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2 October 2008

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Abstract: Following the liberalization of the Greek electricity market, the Greek Regulatory Authority for Energy (RAE) undertook the design and implementation of a simulator for the wholesale market and its interactions with the Natural Gas Transportation System. The simulator consists of several interacting modules representing all key market operations and dynamics including (i) day-ahead scheduling based on bids of market participants, (ii) natural gas system constraints, (iii) unplanned variability of loads and available capacity driven either by uncertain stochastic outcomes or deliberate participant schedule deviations, (iv) real time dispatch, and (v) financial settlement of day ahead and real time schedule differences. The modules are integrated into one software package capable of simulating all market dynamics, deliberate or probabilistic, and their interactions across all relevant time scales. The intended use of the simulator is to elaborate on and allow RAE to investigate the impact of participant decision strategies on market outcomes. The ultimate purpose is to evaluate the effectiveness of Market Rules, whether existing or contemplated, in providing incentives for competitive behaviour and in discouraging gaming and market manipulation. This paper describes the development of the simulator relative to the current Greek Electricity Market Design and key contemplated revisions.

1. Introduction

The development of a liberalized electricity market in Greece began with the enactment of Law 2773/1999, harmonizing the national legislation with Directive 96/92/EC. The Law established new entities within the electricity sector in Greece, including the Regulatory Authority for Energy (RAE) and the Hellenic Transmission System Operator (HTSO), as well as gave general directions for the creation of a competitive electricity market. The initial market design, as described in the Grid and Market Operation Code approved in 2001, did not succeed in its scope of opening the market to new players, as the market share of the incumbent utility (Public Power Corporation - PPC) in 2005 was still at 97% on the supply and at 99% on the retail side.

A subsequent electricity Law (no. 3175/2003) and a new Grid and Market Operation Code (2005) provided for the development of a centrally organized daily wholesale market, where all electricity generated and consumed in Greece would be transacted through it. The Code is progressively put in force over a period extending from October 2005 till the middle of 2009.

In order to evaluate the new electricity market design as well as to develop and analyze potential ways in which the market may evolve, RAE launched an international open procedure call for tenders requesting consultancy services for the "*Development of Greek Electric Power and Natural Gas Systems Simulator Including Planning, Execution and Settlement of Short-Term Wholesale Markets*". According to the call for tenders, the Consultant, in co-operation with RAE, would propose and develop (or acquire) software that would accurately simulate all aspects of the Greek wholesale electricity market, including the requirements posed by natural gas fired generation to the natural gas system. The project was awarded to LCG Consulting, a US-based company with competency in modelling competitive energy markets.

This paper describes the collaborative RAE-LCG effort to design and develop a Simulator that captures the rules embedded in the the Greek wholesale electricity Market Design. Section 2 describes the basic concepts of the Greek wholesale electricity market, Section 3 presents an overview of the Simulator, Section 4 presents the details of each basic module, Section 5 discusses key technical issues concerning module integration and software development, and Section 6 presents the next steps regarding the development of the simulator and its applications.

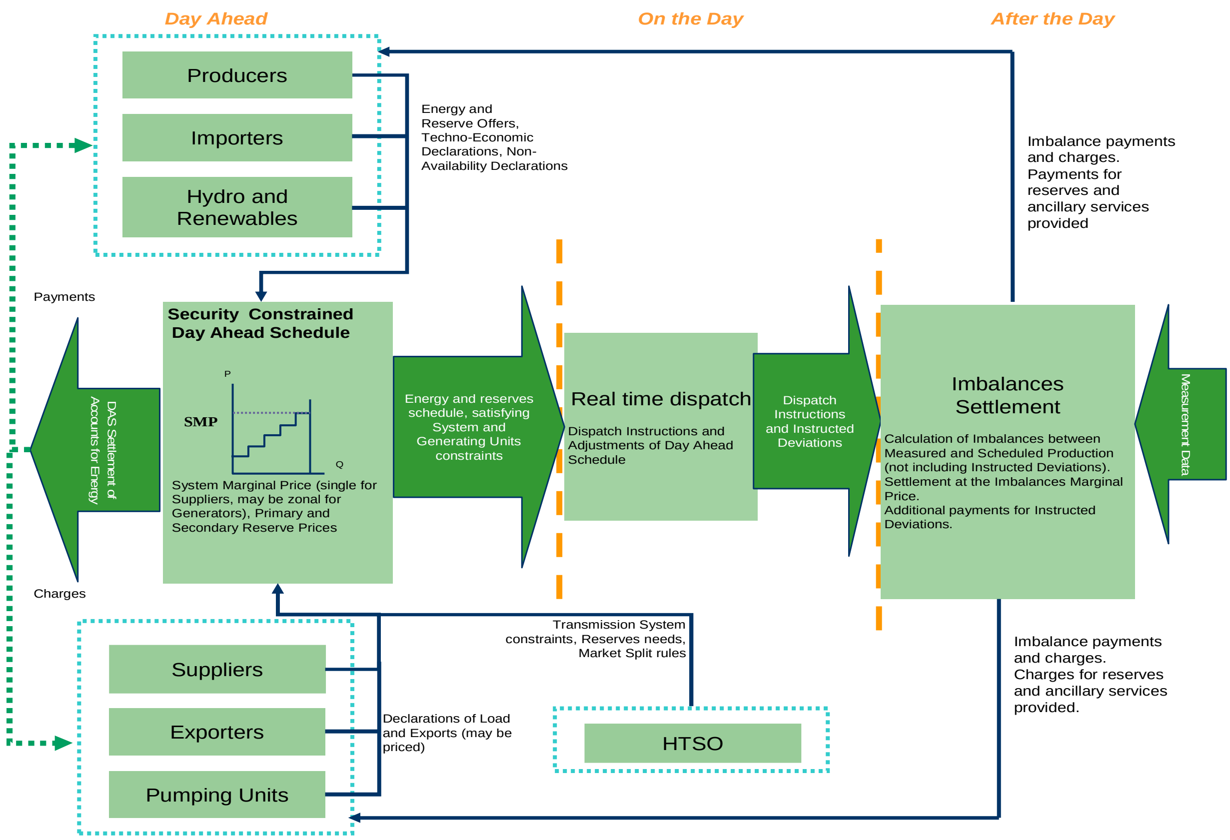


Figure 1. Greek Wholesale Electricity Market Design Schema

2. The Greek Wholesale Electricity Market

Generation on the Greek interconnected electricity system is based mainly on lignite steam units, but also on significant hydro capacity which contributes about 10% of total demand. In 31.12.2007 the total maximum net generation capacity on the interconnected system was 11871 MW, distributed as shown in Table 1.

Plant type	Net capacity (MW)
Lignite units	4808.1
CCGT (n.gas)	1962.1
Oil units	718
Lake Hydro units	3016.5
Natural gas - other	486.8
RES and small cogeneration	769.7
Other cogeneration	109.7

Table 1. Installed Capacity in Greece

As far as the market structure is concerned, the national integrated electricity company, PPC, owns about 95.3% of the installed capacity of 'dispatchable' units (lignite, natural gas, oil and large-hydro). Two competitors hold the remaining 4.7% with two natural gas fired units (390MW CCGT and 150 MW open cycle GT). Considering the RES (wind, photovoltaic, small hydro, biomass, etc) and small co-generation not owned by PPC, then its market share in terms of installed capacity falls to around 90%.

The initial market design adopted a centralised dispatch, with two main restrictions: generators were required to bid their marginal costs and suppliers to own generating capacity equivalent to their customers´ consumption. In 2005 these two restrictions were dropped and a pure mandatory pool model was adopted. Thus, the Greek wholesale electricity market, according to Law no. 3426/ 2005 and the 2005 Grid and Market Operation Code, consists of:

(a) The Day Ahead (DA) market, where the scheduling and clearing of the total energy produced and consumed in Greece, as well as imports and exports, takes place ('mandatory' pool).

(b) The Real Time Dispatch operation

(c) The Imbalances Settlement, which includes the settlement of energy deviations from the DA program and the settlement of the services required for the balancing of the system.

(d) The Capacity Assurance Mechanism, through which part of the fixed costs of the production capacity are covered[1].

All transactions are made via the Day-Ahead market (pool), which does not include bilateral transactions with physical delivery and respective contracts between producers, suppliers and customers. However, bilateral financial contracts may be freely concluded outside the Pool.

2.1 The Day-Ahead (DA) Market. The DA market constitutes the first stage of the wholesale market process and comprises of the following individual markets, which are co-optimized:

- Energy Market
- Energy Reserves Market
- Market mechanism for the allocation of the production near the consumption centers

On a daily basis, participants in the Energy Market submit offers (bids) for energy generation (demand) in the form of a 10-step stepwise increasing (decreasing) function of prices (Euro/MWh) and quantities (MWh) for each of the 24 hour periods of the next day. Producers also submit offers for the Reserves Market, as a single pair of price (Euro/MW) and quantity (MW) for each reserve category (Primary & Secondary reserve[2]).

After the gate closure (at 12.00 pm), the HTSO solves the DA problem based on the bids and offers of the participants. More specifically, the problem is formulated as a Security Constrained Unit Commitment, maximizing the social welfare for all 24 hours of the next day simultaneously, by matching the energy to be absorbed (according to the Load Declarations) with the energy to be injected in the System (based on the Injection Offers, separate for each unit), while meeting a set of constraints. The main constraints are the transmission system constraints, the technical constraints of the generating units and the reserve requirements. The solution of the DA determines how each unit should operate for each Dispatch Period (i.e. each hour) of the Dispatch Day, and also the clearing prices of the Energy and Reserve Markets.

The incorporation in the DA problem of the reserve requirements and of the transmission system constraints, which may well constrain the quantity of energy that flows from the North to the South, minimizes the deviations of the DA Schedule from the real time operation of the Units and therefore reduces the volume of Imbalances Settlement transactions.

The resulting hourly clearing price of the DA energy market (System Marginal Price - SMP) is the uniform price at which the Load Representatives buy the energy they expect their customers will absorb from the System and at the same time is the price paid to the Producers. In most cases the SMP takes a single price for all the Producers, independently of their geographical position. However, if the Transmission System Constraints are activated, this will result in two different Marginal Prices for generation, for the North and South System respectively[3]. The differentiation of the Marginal Price for the Producers reflects the zonal value of electricity and provides the necessary economic signals to the producers for the construction of their units in sites where their value to the System is higher, so as to remove the existing constraints.

All the procedures of DA, including financial settlement of the resulting energy transactions, are concluded within the day that precedes the Dispatch Day (i.e. the day of the physical delivery of energy), referred to as "Day Ahead".

2.2 The Real Time Dispatch operation (RTD). In real-time, i.e. every 5 minutes, the HTSO dispatches generating units already committed by the DA market in order to meet the load and minimise generation costs while ensuring overall system reliability. To this objective, the problem is formulated as a Linear Program, with objective to minimize generation costs subject to constraints for meeting the load (here as load is assumed the load projection for the next 5-min interval), generation units technical constraints, network constraints and reserve requirements

2.3 Imbalances Settlement. Differences between (i) the production and consumption quantities, as well as the reserves scheduled in the DA Market and (ii) the corresponding quantities measured according to the actual operation of the System, are settled during the Imbalances Settlement operation. The participants are credited or debited depending whether they had positive or negative deviations from their DA Schedule. Moreover, all instructed deviations by the Producers are paid at least at their marginal cost. The imbalances are settled at the ex-post zonal SMP calculated by solving again the same DA problem as in the day ahead, but this time using the actual data for the load, RES generation and generation unit availability.

3. Overview of the Simulator

The simulator consists of several modules, which can be classified as simulating modules, or auxiliary modules. Simulating modules utilize main computational engines, many of which are used in more than one module. The main simulator modules are:

[1] We are not going to expand on this mechanism, since it is not part of the Simulator. For more details we refer you to the Grid and Market Operation Code (2005).

[2] At the time this paper is written there is an open public consultation for expanding the Reserves Market by introducing also Tertiary Reserve offers.

[3] The current implementation calls for two zones, however more zones may be created in the future which is already supported by the simulator.

(i) The algorithm that simulates the Greek Day-Ahead Electricity Market Clearing (DAEMC). This is the optimization algorithm that determines the optimal schedule of generation, demand and reserves of the DA market.

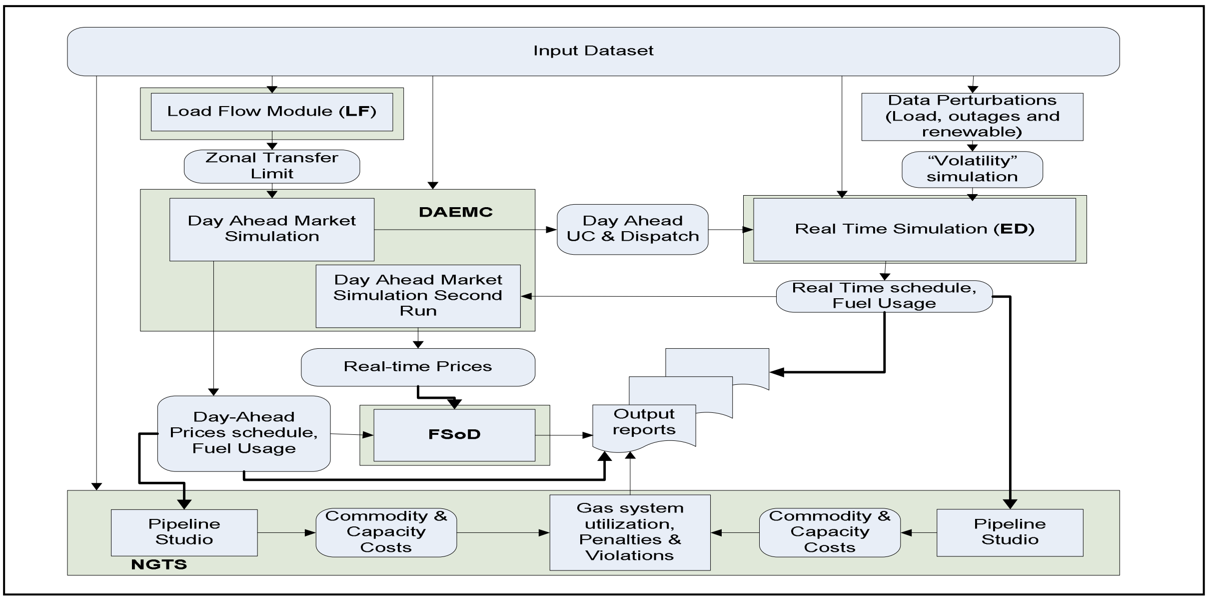
(ii) A module that runs a Load Flow (LF) of the Greek transmission system. The LF module is used to identify the weak points in the transmission system that are likely to impose constraints on the ability to transfer power between different zones. It converts this information to input needed for constraint specification in the DAEMC problem. The module provides estimates of inter-zonal power transfer limits in order to specify transmission constraints needed as input to the DAEMC software module.

(iii) A module that solves the five minute Economic Dispatch (ED) problem using look-ahead information from the DAEMC problem solution. The ED module is used to simulate the real-time operation of the Greek electricity system. It operates on a five-minute basis and it is very consistent to the economic dispatch optimization algorithm used by the HTSO. In order to dispatch the units to meet the load in a manner that respects the entire transmission network it incorporates a Power Flow within its algorithm. A crucial difference between the ED and the DAEMC, is that the ED module does not perform any unit commitment i.e. it is not required to make any decisions regarding start-up or shut-down. Rather, it follows the existing commitment schedule, usually the one that resulted from the DA solution, unless a significant event has taken place leading to a re-commitment. Another functionality of the ED module is to capture variations in the input data that mimic the variations that can be attributed to uncertainty in the real world. These variations are generated by an auxiliary module, the Volatility Module. The purpose of the volatility module is to add a real-time dimension to a scenario by automatically generating deviations between the Day Ahead and the Real Time input data.

(iv) A module that compares the DAEMC hourly schedule to the corresponding outcome of the ED and performs the Financial Settlement of Differences (FSoD) according to the market rules. The FSoD module is used to perform the necessary calculations regarding the energy deviations settled during the Imbalances Settlement. It is the settlement module of the simulator system and its principle task is to perform the credit and charge calculations exactly as they appear in the Grid and Market Operation Code.

(v) A module that runs an appropriate model of the Greek Natural Gas Transportation System (NGTS) to evaluate the operating costs of the NGTS and identify whether, given the planned supply schedule at system gates, the NGTS is capable to meet the location specific quantity and pressure delivery requirements imposed by the consumption for electricity generation scheduled by the DAEMC as well as the rest of the gas consumption as forecasted, or alternatively by the modified consumption for electricity generation that results from DAEMC and ED differences caused by short notice calls on Natural Gas fuelled reserves.

Principally, common methodologies and techniques, related to power systems operation and optimization were the background for these tailor made modules, with the exception of some LCG proprietary techniques. Further, some special modelling and simulating functionalities have been added and integrated in the system by LCG, in the sense of providing even more realism to the operations simulated.



These features are:

- *Demand priority queue logic*: This logic is used to ensure that demand bid queue will be preserved, even in the event of a market split. Demand bids will be cleared in competitive order, regardless of the zone in which they were bid. This logic was necessary since load bids are cleared to the uniform average price, while production bids are cleared to their respective zonal prices.
- *Uninstructed deviations logic*: Uninstructed deviations logic aims to capture the effects when generators do not follow instructions and dispatch orders issued by TSO in real time. While the HTSO follows a specific procedure for flagging these units and then performs the economic dispatch without considering them thereafter, this procedure is based on the experience and logic of the dispatcher and not on some pre-specified procedure on some operations manual. Thus the aim of the uninstructed deviations logic is to lead to a simulated operation very close to the 'real-life' one, in the case of uninstructed deviations.
- *Recommitment logic*: A special logic controlled within the ED execution, which is used to simulate decisions taken in real time regarding alternation of unit commitment and production schedule, when system conditions and sources availability vary greatly from those predicted in the day-ahead.

Furthermore auxiliary modules were developed, mainly to generate and control exchange of data shared by the modules. As aforementioned, one of these auxiliary modules is the volatility module.

4. Detailed Description of the Simulator

4.1. Day Ahead Market Module

The DAEMC module is used to simulate the DA market algorithm, in the form of an optimization which determines the optimal schedule maximizing social welfare for the 24 hourly periods of the next day simultaneously.

The module is practically a classical Unit Commitment (UC) solver, as it performs an optimization, using Mixed Integer Programming (MIP), which determines the best manner in which to startup and shutdown generating units. It does this while considering both the physical characteristics of the units as well as the market implications of any decisions that it makes.

The module considers zonal constraints within its optimization, and can therefore ensure that solutions abide by any transfer limit constraints that exist between various regions.

The DAEMC optimization is formulated as to minimize system costs including

- Cost of energy injected and absorbed
- Cost of primary, secondary and tertiary reserve
- Cost of unit de-commitment
- Cost of unit commitment for contracted reserve, supplementary energy and cold reserve units

In doing this optimization the DAEMC model considers:

- *Energy Balance:* Energy balance for each zone, System Price, Priced Demand Constraint
- *A/S Requirements:* Primary, Secondary, Tertiary Reserve Constraints
- *Unit Constraints:* Upper bound of capacity block, Maximum available production, Technical minimum, Combined energy and reserve margins contribution, Primary, Secondary, and Tertiary Spinning Reserve Capability, Ramp Up/Down, Minimum Uptime/Downtime
- *Zone/Zonal Energy Flow:* Imported and Exported energy limit at interconnection node, Upper limit of branch energy flow, Zonal and system AS constraints
- *Initial Conditions (Initial at time=0):* Current unit operating state, (online or offline), hours in that state (online or offline hours) and in case of online its production level.

Moreover, the ability to introduce generic constraints has been added to the DAEMC module of the Simulator to allow users to capture constraints affecting the energy or ancillary service contribution of certain units or groups of units. The implementation has been made in a flexible manner allowing the summation of the energy contribution of any number units and/or the summation of the primary, secondary and tertiary reserve contribution of any number of units, the inclusion of factors for each of the above contributions by unit and user definition of the constraint operator and "right hand side" value of the constraint.

Slack variables also have been introduced to the model for all constraints which could potentially render the problem infeasible: Energy Deficit, Energy Surplus, Primary, Secondary and Tertiary (Spinning and Non-Spin) Reserve Deficit. Each slack variable in the objective function is associated with penalty, whose value is input by user, imposing the desired priority in relaxing constraints when the model is infeasible.

A generic alarming mechanism has been added allowing informative warnings in the case that certain conditions arise. Currently, alarms are activated if any one of the following four conditions arises:

- Slack Variable Used, for the cases that the problem would have been considered
- Tie Break Situation, for the cases that certain bids are considered to be tied under the definition in the grid code, namely that two (or more bids) are economically equal but are not all accepted at their

bid quantity (which generally means that they are marginal).

- Demand Bid Priority, for the cases that demand bids are cleared in an order which does not adhere strictly to the principles governed by the grid code

The DAEMC module can also be used for intraday commitment in the event that there are unexpected events or large deviations between forecasted and actual load or renewable output. A separate 're-commitment' mechanism as been added to the simulator which monitors the simulated real-time operation of the ED and determines whether an additional unit commitment is necessary at any point during the day. This parallels the capability that the Hellenic Transmission System Operator has currently.

4.2. Load Flow Module

The Load Flow module (LF) provides estimates of inter-zonal power transfer limits. These are then used as input to the DAEMC module.

The module is based upon a commercially available software package called UPLAN, offered by LCG Consulting. This package solves the steady state behaviour of the network through power flow.

The power flow solves an iterative solution of a set of non-linear equations which give the voltage magnitude and phase angles at each bus as well as the real and reactive flow on each line.

As input, the LF requires network data, including each transmission line, transformer and their characteristics such as resistance, reactance, admittance and thermal limits. Further, it requires the injections and withdrawals at each bus. The withdrawals come from the load distribution and assignments which are part of the DAEMC input. The initial injections may be entered manually or can come from the results of running the DAEMC.

In the event that there are violations to any of the transmission flow constraints or if no feasible solutions will balance the generation and load together with the losses that are calculated by the power flow, it may be necessary for the system to utilize a re-dispatch algorithm to manipulate the injections and withdrawals. There may be a number of power flow to re-dispatch iterations before the LF will find a converged, optimal solution.

Finally, since a power flow returns only the actual flows on the transmission lines connecting any two zones, the LF requires that standard practices be performed to calculate the maximum transfer capacity. In particular, it is desired that actual transfer is equal to the maximum transfer allowed. Users will thus develop snapshots of system operation which present extreme conditions, including high zonal or system load, and credible contingencies.

4.3. Volatility Module

During real-time operation, load and generation availability levels may differ from those bid in the DA market and reflected in the DA schedule. Hence, a module is needed to simulate unplanned variability associated with the operation of the electricity market, perturb the DAEMC module input accordingly, and prepare the input for the ED module. This is exactly the purpose of the Volatility module, which lies in between DAEMC and ED modules and is responsible for creating the deviations between the inputs of the two modules.

More specifically, the volatility module is utilized as an instrument to generate "real life" events, following predefined or customized probability distributions, patterns of strategic participant behaviour and the like. It determines generator unit availability changes relative to the state used in the solution of the DAEMC module or output levels set by generator choice as opposed to resulting from a dispatch program or real time dispatch command, and load or renewable energy output deviations. These can be categorized as a) random and unforeseen events (i.e. changes in the load, the renewable sources generation and generator outages) specified by Monte Carlo simulations, or b) deliberate actions on the part of a market participant (e.g. not following a dispatch order), specified by user input. Clear flagging of the respective category is essential so that it can be taken into consideration in the FSoD module.

The implementation of the random events allows users to enter distributions instead of point values for the stochastic parameters. The volatility module then will use the value from the DAEMC and perturb it by sampling from the selected distribution. The distributions available to the user were chosen amongst the most commonly used ones for uncertainty in energy related parameters: Normal, Log Normal, Beta, Gamma, Triangular Distributions. These distributions were chosen so to match observed statistical data and include the necessary correlation between the various Monte Carlo "draws".

During the development of the module two notable issues had to be dealt with. First, there was the discrepancy in the timing and the statistical properties of the DAEMC and ED data. The frequency of the load and renewable production input values is hourly. The DAEMC will take this data and use it directly. The ED, however, requires input discriminating among five-minute intervals and capturing the higher frequency volatility of real time conditions referred to as the "curly" characteristics of the 5 minute input time series. So, the approach followed was to superimpose on the flat hourly data an appropriately selected probability distribution. A linear or cubic spline interpolation was used to achieve consistency between the hourly and 5-minute data. The user can generate more realistic 5-minute ED input data by using a facility which is provided to allow the addition of another random error to the interpolated data.

The second issue has to do with the Multi Interval Optimization performed in the ED. This feature requires that the current interval along with future intervals are solved simultaneously. If only one set of data were generated for forecasts of load and renewables, it would imply that the ED has “perfect foresight” of future intervals in the simulated multi interval horizon. To avoid this, separate input curves were generated to represent the “forecasted” and the “actual” data that is in the ED process; “actual” data is used for the first interval, while “forecasted” data are used for the remaining intervals in the simulated multi interval horizon.

4.4. Economic Dispatch Module

The Economic Dispatch (ED) module dispatches the already committed generating units in 5-min dispatch intervals, refining the day-ahead hourly energy schedules derived by the DAEMC, enforcing the appropriate technical constraints (eg. generating units constraints, network constraints, etc.) while meeting a more granular 5-min load forecast. Thus, the ED is based on

• unit commitment schedule from DAEMC

• bids submitted by market participants

• forecasted load and renewable production (in five-minute intervals)

• technical characteristics of transmission system and generating units

• ΄real-time΄ (simulated) events such as full and partial outages, etc.

The 5-min load forecast simulates actual load that deviates from the hourly load forecast used in the DAEMC to simulate load forecast errors (see Volatility Module above). The forecasted (or ΄real-time΄) five-minute intervals load is distributed to the transmission network buses using appropriate distribution factors.

The ED includes a full AC Power-Flow model providing the capability to enforce network constraints in the dispatch solution both between and inside operational zones.

The overall objective of the ED is to find an optimal dispatch of (already committed) generating units for minimizing cost of supplying energy and ancillary services (maximizing social welfare) with respect to system constraints, i.e. *Min (Generation_Cost + Reserve_Cost – Load_Revenue)*, where:

- *Generation_Cost* represents all energy offers, including imports, for the entire system at all time periods
- *Load_Revenue* represents the revenue from the priced load (bids) and includes all declarations for the full system (including exports) for all time periods.
- *Reserve_Cost* represents primary and secondary reserve offers for the full system at all time periods.

The following constraints are considered:

· Energy Balance for each node (bus)
· A/S Requirements
  o Primary Reserve Constraint
  o Secondary Reserve
· Unit Constraints
  o Upper bound of bidding blocks
  o Maximum available production and technical minimum
  o Combined energy and reserve contribution
  o Primary & Secondary Reserve Capability
  o Ramp Up, Ramp Down rates
  o AGC Ramp rate
· Network Security Constraints
  o Transmission branch flow limit
· Initial Conditions
  o Current unit operating levels (MW)
  o Up or Down times (hours)

The ED module is ΄Multi-nterval΄, i.e. is equipped with a look-ahead capability through a rolling time horizon of a user-defined number of 5-min intervals (typically thirteen). To solve this problem an LP is formulated by taking the committed units from the DAEMC module along with energy and A/S offers and other information such as 5-minute loads and renewable production, generator and transmission outages, the starting conditions and the unit ramping limits to solve a DC optimal power flow for energy and A/S requirements simultaneously for all of the 5-min intervals. It is expected that the ED will be operated using thirteen (or more) 5-min intervals to provide more than one hour of look-ahead capability so as to be able to account for generators’ ramping up/down within that one hour.

Following the solution from the LP, an AC power flow is performed for each 5-minute period to ensure that the DC solution is indeed viable and that there are no voltage violations.

Furthermore, whenever a significant event takes place (e.g. thermal unit or transmission line outage), the DAEMC module is invoked for a recommitment function, using as initial conditions the results of the already performed simulation up to the moment of the significant event.

4.5. Financial Settlement of Differences Module

The FSoD module is used to perform the necessary calculations regarding the energy deviations encountered by the system, based on the settlement rules described in the Grid and Market Operations Code. It provides as well the financial credit and charges sums resulting of these deviations. The module provides its results under the form of easily readable reports which give the intended audience a complete overview of the financial settlements.

The module was constructed as a stand-alone program that is run using the results of the DAEMC and the ED as input. In order to ensure that there will be adequate flexibility in the construction so that the module can be easily adjusted to compensate for any changes in the settlement rules should they occur in the future, a coding interface to the settlement calculations was also implemented. Users are able to change the calculations for settlement for each individual article using the Visual Basic programming language.

4.6. Natural Gas Transmission System Module

In order to investigate the parallel operation of the Greek Natural Gas Transportation System (NGTS) and the Greek electricity market, a special module was required, which would simulate the operation of both systems and provide useful results to RAE, especially regarding the ability of the NGTS to accommodate the expected operation of the gas fired plants, both in the long and the short term, also on the basis of the output of the DAEAMC and ED results and taking into account the needs of the rest of the natural gas consumers in Greece. At the same time, the NGTS module is capable of being used in stand-alone analyses outside of the Simulator if necessary.

The solution that was provided is based on a commercially available package from Energy Solutions, called Pipeline Studio. The system has been in use in many regions throughout the world and therefore includes features and functionalities that are comprehensive and flexible in nature.

As this solution covered the NGTS simulation part only, LCG had to develop an interface between the electric and gas simulators so that fuel usage could be automatically passed from the electricity side of the simulator to the gas side and so that any resulting alarms regarding the feasibility of supplying gas-fired units with the required fuel to support their optimal schedule were passed back and presented in a summary screen.

In case of an alarm, manual coordination is possible and within the capabilities and objectives of the Greek Market Simulator. Under manual coordination, the User would consult the list of alarms generated by the NGTS module, identify generating units with inadequate gas supply, impose energy or capacity limit constraints to these units to reduce electricity production and thus gas demand, and repeat the simulation until an acceptable solution is obtained.

5. Modules integration and Software development

All modules, apart from the NTGS simulation engine, were originally programmed and integrated under a common user interface. The main programming language used is .Net®.

The NTGS module uses externally commercially available software, PipeLine Studio®.

The DAEMC and ED modules utilize the core optimization engine of CPLEX®. The mathematical model is constructed and controlled internally within the module using CPLEX callable libraries routines, rather than transformating it to a common input parsed to CPLEX externally along with some user defined control options.

The LF module uses the commercially available UPLAN software as its core.

The ED module was essentially written from ground up, but contains some proprietary algorithms which were taken from the UPLAN system.

The Volatility and FSoD modules were created uniquely for the simulator.

User Interface

The Graphical User Interface (GUI) of the Simulator has a rich collection of panes and tabs that provide quick and easy access to input data, configuration and execution parameters, and results. The GUI incorporates traditional powerful searching and filtering techniques that facilitate viewing and editing relevant input data. Time dependent data can also be examined graphically with built-in charting capability.

All these typical features found in production-grade market clearing software, are successfully integrated in this market simulator providing a streamlined, user-friendly, and very effective user Interface. Although there is no support for formal automatic data auditing, the GUI promts the user to save the instance of the data as a collection of XML files after any changes, allowing for manual auditing and data version control.

The user can reload an older data set to continue working on a simulation or use it as a base case for a new simulation. The third party product behind NGTS is seamlessly integrated with the rest of the Greek Market Simulator. The User is insulated from the details in the modeling of the natural gas pipeline network and the execution of NGTS. Any resulting alarms regarding the feasibility of supplying gas-fired units with the required fuel to support their optimal schedule are presented in a summary screen.

Configurability

Software architecture is such that allows for maximum configurability providing a versatile simulation environment where the user can edit and change every input data and parameter, which makes it possible to construct any simulation scenario. Nevertheless the data set should be realistic and the constraints and resource operational characteristics must be consistent, in order to provide rational and realistic solutions.

Two very powerful configurability options are generic constraints introduction in DAEMC and rule editing in the FSoD module

Data Model

In order to remain consistent with best programming practices, the Simulator was constructed on top of a relational data model. Relational models ensure consistency between the data present in various parts of the system and enable effective data validation. Typically, relational data models are associated with data residing in relational databases. However, in the interest of providing flexibility, scalability and providing a platform which would reduce the chance of input data inconsistencies, a relational model was used for the data within the application and the XML standard, for the file where the data is stored.

Each input table is displayed and all of the fields present in each table are also displayed. In the case that there are relationships between the tables, each relationship between fields in one table and those of another are shown with connections and key icons in the case that there is foreign key relationship. Foreign key relationships indicate that a unique key field from one table is being used as an identifier in another table. Every piece of data used in the simulator is represented except for the vendor-specific input for the NGTS module.

Inter-Module Dependencies

The DAEMC module requires a significant amount of data to operate properly which will typically come from market information or user input. It has a single dependency with regards to the other modules, which is the LF module. In particular, the LF Module can be used to generate zonal transfer limits which could ultimately become input for the DAEMC.

The ED module requires a schedule to function properly. This schedule comes from the DAEMC module and includes: Hourly commitment and Generation schedule (the units which have been selected for online and their production levels in the Day Ahead market clearing) and Demand Bid clearing (in order to incorporate the correct level of demand in its calculations, the ED module must know which demand bids have cleared in the process).

In order to operate the core engine of the ED module, there must be sufficient input available at the granularity that is needed, i.e. at the five-minute level (as opposed to the hourly DAEMC). It is also the same data that will be used to model differences in the knowledge of the system at the time of the Day Ahead scheduling and the Real Time Dispatch. That is, it is the data that can be used to mimic the uncertainty that is associated with running the system. This data can come from a combination of input by the user and data been created by the Volatility Module

The data subject to this uncertainty consists of five minute renewable “actual curves” and “vision curves”, five minute Demand “actual curves”, “vision curves”, and partial and full generator outages.

The LF is the only module which technically does not have any dependencies. It shares a lot of data as well as logic with other modules, but does not exchange any, information. It is likely, however, that injections required for the power flow will be taken from the results of the DAEMC (this is an automated task).

The basic functionality of the FSoD module is to take the output of other modules and perform the calculations. This mimics the settlement procedures performed by the HTSO that will occur after the conclusion of the operations of the actual market.

The principle module that the FSoD relies on is the DAEMC. In fact, the FSoD relies on the DAEMC optimization engine twice: the DAEMC is run once for the original Day Ahead market solution, and then again for a second time based on the real time information, to provide with ex-post pricing calculations. The reason this is done is because the real-time prices should be developed by the same engine that is used for the Day Ahead.

Regarding the first main run of the DAEMC, the FSoD gets the system and zonal marginal prices by hour, and the hourly generation and demand schedule (accepted demand bids). From the ED module, the FSoD requires hourly measured generation values and hourly Instructed generation. Finally using the engine of the DAEMC the FSod will get only the system and zonal marginal prices by hour, using real time system conditions

Apart from the Greek gas network definition, the NGTS will require input from both the DAEMC and the ED to perform its calculations. The reason for needing both is that the simulator will then be able to predict the differences in the utilization of the gas network based on the different conditions found in the Day Ahead and the Real Time.

In particular, the NGTS will receive the metered generation values from the ED which it will convert into fuel consumption. Similarly, it will receive the hourly schedule from the DAEMC which it will also use to convert into fuel consumption values.

6. Next Steps

The main purpose of the Simulator is to develop and analyze potential ways in which the market operation may evolve. More specifically, during periods that the Market goes through transition to the gradual adoption and implementation of new Grid and Market Operation Code regulations, an important task is to simulate the ex-ante and ex-post market outcomes that will be eventually encountered in reality after the end of the transition period. The aforementioned simulations are intended to assist RAE to learn from virtual reality and anticipate potential problems in the future market operation outcomes. Furthermore, when the Market Code regulations become fully operational, the Simulator will be used to monitor the revealed behavior of market participants.

The current paper discusses the implementation phase of the Simulator, describes the various modules that the Simulator is comprised of, and details the way they are integrated.

The next step is to proceed with the actual use of the Simulator in order to:

- evaluate instances of and strategies used by participants for market manipulation and monopolistic/oligopolistic gaming in the short term energy as well as ancillary services markets as these market designs evolve, and
- assess the effectiveness of current market rules as well as contemplated regulatory policy and market rule redesign.

For these actions, it may be necessary to create special models and methodologies to assist monitoring the markets, as for example,,a bidding model based on gaming which may or may not abide to classical approaches like Cournot, Stackelberg etc. The design of such a game should not necessarily be limited to day ahead or real time market considerations since it may achieve a higher effectiveness by adopting a broader scope that incorporates tariff regulation, business contracting, and competitive import/export considerations. An ideal approach would be to pursue the development of a mathematical model capable of predicting plausible bidding strategies of market players that are compatible with the market rules in place and different objective conditions that may prevail.

Note

In designing and developing the customized Simulator for RAE, LCG Consulting utilized its own proprietary models, codes, algorithms, and other confidential business information.

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