Simulation and Optimization of Systems with Multiple Energy Carriers

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Abstract

There is currently a trend towards a more integrated energy industry. More knowledge and research on complex and integrated energy systems are needed. This paper presents three models which are either available or now under development. First the EMPS model designed for large-scale hydro-thermal power systems will be presented. The paper shows how a natural gas market can be included in the same model. Secondly, the EPF model, which integrates the EMPS model and load flow analysis on a detailed electricity grid, is described. Finally, the development of a generalized methodology to optimize energy transport systems with multiple energy carriers is presented.

1 Introduction

Traditionally, the energy industry has been very fragmented, with separate suppliers of end user energy (gas/petroleum, electricity, district heating etc.), energy transport (sea, rail, road, pipelines or power lines), as well as exploitation of energy resources (mining, offshore, hydro etc.). Similarly, the technical and economic knowledge and the available tools for analysis of smaller or larger energy systems have had the same fragmentation.

Today, there is a trend towards a more integrated energy industry, with e.g. petroleum companies moving into other energy markets like electricity or district heating. Similarly, electricity distribution companies have developed into energy distribution companies providing end user energy based on several energy carriers. This entails the need for more multiple-discipline knowledge and research in the energy sector.

This paper presents three models developed, or under development, by SINTEF Energy Research. Two of these are available and being used in the Nordic electricity market today, while the third is currently under development. The EMPS model, designed for analysis of hydro-thermal power systems, will be presented first. The paper shows how a natural gas market can be added to this model. Secondly, the EPF model, which integrates the EMPS model and DC load flow analysis on a detailed electricity grid, is described. Finally, the development of a generalized methodology to optimize energy transport systems with multiple energy carriers is presented.

2 The EMPS model

The EMPS model [1, 2] is a stochastic model for optimal scheduling and simulation of system performance in hydro-thermal power systems. The model is best suited for systems with a significant portion of hydropower.

2.1 Overview

In the EMPS model the different categories of supply and demand are explicitly represented, including many of the major components such as power plants. Individual players in the market, i.e. producers or consumers, are not modelled. The modelled power system is divided into a number of regional subsystems. The Nordic system may e.g. be modelled as illustrated in Fig. 1.

The EMPS model is well suited to studies of large-scale hydro-thermal systems, and is widely used in the Nordic electricity market. The most common use of the model at present is for forecasting future spot market prices (Fig. 2) [3], but the model is also commonly applied to tasks such as generation scheduling, system expansion planning and other market analyses. The basic time step in the model is one week, with duration curves for different load levels within the week. The planning horizon is up to 10 years. The calculations are based on use of historical inflow and temperature data, typically for 60 years.

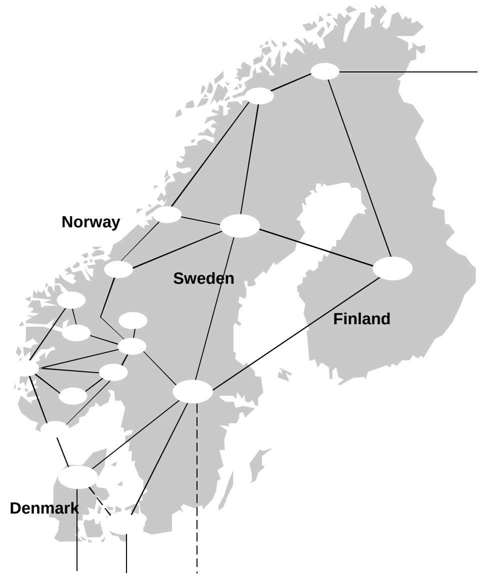

Figure 1 *The Nordic power system in the EMPS model*

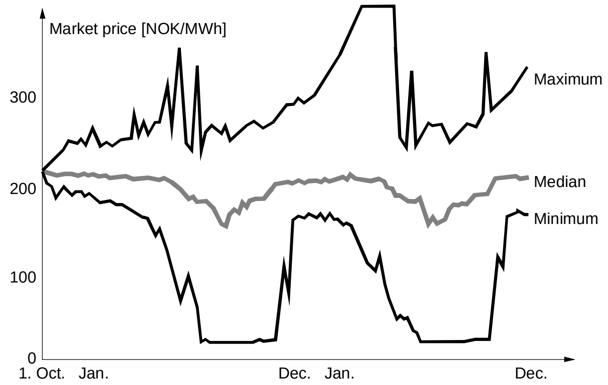

Figure 2 *A sample price forecast from the EMPS model*

The EMPS model consists of two parts:

- A *strategy evaluation part* computes regional decision tables for hydropower in the form of expected incremental water values for each aggregate regional subsystem. These calculations are based on use of stochastic dynamic programming (SDP) for each subsystem, with an overlaying hierarchical logic applied to treat the multi reservoir aspect of the problem.

- A *simulation part* simulates optimal operational decisions for a sequence of hydrological years.

2.2 Modelling a power system

Each subsystem has a single busbar, and may include hydropower, thermal units, demand, and transmission capacity to other subsystems. The transmission system between subsystems is modelled with defined capacities and linear losses. Transmission fees for transport of energy may be modelled.

The *hydropower system* within each regional subsystem may be modelled in detail. Based on standard plant/reservoir modules large and complicated river systems may be modelled. A model of the Norwegian hydro system may e.g. involve from 500 to 800 plant/reservoir modules, depending on the degree of detail.

Thermal generation units are generally defined by their variable costs (based on fuel costs etc.) and capacity. Scheduled maintenance may be included. The expected availability of thermal units may be included by using a convolution technique for constructing an Expected Incremental Cost curve (EIC) for each time step to represent available thermal units [4, 5].

Power demand may be either fixed or price elastic and it may be temperature-dependent. A stepwise duration curve may represent variations within the week.

2.3 The EMPS model strategy part

To limit the computational burden, the strategy part of the EMPS model is forced to utilize an aggregate model representation of the hydro system within each regional subsystem.

Given the stated multi reservoir model description, the objective of the optimization process is to establish a strategy for operating the hydro system that for each stage in time produces the best possible decision vector. By *best* decisions is understood that sequence of turbined and spilled water volumes that contribute to minimizing the expected operational costs during the period of analysis.

Stochastic dynamic programming (SDP) is applied to solving the optimization problem. This involves defining a number of discrete system states for which optimization is carried out. By system states are understood regional reservoir storage levels.

The number of discrete states increases exponentially with the number of state variables in the problem. Thus formal SDP-solution becomes infeasible for the number of reservoirs involved here. For practical solution of the problem an approximate methodology is employed in the EMPS model. An SDP-related algorithm is used as the nucleus for solving each regional subproblem, and an overlaying hierarchical logic is applied iteratively to treat the multi reservoir aspect.

A new optimization algorithm based on Stochastic Dual Dynamic Programming (SDDP) is presently being developed to supplement the current solution technique.

2.4 The EMPS model's simulation part

In the simulation part of the EMPS model system performance is simulated for a chosen sequence of hydrological years. Based on the incremental cost tables calculated previously for each aggregate regional hydro system, weekly operational decisions on power generation (hydro or thermal) and consumption are simulated. A detailed rule-based reservoir drawdown model affords the distribution of each subsystem's aggregated hydro generation among available plants for each level of demand each week.

System simulation using the EMPS model provides the user with a host of results applicable to a number of problems. While the most common use of the model at present is for market analysis and price forecasting, the model has also been used for expansion planning (hydro plants, thermal plants, transmission capacity), long- and mid-term generation scheduling as well as studying the environmental consequences of building new generation capacity.

2.5 Introducing a market for natural gas

The EMPS model can also be applied to modelling a market for natural gas. Supply, transport and consumption of natural gas may be represented in much the same way as electrical power is included in the model already.

A number of gas subsystems and gas pipelines may be introduced in parallel to the electrical system. The gas subsystems may or may not represent the same geographical areas as the electrical subsystems, but they must always be modelled separately. The same is the case if different qualities of natural gas are involved.

- *Supply* of natural gas may be a fixed flow, an adjustable flow with volume and flow constraints, or price dependent.

- *Consumption* may be fixed or price elastic, and may be temperature dependent.

- *Pipelines* may be modelled with the same characteristics as power transmission lines, with costs for transported gas.

- *Gas power plants* may be modelled using transmission lines to represent them. These would be one-way transmission lines, from gas to electrical subsystems, with the appropriate gas to power conversion factor. This would imply a linear conversion, since only linear losses are included in the model. A piecewise linear conversion rate could be attained by introducing several parallel transmission lines to represent each power plant.

- Local *gas storage* can be modelled as pumped storage; this would, however, require some minor modifications to the model.

- Combined heat and power (CHP) can be included, but dependency between generated heat and consumer demand for power or gas cannot be included without some development of the model.

A case study

A sample case has been run to demonstrate the feasibility of including a gas market in the model. Fig. 3 shows the gas system introduced in this case. The same results that are produced for the electrical system may be extracted for the gas system, e.g. gas transport between subsystems, gas consumption, and marginal gas prices for each time step.

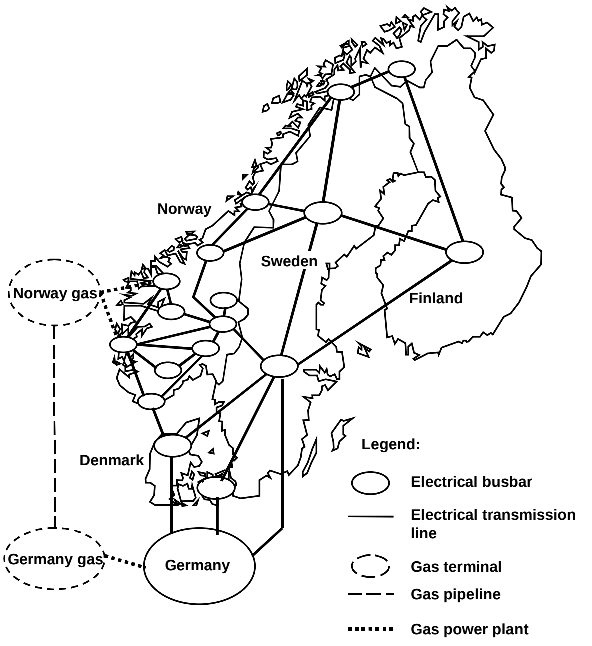

Figure 3 Including a sample gas market in the EMPS model

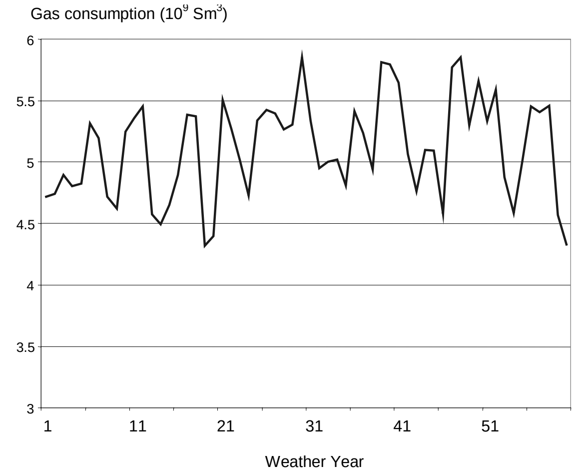

Figure 4 Simulated annual consumption of gas in the German gas power plant

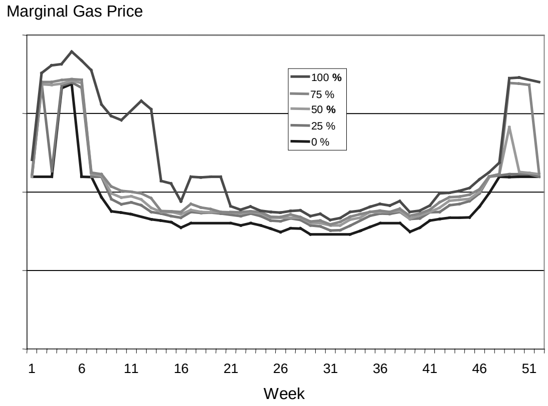

Figure 5 Simulated marginal price in a spot market for natural gas (0, 25, 50, 75 and 100 percentiles).

3 The EPF model

3.1 Overview

The Energy and Power Flow (EPS) model consists of three parts [6, 7]:

- The EMPS model
- A load flow algorithm
- Grid overload and loss handling algorithms

The seasonal and multi-annual handling of the hydro power system for a future stage is evaluated in the EMPS model with respect to inflow statistics, thermal production capacity, firm power demand and spot-price market obligations. Results from the market simulation are hydro system operation, consumption, exports and imports, thermal generation and possibly load curtailment. These results are transferred to the load-flow algorithm package.

With given voltages, a fast and simplified DC-load-flow is normally performed, but full AC load flow may also be applied if the computation time is of minor interest. Normally over 40000 load-flow calculations are to be performed in one simulation.

The Norwegian Main Grid is modelled with close to 1000 nodes, representing the main grid at 400, 300 and 132 kV levels. The Swedish system is currently modelled with a 25-node equivalent representing the main structure at 400 and 220 kV levels. Sweden also has exchange possibilities with Finland and Germany. Work is going on in co-operation with the respective grid owners to include more details of the Swedish and Finnish main grids as well as a better modelling of hydro and thermal power production possibilities.

3.2 Grid overload algorithm

Overload in lines or groups of lines due to thermal or stability considerations, is normally not taken into account in ordinary load-flow calculations. To handle this problem, a price-area algorithm is used in the integrated EPF-model similar to the current procedure used by the Nordic power pool (Nord Pool). If there are overloads in lines or groups of lines in the load-flow model, extra power transfer restrictions are applied in the production and market model (EMPS model), thus creating price areas. With appropriate restrictions, the new market solutions in the price areas will give a power flow within the predefined limits.

Handling of transmission restrictions in the iteration process between the market clearance model and the load-flow model is illustrated in the following simple two-area model of Fig. 6.

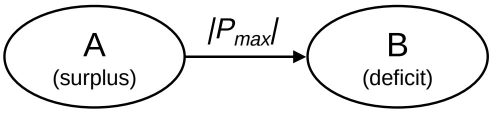

Figure 6 Two area model system

Power transfer is limited between the surplus Area A and the deficit Area B. Without transfer limitations between the areas, the ideal market clearance is found between the sum of the supply and demand in both areas, as illustrated in Fig. 7.

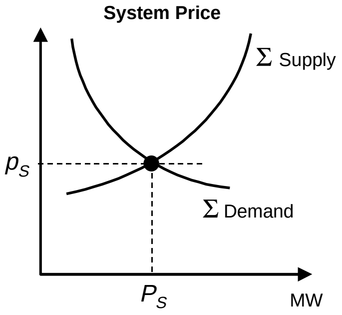

Figure 7 Market clearance without transfer restrictions

However, if market clearance without transmission limitations overloads the line or group of lines connecting the two areas, a new market clearance is found in each area to bring power transfer within the predefined limits. This is illustrated in Fig. 8.

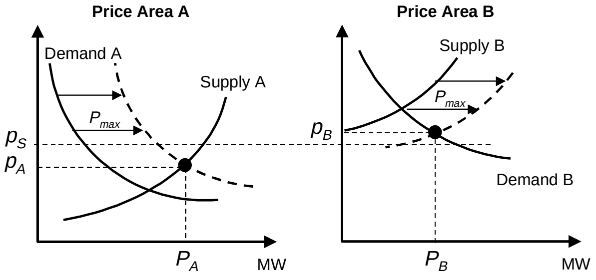

Figure 8 Market clearing with transfer restrictions

The local *demand* curve in the surplus area is displaced with the transfer capacity (equal to additional market possibilities for suppliers in Area A), while in Area B the local *supply* curve is displaced (additional supply for consumers in Area B). Compared to the unrestricted system price, the new clearing prices will cause decreased price and thus decreased supply/increased demand in the surplus area, and increased price and reduced demand/increased supply in the deficit area.

3.3 Model benefits

The EPF model simulates a market clearing process where transmission restrictions are take into account, allowing an improved calculation of main grid utilization including congestion and losses. This model enables an improved socio-economic evaluation of new investments in the main grid and more correct calculation of transmission tariffs based on marginal costs. Traditional results from the EMPS-model, like market analysis and area price forecasting, are also improved.

Every load level in the EMPS model is analysed in the load-flow model to uncover overload in power transfer between areas. The iteration process will bring the power transfer within limits. In the same process, grid losses are brought into the market clearance process as a part of the power demand. For each market clearance analysed, results like power flow and losses are available, as well as marginal losses between selected nodes. With e.g. 50 years of inflow statistics and 4 load levels each week, a total of 10400 load flow situations are available, generating utilization curves for individual lines or groups of lines, capacity losses and yearly energy losses.

Fig. 9 shows an example of how the utilization changes when the capacity between two areas is increased from 900 MW (dashed line) to 1200 MW.

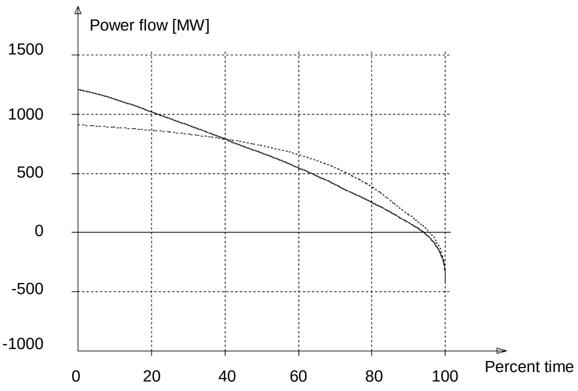

Figure 9 Changes in line utilization due to capacity increase between areas

Table 1 shows the results of this capacity expansion regarding yearly costs of main grid losses and cost of congestion for the 900 and 1200 MW capacity lines.

Table 1: Simulation results

Capacity	900 MW	1200 MW
Cost of losses [MNOK/year]	1192.9	1245.1
Congestion cost [MNOK/year]	48.4	12.0

The initial transmission capacity of 900 MW caused a congestion cost of 48.4 MNOK/year. Increasing the capacity to 1200 MW reduces the congestion cost to 12 MNOK/year, but at the expense of increased losses in the system as a whole due to increased transmission. This transmission reinforcement is thus probably not beneficial when the cost of losses is taken into account.

4 Transport systems with multiple energy carriers

4.1 Overview

A general energy transport system consists of energy sources, transmission, storage, and conversion between different energy carriers as well as end user markets. A new research project with focus on the energy transport systems from energy resource to consumer markets has been started in 1999 including elements from both the fields of electrical and thermal engineering. The project considers different alternative *energy carriers*, such as electrical energy, gas, LNG, oil and coal, *conversion* between different energy carriers (gas- or hydro power plants, CHP, heat pumps, LNG factories etc.) as well as *energy storage* capabilities like hydro storage, gas cavern and LNG storage in the same model.

A flexible and robust methodology for integrated analysis of complex energy transport systems with multiple energy carriers is under development, including technological, economic and environmental aspects. This methodology will be very flexible, and will enable integrated energy companies to carry out comprehensive analyses of their investments as well as overall optimization of their energy supply systems. Also, governmental bodies will be able to do comprehensive scenario studies of energy systems with respect to environmental impacts and consequences of different regulation regimes. Knowledge and experience from existing analysis tools for large scale electricity systems like the EMPS and EPF models will be utilized in this work and applied to infrastructures and conversion processes for other energy carriers.

4.2 Model structure

The analyses are based on a system model with two main levels: A set of generalized *components* with a standard interface combined in a network, utilized by an overlaying *network simulator*. Each component will represent an energy conversion or storage process (P_i), or a transmission channel for a given energy carrier (T_j). The internal mathematical description of each component in the network will have different degrees of complexity depending on its characteristics. The user of the model will be able to build an arbitrary network based on different standard modules, as well as to define new modules for special purposes.

On the overall system level, however, the components are described only with a few general parameters. A generalized network topology consisting of nodes and branches can then be constructed to represent the overall energy system, and the overall system analyses can be carried out using techniques and optimizing methods from more general network theory, in principle without knowledge of the specific types of components involved.

4.3 Component modelling

Conversion processes appear at several instances in an energy transportation network - from resource to energy carrier, from one energy carrier to another and from the energy carrier to end-use. *Energy storage components* might appear as pumped-storage power plants, salt caverns for natural gas or LNG stocks. The *transport channels* are characterized by the transport of energy over a certain distance with a given energy carrier. Note that there are no *distance elements* in the processes, and no *conversions* in the transport channels.

The components in the energy network are modelled in an object-oriented structure, with common output data sets to the optimization routine. The component specific routines are constructed with a top-down modelling, where the level of detail can be enhanced as needed. (see Fig. 10).

The efficiency of the components is usually non-linear with respect to output, which implies that the correspondence between the energy inflow and the energy output of the components are non-linear. To enable optimization with linear programming routines, the correlation between energy inflow and output has to be linearized. The linearity also applies to the costs and the emissions of the components. Although the components must be linearized before optimization, the specific component routines are able to utilize a non-linear description internally for generating a linearized model for the optimization algorithm.

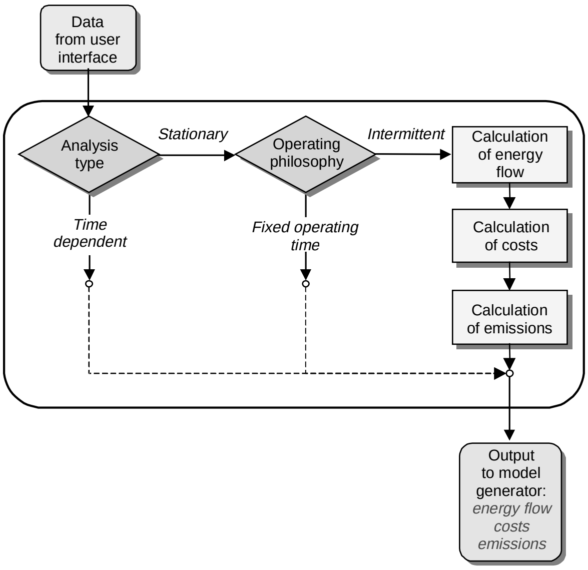

Figure 10 Component procedure structure

Piecewise linearization is used for representing components with non-linear behaviour. This gives the following three data vectors for energy flow, costs and emissions describing the components in the optimization network:

$$W = [\ n, W_{out,1}, W_{in,1}, ..., W_{out,n}, W_{in,n}\ ]$$

$$C = [\ n, W_{out,1}, C_1, ..., W_{out,n}, C_n\ ]$$

$$E_j = [\ n, W_{out,1}, E_{j,1}, ..., W_{out,n}, E_{j,n}\ ],\ j = 1..J$$

where:

n - Number of points on the linearized curve
W_{out} - Energy flow out of component
W_{in} - Energy flow into component
C_i - Energy flow cost through comp. at $W_{out,i}$
$E_{j,i}$ - Emission of pollutant j, at $W_{out,i}$
J - Number of pollutants.

In a stationary analysis (yearly mean calculations), the components can be represented with an optimal operation point, with intermittent operation. For components running a fixed number of hours, the efficiency curve is modelled with a piecewise linear curve.

4.4 Optimization

The output vectors from the component procedures are fed to a Model Generator that builds the linearized system of equations including equality and inequality constraints. At present, this system is optimized with the generic MatLab LP algorithm, but more sophisticated algorithms will be implemented at a later stage. The current implementation does not take into account costs for starting or stopping of conversion processes like power plants. The program structure is shown in Fig. 11.

Two types of analyses are supported:

- *Operational optimization (Time dependent)*
  This module calculates the optimal operation of a given energy system in a specified time period, in terms of energy flow and energy storage management. The calculation may include restrictions and taxes on total process emissions.

- *Investment optimization (Stationary)*
  Based on calculated operational costs and given investment costs, an optimal portfolio of investments is selected from a list of alternatives. The selection is based on Dynamic Programming algorithms.

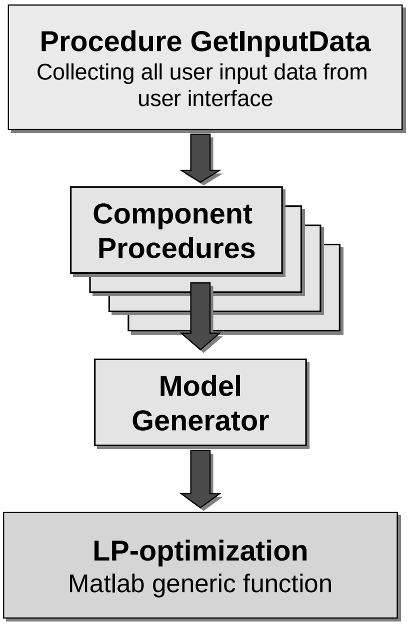

Figure 11 Component procedure structure

4.5 Energy quality

The general approach in the planning of energy systems is to optimize a network of processes and transmission channels based on an object function that weights the properties of the elements in the network. However, the total efficiency in the energy chain, environmental emissions, costs, impacts on nature, aesthetics etc. are not always quantifiable or easy comparable variables. It is still important that these aspects are visible in an overall system analysis, either as a result of an economic optimization or as an element included in the optimization. To obtain a more flexible value evaluation of the different processes than for instance just a sum of the costs and the environmental emissions, an additional variable *'energy quality'* can be defined as a set of comparable properties for each component. This variable will be implemented in the optimization together with classic properties like investments and operational costs.

4.6 Description of sample system

A case from current energy system planning in Norway can be used to demonstrate the possible use of the described model.

Utilization of the 'Snøhvit' gas reservoir, which is located in the Barents Sea north of Norway, is currently under consideration. Very large energy resources have to be transported to markets close to the population centres in Scandinavia or in Continental Europe. There are mainly three alternative choices of energy carriers for this transport:

- Gas pipe onshore or offshore to the existing infrastructure in the North Sea
- Conversion of the gas to LNG and transport by ship
- Gas power plant and high voltage DC lines (HVDC) to one or more energy markets

Simultaneously, there are plans for increasing the hydroelectric power production at 'Svartisen' in northern Norway with 300 MW. Such an increase in electricity production in this area will cause a need for reinforcements of the existing electricity grid to the same consumer markets in the south.

Traditionally, these two projects would have been analysed independently of each other. The possibility of combining the two projects will provide new aspects to the cost and revenue evaluation, as well as greater flexibility in analyses of the environmental impacts. For instance, a system where the power from 'Snøhvit' and 'Svartisen' is fed into the same HVDC network will introduce new system solutions compared to the other "classic" alternatives. The two projects and possible alternatives for HVDC-lines are illustrated in Fig. 12.

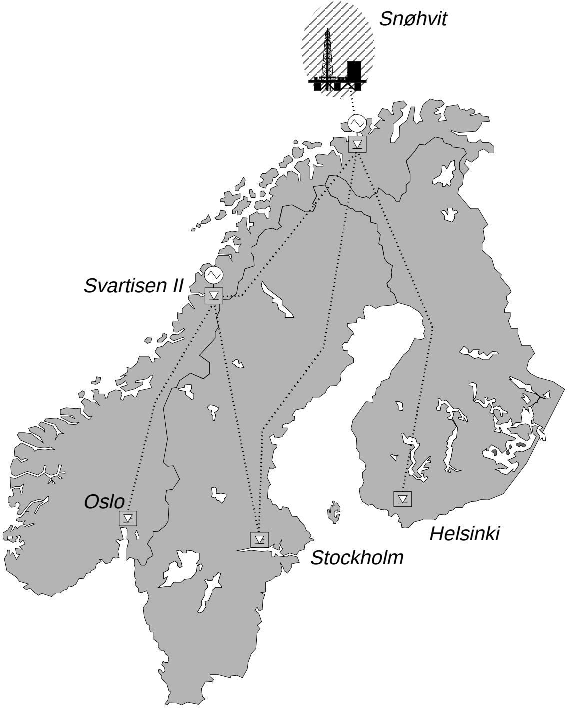

Figure 12 Combined gas and hydroelectric power transportation system

Building a system model for this case, presently with a limited selection of components, results in a model structure as shown in Fig. 13. The respective energy carriers are indicated for the transport channels T_j. A hydropower plant is an energy source normally connected to a high voltage AC system, but electric energy can also be converted to high voltage DC for transport. Note that while most transport channels in Fig. 13 are single components connecting two defined geographical locations, the AC system will consist of the total synchronous Nordic electricity grid.

A generalized network topology consisting of nodes and branches can be constructed to represent the overall energy system. The system with processes P_i and transport channels T_j from Fig. 13 is represented as shown in Fig. 14, where both processes and transport channels are generalized to network “branches”.

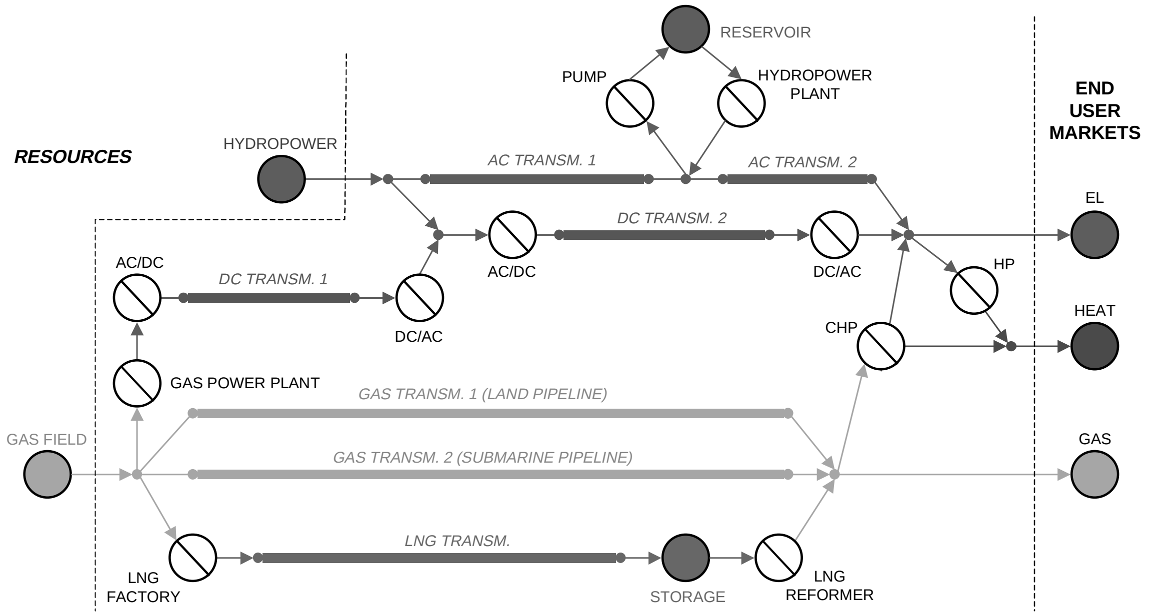

Figure 13   System model of sample case

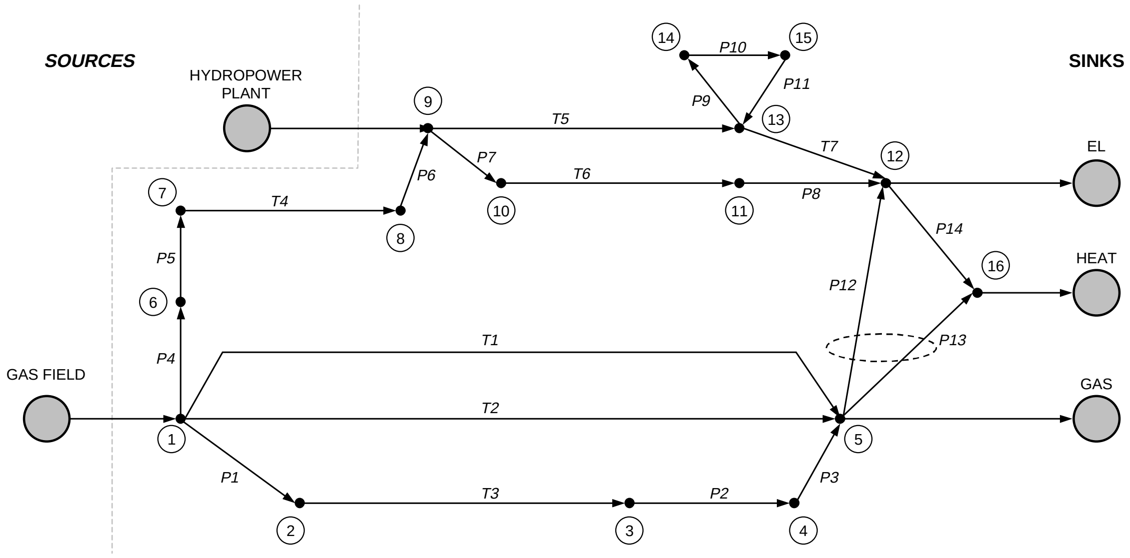

Figure 14   Generalized network model of sample case

5 Summary

This paper has presented three tools that are, or will be, used to analyse complex energy systems with multiple energy carriers. The existing EMPS and EPF models have been developed for large-scale hydro-thermal power systems. The former is currently being applied to modelling markets and transmission systems for natural gas; the latter combines the electricity market clearing process with calculation of main grid utilization, losses and transmission restrictions. Finally, a new model is under development that will enable analysis of complex energy transport systems with multiple energy carriers.

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