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12

Combined operational planning of natural gas and electric power systems: state of the art

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1. Introduction

The growing installation and utilization of natural gas fired power plants (NGFPPs) over the last two decades has lead to increasing interactions between electricity and natural gas (NG) sectors. From 1990 to 2005, the worldwide share of NGFPPs in the power generation mix has almost doubled, from around 10% to nearly 19%; reaching in 2007, for instance, the 54% in Argentina, the 42% in Italy, the 40% in USA, and the 32% in UK (IEA, 2007; IEA, 2009a). The installation of NGFPPs has been driven by technical, economic and environmental reasons. The high thermal efficiency of combined-cycle gas turbine (CCGT) power plants and combined heat and power (CHP) units, their relatively low investment costs, short construction lead time and the prevailing low natural gas prices until 2004 have made NGFPPs more attractive than traditional coal, oil and nuclear power plants, particularly in liberalized electricity markets. Additionally, burning NG has a smaller environmental footprint and a lower carbon emission rate than any other fossil fuel.

NGFPPs are the link between electric power and NG systems, since they play the role of producers for the former and consumers for the latter. Therefore, the growing use of NGFPPs has had a great impact on the NG market. Power generation accounted for around half of growth in gas use from 1990 to 2004; over the most recent five years, this proportion rose to nearly 80% (IEA, 2007). This fact is especially notable in those countries where large capacities of NGFPPs have been installed.

Two major indexes indicate the level of interrelations between electric power and NG systems. The first one is NG demand for power generation as a share of the total NG consumption, and the second one is the share of electrical energy produced by NGFPPs. Both shares depend not only on the NGFPPs installed capacity, but also on relative fuel prices (NG, coal, oil derivatives products) and the availability of other energy resources (hydroelectricity, wind power). Fig.1 shows year 2007 indexes for several countries and also on a global basis (IEA, 2009a, b). Significant values of both indexes are typically a sign of strong interdependencies. Fig. 1 includes some of the countries with the highest indexes in the world, such as Argentina, Italy, Malaysia, the Netherlands, Russia and Turkey.

The interdependencies between electric power and NG systems can be described from a technical-operational viewpoint. The NGFPPs dispatch determines the total amount of NG

consumption and its flows through the pipelines. On the other hand, the NG availability for NGFPPs is constrained by the maximum capacity of gas injection into the pipeline system (from producers, regasification terminals and NG storages), the limited transmission capacity of pipeline network, and priority scheme for the supply of NG in case of shortages, in which residential and commercial customers typically take precedence over large consumers and NGFPPs. Contingencies in NG infrastructure (e.g., interruption or pressure loss in pipelines) may lead to a loss of multiple NGFPPs, and thus jeopardize the security of the power system.

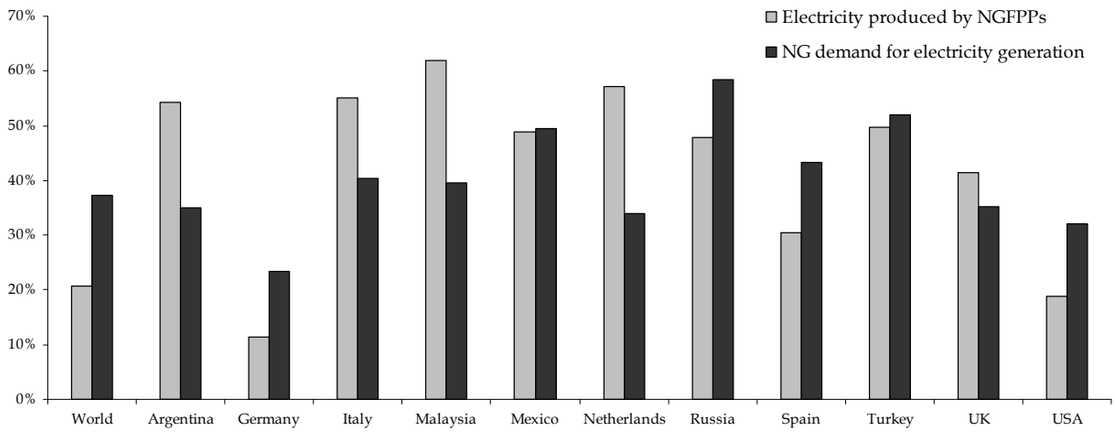


Fig. 1. Indexes of interactions between electric power and NG systems in 2007

These interactions can also be explained from a market perspective. The regulatory frameworks and the type of markets implemented in electric power and NG systems set the extent and the dynamics of the existing interdependencies. Generation companies that own NGFPP participate simultaneously in both markets, therefore, they are best suited for price arbitrage between both commodities. Liberalized and flexible market structures facilitate this practice which is required to reach an electricity and gas *partial economic equilibrium*. According to electricity and NG market prices, and the marginal heat rate of their plants, these companies can decide to use gas and sell electricity in the power market, or resell previously contracted gas on the NG market and purchase electricity to meet their commitments. Therefore, electricity and NG market prices are increasingly interacting between them, which is particularly noticeable when no direct oil indexation is applied to NG pricing (IEA, 2007).

From 2005 to the first half of 2008, the raising NG prices have eroded the competiveness of NGFPPs, decreasing the pace of growth in NG use for electricity generation and reducing the incentives for future investments in these technologies. Nevertheless, as NG prices have converged to lower levels during 2009, the NGFPPs have recovered their investment attractiveness. For the coming decade, NGFPP capacity is estimated to continue to account for the bulk of electricity generation capacity additions. Beyond the factors in favor of NGFPP investments pointed out above, NGFPP could become one of the swing resources utilized to provide flexibility in power systems with large shares of intermittent renewable generation, underpinning the investments in these technologies (IEA, 2009d). On the other hand, from NG market perspective, the electric power sector accounts for 45% of the

projected increase in world NG demand by 2030. As a result, the power sector's share of global NG use will rise to 42% in 2030 (IEA, 2009c).
Under the light of all the conditions previously described, there is a strong and rising interdependency between NG and electricity sectors. In this context, it is essential to include NG system models in electric power systems operation and planning. On the other hand, NG system operation and planning require, as input data, the NG demands of NGFPPs, whose accurately values can only be obtained from the electric power systems dispatch. Therefore, several approaches that address the integrated modeling of electric power and NG systems have been presented. These new approaches contrast with the current models in which both systems are considered in a decoupled manner.
Among all the issues that arise from this new perspective, this chapter presents a complete survey of the state of the art in the combined operational planning of NG and electric power systems. The review covers the different time horizons considered in the operational optimization problems, ranging from the long-term (2-3 years) to the single period analysis.
This chapter is organized as follows. Firstly, the general characteristics of electric power and NG systems are described and compared. Secondly, the typical energy systems planning procedure, whose results provide the framework for the operational planning, is introduced. Then, the coordinating parameters used under a decoupled dispatch of electric power and NG systems are explained. Finally, the most relevant economic and market issues associated to this new situation of strong interactions between electric power and NG sectors are described and analyzed.

2. Natural Gas and Electric Power Systems

Energy infrastructure is composed of all the energy systems involved, which provide the energy required by different consumers. The technical energy systems include production, processing, treatment, transportation and storage facilities, which comprise the supply chain from primary energy sources (oil, coal, natural gas, nuclear, solar, wind) to the final energy carriers required by consumers (electricity, natural gas, district heat). In this task, electric power systems play two important roles in energy supply: allows the use of primary energy sources such as nuclear, hydroelectric and wind energy that otherwise were useless, and allows flexibility because most energy sources can be transformed to electricity. Fig. 2 shows a general scheme of the energy system supply focused on the electric power systems and the primary energy resources that converge to them.
In particular, electricity and NG are energy carriers, i.e., a substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes (ISO, 1997). While NG is a primary energy because exists in a naturally occurring form and has not undergone any technical transformation, electrical energy is a secondary energy, since it is the result of the conversion of primary energy sources. However, NG and electric power systems have a remarkable common feature which is that extensive networks are used to transport the energy from suppliers to customers. NG can also be carried in the form of Liquefied Natural Gas (LNG), which requires liquefaction trains, LNG ships and regasification terminals to accomplish with transport and re-inject the gas into the network. Pipelines transportation is more cost-effective over short and onshore distances, while LNG is typically used in transcontinental carriage (IEA, 2007).

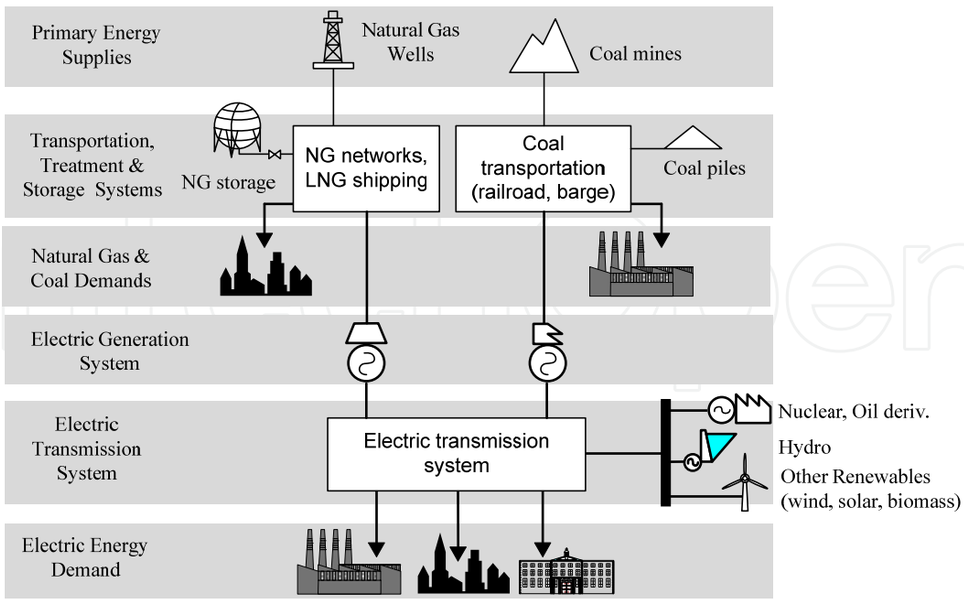


Fig. 2. Electric energy supply system and the converging energy resources

Table 1 shows the similarity in the organizational structures of electric power and NG systems.

Segments	Natural Gas Sector	Electricity Sector
Production (suppliers)	Gas Wells LNG regasification terminals	Electrical power plants (coal, nuclear, gas, hydro)
Transmission	High pressure network	High voltage network
Distribution	Medium/low pressure network	Medium/low voltage network
Consumption	Small consumers (commercial and residential customers) Large consumers (NGFPPs, industries, liquefaction trains)	Small consumers Large consumers

Table 1. Organization of electric power and NG systems

Fig. 3 shows a schematic representation of interconnected NG and electric power systems. The electric power system consists of a 3-bus network connecting NGFPPs, hydroelectric power plants, non-gas thermal power plants to electrical loads. The NG supply system is analogous to the electric power system, with high-, medium- and low-pressure pipelines connecting remote sources - gas wells and LNG regasification terminals – to large/small consumers and NGFPPs.

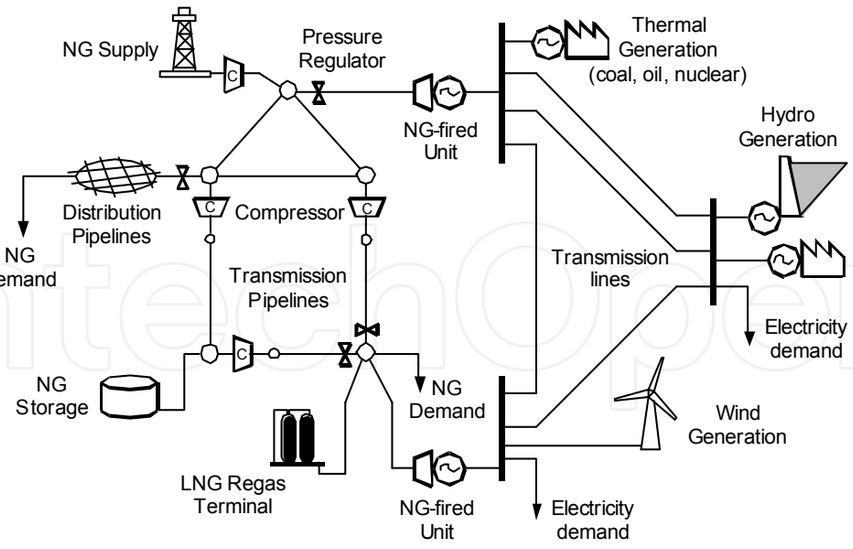


Fig. 3. Natural gas and electricity systems

In electric power systems, large generation units (hydro, nuclear, coal, etc.) are far from consumption centers, so the energy delivery involves several voltage levels (from 500kV to 0.4kV) of transmission and distribution networks to interconnect production areas to consumption centers. The electric power generation system consists of a heterogeneous set of technologies (hydro, CCGT, nuclear, coal/NG fired steam turbine, wind, etc.) with different capacities and operating constraints.

In electrical networks, the steady-state electric power flows are governed by Ohm's and Kirchhoff's laws. These laws can be expressed by means of nodal power balances and line power flows. Mathematically, the power flow through a transmission line depends on the complex voltage difference at its ends and its physical characteristics (serial and shunt resistance-reactance). The maximun capacity of each line is limited to its thermal limit (maximum conductor temperaure) or to stability margins set for the whole electrical network. The energy losses in the electrical networks are due to line resistance (Joule losses) and to a lesser extent to shunt losses (corona effect). The conversion between different voltage levels is performed by means of power transformers. The supervision, control and protection of transmission and distribution networks are performed by complex systems of switchgears and instrumentation equipments.

Like in the electricity production segment, a great diversity of technical characteristics can be found among gas suppliers. Gas wells (commonly located at sites far from load centers) and LNG regasification terminals (harbor locations) have a wide diversity of capacity and operating constraints.

NG transmission and distribution networks provide the same services as their electricity counterparts. Transmission pipelines undertake the responsibility of transporting NG from producers to local distribution companies or directly to large consumers. Distribution networks generally provide the final link in the NG delivery chain, taking it from city gate stations and additional gas supply sources to large and small customers.

Four basic types of facilities are considered in the modelling of NG transmission network: pipelines, compression stations, pressure regulators, and nodes (gathering or interconnection hubs)

A priority scheme for the supply of NG is generally in place for the situation where not enough gas is available to supply all the NG demands. Residential and commercial customers typically take precedence over large consumers and NGFPPs in this allocation.
With some similarities to electric power systems, the steady-state gas flow through a pipeline is a function of the pressure difference between the two ends, gas properties (e.g., compressibility factor, specific gravity) and physical characteristics of the pipe (e.g., diameter, length, friction factor), (Osiadacz, 1987). Therefore, the pressure represents the state variable which its analogous in power systems is voltage.
During transportation of NG in pipelines, the gas flow loses a part of its initial energy due to frictional resistance which results in a loss of pressure. To compensate these pressure losses and maximize the pipeline transport capacity, compressor stations are installed in different network locations. In contrast to electricity networks, where theoretically no significant active power is necessary to maintain a certain voltage, compressors are usually driven by gas turbines. The amount of NG consumed at compressor stations basically depends on the pressure added to the fluid and the volume flow rate through it. However, the operating pressures are constrained by the maximum pressure allowed in pipelines and the minimum pressure required at gate stations. Therefore, the transmission capacity of a gas pipeline is limited.
Valves are protective and control devices whose functions are similar to switchgears in electric power systems. Isolating valves are used to interrupt the flow and shut-off section of a network. Pressure relief valves can prevent equipment damage caused by excessive pressure. Pressure regulators can vary the gas flow through a pipeline and maintain a preset outlet pressure.
Compressor stations and pressures regulators enable a high degree of control of NG flow through the networks. On the other hand, currently it is neither economical nor practical controlling individual power transmission line flows using flexible alternating current transmission system (FACTS).
A comparison between electric power and NG systems is summarized in Table 2.

Characteristic	Power Electric System	Natural Gas System
Energy type	Secondary	Primary
State variables	Voltages	Pressures
Transmission losses (large systems)	Joule effect, up to 3%	Gas consumed in compressors stations, up to 7%
Flow modelling	Steady-state can be assumed for operational simulations	Transient-state is required for operational simulation (time steps shorter than several hours)
Supply hierarchy	Not required in normal operation state	Frequently required in normal operation state. Usually NGFPPs and industries have lower priority
Individual flow controllability	Currently neither economic nor practical at (FACTS)	By means of compressors and compressor stations
Storage facilities	Not yet technically or commercially feasible	Widely used in Europe and USA, not common in Latin America

Table 2. Differences between electric power and natural gas systems

While steady-state operation of power electric systems requires a constant balance between supply and demand, gas storage facilities are typically used to load balancing at any time, on hourly, daily, weekly or seasonally basis, keeping a NG supply as constant as possible. Additionally, large underground storages perform, principally, a supply security (strategic stock) function.

Unlike electricity, which large scale storage is not yet technically or economically feasible, natural gas can be stored for later consumption. There are three major types of NG storage facilities: a) underground storages (depleted gas/oil fields, salt caverns and aquifers), b) LNG tanks and c) pipelines themselves (the amount of gas contained in the pipes is called "line-pack" and can be controlled raising and lowering the pressure). These storage facilities are different in terms of capacities (working volume) and maximum withdrawal rates.

Other important difference between NG and electricity systems is that electricity moves at speed of light, while NG travels through the transmission network at maximum speed always lower than 100 km/h (reference value). These facts imply that the dynamic behaviour of NG systems is much slower than the dynamics of electric power systems. Thus, while steady-state electric power flows are assumed for multi-period simulation with time steps longer than half hour (even up to several minutes), NG flows multi-period simulations with time steps shorter than several hours require pipeline distributed-parameters and transient models (Osiadacz, 1987, 1996). However, many simplified models have been developed to NG flows simulation (Osiadacz, 1987) and transmission system optimization (Osiadacz, 1994; Ehrhardt & Steinbach, 2005).

3. Energy Systems Planning

Nowadays, there is consensus among policy makers that energy sector investment planning, pricing, operation and management should be carried out in an integrated and coordinated manner in order to achieve an economic, reliable and environmentally sustainable energy supply. A hierarchical and sequential procedure is typically used to tackle this huge and complex decision-making problem.

The so-called energy models are the first stage in this hierarchical energy planning procedure. In such models, all (or most) energy carriers are considered in an integrated approach. Several of these energy models have been developed to analyze a range of energy policies and their impacts on the energy system infrastructures and on the environment. Others are focused on the forecast of energy-service demands. An overview and a classification of some of the most relevant energy models, like TIMES (integrated MARKAL-EFOM system) (Loulou et al., 2005), MESSAGE (Messner & Schrattenholzer, 2005), ENPEP-BALANCE (CEESA, 2008) and LEAP (SEI, 2006), are described by Van Beeck (1999). These models are focused on a long term planning horizon (more than 10 years) and can be tailored to cover local, national, regional or world energy systems. The interactions between the energy sectors and the other sectors of the economy (e.g., transport, industry, commerce, agriculture) can be taken into account through model extensions or represented by means of constraints.

Because the dimensions of the problem, energy models are developed neither to represent the characteristics of different transport modes, nor to model the complex physical laws that governs electric power and NG systems. Usually, only nodal energy balances per each

energy carrier are considered. Another limitation of these models is related to energy storage facilities, which are typically oversimplified or disregarded.
The results of energy models provide the framework for the following stages, in which each energy carrier system is planned and operated in a decoupled manner. Thus, specific procedures and strategies are implemented according to specific value system, e.g., economic, technical, political and environmental context. Usually, single energy carrier system expansion and operation planning are carried out considering the other energy carriers availabilities and prices as coordinating parameters. Electric power systems are a good example of this approach: they are planned and operated without taking into account the integrated dynamics of the fuel infrastructures and markets, i.e., costs and capacities of fuel production, as well as storage and transportation. The main assumption, in which this decoupled planning and operation approach, is based on the fact that there have not been significant energy exchanges between the energy carriers if they are compared with the total amount of energy supplied by each energy carrier.
More recently, new approaches to energy system planning have been presented. They are focused on a higher technical description of some energy sectors and their transport modes. The model presented by Bakken et al. (2007) includes the topology of several energy systems, and the technical and economic properties of different investment alternatives. Among other energy modes of transport, simplified electricity and NG networks are considered. This approach minimizes total energy system costs (i.e., investments, operating and emissions) for meeting predefined energy demands in a time horizon of 20–30 years. Hecq et al. (2001) and Unsihuay (2007b) propose specific methodologies and tools to address particularly the integrated NG and electric power systems planning. The network models consider not only the electricity and gas nodal balance, but also the loss factors and constrained capacity for each of the pipelines and electric network lines.

4. Coordination of Natural Gas and Electric Power Systems Operations

Nowadays, the operational planning of electric power and NG systems are carried out in a decoupled manner, i.e. different operational optimization problems are performed where each system is self-contained. However, this does not mean that both systems are totally independent. In fact, the existing interactions are modeled by means of fixed coordinating parameters. Typically, three types of parameters can be identified:

a) The NG prices considered in the production cost functions of each NGFPP;
b) The NG availability for the NGFPPs; and
c) NG consumption at each NGFPP

While, the electric power operational planning requires, as input data, the (a) and (b) set of parameters, the NG operational planning needs, as input data as well, the (c) set of parameters.
The decoupled approach consists in two stages. Firstly, the operational planning of electric power system is performed, being the NGFPP's consumption a byproduct of this procedure. Then, the operational planning of the NG systems can be carried out. The results of this last procedure include the NG marginal costs at each NGFPP location and NG actually supplied to each NGFPP.

However, the following situations can occur:

1. The total NG supply is not sufficient to meet the total NG demand, including the NGFPPs' demands. The NG supply to NGFPPs can be curtailed before than other demands, since NGFPPs usually have lower priority of supply.
2. The limited transmission capacity in the NG network can imply that the same situation described in 1) occurs in a specific node.
3. The fixed NG prices, which determine the NGFPPs' production costs, cannot match with the NG marginal costs at nodes where NGFPPs are placed. These marginal costs depend on the NG consumption in the compressor stations (NG network losses) and the binding pipeline's (transmission) capacity constraints..

If any of these situations actually occur, a re-dispatch of the electric power is required updating NG prices and availabilities for each NGFPP according the results obtained from the NG operational planning. Therefore, both operational planning models must be run iteratively. The convergence of procedure is slow and may be hard to reach when NG consumption in NGFPPs is a significant share of the total NG demand.
On the other hand, in a combined operational planning of NG and electric power systems, the described coordinating parameters are endogenous results of the optimization problem. This ensures that the optimal operating schedule for both is achieved simultaneously.

5. Combined Operational Planning of Natural Gas and Electric Power Systems

Several approaches that address the integrated modeling and analysis of energy systems in a more comprehensive and generalized way have been presented. These approaches consider multiple energy carriers; particularly electricity and NG systems interactions and combined operation have been investigated.
An assessment of the impact of NG prices and NG infrastructure contingencies on the operation of electric power systems is presented by Shahidehpour et al. (2005). A security-constrained unit commitment model, in which NG availabilities and prices are external parameters, is used to perform these evaluations. Conversely, Urbina & Li (2008) analyze the effect of pipelines and transmission lines contingencies by means a combined electric power and NG model.
A review of the main approaches and models, which deal with the integrated operational planning of multiple energy carrier systems, is presented in following subsections. This review is based on the survey collected by Rubio et al. (2008). The different approaches are conveniently grouped according to the considered time horizon.

5.1 Long- and Medium-Term

Quelhas et al. (2007) propose a generalized network flow model of an integrated energy system that incorporates the production; storage (where applicable); and transportation of coal, NG, and electricity in a single mathematical framework, for a medium-term operational optimization (several months to 2-3 years).
The integrated energy system is readily recognized as a network defined by a collection of nodes and arcs. Fuel production facilities, electric power plants and storage facilities are also

modeled as arcs. A piecewise linear functions are applied to represent all cost and efficiencies. Since the problem is entirely modeled as a network and linear costs, a more efficient generalized network simplex algorithm is applied, than ordinary linear programming. The total costs considered are defined as the sum of the fossil fuel production costs, fuel transportation costs, fuel storage costs, electricity generation costs (operation and maintenance costs), and the electric power transmission costs. The objective of the generalized minimum cost flow problem is to satisfy electric energy demands with the available fossil fuel supplies at the minimum total cost, subject to nodal balances, maximum and minimum flow in each arc and emission (sulfur dioxide) constraints.
Additionally, the hydroelectric systems (hydropower plants and reservoirs) are also taken into account by Gil et al. (2003), but the emission constraints are not considered in this model. Correia & Lyra (1992) present also a generalized network flow model including only hydroelectric, NG and sugar cane bagasse as energy resources.
Bezerra et al. (2006) present a methodology for representing the NG supply, demand and transmission network within a stochastic hydrothermal scheduling model. The NG demand at each node is given by the sum of forecasted non-for-power gas and NGFPPs consumptions. The gas network modeling comprise: a gas balance at each node; maximum and minimum gas production, pipelines flow limits; and loss factors applied to gas flows (to represent the gas consumed by compressor stations). NG storage facilities are not been taking into account in this approach. The stochastic dual dynamic programming (SDDP) algorithm is used to determine the optimal hydrothermal system operation strategy, which minimize the expected value of total operating cost along the time horizon (2-3 years typically). While the total cost includes the fuel and shortage costs relating to electricity supply, the shortage costs associated to non-for-power NG load shedding are not considered. The NG prices are fixed from the outset and they are not results of the optimization process.

5.2 Short-Term

Unsihuay et al. (2007c) present a new formulation in order to include a NG system model in the short-term hydrothermal scheduling and unit commitment. NG wells, pipelines and storage facilities are considered, while nodal balances and pipelines loss factors are taking into account for a simplified gas network modeling. Gas storages are modeled similarly to water reservoirs. A constant conversion factor is used as input-output conversion characteristic for NGFPPSs. A dc power flow modeling without losses is applied to determine electric power flows. The problem is formulated as a multi-stage optimization problem, whose objective function is to minimize the total cost to meet the gas and electricity demand forecast. This total cost is the sum of the non-gas fired generators fuel costs, the startup costs of thermal units and the NG costs calculated at each gas well. The optimization procedure is subject to the following constraints: a) electric power balance at each node, b) hydraulic balance at each water reservoir, c) NG balance at each node and gas storage, d) initial and final water and gas volumes at reservoirs, e) electric power generation limits, f) maximum electric power flow through lines, g) NG withdrawal limits at gas wells, h) pipelines maximum transport capacity, i) bounds on storage and turbined water volumes, j) bounds on storage and outflow gas volumes, k) minimum up and down time of thermal units, and l) minimum spinning reserve requirement.

To solve the integrated electricity-gas optimal short-term planning problem an approach based on dual decomposition, Lagrangian relaxation and dynamic programming is employed.

Li et al. (2008) and Liu, et al. (2009) present the electric power security-constrained unit commitment problem including a NG network model. While in (Li et al., 2008) the NG flows are calculated through a nodal gas balance model, the steady-state physical laws (pressure differences) that govern NG flows are modeled in (Liu, et al., 2009). In both approaches, local NG storages at each NGFPP are considered. Particular and detailed modeling of fuel switching capabilities is described in (Li et al., 2008). Liu, et al. (2009) apply a decomposition method to separate the NG system optimization from the electric power security-constrained unit commitment problem, and treat it as a feasibility check subproblem.

A multi-period combined electricity and NG optimization problem is presented in (Chaudry et al., 2008). The modeling in this approach takes into account not only NG storages facilities, but also the NG contained in the NG network, so-called line pack. The optimization is performed with one month as time horizon with daily time steps. However, the authors include an approximation of the transient NG flows using the finite difference method. A detail model of NG storage injection and withdrawals rates is described.

5.3 Single Period - Snapshot

An et al. (2003) present a combined NG and electricity optimal power flow. The authors deal with the fundamental modeling of NG network, i.e., the steady-state nonlinear flow equations and detailed gas consumption functions in compressor stations. A complete formulation of the NG load flow problem and its similarities with power flows are shown in detail. Ac power flow modeling is applied to determine power flows in the electricity network. The objective function is formulated in terms of social welfare maximization. Thus, the total cost are represented by the generation costs due to non-gas electrical plants and gas supply costs, while the total benefits correspond to the electrical and gas consumers benefits. The benefits that would be allocated to NGFPPs are disregarded since the NGFPPs costs are also not considered.

Unsihuay et al. (2007a) also deal with the integrated NG and electricity optimal power flow. Nonlinear steady-state pipelines flows and compression station are modeled. However, the gas consumption in compressor stations is not considered. The objective function in this approach is to minimize the sum of generation costs due to non-gas electrical plants and costs of gas supply.

Urbina & Li (2007) propose a combined optimization model for electric power and NG systems. The objective is to minimize the electric power production costs subject to the NG transport limitations. A piecewise linear approximation is used to model the NG flows through the pipeline network. Since the steady-state NG flow is a non-convex function, the piecewise approximation is formulated using integer variables. Thus, a mixed integer linear programming is applied to solve the optimization problem.

Mello et al. (2006) and Munoz et al. (2003) present a model to compute the maximum amount of electric power that can be supplied by NGFPPs, subject to NG systems constraints. Nonlinear steady-state NG flows and the effect of compressor stations to enlarge the transmission capacity are included in the NG network modeling. Like in Unsihuay et al. (2007a), the amount of gas consumed in the compressor stations is neglected.

Geidl & Andersson (2007) introduce a comprehensive and generalized optimal power flow of multiple energy carriers. This paper presents an approach for combined optimization of coupled power flows of different energy infrastructures such as electricity, gas, and district heating systems. A steady-state power flow model is presented that includes conversion and transmission of an arbitrary number of energy carriers. The couplings between the different infrastructures are explicitly taken into account based on the new concept of energy hubs. With this model, combined economic dispatch and optimal power flow problems are stated covering energy transmission and conversion. Additionally, the optimality conditions for multiple energy carriers' dispatch are derived, and the approach is compared against the standard method used for electric power systems.

Arnold & Andersson (2008) address the combined electricity and NG optimal power flow (OPF) using the approach proposed by Geidl & Andersson (2007). The OPF problem is solved in a distributed way where each energy hub (combined electric power and NG node), also referred to as control area, is controlled by its respective authority. Applying distribution control techniques, the overall optimization problem is divided into subproblems which are solved iteratively and in a coordinated way. Under this approach different operating targets (e.g., cost minimization, emission caps, security criteria) can be applied at each energy hub.

Hajimiragha et al. (2007) extend the model of Geidl & Andersson (2007) to consider hydrogen as another energy carrier.

Rajabi & Mohtashasmi (2009) present a new model which integrates the NG transport cost in the electric power economic dispatch problem. The NG flows are modeled through the steady-state nonlinear equations and transport cost is defined as the sum of NG consumption in compression stations. The non-for-power NG demand is disregarded.

Ojeda-Esteybar et al. (2009) present a comparison between the decoupled and the combined approach for the optimal dispatch of electric power and NG systems. Rubio-Barros et al. (2009) present a detailed an extensive analysis of the coordinating parameters, which are the reasons for the inefficiencies in the decoupled approach.

6. Economic and Market Issues

Electricity and gas sectors have been liberalized to a certain extent in many countries, introducing competition at varying degrees and at various levels of the value chain. Essentially, these restructures have been attained by unbundling the different segments of the industries. In the electricity sector, the production segment (generation) was separated from the service segments (transmission & distribution). In the same way, the NG sector was split up into a production segment (upstream) and pipeline network services (midstream & downstream). Like in the electricity system, gas transmission and distribution companies provide open pipelines access to other market participants for gas delivery which has permitted producers to sell gas directly to end users and marketers. Different types of markets have been established, allowing the interaction between production sector (suppliers) and consumption sector (demands).

Since a significant share of total NG consumption is used to produce electricity; the market prices of both energy carriers are linked. Therefore, the NGFPPs play a key role in the electricity and gas price dynamic because they are the market participants that allow the

arbitrage between the two commodities. Liberalized markets for both commodities promote the arbitrage, and therefore contribute to the price convergence.
The increasing links between gas and electricity also offer both a threat and an opportunity regarding energy supply security. Flexibility facilities, such as energy storage (e.g., gas storage, water reservoirs) and fuel switching (in NGFPPs or steam power plants) are important resources to ensure the gas and electricity supply security and to reduce prices volatility. Additionally, efficient gas and electricity markets tend to reduce gas demand as prices increase, saving gas at times of high demand or low supply.
Different experiences in liberalized electricity markets show that one of the most powerful consumer's mean to avert supplier's market power is the presence of a well-functioning, transparent and liquid wholesale market. Therefore, it is likely that a liquid and competitive wholesale market for NG provides also a powerful tool to counterbalance potential upstream market power in gas. There are numerous policy challenges in establishing well-functioning gas and electricity markets to ensure affordable and reliable energy supply. The short-term price spikes are of paramount importance in order to create resilience to short-term but severe disruptions since these spikes reflect the immediate need for balanced, cost-effective and significant responses. Price caps or other market alterations mitigate these signals and the necessary market response, such as reduced demand, increase supply or storage changes.

6.1 Gas Price Formation

The growth of world oil prices has also produced an increase or readjustment of NG price. This correlation is mainly because both fuels are substitutes of each other; especially in the electricity sector.
The economic theory postulates that in a competitive market, like a mature NG market (e.g., USA, UK), the price maker is defined by short-term prices (spot price on Henry Hub or National Balancing Point) or by standard quotations in a Stock Exchange (NYMEX, ICE). Therefore in markets of this nature, the price reflects the interactions between supply and demand. However, in many markets (e.g. European countries, except UK; Japan; Korea) the linkage between NG and oil prices is still rigidly formalized by contracts which include indexation formulas. In NG monopolies, prices are obtained by subtracting the total costs of transmission and distribution from the final convergent energy market price (electricity price).
In NG markets, like in other commodity markets, exist long-term supply or demand contracts with indexed prices over the time and penalties in any case of lack (called deliver-or-pay or take-or-pay contracts). Usually, a significant share of the NG is traded through this long-term arrangement, thus they establish a price reference for the rest of markets with shorter delivery time.
Until a few years ago, NG markets were considered as regional markets due to the lack of sufficient interchange among them. Currently the NG is becoming an increasingly global commodity due to the rapid growth in the installed LNG infrastructure and the development of LNG markets (IEA, 2007).
The NG prices paid by the consumers are calculated as the sum of the wellhead price (or wholesale market price), the transmission cost and the distribution cost.
It important to point out that the interactions between electric power and NG markets are closely related with NG price foundations and how they respond to the demand variations.

Also, the transport cost allocation methodologies used in electric power and NG systems can have an important impact on the interactions. Morais & Marangon Lima (2003, 2009) analyzes the effects of applying different transmission cost allocations to electricity and NG networks. The authors show that coordination is needed between the applied methods in each network, otherwise wrong economic signal are sent to market players, in particular to NGFPPs.

6.2 NGFPPs Perspective

NGFPPs participate simultaneously in electricity and NG markets. NGFPPs can now purchase NG with great flexibility, through bilateral contracts or through the spot market. On the other hand, the wholesale electricity market is an important part in the decision-making process for NGFPPs. When the market implied marginal heat rate (which is the equivalent heat-rate calculated using the clearing price for electricity divided by the prevailing NG price) is lower than the marginal production heat rate of the NGFPP, the generating company that owns this NGFPP prefers to purchase electricity to meet its commitments instead of generate it itself and resell the previously contracted gas on the spot NG market (Chen & Baldick, 2007).

Another way of looking at the same problem is through the so-called spark spread, which is defined as the difference, at a particular location and time between the fuel cost of generating a MWh of electricity and the price of electricity. As a result, a positive spark spread indicates the power generator should buy electricity rather than produce it.

Other service that can be provided by NGFPPs is called tolling, where a power generator receives fuel from a beneficiary and delivers electric power to the same beneficiary in return for a service fee.

Some aspects of the NGFPPs role in the electric power and NG markets have been addressed in recent studies. Chen & Baldick (2007) propose a short-term NG portfolio optimization for electric utilities that own NGFPPs. This approach considers the financial risk associated with the portfolio and a risk preference function of the electric utility. The portfolio includes base load contracts, intra-day contracts, swing supply and withdrawals from storage facilities as NG supply resource options. Purchasing electricity from the wholesale market, selling NG in the spot market and injections in storage facilities are also the alternatives taken into account to supply a given electricity demand. The approach excludes the option of selling electricity to the wholesale market. Usama & Jirutitijaroen (2009) present a profit-risk maximization model focused on NGFPPs involvement in spot and forward markets. This approach uses the conditional value-at –risk as risk measure within the optimization problem. In both approaches price-taking is assumed, and thus the market fundamental behaviour as result of the price arbitrage are disregarded.

Takriti et al. (2001) discuss the problem of heading between the NG and electricity markets. The problem is addressed from an energy marketer perspective that purchases NG from the open market and sells it to contracted customers, but the marketer also has the option to generate electricity and sell the produced electric power to the wholesale market. A NG storage facility is also another balancing resource considered in the model. Hence, based on multiple forecasts for NG customers' demands, NG prices and electricity prices, a stochastic optimization is performed to find the optimal heading strategy.

NGFPPs might also want to resell their firm (take-or-pay) NG contracts every time the consumption of these amount of gas implies economic losses given certain electricity market conditions. Street et al. (2008) investigates the creation of a secondary market, where

NGFPPs offers flexible NG supply to industrial NG consumers, who would receive the NG originally assigned to the NGFPPs only when the latter are not dispatched. All the periods, in which the NGFPPs are committed, the industrial NG consumers should resort to alternative fuels or NG supply. The success of this secondary market depends on the price of the flexible NG supply contracts. Thus, the authors present a stochastic model to look into a range of prices and the feasibility of this type of market.

6.3 Social Welfare

The objective function of a comprehensive (including the demand response) gas and electric optimal operational planning should be the maximization of social welfare during the considered time horizon. This social welfare is the total gross demand surplus due to gas and electricity consumption minus the total system operating cost (gas supply costs and non-gas electric power plant costs). An et al. (2003) present an assessment of the differences in the social welfare for both, integrated and decoupled gas and electricity optimal power flows. They show that there is a social welfare loss (deadweight) for the decoupled case; except when outset gas prices match the prices obtained in the integrated case.

Ojeda-Esteybar et al. (2009) and Rubio-Barros et al. (2009) present a comprehensive economic impact assessment of decoupled approach for the optimal dispatch of electric power and NG systems. The authors show that a higher economic efficiency is achieved and guarantee only if both energy systems are considered in an integrated manner.

7. Conclusions

Different simplified energy models have been proposed for policy analysis, forecasting, and to support regional or global energy planning. Although economic and physical performances of individual subsystems are well studied and understood, there has been little effort to study the characteristics of integrated systems, especially in the medium- and short-term due to the complexity of the required models.

The interdependencies between electric power and NG systems have shown the need of new approaches and models able to take into account these increasing interactions.

The inclusion NG system model is of paramount importance for the electric power systems planning. New methodologies for the integrated expansion and operation planning of both systems are required. Also, NG infrastructure must be considered in power system reliability assessment.

It is envisioned that energy companies and government agencies must consider an integrated approach for the operation and planning of NG and electricity infrastructures to ensure that the most economical and secure policies are used in the foreseeable future.

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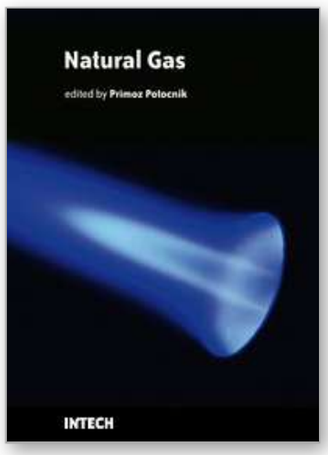
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The contributions in this book present an overview of cutting edge research on natural gas which is a vital component of world's supply of energy. Natural gas is a combustible mixture of hydrocarbon gases, primarily methane but also heavier gaseous hydrocarbons such as ethane, propane and butane. Unlike other fossil fuels, natural gas is clean burning and emits lower levels of potentially harmful by-products into the air. Therefore, it is considered as one of the cleanest, safest, and most useful of all energy sources applied in variety of residential, commercial and industrial fields. The book is organized in 25 chapters that cover various aspects of natural gas research: technology, applications, forecasting, numerical simulations, transport and risk assessment.

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