Optimization of Load Flows in Urban Hybrid Networks

Thomas Kaufmann, Dominik Bothe, Wolfgang Gawlik and Karl Ponweiser

Abstract A sustainable supply of energy in urban regions requires an adequate infrastructure and operation. At present, the different energy sources (i.e., electricity, gas, district heating) are used separately without any connection to each other. To increase the flexibility of energy supply, the usage of energy hubs is a possible way. Energy hubs are connection points between the energy sources that comprise the key elements of so-called hybrid networks. Using the energy/hub approach, surpluses and power shortages from a specific energy network can be avoided. The hubs offer various technologies of energy conversion and can include electrical and thermal storage. Thus it is possible to convert electrical into thermal energy (heat pump, electric heating), chemical (gas) into thermal (furnace), or electrical energy (micro gas turbine) into, respectively, thermal and electrical energy (combined heat and power) depending on the used technology. The correct operating strategy for these energy hubs is an essential factor in order to minimize CO_2 emissions of urban energy systems. Therefore, a simulation model was developed in MATLAB$^{®}$. The minimization of CO_2 emissions is based on a mixed-integer linear optimization of the overall system, consisting of the supplying infrastructure, energy hubs, and thermal/electric loads. First results have been obtained by a case study for an urban region supplied by three different energy carriers (gas, electricity, and district heating).

Keywords Multi-energy system · Hybrid network · Energy hub · MILP · Power flow calculations

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1 Introduction

Current developments in the European energy markets are influencing the operational strategy of energy suppliers. In particular, providing electricity and heat for urban regions faces new challenges regarding economic and ecological aspects. The energy turnaround (Ekardt 2014) requires innovative approaches and methods to achieve a sustainable supply of energy. Increasing energy demand as well as a growing number of intermittent renewable-energy sources and storages result in new requirements for current energy-supply structures. One possibility to reach a sustainable supply of energy is to model hybrid networks by using the energy-hub approach (Geidl et al. 2007). In this way, it is possible to react more flexibly to constantly changing requirements for supplying energy. Thereby, a hybrid energy and infrastructure system for urban regions is developed here. The term hybrid describes the interaction between different energy infrastructures.

2 Methodology

For analyzing a hybrid-energy infrastructure system, a mixed-integer linear programming (MILP) model is implemented in MATLAB® and solved by Gurobi Optimizer (Gurobi Optimization 2015). In the following subsections, the used-power flow calculation for the electricity grid, hydraulic calculations for natural gas networks, thermal-hydraulic calculations for thermal networks, coupling of infrastructures with energy hubs, and the overall optimization problem will be discussed.

2.1 Electricity Network

The model of the power grid describes a medium-voltage grid in an urban area. Power-flow calculations are usually executed by iteratively solving a nonlinear system of equations. The use of this method in a linear optimization problem requires some simplification in the power-flow equations, which are achieved by the DC-power-flow method (Wellssow 1986). The linear characteristics of the DC-power flow have the advantage that the calculation method can be directly implemented as a constraint in a linear optimization problem. Results from this method are the active power transportations in the considered electric grids. Voltage levels on nodes, transported reactive power, and transmission losses are not calculated. Loss estimation is possible by evaluating the quadratic relationship between losses and line current. In urban areas, short line-lengths and high load-densities are characteristics of electric grids. Therefore, voltage issues and line losses are negligible.

2.2 Thermal and Gas Networks

In the field of hydraulic simulation of fluidic networks, it is possible to use various steady-state methods for calculating pressures and velocities in the considered network. The choice of available methods depends on the structure of the district heating network (DHN). DHN designs are basically split into two groups, radial and meshed networks. The hydraulic properties of radially structured systems can be determined directly by consideration of the boundary conditions. The handling of meshed networks requires an iterative procedure. In Vldimarsson (2014), typical and popular approaches like the Hardy Cross method are presented. Stevanovic et al. (2007) present a method for calculating hydraulic characteristics based on the loop model of the network and the method of square roots for solving the system of linear equations. Ellis and Simpson (1996) investigated the Linear Theory Method (LTM), the Newton-Raphson method, and a hybrid method combining both, the LTM and Newton-Raphson method in terms of efficiency.

The hydraulic simulation of the gas network and district heating network is based on the Linear Theory Method. Additional to a hydraulic analysis, the thermal behavior of the district heating network can also be examined. For this purpose, a combined thermo-hydraulic calculation method is applied.

The hydraulic calculation of the district heating system works as for the gas network and serves as input for the thermal calculation, which is based on the discretization of the pipe network with the Finite Volume Method. In this way, a transient and detailed simulation of the thermal network is possible (see Fig. 1).

2.3 Energy Hubs

For the coupling of energy network infrastructures, energy hubs have to be defined. This will enable an interface between the grid infrastructures (electricity, natural gas, and heat) to be determined. Figure 2 shows an exemplary structure of an
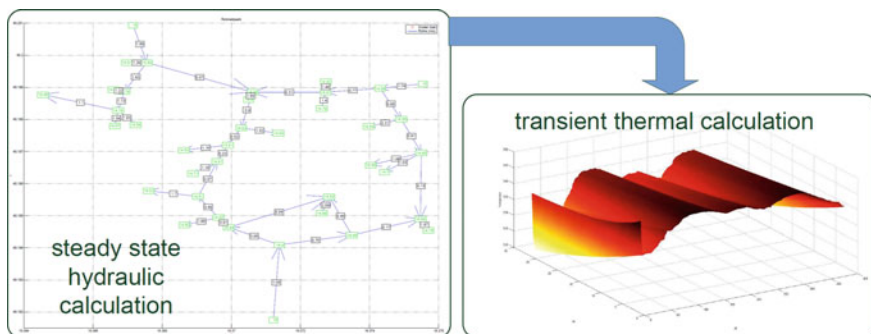

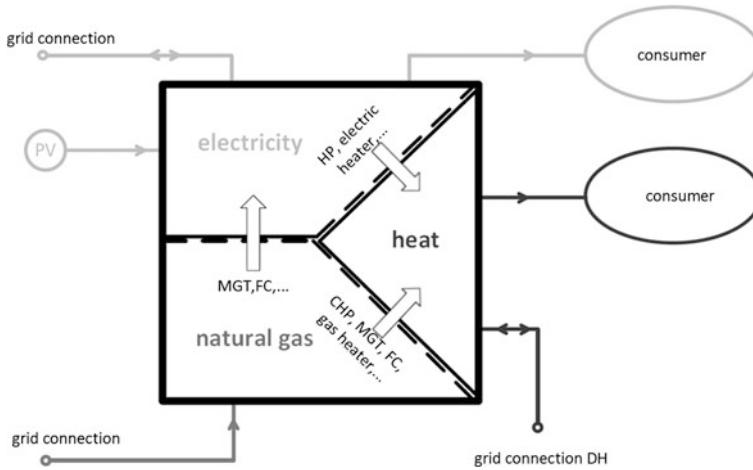**Fig. 1** Combined thermo-hydraulic simulation

Fig. 2 Schematic illustration of an energy hub

energy hub. A Matrix, which is populated by the efficiency factors of the conversion technologies, provides an interface between different energy infrastructures. Additionally, storage technologies and renewable-energy sources can be integrated. The number and placement of energy hubs in an urban area depend on connection points that are defined by spatial proximity between different energy infrastructures. Energy hubs can be used for different applications, for example:

- Industry (refineries, steel industry),
- Complexes of buildings (airports, hospitals, shopping center),
- Limited geographical spreads (urban areas) and
- Island grids (plane, train, ship).

From a systemic point of view, the energy-hub approach has some advantages compared to conventionally separated energy supplied infrastructures, namely, improved reliability, more flexible loads, and optimization potential (costs, emissions, availability).

2.4 Optimization

The optimization problem is implemented in the YALMIP (Löfberg 2004) toolbox for MATLAB®. YALMIP expresses the defined constraints, decision variables, and objective function in canonical form before solving with Gurobi. Combining storage technologies and piecewise linearization creates a MILP optimization problem. Power-flow equations for calculations in electrical grids can be directly formulated as constraints. Due to quadratic velocity-terms in hydraulic networks, equations for flow calculations have to be linearized using piecewise linearization

methods before being included as constraints in the optimization problem. The input vector of the energy hub is defined as a decision variable, so the optimization determines the optimal input powers for each energy hub depending on the current objective. The objective function can be selected in order to, for example, minimize line utilization in power grids, minimize pressure losses in thermal networks, and minimize costs. In this paper, the objective function minimizes the CO_2 emissions for load supply to consumers. A case study in the next section shows an implementation of this optimization model in an urban area.

3 Case Study

The area around the location of the TU Wien serves as a case study for the simulations. The multi-energy system consists of an electrical, a thermal, and a natural-gas network. Additionally, two energy hubs with different energy conversion technologies are taken into account.

3.1 Networks

GIS data of the networks represent the basis of the applied method. Therefore, the networks of the case study were generated with the software tool QGIS which enables it to locate the infrastructure elements like feed-in points, consumers, and the route of the cables and pipes of the considered area (see Fig. 3). The blue lines indicate a medium voltage segment with two segments and seven load points. The used operational data of the electrical network in an urban region originates from a statistical survey (Otto 2012). The orange-colored gas network has low-pressure behavior and one feed-in point. The red coloured lines present a section of a primary district heating network with two feed-in points.

3.2 Load and Production Profiles

The load profiles of the electrical- and thermal-energy demand of the case study are given for 1 week with an interval of 15 min (672 values). These profiles are split into two groups, one for households and one for industry. Energy hubs in the case study were defined either as industrial consumers or as households.

Thermal-load profiles are based on the standardized daily consumption generated with the Sigmoid-model. This model uses a direct dependency of the heat demand on the daily mean temperature. For the case study, a daily mean
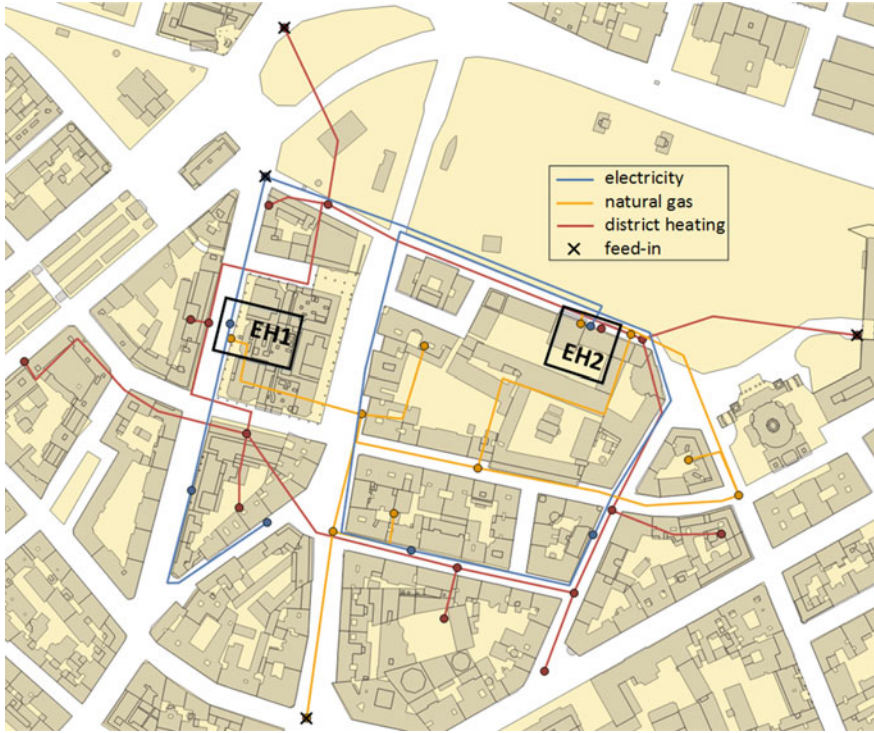
Fig. 3 Model of an urban hybrid network

temperature of 10 °C was chosen. The electrical load profile corresponds to the VDEW standard load profile H0 for households and G1 for industrial usage. Production profiles of the photovoltaic systems consider sunny and variably cloudy days, which are distributed over 1 week.

3.3   Definition of Energy Hubs

The energy hubs used in the case study have several connections to energy-supply infrastructures and are equipped with different coupling technologies to satisfy thermal and electric consumption. Energy Hub 1 is connected to the electric and natural-gas grid. By using a heat pump and gas heating, the thermal load can be supplied by two different technologies. Additionally, a thermal storage is included. Energy Hub 2 has connection points to all energy supply infrastructures (electric, thermal, and natural gas). The heat exchanger (HE) supplies the thermal load from a district heating infrastructure. The used combined heat and power (CHP) station generates electricity and heat simultaneously to cover electric and thermal loads. As in Energy Hub 1, a

thermal storage is included that can be charged by CHP, HE, or immersion heaters shown as direct heating in the energy hub. Immersion heaters are used to store surplus energy from photovoltaics in contrast to cutting off feed-in power to prevent high line utilization in the electric grid. Figure 4 shows the used energy hubs.

Conversion efficiencies of the used coupling technologies are defined in Table 1. In the performed optimization, converter efficiencies are included as constants. Therefore, partial load behavior of converters is not considered.

3.4 Scenarios

With the introduced method for optimizing load flows, the effects of different energy conversion systems and supplying methods of electrical and thermal energy on the CO_2 emissions and the loads of the energy networks are examined. In Table 2, the eight analyzed scenarios are listed. Scenario "status quo mix" represents the reference scenario where the energy infrastructure disposes of neither

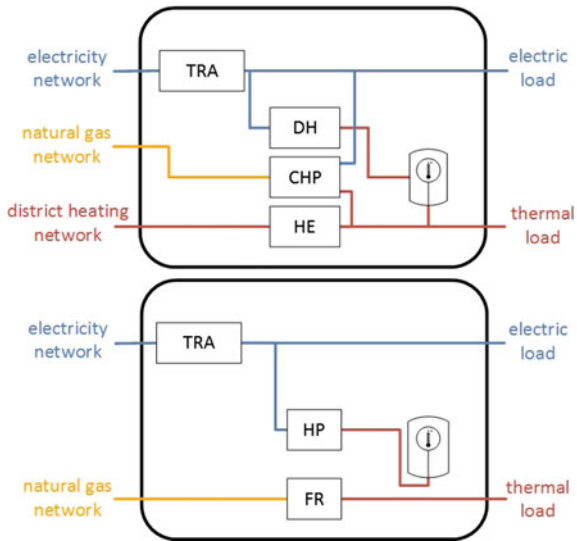**Fig. 4** Energy Hub 1 (*bottom*), Energy Hub 2 (*top*)

Table 1 Conversion efficiencies of used coupling technologies

Technologies	Efficiency
Transformer	99 %
Heat pump	COP = 2.5
Gas furnace	80 %
Immersion heater	100 %
CHP	$\eta_{el} = 40$ %, $\eta_{therm} = 40$ %
Heat exchanger	95 %

Table 2 Description of simulated scenarios

Scenarios	Energy hubs	Storage and renewables	Origin of electricity
Status quo mix	No	No	Power mix
Status quo eco	No	No	Eco power
Status quo mix pv	No	Yes	Power mix
Status quo eco pv	No	Yes	Eco power
Scenario mix energy hub	Yes	No	Power mix
Scenario eco energy hub	Yes	No	Eco power
Scenario mix all	Yes	Yes	Power mix
Scenario eco all	Yes	Yes	Eco power

energy hubs nor storages nor feed-in of renewable energy. The other scenarios differ in terms of the existence of energy hubs with thermal storages and the possibility of using renewable energy (photovoltaic).

All data used in the case study for CO_2 emissions is from ESU-services (2012). The kind of electric energy production is expressed in grams of CO_2 emissions per kWh electric energy. Thus, there are two different sources of electricity. The first one is a mixed generation with CO_2 emissions of 550 g/kWh ("power mix"), and the second is an absolutely ecological generation with CO_2 emissions of 40 g/kWh ("eco power"). For the valuation of the impact of the thermal energy consumption, CO_2 emissions of 260 g/kWh for the thermal energy provided by natural gas and 80 g/kWh for the thermal energy provided by district heating are assumed.

4   Results

All results shown in this section are based on the scenarios defined above. Optimal power flows in energy networks with respect to line utilizations in electrical grids, node pressures in gas networks, and node temperatures in district-heating networks are calculated. The objective function minimizes the CO_2 emissions in the energy hubs. In Table 3, the resulting CO_2-emission reductions based on the reference scenario "status quo mix" are listed. It can be seen that taking green electricity instead of a power mix can reduce the emissions by about 40 %—without using any renewables or energy hubs. Using renewables without energy hubs does not lower emissions in the case of green electricity use. The reason for this is that the thermal load, as the major part of the total load, is being supplied by natural gas or district-heating systems. Using energy hubs and green electricity, without considering renewables in energy hubs, quarters emissions compared to the reference scenario. When using energy hubs and photovoltaic, emissions come to one tenth of the emissions compared to the reference scenario. Further reduction is not possible due to load flow limitations in the supply infrastructures.

Afterwards, results from "scenario mix all" are described in detail. This means energy hubs and renewables (photovoltaic system) are used, and electric energy

Table 3 Resultant CO_2 emissions for various scenarios

Scenarios	CO_2 emissions (%)
Status quo mix	100
Status quo eco	59
Status quo mix pv	66
Status quo eco pv	56
Scenario mix energy hub	67
Scenario eco energy hub	23
Scenario mix all	24
Scenario eco all	10

comes from a power mix. Resulting input powers of the energy hubs, as well as their storage utilization, are shown in Fig. 5. It can be seen that for Energy Hub 1, electric energy is used most of the time to satisfy load requirements, because of lower emissions from heat pumps compared to gas furnaces. Natural gas is needed only when maximum line utilizations of electric lines are reached. This is the case when high thermal and electrical loads occur and no feed-in of renewable energy is available.
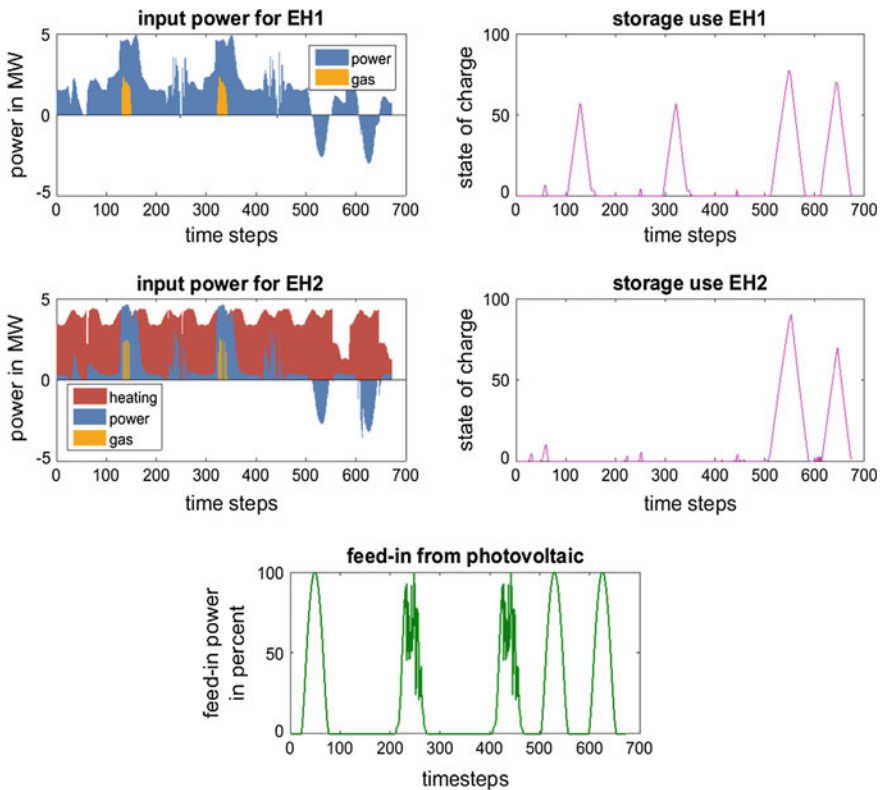

Fig. 5 Input powers for energy hubs and storage utilization

Input powers from Energy Hub 2 show roughly the same behavior. On days without feed-in from renewables, natural gas and electric power from energy networks are used based on consideration of line utilizations and node pressures. For better traceability of these results, Fig. 6 shows the used energy infrastructures
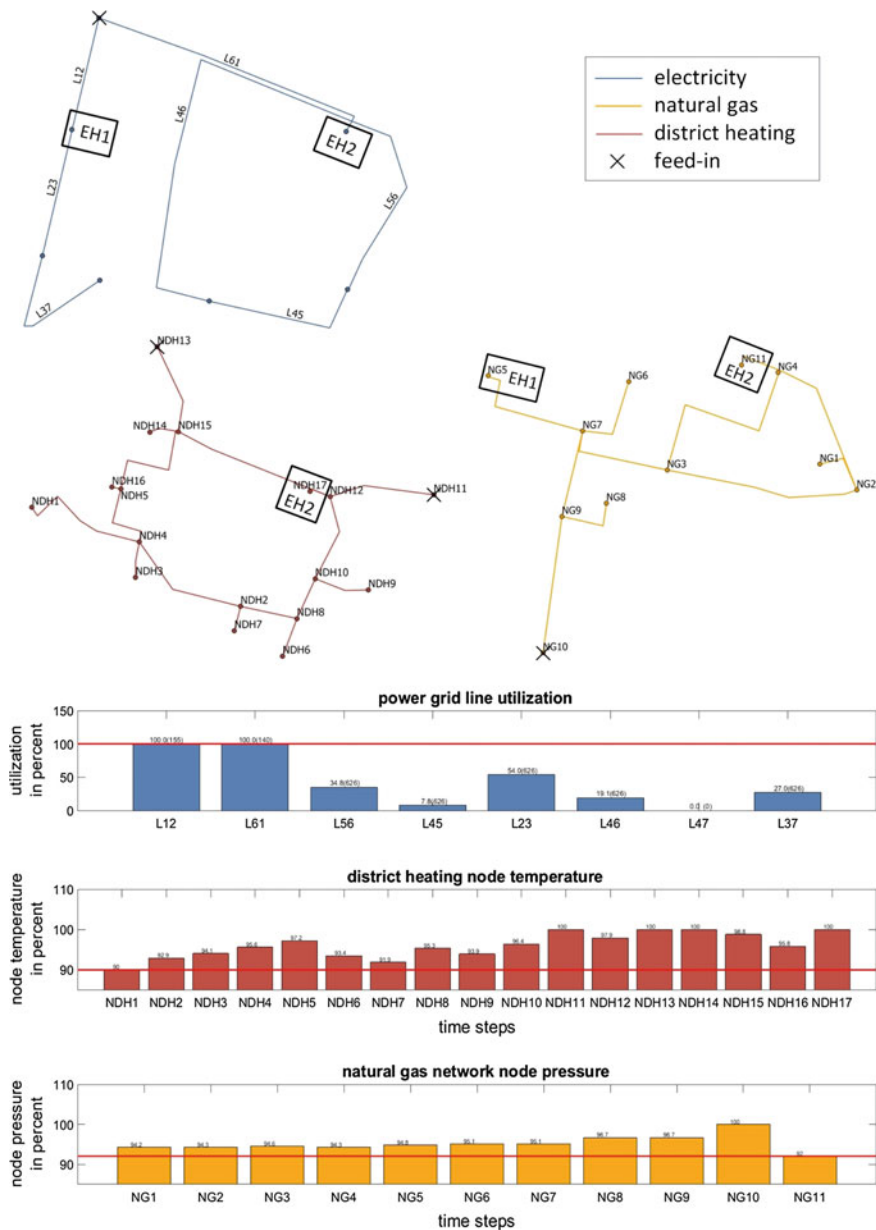

Fig. 6 Utilization of the electrical, gas, and thermal network

isolated, with energy hubs as interconnection points and line utilizations, node pressures, and node temperatures with designated limits.

5 Conclusion

The introduced methodology of optimizing load flows in hybrid networks demonstrates the potential of increased flexibility for supplying electricity and heat by using energy hubs. In consideration of network infrastructures, conversion technologies, and the behavior of consumers, it is possible to optimize the operation of hybrid networks of a given urban area. The objective function of interest can vary from CO_2 emissions over costs to individual objectives, always under the constraint that no load exceeds the allowable values of the considered network.

The results of the case study show how energy hubs could be operated to minimize the output of CO_2 emissions to supply the demand of electrical and thermal energy by consumers. Further steps are the implementation of efficiencies depending on the part-load behavior of conversion technologies.

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