# Impact of Solar Energy on the Integrated Operation of Electricity-Gas Grids

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## Abstract

Photovoltaic energy is one of the clean and efficient energies which has been developing quickly in the last years. As the penetration of solar plants is increasing in the electricity network, new problems have arisen in network operation. This paper models a high penetration factor of solar energy in the electricity network and investigates the impact of solar energy growth on both the generation schedule of different power plants and in the natural gas transmission network. Fuel management of gas power plants is modeled through simulation of the natural gas transmission network. To this end, an increase in the penetration of solar energy in the electricity network inevitably leads to a sudden increase in the output of gas fired units and a linear and integrated model with the electricity and the natural gas transmission networks has been presented to analyze both of them at the same time to better depict the impact of a high penetration of the solar energy in natural gas transmission grids. In this method, natural gas transmission network and Security Constrained Unit Commitment (SCUC) are presented in a single level program. Gas network constraints are linearized and added to the SCUC problem. The stress imposed on the gas network due to a sudden increase in the load of the electricity network is investigated. Conclusions are duly drawn.

*Keywords: Duck Curve; Ramp Rate; Natural Gas; Solar Energy; SCUC.*

## Nomenclature

*Constants*

| | |
|---|---|
| $a_{pb}$ | Inductance of power line between bus $p$ & $b$. |
| $C$ | Efficiency of units. |
| $CG$ | Gas production cost. |
| $CS$ | Natural gas storage production cost. |
| $DR_i, UR_i$ | Ramping up/down limit of unit i [MW/h]. |
| $e$ | Number of hours when the unit is ON. |
| $G$ | Pipeline constant. |

| | |
|---|---|
| $GL$ | Gas load |
| $GP^{\max}, GP^{\min}$ | Max/min capacity of gas supplier. |
| $MxFlow$ | Limit of Power flow in line *b* [MW]. |
| $N$ | Number of generators. |
| $NN$ | Number of nodes. |
| $P_D$ | Electrical demand. |
| $P_{i,\max}, P_{i,\min}$ | Minimum/maximum generating capacity of unit *i* [MW]. |
| $R_t$ | Spinning Reserve at time *t*. |
| $RV^{\max}$ | Upper limit of the natural gas storage tank. |
| $RV^{\min}$ | Lower limit of the natural gas storage tank. |
| $SP$ | Capacity of Natural gas storage [$m^3$]. |
| $STO$ | Number of natural gas storage. |
| $SUP$ | Number of the natural gas supplier. |
| $T$ | Number of hour periods. |
| $\sigma$ | Contracted fuel price of units [$/MBtu]. |

*Variables*

| | |
|---|---|
| $GP$ | Output of natural gas supplier. |
| $I$ | Binary variable ON/OFF status of the unit. |
| $P$ | Generation dispatch of units. |
| $q^{in}, q^{out}$ | Input/output volume of gas storage [$m^3$]. |
| $q$ | Natural gas flow [$m^3/s$]. |
| $SR$ | Natural gas storage output rate. |
| $ST, SD$ | Startup and shutdown consumed fuel. |
| $y_{i,t}, z_{i,t}$ | Startup and shutdown consumed fuel. |
| $\gamma$ | Phase shifter angel. |
| $\theta_r$ | Voltage angle of bus *r*. |

| | |
|---|---|
| $\pi$ | Pressure of the nodes [kpa]. |

*Index and Sets*

| | |
|---|---|
| $i$ | Index of generating units. |
| $j$ | Index of contingency. |
| $m$ | Index of power transmission line |
| $S$ | Index of natural gas storage. |
| $t$ | Index of hours. |
| $w$ | Index of gas supplier. |
| $(p,b)\in m$ | Index of the bus in power transmission network. |
| $(x,z,s,w)\in h$ | Index of node in natural gas transmission network. |

## 1. Introduction

### A. Motivation

Renewable energies like solar energy can be modeled as a negative load for the power network. Due to the nature of solar energy, which depends on solar irradiation, solar energy generation occurs only throughout the day and can vary significantly during 24-hour.

The power rate can be compensated by flexible and high ramp rate units. Gas-fired units are among the fastest units; they can start immediately and increase their output power rather quickly. But, when several gas plants start simultaneously, the gas transmission network will face a considerable stress in different nodes. In this paper, an integrated model is proposed for the electricity network with natural gas transmission network for a high penetration of studying the impact on the photovoltaic energy in both grids.

### B. Literature review

There are different solutions to the high penetration of solar energy in the power grid. Energy storage sources and batteries have been proposed to store solar energy during the day and return it to the network when required [1]. Three approaches for high renewable penetrations are considered, via three Australian case studies; wind plus storage integration; wind, solar PV, plus storage integration; and wind and solar PV integration, without storage [2]. Changing the load pattern and reducing peak load by managing demand and employing demand response programs has also been proposed [3]. Flexible or rapid start units with high ramp rates like gas units provide reserve contributions in a system with interruptible loads [4].

Gas units are fast response and are good candidates for covering uncertainties of renewable energy output due to their flexibility and programmability [5]. In a network with high penetration factor of solar energy, high ramp rate units like gas and hydro units could compensate all sudden changes of the renewable outputs. As a consequence, natural gas transmission might touch different constraints in supplying and transmitting.

Stochastic conditions of the power system including random outages of transmission lines, generating units and hourly load forecast errors into Security Constraint Unit Commitment (SCUC) with natural gas network constraints are modelled in [6]. The nonlinear natural gas network constraints are converted into linear constraints using a piecewise linear approximation in 3-D Euclidean space and incorporated into the stochastic model in [7]. In [8], the non-convex and nonlinear natural gas flow is relaxed into second-order cone (SOC) constraints, then the second-order cone based Column & Constraint Generation (C&CG-SOC) method is employed to improve the operational reliability at the normal state.

There are different methods for modeling ramp rate of power plants. In [9], the increasing rate of plants in terms of output energy which is a function of time is modeled as a nonlinear function. In [10], different ramp rate models are introduced and a Mixed Integer Linear Programming (MILP) model is introduced to increase the rate of gas units in unit commitment. Accurate modeling of units' increasing rate not only increases the accuracy of generation planning and matches with conditions but also affect electricity market and leads to winning of the plants in the competitive market, this study is done in [11].

High penetration of solar energy in a different section of the power system causes different problems in the modeling and operation of power systems. In [12], a dynamic control method is proposed for increasing ramp rate of large-scale solar plants in which solar plants cannot reduce their power significantly in a short time. In [13], electricity load with high penetration factor of renewable energies based on replacing system state instead of load level is modeled. Effect of penetration of the wind and solar energy in energy markets is investigated in a case study in the Australian National Electricity Market [14]. At high renewable penetrations, storage utilization rates are sensitive to renewable energy outputs and market bidding structure [15]. In [16], employing energy storage resources and their sizing based on Monte-Carlo model for matching load and generation in small networks and micro-grids where penetration of renewable energies is high has been proposed. Operation and frequency control of the electricity network with high penetration of renewable energies and using DC converters for increasing control flexibility in [17] in Korea network has been investigated.

Results of investigating simplified energy infrastructure of Great Britain in 2030 Gone Green scenario for diverse gas load and wind availability conditions show that large gas demands decrease the line pack and cause gas-fired units to shut down due to minimum pressure violations [18].

In some distribution networks with high PV penetration, electricity flows from consumer to feeder. In [19], demand response is used to decrease voltage swell and control voltage in the distribution network. By managing feeder power and achieving a flat feeder power profile, controlling voltage level along feeders is feasible. To this end, allowed capacity of installing PV and battery in feeders of distribution network has been investigated in [20]. In [21], optimal planning of the distribution network has been developed using high penetration of solar energy.

All of the previous works look to the high penetration of renewable energy from the power grid point of view and present different solutions to tackle any unpredictable situation in the future. Some new challenges that have appeared in the power system networks could have different consequences on the other energy networks. Today's having an effective collaboration between various energy networks could highly increase the security of operation of the networks by considering the economic issues.

### *C. Aims and Contributions*

In power systems with high penetration of solar energy, the units with minimum ramp up and minimum up time have to be started and increase their outputs at initial times of night or at the same time as the sun sets. Constraints of these concepts and ramp rate limits in power systems with high solar energy become more important in operation. It puts fuel limit on thermal units when several units should start and increase their outputs in a short time.

High penetration of solar energy in the electricity network has challenged its operation. Considering the relationship between the power network and the natural gas transmission network, this paper presents an algorithm for investigating the effect of a high penetration of solar energy on the natural gas transmission network. The problem of a high penetration of solar energies is particularly acute for natural gas networks, because the gas-fired units are fast and usually supply the steep slope of the increase of electricity demand. It will impose a second peak load on the gas load curve. The natural gas network is not so flexible and natural gas as a fluid has inertia that could not reply to the second peak on the network as thriving as possible. So it could impose another constraint on the growth of solar energies on the power system that should be taken into account on the expansion planning of the power system networks.

Due to the nonlinearity of the gas network equations, a linearization process is proposed using Fortuny-Amat transformation method. A linear model for gas networks has been presented in the paper and it is linked with the SCUC problem to form an integrated model that could be solved in a single level. In the proposed modeling, the effect of increasing solar energy in utilizing the electricity network and the gas network can be considered simultaneously.

Hence, a linear and integrated model with the electricity transmission network and the natural gas transmission network is presented to analyze the effect of a sudden increase in gas plants' generation caused by an increase in the penetration factor of solar energy in the electricity network. Natural gas transmission network and SCUC are presented in a single level program. Gas network constraints are linearized and added to the SCUC problem. The stress imposed on the gas network due to a sudden increase in the load of the electricity network is investigated.

### D. *Paper Organization*

The rest of this paper is organized as follows: in section 2, the impact of a high penetration of solar power on the load curve is presented; Section 3, introduces the integrated model of gas and SCUC. In section 4, results obtained from modeling the method proposed in this paper on a test network are presented. Finally, conclusions and recommendations are presented in section 5.

## 2. Duck Chart and Penetration of Solar Energy

With the development of solar energy technologies and the decrease in installation costs of solar cells, they have been widely used in the world such that it has reached from 23GW in 2009 [22] to 303GW in 2016 [23], and it is predicted to reach 4600GW by 2050. The nature of solar energy and its consideration in the operation of power system changes the behavior of the electricity load curve. For instance, in a study in California, load increased 13000 MW in 3 hours and this created a lot of problems for system operators. This curve is named duck curve [24], Fig. 1.

To reliably operate in these conditions, ISO requires flexible resources defined by their operating capabilities and requires flexible resource capabilities. So, the unit must be able to start and stop multiple times per day and change ramp directions quickly because over generation occurs as the ISO prepares to meet the upcoming upward ramps that occur in the morning and in the late afternoon. It needs to match supply and demand at the whole time, controllable and flexible resources should change their output levels and start and stop as dictated by real-time conditions of the grid. To manage the green grids, it needs flexible resources to be installed in the right location. The ISO is collaborating on rules and new market mechanisms that support and encourage the development of flexible resources to ensure a reliable future grid.

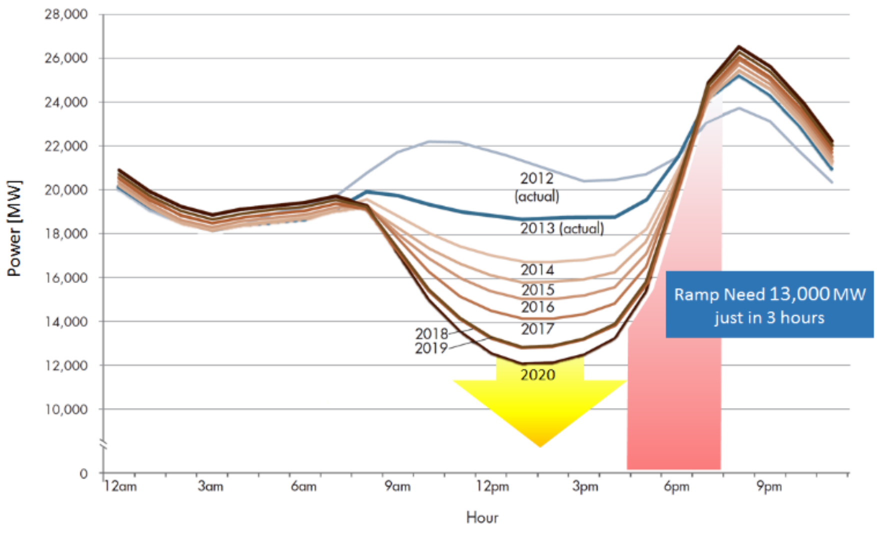


Fig. 1. CAISO duck chart [24]

## 3. Integrated Model of Gas and SCUC

With the development of gas plants and the importance of providing their consumption gas, continuity and connection of electricity network and natural gas transmission network are increasing. Thus, modeling the electricity network in which constraints of the gas transmission network are also considered is of great importance.

Along with different methods of electricity and power networks modeling, an integrated model which considers constraints of gas transmission network along with constraints of the electricity network and not as a separate issue might facilitate conducting different studies. In the following, an integrated model of gas and electricity network is proposed.

In Fig. 2 a block diagram is provided to clarify the model. The elements of the organizational flowchart illustrate the considered aspects modeled by the proposed approach.

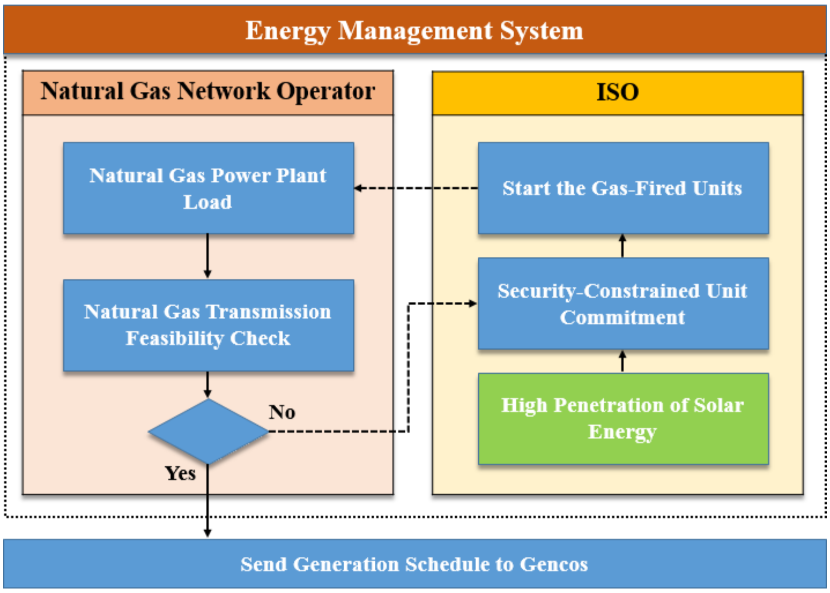


Fig. 2. Coordination strategy for the impact of solar energy on electricity and natural gas network

### A. Objective Function

Power systems are operated with different objectives by system operators including minimizing network cost based on fuel cost and other plant costs. Moreover, maximizing social welfare which is the difference between demand and supply costs can be the system objective function.

In order to propose an integrated model of gas network and electricity network, objective function should include costs of gas network in addition to the electricity network.

Thus, the objective function is to minimize the costs of both networks.

$$Min \quad \sum_{t=1}^{T}(\sum_{i=1}^{N}\sigma_i(C_{i,t}P_{i,t}+ST_{i,t}+SD_{i,t})+ \sum_{w=1}^{SUP}CG_{w,t}GP_{w,t}+\sum_{s=1}^{STO}CS_{s,t}SP_{s,t}) \tag{1}$$

In addition, minimizing plant costs might be performed based on a bid of plants because plants propose bid based on their own costs to maximize their profit, thus it can replace fuel cost of plants.

### *B. Constraints*

Unit commitment (UC) problem is to decide which units to interconnect over the next *t* hours, where *t* is common as few as 2 but more commonly it is 24 or 48 hours or even 1 week. The problem becomes security constrained when constraints are imposed to ensure that line flows do not exceed chosen limits following a contingency.

Power systems operators are faced with different constraints where some of them are related to generation units and some others are related to operating constraints and transmission network.

Spinning reserve limits:

$$\sum_{i=1}^{N}P_{i,\max}I_{i,t} \geq P_{D,t}+R_t \tag{2}$$

Ramping rate limits:

$$P_{i,t}-P_{i,t+1} \leq DR_i(1-z_{i,t})+z_{i,t}P_{i,\min} \quad \forall i,\forall t \tag{3}$$

$$P_{i,t+1}-P_{i,t} \leq UR_i(1-y_{i,t})+y_{i,t}P_{i,\min} \quad \forall i,\forall t \tag{4}$$

Max/min constraint of power generations:

$$P_{i,\min}I_{i,t} \leq P_{i,t} \leq P_{i,\max}I_{i,t} \quad \forall i,\forall t \tag{5}$$

Minimum ON time constraints: This constraint signifies the minimum time for which a committed unit should be turned on. Most often, if a plant is turned on, it has to run for the time unit, and when turned off, it will be out for the time. A new variable is defined to describe these plant characteristics. $e$, is the number of hours when the unit is ON.

$$y_{i,t} \leq I_{i,t+TU(i,e)} \quad \forall i,\forall t \tag{6}$$

*TU (i,e)* is presented as follows:

$$TU(i,e)=\begin{cases} e & e \leq T_i^{on} \\ 0 & e > T_i^{on} \end{cases} \quad \forall i \tag{7}$$

Minimum OFF-time constraints:

$$z_{i,t} + I_{i,t+TD(i,e)} \leq 1 \quad \forall i, \forall t \tag{8}$$

*TD (i.e)* is presented as follows:

$$TD(i,e) = \begin{cases} e & e \leq T_i^{off} \\ 0 & e > T_i^{off} \end{cases} \quad \forall i \tag{9}$$

Normal Power transmission constraint:

$$a_{pb}(\theta_{p,t} - \theta_{b,t} - \gamma_{pb,t}) \leq MxFlow_m \quad \forall m, (p,b \in m), t \tag{10}$$

Security Power transmission constraint:

$$a_{pb}^{(j)}(\theta_{p,t} - \theta_{b,t} - \gamma_{pb,t}) \leq MxFlow_m^{(j)} \quad \forall m, (p,b \in m), j, t \tag{11}$$

### C. Natural gas transmission network

During the day, as solar energy increases, gas consumed by plants is decreased and more gas is transmitted to other loads. As the generation of gas plants increases, more flow will pass the pipes which have been under less stress during the day, and this results in sudden pressure drop in other nodes. The compressibility of natural gas makes supplying a large gas load suddenly added to the network to be performed with latency if transmission pipes are not low-load and under stress. This effect shows itself in dynamic studies.

### D. Natural gas flow

The natural gas transmission network is one of the most complicated and nonlinear exploitation and modeling systems due to its compressibility nature which includes different components like transmission pipe, compressor, storage, load and supplier and behavior of natural gas in each of these components is different. In [25], the behavior of natural gas in all components is modeled. Its transient studies are given in [26]. A heuristic method for modeling the natural gas network is presented in [27]. Since the objective of this paper is to model an integrated gas and electricity network simultaneously, gas network modeling should be able to be linked with the SCUC problem. One of the methods for calculating load flow in the gas network is employing the Weymouth Static Equations. This equation is obtained from transient equations governing fluid transmission in a steady state which is as follows:

$$q_{xz,t}\left|q_{xz,t}\right| = G(\pi_{x,t}^2 - \pi_{z,t}^2) \quad \forall (x,z \in h), \forall t \tag{12}$$

The gas transmission equation is completely nonlinear and its modeling for optimization problems will not result in a certain solution which puts convergence of the problem at risk. In addition, gas behavior in other components of the gas network is modeled either linearly or nonlinearly [28]. There are different methods for linearizing the above equation and its relation to electricity network studies are presented. In [29], Bender's decomposition method is used to linearize the gas network in Newton-Raphson equations and at load flow stage. In this paper, Weymouth equation is linearized for integrated modeling the two networks.

### *E. Natural gas storage*

Although natural gas production rises steadily from 2005 through 2014 due to an increase in shale gas production, day-to-day production remains relatively steady throughout the year [30]. However, demand changes considerably with seasons. Natural gas storage enables producers and purchasers to store gas during periods of relatively low demand, then withdraw the gas during periods of relatively higher demand and prices.

In order to maintain steady state natural gas flow in the system, large quantities of natural gas are stored in natural gas storage tanks. When a contingency on gas transmission pipeline occurs in the peak periods, storage facilities are committed and added to the natural gas transmission grid. Natural gas storage tanks are scheduled in a long-term or midterm optimization problem [31]. In [32], a method has been presented to model pipeline storage properties which is based on the difference between input and output of gas in a pipeline; in this model, natural gas storage is modeled as a supplier of natural gas in the system.

The output rate of natural gas storage and volume of storage facilities are given as follows:

$$SP_{s,t} = SP_{i,t-1} + q_{s,t}^{in} - q_{s,t}^{out} \quad \forall (s \in h), \forall t \tag{13}$$

$$q_{s,t}^{in}, q_{s,t}^{out} \leq SR_s \quad \forall (s \in h), \forall t \tag{14}$$

$$RV_s^{\min} \leq SP_{s,t} \leq RV_s^{\max} \quad \forall (s \in h), \forall t \tag{15}$$

Limits of output rate and volume of tank constraints data will be governed by gas companies.

### *F. Linearizing*

Since both sides of the gas flow equation are second order and nonlinear, using usual linearizing methods is difficult. In the proposed linearizing method, all variables of Weymouth equation like pressure at the beginning and at the end of lines are linearized with respect to their variable independently, first. For example, the pressure of each node is obtained as a second order curve between minimum and maximum allowed pressure.

As shown in Fig. 3, this curve is modeled piecewise linearly. Now, instead of using a second-order parameter in terms of pressure, a linear curve is obtained.

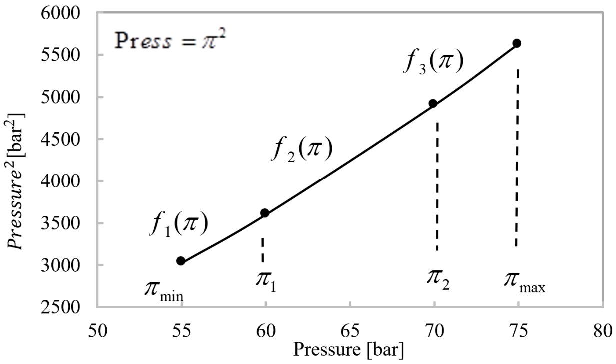


Fig. 3. Piece wisely approximation of pressure curve

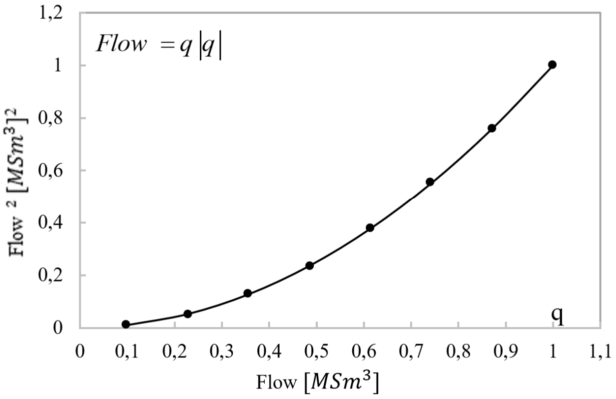


Fig. 4. Piece wisely approximation of flow curve

Such linearizing method can be applied to flow variable also, Fig. 4. Flow passing through the pipelines can be obtained with respect to several data available from the flow of each transmission pipe which can be done numerically and empirically in each gas transmission network through considering different arbitrary numbers for pressure at both ends of the pipe in the above equation. Now, flow variable can be plotted with respect to itself as on the left side of Eq. (12). Since the direction of gas flow in each pipe might be different; in order to show direction change in the gas pipe, the linearized curve has negative values also.

Now pressure of all nodes and flow passing from all pipes are linearized independently with respect to themselves and the linearized variable can be replaced by the main variable in load flow equations. Thus, Weymouth equation can be rewritten as follows:

$$Flow_{xz} = G(Press_{x,t} - Press_{z,t}) \quad \forall (x, z \in h), \forall t \qquad (16)$$

Now, these piecewise curves for pressure and flow of each node and pipeline can be transformed into equivalent linear constraints by using the Fortuny-Amat transformation, respectively [33]. For example, the pressure of one node shown in Fig. 3 with 3 piecewises could be modeled as follow:

$$Press_x + Mv_x^1 + M(1-v_x^2) + M(1-v_x^3) \leq f_1(\pi) + 3M \qquad \text{(17-a)}$$

$$Press_x - Mv_x^1 - M(1-v_x^2) - M(1-v_x^3) \geq f_1(\pi) - 3M \qquad \text{(17-b)}$$

$$Press_x + M(1-v_x^1) + Mv_x^2 + M(1-v_x^3) \leq f_2(\pi) + 3M \qquad \text{(17-c)}$$

$$Press_x - M(1-v_x^1) - Mv_x^2 - M(1-v_x^3) \geq f_2(\pi) - 3M \qquad \text{(17-d)}$$

$$Press_x + M(1-v_x^1) + M(1-v_x^2) + Mv_x^3 \leq f_3(\pi) + 3M \qquad \text{(17-e)}$$

$$Press_x - M(1-v_x^1) - M(1-v_x^2) - Mv_x^3 \geq f_3(\pi) - 3M \qquad \text{(17-f)}$$

$$\pi_x - Mv_x^1 - M(1-v_x^2) - M(1-v_x^3) \geq \pi_{\min} - 3M \qquad \text{(17-g)}$$

$$\pi_x + Mv_x^1 + M(1-v_x^2) + M(1-v_x^3) \leq \pi_1 + 3M \qquad \text{(17-h)}$$

$$\pi_x + M(1-v_x^1) + Mv_x^2 + M(1-v_x^3) \leq \pi_2 + 3M \qquad \text{(17-i)}$$

$$\pi_x - M(1-v_x^1) - Mv_x^2 - M(1-v_x^3) \geq \pi_1 - 3M \qquad \text{(17-j)}$$

$$\pi_x - M(1-v_x^1) - M(1-v_x^2) - Mv_x^3 \geq \pi_2 - 3M \qquad \text{(17-k)}$$

$$\pi_x + M(1-v_x^1) + M(1-v_x^2) + Mv_x^3 \leq \pi_{\max} + 3M \qquad \text{(17-l)}$$

$$v_x^1 + v_x^2 + v_x^3 = 1 \qquad \text{(17-m)}$$

In the above formulation, the value of M is large enough. A binary variable $v_i^1, v_i^2, v_i^3$ represents the activation of each line piece wisely.

In order to balance each node in the load flow of the gas network, the linearized model is used such that the problem converges faster.

$$GP_w^{\min} \leq GP_{w,t} \leq GP_w^{\max} \quad \forall (w \in h), \forall t \qquad (18)$$

$$\sum_{h=1}^{NN} q_{h,t}^{out} - q_{h,t}^{in} + SP_{h,t} - GL_{h,t} - Flow_{hx} = 0 \quad \forall (e \in h), \forall t \qquad (19)$$

Equation (19) is based on mass conservation law. Now there is a linear model for a natural gas network that could be linked to SCUC problem.

## 4. Numerical Results

### *A. Case study*

The performance of integrated power and gas transmission network model derived in the present study has been tested on the

IEEE 24-bus power system and Belgian 20-node gas transmission system. The topology of power and gas network is shown in Fig. 5.

The power system has 24 buses, 38 branches, 17 loads, and three gas-fired units; four oil-fired units, five photovoltaic units and three hydro units. The gas network has 20 nodes, 21 pipelines, 2 suppliers, 4 storages, and 9 non-electrical loads. All domestic demands and commercial gas loads have a higher priority compared to electrical gas loads and it is assumed that they have firm transport contracts. And natural gas power plants have interruptible transport contracts. All data of the test network are available at [34].

In order to discuss the efficiency of the proposed approach as well as the impact of high penetration of solar system on natural gas transmission system in operation, two cases are considered which are discussed in the rest of this section.

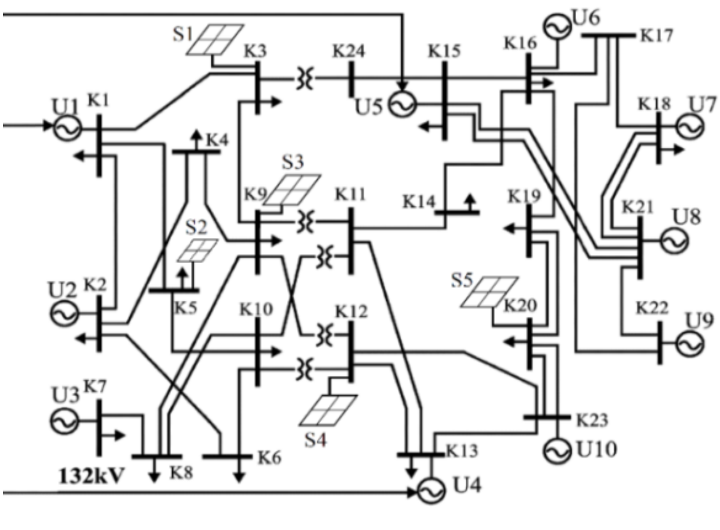
### *B. Impact of high penetration of solar generation on SCUC*

When photovoltaic generation is in normal mode, hourly SCUC solution is calculated by considering natural gas transmission constraints and the solar plant is modeled as a negative load and operation cost is 5.54 M$.

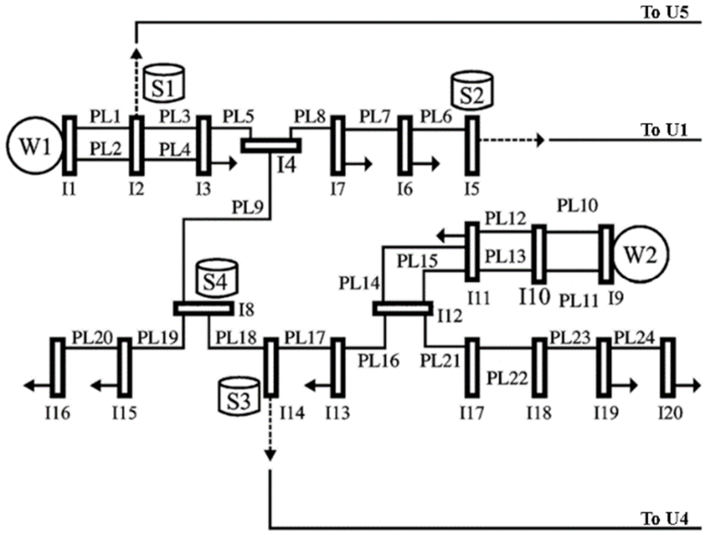
The natural gas network constraints are ignored and just the impact of high penetration of solar power plants in different scenarios is studied. In every level, solar output has increased 10 percent. The installed thermal and hydro capacity of the test power system is 3.445 GW, the installed solar capacity is 0.551 GW and the peak load is about 2.964 GW at 7 P.M.

The power load curve and solar output plants in different penetration factor are presented in Fig. 6. In this figure, PL is the power load. The overall behavior of solar power plants is usually the same. The total trend of the PV has been drawn from [35].

Increasing solar energy generation at each stage reduces load throughout the day. Besides, the ramp rate increases even more. At each stage, not only generation of the units is increased but also gas and hydro units are started. Fig. 7, shows the total generation of natural gas power plants while increasing penetration of solar energy. As can be seen, natural gas power plants output is highly affected by the high penetration of PVs. When solar energy increases, the difference between maximum and minimum of total gas units output increases simultaneously.  Fuel consumption of gas unit between 4 P.M. to 6 P.M. will increase suddenly.



(a) Electricity network



(b) Natural gas network

Fig. 5. Topology of 24-bus power system linked with natural gas transmission network

Load curve variation of the electricity network and supplying new load considering existing units is feasible by starting and stopping fast response units. Thus, the new load is followed by subsequent turn on and turn offs which are given in Table I.

A 40% increase in generation of solar plants changes consumption of water, natural gas and gasoil of vapor plants which is shown in Fig. 8.

If the initial consumed amount is assumed as a base and to be 100%, increasing energy in next steps and its effect on initial energy are shown in this figure.

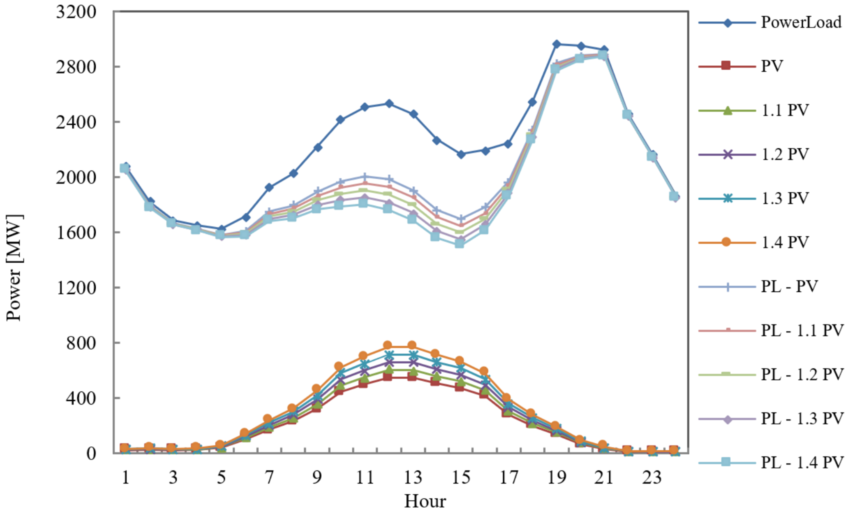


Fig. 6. Effect of photovoltaic generation on Electrical load curve in different PV penetration factor.

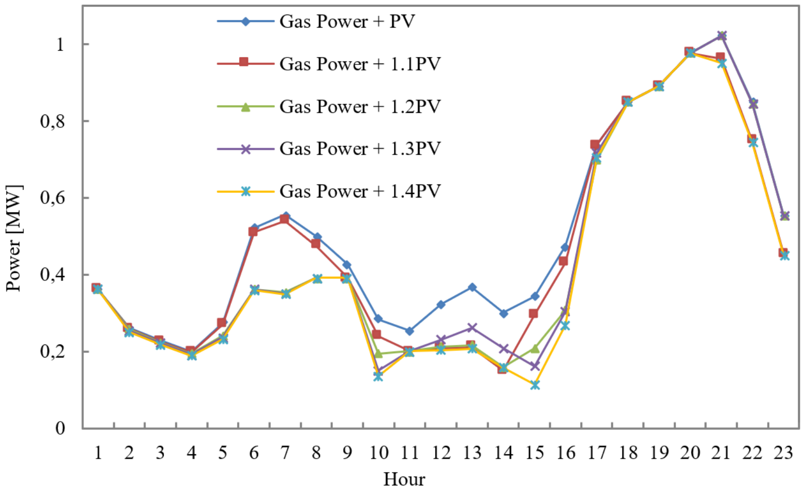


Fig. 7. Total generation of natural gas units in different penetration factors of photovoltaic power.

Table 1. Number of Start-up and shutdown of units in the network in high penetration of solar energy

| **PV PENETRATION** | **Number of Start-up** | **Number of Shutdown** |
|---|---|---|
| PL-PV | 3 | 2 |
| PL-1.1×PV | 4 | 2 |
| PL-1.2×PV | 5 | 2 |
| PL-1.3×PV | 5 | 3 |
| PL-1.4×PV | 6 | 3 |

Although an increase in solar energy reduces consumption of other energy resources in the network, its impact on natural gas consumption is inverse and natural gas consumption to cover high ramp rate of load curve in when there is not any solar energy would increase. On the other hand, natural gas is provided through the gas transmission network; thus, this increase in consumption may result in pressure drop and congestion in the gas transmission network. Thus, in the following, the effect of high penetration of solar energy in the electricity network on gas transmission network is investigated.

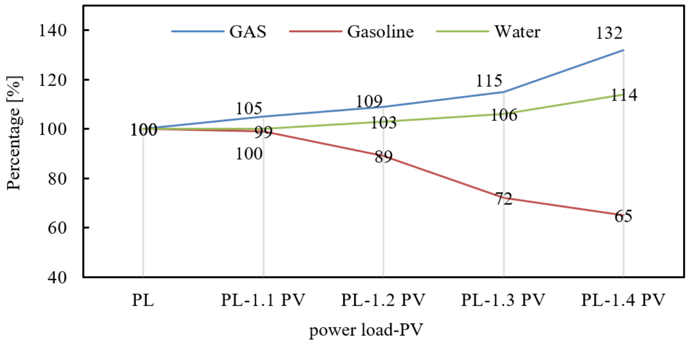


Fig. 8. Behavior of other sources of energy in high penetration of solar energy

### C. *Impact of high penetration of photovoltaic generation on natural gas transmission*

The proposed integrated model for gas network and electricity network in the presence of high penetration of solar energy is evaluated completely at this step. As solar energy increases during the day, the gas network's load is also reduced. At initial hours of the night, a sudden increase in gas consumption results in a pressure drop in the gas network. As solar energy increases, not only the load of electricity network but also a total gas load of the gas network will change because gas power plants are major consumers of the gas transmission network. As can be seen in Fig. 9, like the electric load curve, the gas network load is also reduced during the day and this is followed by a significant increase in generation of the gas plant during the night. High penetration of PV in power systems could also change the behavior of gas load curve in the natural gas grid. Since gas network peak and electricity network peak are not simultaneous, high penetration of solar energy creates a new peak which is caused by starting gas plants and high energy penetration coefficient results in two peaks in the gas network.

The increasing rate of natural gas demand needs to be supplied. So, the natural gas storage is very effective to supply this high ramp up and compensate the pressure drop. In this natural gas network, there are 4 gas storages. High penetration of PVs will change the operation of gas storage. The result of increasing solar generation on gas storage is shown in Fig. 10. Their maximum output is in the initial time of night. Increasing generation of gas plants results in pressure drop of the gas network. Fig. 11 shows the pressure drop interval in the gas network which occurs at 18p.m. which is simultaneous with starting gas units. As shown in this figure, at this hour, pressure has dropped at most nodes and network will face much more stress.

Security constraint in gas network reduces the generation of gas networks and increases generation of hydro-plants to cover increasing rate of load. Two gas load peaks in the gas network reduce nastiness of gas network; at first peak, generation of suppliers is increased and gas stored in gas pipes is used to compensate pressure drop and gas transmission is operated. But at the second peak which occurs in a short interval after the first peak, pressure drops even more since the volume of gas stored in the pipes has reduced and pressure of more points drops below the allowed limit; therefore, gas network security and consequently security of electricity network will be at serious risk.

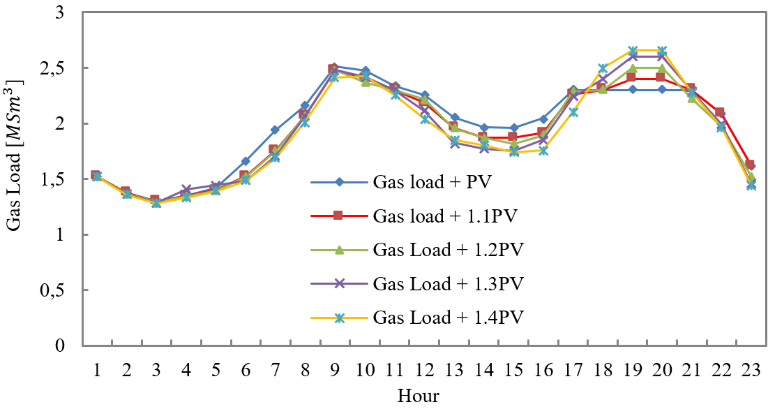


Fig. 9. Impact of high penetration of solar energy on natural gas load curve.

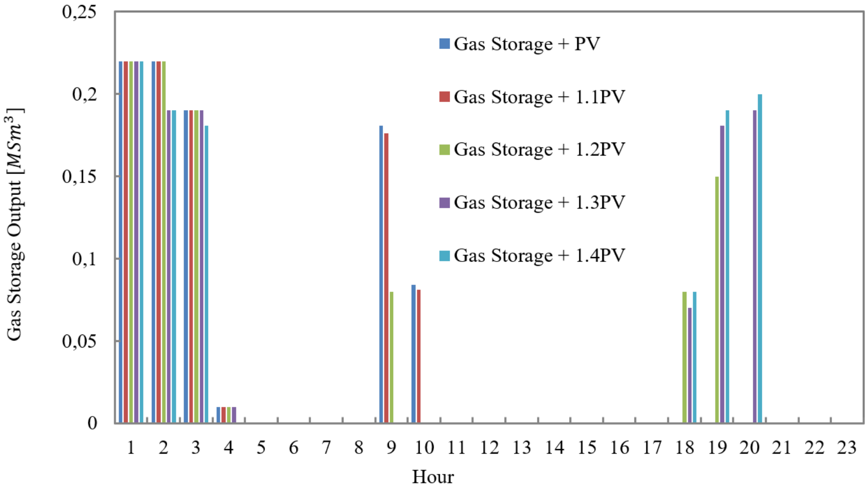


Fig. 10. Natural gas storage output in high penetration of photovoltaic energy.

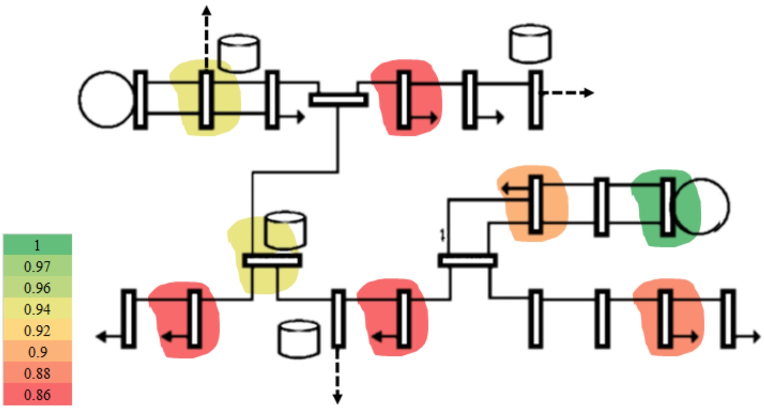


Fig. 11. Pressure drop in gas transmission network at 18:00.

## 5. Conclusion

Solar energy is one of the cheapest and cleanest renewable energies, which is being widely used. Its energy output nature depends on the existence of sun light, and its high penetration factors in the electricity network create some problems for the security and stability of the system. In this paper, gas plants with high ramp rate are considered as the main units for the increasing generation at sunset and the effect of this sudden increase in generation of the gas plant on the gas transmission network is investigated by introducing an integrated model of gas and electricity network. In the proposed model, the load flow of the gas network is considered in addition to the constraint of the electricity network through linearizing the gas network equations. The proposed model is tested on an IEEE network. The results showed that, while the consumption of gas plants increased, the gas network faced a sudden pressure drop on many of the nodes and, as a result, less gas was transmitted to these networks and the gas plant cannot offer its maximum power at the intended interval, requiring generation of other power plants. What's more, in the day ahead operation of the gas network, a high penetration of photovoltaic units will lead to add another peak to the gas load curve simultaneously with sunset when the gas unit will be started, which could reduce the potential of the gas network to use from its inertia in facing unexpected events. The natural gas network is not so flexible and natural gas as a fluid has an inertia that could not reply to the second peak on the network as thriving as possible. So, it could impose another constraint on the growth of solar energies on the power system that should be taken into account on the expansion planning of the power system networks. Security analysis of the power transmission network with a high penetration of renewable energies could be better checked by an AC load flow as a future work.

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