yes	Yes
Operation optimization	Yes	Yes	No	Yes	Yes	Yes	Yes
Electricity	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Heat	No	Yes	Yes	Yes	Yes	Yes	Yes
Transport	No	No	Yes	Yes	Yes	No	No
Objective	NPC	NPC	NPC	NPC	NPC	Investment. cost & OPEX	NPC & emissions
Solutions	Single	Single	Scenarios	Single	Single	Pareto	Pareto
Horizon	1 year	≥15 years	50 years	1 year	50 years	1 day	1 year
Time-step	Minute	>hourly	Few hours a year	Hourly	Few hours a year	8 hours	Hourly
Geography	Local	Local & regional	Global & local	National & regional	Regional	Local & regional	Local & regional
Equilib.model	No	No	Yes	No	Yes	No	No
Scenario	No	No	Yes	Yes	Yes	No	No
Storage	Yes	No	No	No	Yes	No	Yes

and storage technologies to satisfy the demand for water at different temperatures for different end-purpose and the electricity, as shown in Figure 1. The following data are thus required, and the following formulation is proposed [Stefanidis 2015].

Input Data

- Hourly load profiles: electricity demand, heating load (30° C), hot water demand (60° C)
- Solar irradiation
- Costs: Electricity (supplied by the grid) costs, gas costs, district heating costs
- Technology characteristics: Capital expenditures (CAPEX), operational expenditures (OPEX), efficiency factor, CO_2.

Objective: minimize CAPEX, OPEX, Emissions

The net present cost C of the energy hub for the total period of consideration is calculated in (1), while the annual carbon dioxide emissions Q are calculated in (2):

$$C=\sum_{y}\left(\left(\frac{1}{1+i}\right)^{y}\frac{H}{w}\right)+Z^{sys}+\sum_{\pi}\left(\sum_{y}\left(\left(\frac{1}{1+i}\right)^{y}Z_{\pi}\upsilon_{\pi,y}\right)-\left(1-\frac{\kappa_{\pi}}{\xi_{\pi}}\right)Z_{\pi}\left(\frac{1}{1+i}\right)^{Y}\right) \quad (1)$$

$$Q=\sum_{t}\sum_{e}\left(\sum_{\pi}\left(e^{d}_{\pi,e}J_{t,\pi,e}\tau\right)+I_{t,e}e^{ind}_{e}\right) \quad (2)$$

where y is the set of years $y\in\{1,2,\dots,Y\}$, Y is the period of analysis in years, w is the fraction of the total simulated hours number to 8760, i is the annual discount factor in %, H is the annual operating cost, Z^{sys} is the investment cost of the system, π is the set of energy technologies, Z_π is the investment cost in technology π, $\upsilon_{\pi,y}$ denotes if a replacement of π is needed in year y, κ_π is the remainder from dividing the period of analysis to the lifetime of technology π, ξ_π is the estimated lifetime of the technology π, t –represents the set of time steps, e is the set of energy carriers, d is the set of days, $e^{d}_{\pi,e}$ is the per unit emissions of energy carrier e when used in technology π, $J_{t,\pi,e}$ is the input of the energy carrier e to technology π in the hour t, τ is time interval in hours, $I_{t,e}$ is the import of energy carrier e in hour t, e^{ind}_{e} is the indirect emissions from import of energy carrier e.

Equality and inequality constraints:

- Capacity of the devices: power input and output
- Energy conversion flow
- Power balance
- Storage and demand response
- Physical installation space
- Fixed and variable costs and emissions.

Output (set of solutions)

- Installed capacity for each technology
- Net present costs (NPC)
- Emissions.

Implementation

The optimizations are implemented in GAMS and the CPLEX solver is used [GAMS, 2018]. To enable the application of the linear optimization solvers, piecewise linearization was applied to the investments in the technologies, Z_π.

In a multi-objective optimization problem, the objectives are frequently conflicting. The weighting method is commonly applied for the analysis of the multi-objective solutions, i.e. the different objectives are normalized and weighted, then are summed-up in a single value for the final objective function. Alternatively, all the solutions

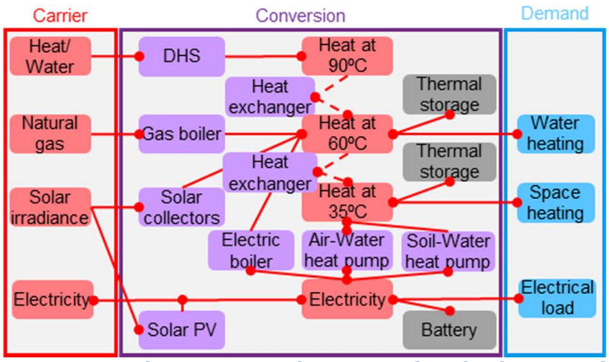

Figure 1. Multi-energy supply: potential technologies and conversion steps. Colour legend: *energy resource*, *conversion technologies*, *storage technology*, *energy demand*.

can be combined to create the Pareto set, which illustrates the trade-offs between the two objectives, whereas a Pareto frontier is a subset of solutions, such as an objective cannot be improved without deteriorating the state of the other objective [Pareto, 1912]. For example, the NPC cannot be further lowered without an increase in the annual emissions. In order to derive a Pareto optimal frontier, the augmented e-constraint method (AUGMECON) is applied [Mavrotas, 2009].

SIMULATIONS AND RESULTS

Test Case Data

The functionality of the tool and the applicability of the chosen methodology are tested in a real site located in the proximity of Baden in Switzerland. The site is a greenfield area planned to be a modern, high-technology residential settlement that uses possibly the most economical and sustainable energy supply technologies. In total, it is estimated that the population of the settlement is 1 912 people, while the total net floor area of the settlement

Table 2. Data for the extrapolation of capital expenditures

Energy Technology	Reference invest., CHF	Reference size and unit
Gas Boiler (1)	8 329	90 kW
Soil-Water Heat Pump (2)	17 404	17.2 kW
Air-Water Heat Pump	12 370	10.7 kW
Solar Collectors (4)	1 161	2.3 m^2
Solar PV (5)	20 000	10 kWp
Thermal Storage (60ºC) (6)	5 252	950 l
Battery	700	1 kWh
Electric Boiler	8 540	13.3 kW
Thermal Storage (35/65ºC) (7)	5 252	950 l
Heat Exchanger (90ºC - 60ºC)	5 252	950 l

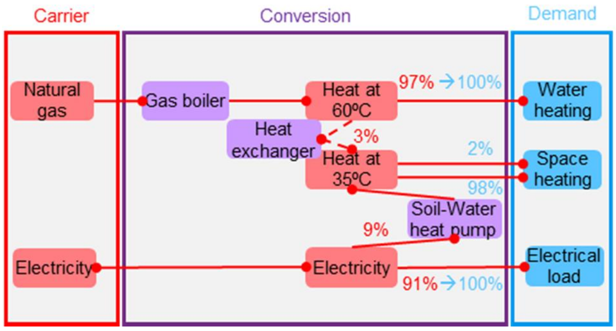

Figure 2. Electricity and heat supplies during one week with the Minimum Net Present Cost design

is 85 114 m^2. The total available roof area is estimated to be 5 000 m^2.

Table 2 shows reference capital expenditure for the technologies, which are numbered in the brackets. District Heating System (3) is assumed to be already constructed and does not incur any cost.

Natural gas price is 8.2 rp/kWh, district heating 9.7 rp/kWh, electricity 12.6-18.5 rp/kWh. Annual electricity demand per household is assumed to be 6 MWh. Space heating is required during 6 months of the year, totalling to 26.5 kWh/m^2/year, hot water needs are somewhat constant over the year and vary between 1.2 and 1.77 kWh/m^2 per month depending on the house type. Complete input data can be found in [Stefanidis 2015].

Results

Figure 3 shows the calculated Pareto frontier of the system design solutions, where each of the points corresponds to a set of technologies with defined installed capacities, as shown in Table 3. The numbering of technologies is consistent with one in Table 2.

The solution Min.C that minimizes the NPC of the system, including the cost for the emissions, is shown in

Table 3. Installed capacities of the devices, kW

Tech.	Min.Q	G	E	C	B	A	Min.C
(1)	-	-	-	-	303	467	574
(2)	1 159	1 016	1 016	1 001	942	939	916
(3)	361	216	216	237	229	83	-
(4)	1 201	895	895	793	482	-	-
(5)	3 799	4 008	403	-	-	-	-
(6)	27 710	2 735	2 735	2 303	30	-	-
(7)	13 855	1	1	-	-	1	-

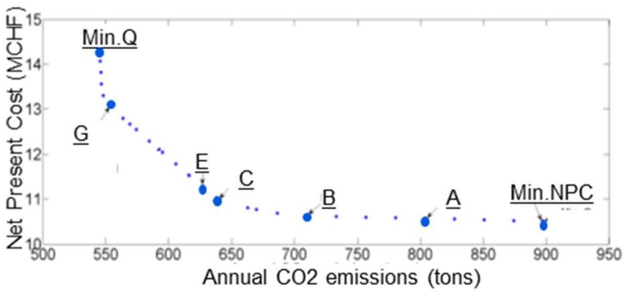

Figure 3. Pareto frontier of system design solutions for electricity and heat supplies.

Figure 2 and Figure 4. The figures show the solution during one winter week and how the demand is covered by various energy carriers, e.g. 3% of hot water stream at 60 degrees is used to cover 2% of the space heating via heat exchanger.
The case study for the energy supply solution shows:

§ Variation in NPC is 10.5 – 14 MCHF, and total energy solution costs are ~2% of total investment in the development project for this settlement.
§ PV panels and solar thermal collectors lower CO_2 emissions, but increase the costs of the energy supply solution.
§ The soil-water heat pump is efficient, while the electric boiler and the air-water heat pump are not the preferred means for energy supply.
§ The choice between the gas boiler and the district heating is up to the preferences of the decision maker
§ The battery is not yet cost-efficient as storage for the assumed price level, while the thermal storage is.

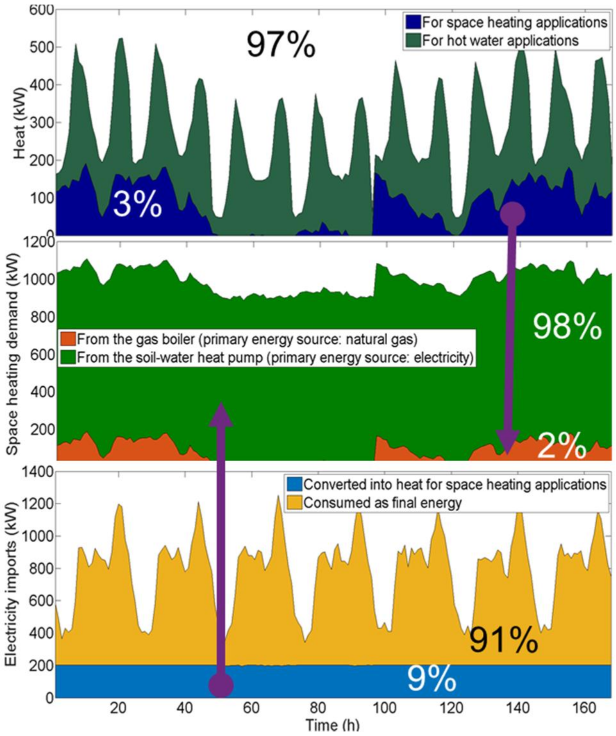

Figure 4. Operational profiles of power and heat supply during one winter week with the least cost technological solution.

CONCLUSIONS AND FUTURE WORK

The paper presents a methodology and a tool, OptiHub, for optimal design of multi-energy (i.e. electricity, heating, hot water) supply of a site. The methodology is tested on a greenfield settlement; it is demonstrated to be feasible and it can be used for pre-feasibility analysis for sites with relatively simple thermal processes (as opposed to the industrial sites). It can also be used to identify potential improvements in the operation of new technologies, such as storage. OptiHub tool is based on mixed-integer linear programming and can successfully solve an energy supply design of a site (e.g. residential settlement), while balancing environmental targets against investment, operation and maintenance costs. A set of solutions for an energy hub can be conveniently analysed and assessed with Pareto frontier. The augmented e-constraint method is used to the significantly improve the computational time to obtain Pareto frontier, while slightly deteriorating the accuracy of the calculations. The tool can be improved to investigate the potential of participating in the ancillary services market using demand management techniques.

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