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Schwarz, R.; Lacalandra, F.; Schewe, L.; Bettinelli, A.; Vigo, D.; Bischi, A.; Parriani, T.; Martelli, E.; Vuik, K.; More Authors

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R. Schwarz, F. Lacalandra, L. Schewe, A. Bettinelli, D. Vigo, A. Bischi, T. Parriani, E. Martelli, K. Vuik, R. Lenz, H. Madsen, I. Blanco, D. Guericke, I. Yüksel-Ergün, and J. Zittel

1 Gas Pipeline Design

Natural gas is considered by many to be the most important energy source for the future. The objectives of energy commodities strategic problems can be mainly related to natural gas and deal with the definition of the "optimal" gas pipelines design which includes a number of related sub problems such as: Gas stations (compression) location and Gas storage locations, as well as compression station

R. Schwarz · R. Lenz · I. Yüksel-Ergün · J. Zittel
Zuse Institute Berlin (ZIB), Berlin, Germany

F. Lacalandra
QuanTek, Bologna, Italy

L. Schewe
University of Edinburgh, Edinburgh, UK

A. Bettinelli · T. Parriani
Optit, Bologna, Italy

D. Vigo
University of Bologna/Optit, Bologna, Italy

A. Bischi
Skolkovo Institute of Science and Technology, Moscow, Russia

E. Martelli
Politecnico di Milano, Milan, Italy

K. Vuik
Delft University of Technology, Delft, Netherlands

H. Madsen (✉) · I. Blanco · D. Guericke
Technical University of Denmark, Lyngby, Denmark
e-mail: hmad@dtu.dk

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design and optimal operation such in [255]. Needless to say these problems involve amount of money of the order of magnitude of the tens of billions EUR and often these problems can be a multi-countries problem. From the economic side, the natural gas consumption is expected to continue to grow linearly to approximately 153 trillion cubic feet in 2030, which is an average growth rate of about 1.6% per year. Because of the properties of natural gas, pipelines were the only way to transport it from the production sites to the demanding places, before the concept of Liquefied Natural Gas (LNG). The transportation of natural gas via pipelines remains still very economical.

From an optimization standpoint, the gas pipeline design problems can be divided in the following main sub problems:

1. how to setup the pipeline network, i.e. its topology;
2. how to determine the optimal diameter of the pipelines;
3. how to allocate compressor stations in the pipeline network;

Typically, the mathematical programming formulations of these optimization problems contain many nonlinear/nonconvex and even nonsmooth constraints and objective functions because of the underlying physics of the gas flows that need to be considered. The classic constraints are the so-called Weymouth panhandle equations, which are a potential-type set of constraints and relate the pressure and flow rate through a pipeline.

As in many other situations, problems 1–3 are a single problem but a divide et impera principium is applied. Therefore the problems 1 and 2 are somehow determined via simulations and normally there are—in the first but also in the second problem—many economic drivers, and also political drivers when many countries are involved. From a technical point of view, problem 3, the allocation of the compressor stations, is probably the most challenging. Because of the high setup cost and high maintenance cost, it is desirable to have the best network design with the lowest cost. This problem concerns many variables: the number of compressor stations which is an integer variable, the pipeline length between two compressor stations, and the suction and discharge gas pressures at compressor stations. This problem is computationally very challenging since it includes not only nonlinear functions in both objective and constraints but, in addition, also integer variables.

In the case of transmission networks, existing infrastructure is already available, but needs to be expanded to increase the capacity. To this end, new pipelines are often built in parallel to existing ones, effectively increasing the diameter. On the other hand, for the exploitation of new gas fields or off-shore transportation, pipeline systems are designed from scratch with no predetermined topology. Capacity planning and rollout has a time horizon of several years. Accordingly, some optimization models consider multiple stages of network expansion. Many of the planning problems are formulated as mixed-integer non-linear programs (MINLP) with integer variables and nonconvex constraints. To solve these models directly, solvers apply outer approximation and spatial branching. Alternatively, the problem functions can be approximated piecewise linearly, yielding a mixed-integer linear program (MILP) formulation. A survey paper concerned with water networks is also relevant here [90]. Specialized algorithms make use of the fact that certain subproblems with fixed integer variables have a convex reformulation, which can be solved efficiently and used for pruning [212, 356].

The design of pipeline topologies from scratch is solved with a decomposition, where first a topology is fixed heuristically, and improved by local search. The pipeline diameters are then solved separately [366].

In the case that the network has a tree topology, Dynamic Programming has been applied, both for the choice of suitable pipe diameters [366] as well as compression ratios [58].

Another important aspect is how to treat varying demand scenarios. A finite number of different scenarios can be tackled using decomposition techniques [385]. When the network has a tree topology, also robust variants can be reduced to finitely many scenarios [362].

2 District Heating Network Design

In the current energy market context, District Heating (DH) has an important role, especially in countries with cold climate. DH often leverages on Combined Heat and Power (CHP) units, capable to reduce the consumption of primary energy to fulfill a given electric and thermal request, as well as on existing significant sources of heat generated by industrial processes or waste-to-energy heat generation. Additionally, heating networks will need to increase their flexibility in operation due to an increasing mix of renewable sources, both heat sources or green electricity utilized by heat pumps, distributed generation and smart consumers as well as DH operational temperature reduction and heat storage integration [277, 426].

From a management standpoint, the design of the district heating network is a strategic business issue, since it requires large investments due to the cost of materials and civil works for the realization of the network. Proper strategic design of the network (i.e. definition of the most convenient backbone pipelines to lay down) and tactical targeting of most promising potential customers both aims at maximizing the Net Present Value (NPV) of the investment.

Finding the extension plan for an existing (or eventually empty) DH network that maximizes the NPV at a given time horizon is a challenging optimization problem that can be stated as follows. Given:

- A time horizon (e.g., 15 years)
- A set of power plants, with specific operational limitations (maximum pressure, maximum flow rate,. . .);
- An existing distribution network, with information on the physical properties of the pipes (length, diameter,. . .);
- A set of customers already connected to the network with known heat demand;
- A set of potential new pipes that can be laid down;
- A set of potential new customers that can be reached;

find:

1. The subset of potential new customers that should be reached;
2. Which new pipelines should be installed;
3. The diameter of the new pipes

that maximize the NPV.

Research on modelling approaches for representing the behavior of the thermo-hydraulic network through sets of non-linear equations can be found in the literature (see for example [52] and [343]). Solving systems of non-linear equations is difficult and computationally expensive. For this reason, aggregation techniques of the network elements are often used to model large district heating networks, at the expense of some accuracy [258, 259, 272, 450, 452] and [272].

In [25], an integer-programming model is proposed for the optimal selection of the type of heat exchangers to be installed at the users' premises in order to optimize the return temperature at the plant. The authors achieve good system efficiency at a reasonable cost.

Bordin et al. [54] present a mathematical model to support DH system planning by identifying the most advantageous subset of new users that should be connected to an existing network, while satisfying steady state conditions of the thermo-hydraulic system. Bettinelli et al. [42] extend the model proposed by Bordin et al. [54] with the selection of the diameter for the new pipes and a richer economic model that takes into account

- Production cost and selling revenues;
- Cost for installing and activating new network links;
- Cost for connecting new customers to the network;
- Amortization;
- Taxes;
- Budget constraints.

Moreover, while the investment on the backbone pipelines is done on the first year, new customers are not connected immediately, but following an estimated acquisition curve (e.g., 25% the first year, 15%, the second year, …). Hence, the corresponding costs and revenues have to be scaled accordingly.

The thermos-hydraulic model must ensure the proper operation of the extended network. The following constraints are to be imposed:

- Flow conservation at the nodes of the network;
- Minimum and maximum pressures at the nodes;
- Plants operation limit: maximum pressure on the feed line, minimum pressure on the return line, minimum and maximum flow rate;
- Pressure drop along the links;
- Maximum water speed and pressure drop per meter.

Continuous variables model pressures at nodes and flow rate on the links and binary variables model decisions on the connection of new customers, on the installation of new links, on the diameter choice and on flow direction on the links. The latter are necessary since DH networks contain cycles: the potential network usually corresponds to the street network. Thus, it is not possible to know the flow direction on the links a priori (at least not for all of them) and such decision must be included into the model. The pressure drop along a pipe is a non-linear function that depends on the flow rate and on the diameter of the pipe. This can be approximated using a piecewise linear function that translates into a set of linear constraints. The higher the number of segments in the piecewise linear function, the smaller will be the approximation error. At the same time, the number of constraints grows (there is one piecewise-linear function for each combination of pipe and diameter) and the solving time increases. To keep the number of segments small, while obtaining a good accuracy, breakpoints of the piecewise linear function can be concentrated in the most probable range of flow rate.

DH networks can be quite large (hundreds of existing and potential users, thousands of links) making it difficult to solve the full MILP directly. Solution methods developed in [42] approach the problem in three steps.

1. Solve the linear relaxation of the MILP model and use it to select water direction in all the pipes. Then, solve to integrality the MILP model, with the directions fixed, obtaining a first heuristic solution.
2. In the solution found at step 1, the conflict points, which are the nodes of the network where different water direction meet, are detected. The flow direction is released for the nodes close to conflict points, and the MILP model is solved again, obtaining a second heuristic solution.
3. The full MILP, initialized with the best solution found in the previous steps, is solved until either optimality or the time limit is reached.

The company Optit S.r.l. has developed a decision support system, in collaboration with the University of Bologna, based on the modelling mentioned above that has been successfully used in two of largest multi-utility companies operating in the Italian DH market. The application leverages on open source Geographical Information System (GIS) to allow a simple user interface and a number of plug-in tools to manage the specific optimization issue.

3 Optimal Design of Energy Hubs and CCHP Systems

The optimal design of energy hubs and combined cooling, heating and power (CCHP) systems consists in determining the energy technologies (i.e., power generation units and energy storage systems) to be installed and their sizes which minimize a certain cost function (e.g., the total annual cost given by annualized capital and operating expenditures) while providing electricity, heating and cooling power to a set of users. In the presence of multiple users and possible installation sites, it is necessary to determine the units to be installed in each site and the required energy network connections between sites.

The problem turns out to be a very challenging nonconvex MINLP [112] with a large number of binary variables, because it has to include not only the design variables (units selection and sizes) but also the operation variables and constraints for the whole system lifetime. Due to the variable energy demand profiles and electricity prices, the loads of the installed units must be continuously adjusted so as to meet the demands and maximize the revenues. Thus, when designing the system, the part-load performance and the operational flexibility (e.g. ramp constraints) must be evaluated for the set of expected operating conditions. As a result, in most formulations (see review in [112]), the design optimization problem includes also the operational/scheduling problem with a considerable increase of problem size and complexity.

The design problem is more complex than the scheduling problem not only because of the larger number of variables and constraints (design + scheduling variables) but also for the nonlinearity of the functions relating to units' sizes with energy efficiency (larger units feature higher energy efficiency [112]), and investment costs. The approaches proposed to tackle the resulting nonconvex MINLP problem can be classified in two main families:

1. linearization of all nonlinear functions so as to obtain a single large scale linear problem (MILP) [444] and [161].
2. decomposition of the problem into a design level (upper level or master problem) and a scheduling level (lower level) [138, 218] and [112].

At the upper level the selection and sizing of the units is optimized by either solving a simplified (and linear) design and operational problem [218] or using evolutionary algorithms [112, 138]. At the lower level, for each fixed design solution, the operational scheduling problem is solved.

In order to limit the size of the problem, it is possible to reduce the number of expected operating periods (i.e., days or weeks) by considering only the most representative ones (i.e., "typical days" [138] or "typical weeks" [112]). Starting from historical data of the users' energy demand, data clustering algorithms, such as the k-means algorithm [155, 188], can be effectively used to group similar operating periods (i.e., daysweeks with similar profiles of energy demands) into clusters and select a few representative demand profiles to be included in the design problem.

4 Operational Network and Storage Management

Originally natural gas was treated as a byproduct of crude oil or coal mining and was spared. The flares in the mining field were usually natural gas. Not until the introduction of pipelines did the natural gas become one of the major sources of energy. The earliest gas pipelines were constructed in the 1890s and they were not as efficient as those that we are using nowadays. The modern gas pipelines did not come into being until the second quarter of twentieth century. Because of the properties of natural gas, pipelines were the only way to transport it from the production sites to the demanding places, before the concept of Liquefied Natural Gas (LNG). The transportation of natural gas via pipelines remains still very economical, but it is highly impractical across oceans. Although the LNG market is burgeoning in high speed now, pipeline network remains the main transportation system for natural gas.

From the operational stand point, the main objective for the optimization model is to ensure optimal routing and mixing of natural gas. The objective for the model is to deliver the nominated volumes in the different import terminals within a time period. This objective can be reached in several ways, and in order to influence the operation of the network some penalties are introduced in the objective function. This is done to influence the impact of the following goals:

- Maintain planned production from the producers, where this is physically possible.
- Deliver natural gas which meets quality requirements in terms of energy content.
- Deliver within the pressure requirements of the contract.
- Minimize the use of energy needed in order to deliver the natural gas to the customers by minimizing the pressure variables.

The goal of the network and storage operation is to route the gas flow through the network in order to meet demand in accordance with contractual obligations (volume, quality and pressure). A set of constraints are therefore to be satisfied, the following list describes them:

- Production capacity: total flow out of a production node cannot exceed the planned production of the field in that node;
- Demand: the total flow into a node with customers for natural gas must not exceed the demand of that node;
- Mass balance for each node: this constraint ensures the mass balance in the transportation network;
- Pressure constraints for pipelines: this is probably the most important and complex constraint, since it calls for the satisfaction of the equation to describe the nonlinear relationship between flow in a pipeline as a function of input and output pressure. Normally this is done by using the Weymouth equation. This equation can be linearized through Taylor series expansion around a point representing fixed pressure into the pipeline and fixed pressure out of the pipeline respectively. Some physical pipelines between nodes where the distances are very limited can be modeled without pressure drops by the Weymouth equation simplifying part of the modeling of bidirectional pipelines.
- Modeling bidirectional pipelines: Sometimes a bidirectional flow must be ensured, so specialized constraints with binary variables must be inserted to model this to make sure that there only flows gas in one direction in the pipeline.

- Gas quality and blending: Gas quality is a complicating element because we have to keep track of the quality in every node and pipeline, and this depends on the flow. Where two flows meet, the gas quality out of the node to the downstream pipelines depends on flow and quality from all the pipelines going into the node

Apart from the pure network operation and optimization, also the storage must be taken into account in the whole operational problem. Indeed as a consequence of the liberalization process in the natural gas industry, the natural gas markets have become more dynamic. The spot markets and the possibility to trade gas in forward markets have increased the importance of gas storage. The main problem of the storage management is related to the simple fact that one wants to take advantage of the strong seasonal pattern in prices. Since the primary use of natural gas is for heating and production of electricity, the fundamental price determinant in the markets is the weather.

However, modelling the storage in a realistic way is not as simple as it may seem, in fact the maximum in—and outflow rates of the storage varies with the current storage level. The maximal injection rate is a strictly decreasing convex function of the storage level. Likewise the outflow rate can be given as a strictly increasing convex function of the storage level. Other concepts such as Cushion gas and Working gas must be considered in order to model the storage in a correct way.

All the variants of the network and storage operational problem can be complex MILP or MINLP, with typically non convex continuous relationships.

5 Gas Network Flow Optimization

A gas network has a number of entry and exit points. Shippers independently contract the right to use the network on these points. Only at the time of actual use, the combination of entries and exits is known. One of the questions is, if all possible future transport use by the shippers can be met.

Past In the past the situation of gas transport was merely static. So it was possible to take a long period (years) and use expert knowledge to generate severe realizations (these are called shipping variants) that should be considered to check whether a new contract can be honoured.

Present Currently a method is used, based on simplified models, to generate a limited set of shipping variants which should be considered when a new situation occurs. Since the changes in law and new energy sources lead to many more different situations such a method should be fast, robust, structured, objective, based on simple principles and generates a small set of shipping variants. The proposed method satisfies most of the requirements and reproduces known shipping variants obtained by expert knowledge.

Future Although the method works well for the current situation it is important to base the method on a firm mathematical basis. Furthermore it would be nice to reduce the number of shipping variants even more.

Open questions are:

- Which physical quantities, metrics and techniques should be used to find those transport conditions that determine the size of the infrastructure?
- Which techniques are available to sufficiently reduce the obtained set in order to find an exhaustive subset whose elements are mutually exclusive, given a required accuracy?
- What mathematical optimisation tools can be used to maximise the load and minimise the number of scenarios, given that all transport paths from entry to exit need to be covered?

For the problem a variety of optimization methods have been used: From linear programs to mixed-integer nonlinear programs. The choice of method depends first and foremost on the chosen model for the pressure drop in pipes and whether one uses a time-dependent model or not. Among the easy cases are the following: If the network is topologically simple, say a so-called gun barrel or tree-like network, then dynamic programming approaches are the state-of-the-art (see [71]). If one chooses to use a stationary model, then it can be reasonable to use an algebraic solution of a simplified system, a special case of these is known as the so-called Weymouth equation. The problem then is a mixed-integer nonlinear program which can be tackled directly with off-the-shelf MINLP solvers for small networks or using specialized methods for larger networks (see e.g. [213, 243]). Popular choices for methods include using piecewise linear approximations/linearizations to obtain MILP models [166, 167, 296], MPEC-based models (see [31, 380]). Neglecting the discrete decisions leads to NLP models which can be solved to local optimality (see [382]). But also these equations can be simplified even further. A possibility is to locally linearize them around a working point, an approach that is very successful in practice (see [203]). If one opts to use the full Euler equations in the instationary setting one obtains a mixed-integer PDAE-constrained optimal control problem that is intractable for current methods except for very simple networks. Another approach with high physical accuracy is to use a (sub)gradient-based approach on top of an accurate simulation tool (see [222] and [431]). In order to reduce the high degree of nonlinearity that results from the gas dynamics, different approaches simplify the full Euler equations to the isothermal case, i.e. assuming constant temperature of gas. Additionally, the usage of different discretization schemes for the underlying isothermal Euler equations results in different transient gas flow models. For example, [106] use a piecewise-linear representation of the nonlinearities leading to MILP models. Alternatively, [460] and [288] neglect the discrete nature of the active elements and solve the resulting NLP models. [63] present a new discretization scheme that admits to keep the algebraic structure of the stationary Weymouth equation which is used to obtain globally optimal solutions of the MINLP model.

6 Optimal Operation of District Heating Systems

Future power systems with a large penetration of fluctuating renewable energy production from wind and solar power generation call for demand flexibility. In Denmark, for instance, on average 44% of the power load in 2017 was covered by wind power production, and during several hours the wind production was well above 100% of the electricity load, which was possible partly because of the flexibility of the widely used DH systems.

Heating and cooling represent a huge part of the total energy consumption. According to 2014 Eurostat figures, in the EU around 30% of the primary energy is used to produce heat, and 40% is used for electricity, including electricity for heat production [241]. The dynamics and inertia of thermal systems and the low-cost storage capabilities for hot water, imply that DH systems are capable of playing an important role in the future intelligent and integrated energy system. As mentioned above, in Denmark DH systems already play a very important role in the integration of the fluctuating renewable energy production and for providing energy balancing services to the power grid.

Historically DH systems are often considered as single systems, but this is rather due to the historic emphasis on energy supply as subsystems of different supply sources (e.g., gas, coal, and electricity). However, today they act as a key element for integrating the different energy systems, and they provide some of the needed flexibility to the power system [300]. DH systems also provide an eminent possibility of using excess heat from e.g. industrial production and cooling in super markets.

This section briefly describes the operational optimization problems involved in various parts of DH systems, and some methodologies and tools for solving these problems will be indicated. For operational convenience we will split the discussion into a number of subsystems, which can provide flexibility to the overall DH system. Each subsystem leads to an optimization problem and calls for adequate related methodologies for providing the optimal operation. The optimal operation of the following subsystems are considered:

- DH plant, including production and storage facilities.
- DH network with the pipes and pumps.
- DH users, which might also consist of secondary distribution networks.
- DH connected heat pumps and boilers.

In general, DH systems often consist of a spectrum of different possibilities for heat production. For example, thermal solar plants are becoming increasingly popular nowadays. However, the solar energy production is often hard to predict, and hence this calls for methods like probabilistic forecasting and optimization under uncertainty [311]. Here methods like stochastic programming and stochastic control theory are obvious for solving the operation problem in near real time. Therefore, the operation of the total DH system can be considered as a set of nested stochastic programming and control problems, which are presented in more detail in the remainder of this section. In the following description only district heating will be considered, but almost the same principles can be used for district cooling.

Operation of DH Plants The portfolio of production units in a DH system, comprising of combined heat and power (CHP) plants and heat-only units, can be used to react to current state of the energy system and thus increase efficiency and reduce imbalances. In periods with high generation of intermittent renewable power resources, the generation can be shifted to heat-only units, which maybe even consume power (e.g. heat pumps) to lower the imbalance in the grid, while fulfilling the heat demand. In periods with less power production from wind and photovoltaic, CHP plants can provide power to the market while producing heat. Thus, the coupling of the operation of the district heating system to the electricity markets is important [277]. The key to reducing costs in the operational production is by considering all production units as a portfolio to make use of the flexibility. By optimizing the entire portfolio, the interplay between the units can be used to further reduce costs and increase income from the market. During the optimization several restrictions have to be considered, such as the capacities of the producing units and connected thermal storages as well as technical characteristics of the units (e.g. start up/shut down times and costs).

In recent years, the production of heat from the installed small CHP plants has slightly decreased in favor of heat-only units such as boilers and heat pumps, due to the reduction of the electricity prices. The design of today's electricity market forces CHP producers to present power production offers 1 day before the actual energy delivery. Consequently, forecast uncertainties in prices and heat demand must be considered for an optimal planning of DH systems. Furthermore, the above mentioned increase in solar thermal production introduces an additional source of uncertainty from the heat production side.

To efficiently operate this mixture of heat production units while reducing the operational costs, several optimization techniques such as MILP, Lagrangian relaxation, heuristics, or fuzzy linear programming have been proposed. However, the use of MILP prevails over the other methods due to the easy implementation of these programs in available commercial solvers. In addition, the formulation of two-stage stochastic and robust MILP problems allows the integration of uncertainty in the optimization problem yielding in better operation plans for CHP plants [103, 467]. The use of two-stage stochastic programs to optimize the heat production of different heat-only, storage and CHP units translates into more flexibility in the real-time operation [322]. Finally, stochastic programming has been proven to be an effective tool to make use of DH networks to integrate the uncertain production from renewable energy sources [200].

Operation of DH Networks The problem of determining the optimal operation of DH network relates to finding the optimal combination of flow and temperature profiles that provide the minimal operational cost. Pumping costs are, however, often an order of magnitude smaller than the costs related to the heat loss induced by having a too high supply temperature profile in the network [378]. Consequently, a reasonable control strategy for DH networks is to keep the supply temperature from the district heating plant as low as possible. This is in particular the case, if the heat production takes place at a CHP plant [284, 285].

The control of the temperature is subject to some constraints. For instance, the total heat requirement for all consumers must be supplied at any time and location, such that each individual consumer is guaranteed some minimum supply temperature. A lower supply temperature leads typically to large savings, since this implies lower heat losses from the transmission and distribution networks as well as lower production costs.

As described in [285], the optimal operational problem can be formulated as a stochastic problem which can be solved using dynamic programming. Furthermore, given probabilistic forecasts for the heat load, cf. [321], and stochastic models for the dynamics in the network, the problem can be described as a problem which can be solved using stochastic control theory.

A DH system is an example of a non-stationary system, implying that model parameters have to be time varying, e.g., the time-delay from the plants to the end-users is unknown and time-varying. Therefore, the methods used in conventional predictive control theory have to be modified [347]. The modified controllers have been incorporated in a software package, PRESS (HeatTO), developed at the Technical University of Denmark. PRESS (HeatTO) has been applied and tested, e.g. at Vestkraft in Esbjerg, Denmark, and significant savings have been documented [284].

Operation of DH End-Users The end-users in DH system can provide flexibility by storing energy in the thermal mass of the buildings or in a local water tank. In [186] it is shown how nested stochastic control problems can be defined such that the thermal mass of buildings can provide services to the future smart grid. This is further explained in [286].

Furthermore, in order to avoid, e.g., costly upgrades of the existing network in large cities, it will be more and more important to control the maximum energy used within a certain interval. This can be obtained by a control that directs the maximum flow towards specific end-users or districts.

Dynamic tariffs provide another option for enabling flexibility in DH networks. For instance, to reduce the peak consumption in the morning, an extra price or penalty can be utilized during peak hours.

Operation of Heat Pumps and Boilers It is suggested in e.g. [286] that dynamic electricity prices can be used to control the electricity consumption and hence to enable the needed flexibility for integrating large shares of fluctuating and intermittent renewable power generation.

Time-varying price signals are an example of a penalty signal that can be linked to the optimization and control problem in order to arrive at a cost optimal solution by demand response. Another example are real-time marginal CO_2 signals that can be used as a penalty signal linked to the optimization problem. Then the optimal solution will minimize the CO_2 emission associated with the optimal control or operation.

Different penalty signals will lead to different optimal solutions for the problem and the choice depends on the context or societal ambition. Three of the most obvious penalty signals are the following:

- **Real time CO_2**. If the real time (marginal) CO_2 emissions related to the actual electricity production is used as penalty, then the optimal control will minimize the total carbon emission related to the power consumption. Hence, the heat production provided by the heat pump or boiler will be *emission efficient*.
- **Real time price**. If a real time price is used as penalty, the objective is obviously to minimize the total cost. Hence, the optimal operation is *cost efficient*.
- **Constant**. If a constant penalty is used, then the controllers would simply minimize the total energy consumption. The optimal control will the provide a systems which is *energy efficient*.

It is clear that a DH system with controllers defined by an objective of minimizing the total emission would in general lead to an increased use of energy. However, this may happen during periods with, e.g., a large amount of wind power production and where the alternative would be to stop some wind turbines.

7 Gas Networks in Energy Systems Sector Integration

Transition of energy systems from fossil to renewable energy sources took a boost after 21st Conference of the Parties (COP21) in 2015, where participants of United Nations Framework Convention on Climate Change signed the Paris Agreement. They committed to reduce greenhouse gas emissions gradually until 2050 [417]. The aimed reductions in greenhouse gas emission in 2030 and 2050 are known as COP21 goals. To reach these goals there are several potential pathways and increasing the share of renewable energy sources (RES) in electricity production is one of them [361]. Regarding the share of electricity in final energy consumption and share of electricity production in greenhouse gas emissions [133, 216] as well as varying nature of RES, a holistic view to the energy production and transmission systems together with energy consuming sectors is required to reduce the greenhouse gas emission as aimed while maintaining the security of supply of energy. This brings the sector coupling notion into the scene.

The concept of sector coupling is defined by the International Renewable Energy Agency [326] as co-production, combined use, conversion and substitution of different energy supply and demand forms—electricity, heat and fuels. The readers are referred to [361] and [60] for extended literature review on sector coupling. As seen from the studies in the literature, the main challenge in modelling sector coupling is the computational complexity induced by integrating several models of sectors included in the study. Hence, the studies in the literature either include a smaller number of sectors, i.e., electricity and gas, or reduce the spatio-temporal span of the study, i.e., including only a single country or a restricted region [60, 81].

In a very recent study commissioned by European Parliament [132] sector coupling is separated in two groups.

- "end-user sector coupling" involves the electrification of energy demand while reinforcing the interaction between electricity supply and end-use [316].
- "cross-vector coupling" involves the integrated use of different energy infrastructures and vectors, in particular integration of electricity, heat and gas.

In this section, we focus on how other energy vectors are integrated into gas infrastructure in different scenarios for cross-vector sector coupling on the supply side. Gas networks' interaction with energy systems are twofolds.

- Gas networks as gas provider for gas-powered plants (GPPs): Gas networks main function is to transport gas from suppliers to the final consumers that include industry, household users as well as gas-fired power plants (GPPs). Hence, the main interaction between the gas networks and energy system is through the supply of gas to the GPPs that produce electricity. However, with the increase in share of RES that are stochastic in nature, in electricity production GPPs—as more agile electricity production facilities—have been used to balance the demand for electricity with a potential of resulting in a rapid and larger scale fluctuation in gas network demand then it used to be. This brought the question whether the gas demand required to produce electricity especially at peak demand times can be met from the gas suppliers, i.e., indigenous production sites, LNG facilities or other countries that the gas is imported, given the existing gas network infrastructure. State-of-the-art academic studies focusing on this question focus on very limited scales such as 5–10-node small networks designed for research or simplified small networks, i.e., 79-node UK network [20, 72, 80, 144, 302, 449]. On the other hand, Beulertz et al. [43], propose a flexible modeling framework including integration of other energy vectors to gas infrastructure, which is going to be tested by a case study aiming at investigating a multi-modal European energy concept. They use a stationary gas model to evaluate the feasibility of the optimal multi-model energy mix found in the case study using a multi-modal investment model, European unit commitment model and electricity grid model. In this context, gas networks serve as a flexibility option to the electricity network by their ability to store gas in pipelines and underground gas storage facilities connected to the gas network. The electric-powered compressor stations in gas network that use electricity to compress gas to increase the pressure of gas in the pipes of the network are other means of interaction in the context of security of supply of gas to GPPs (See Sect. 11).
- Power-to-gas: Power-to-gas (P2G) is an emerging technology that provides flexibility to energy system by converting surplus electricity produced by RES to hydrogen or synthetic methane, and feed it into the gas network. On the other hand, gas power stations convert gas into electricity in peak demand situations with not enough RES available. Thus, P2G lies in the interface of gas and

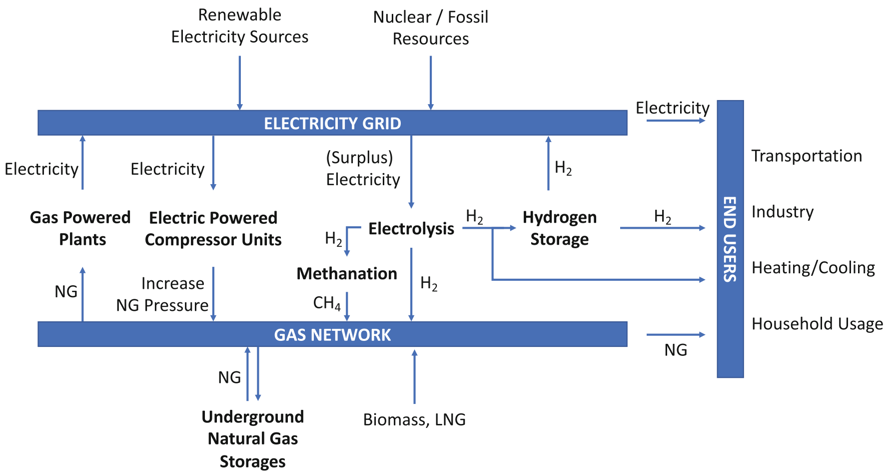

Fig. 1 Interaction of gas network and energy system through P2G

electricity network, where the amount of gas fed into the gas network is limited by the network's technical capacity and properties of the gas fed into the network. Interaction of gas network and energy system through P2G is presented in Fig. 1.

The main challenge for integrating other energy vectors into gas network models arise from the physical nature of gas and electricity. Gas flows in pipelines according to thermodynamic laws making it slow to move in the network with a velocity about 20 km/h, that is the speed of a bicycle. Hence, a demand in a gas network cannot be met instantaneously and the duration depends on the amount of the demand as well as the amount of gas in the network at a particular time. In addition, physical models for both gas networks (see Sect. 5) and electricity networks (see Sect. 7) possess non-linear natures that make them difficult to solve. For example, Clegg and Mancarella report about 140 min run time for optimal power flow model and about 100 min for transient gas network optimization model for monthly modeling of an equivalent 29-busbar system and a 79-node gas network [80]. Hence, the studies that evaluate the integration of gas networks and electricity networks use different approaches regarding the system scenarios and modeling approaches, as well as various spatio-temporal resolutions [20, 43, 72, 75, 80–82, 144, 202, 302, 449, 461].

The gas and electricity systems currently operate independent from each other and how the gas and electricity systems work depends on technological and operational developments in both sectors as well as the individual regulatory developments [316]. The studies that evaluate integrating electricity network models to gas networks use scenarios of different integration levels, which vary from scenarios involving separate operation representing current status-quo to fully coordinated operation, to evaluate the integration of gas networks and electricity networks.

- Separated operation of systems: They solve electricity network model and gas network model separately and use demand results from electricity network with gas network to find out whether a feasible solution exists in the gas network [43, 461].
- Interconnected gas network and electricity network systems: The electricity and gas network models are solved using iterative or sequential algorithms, in such a way that they use each other's results to fix/improve their solutions [20, 43, 80–82, 461].
- Integrated gas network and electricity network systems: They use a single model for finding a cost optimal operational setting for both gas and electricity models [20, 72, 144, 302, 316, 449].

From the modeling point of view, the integration is studied using detailed physical models of gas networks and electricity networks, or simple economic or energy flow model for at least one of the networks, i.e., simple economic model for electricity network and a detailed physical model for gas network [75], or vice versa [202].

In the studies where physical models are used for both systems, the gas network is modeled using either a stationary gas network flow model [43, 81, 82], or as transient network flow model on very limited scales such as 5–10-node small networks designed for research or simplified small networks, i.e., 79-node UK network [20, 72, 80, 144, 302, 449]. Although the former is practically less data demanding and computationally less expensive, it does not account for intra-day flexibility of the gas network [243], which is important to evaluate the feasibility of gas network operation subject to the fluctuations in gas demand caused by GPPs. In order to account for intra-day flexibility of gas networks, stationary models are augmented with linepack analysis [81].

ENTSO-G and ENTSO-E address P2G as a promising technology for integrating wind and photovoltaic production into the overall energy system, that is complementing other technologies like integration using the power grid, electric power storages and power to thermal storage [114]. For this matter, the EC and the European Council support the approach of implementing P2G facilities from the system perspective after a first assessment [114]. So that P2G is studied in the interface between gas and electricity networks in the context of integrating other energy vectors to gas networks.

Studies evaluating the potential of P2G technologies and pathways generally focus on the following three practicalities [352].

- Production: Efficient production of technologies and processes from electricity to gas are studied [33, 379].
- Distribution and transmission: There are some concerns about hydrogen injection in natural gas grid since hydrogen embrittlement can lead propagation of cracks in the iron and steel pipelines, hydrogen leakage is riskier than natural gas leakage, etc. [301]. However, it is generally agreed that low concentration of hydrogen in the natural gas grid has no serious safety issues. On the other hand, converting gas network to hydrogen networks and operation of hydrogen

networks that are separate from natural gas networks are also studied [105, 185, 396].
- End use: Household appliances or industrial machinery should be made suitable to using hydrogen blended gas. Heat pumps and transport vehicles using Hydrogen only are another potential use of Hydrogen generated by P2G [352, 379].

For extensive review of P2G studies in the literature, the readers are referred to [50, 185, 352]. [19, 43, 50, 80, 82, 349, 350] are examples for studies that model P2G when evaluating the feasibility of gas network and electricity network interconnection.

General practice in studies in literature that model P2G in the interface of gas and electricity networks is to assume that the gas network has an appropriate level of allowed hydrogen volumetric share in the gas network. This level imposes limits to amount of gas fed into the gas network by P2G affecting the dispatching of electricity production schedules in the electricity network side. Thus, restrictions to the application of P2G are implied to electricity grid models, although the level of allowed hydrogen into the gas grid changes among countries such that UK allows 1% whereas the limit in The Netherlands is 12% [352]. These restrictions imposed by limited transport capacities of the gas network and allowable amount of hydrogen are calculated by gas network models as linepack of the pipelines that depends on the volumetric gas flow and in gas network model the effect of hydrogen is not considered [349, 350, 352]. The reader, who is interested in effects of blended hydrogen in gas pipelines, is referred to [185] for energetic aspects of hydrogen through pipelines and percentwise mixing of hydrogen into a natural-gas bulk.