# Expansion planning of the Iranian gas and electricity energy systems: An integrated approach

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**Following increases in interdependencies of gas and electricity energy systems (G&ES) in parallel with the incremental growth of demands for the relevant energy carriers, the need for a more optimal capacity expansion planning approach, in particular in developing countries, is felt more than before. By considering the most important factors that can affect expansion strategies of the Iranian G&ES, the present paper proposes a comprehensive planning model for the expansion of the G&ES using an integrated approach. The interactions between the energy systems (ESs), environmental issues, renewables penetration rate under the implementation of supportive energy policies in a semi-deregulated environment, and the possibility of employing the salt caverns and/or depleted fields for storing natural gas, are included the aforementioned factors. Formulated as a mixed-integer linear programming problem in the GAMS software environment, the model aims to identify the least-cost planning schedule of candidate infrastructures, while applied techno-economic constraints are satisfied. Two different scenarios are conducted to investigate the superiority of employed planning methodology. The simulation results demonstrate that in order to cope with the challenges, co-expansion planning of the G&ES in a coordinated framework can reach more optimal and realistic strategies compared with the traditional separate expansion planning models. In addition, analysis shows that the integrated expansion planning of the ESs gives the opportunity of exploring the impact of different aspects on each other and better perception of the interactions with planners.** 

***keywords:*** *Integrated expansion planning, Iranian gas and electricity systems, Gas storage systems.*

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## NOMENCLATURE

### Indices

$i, s, n, b, t$ Index corresponding to an infrastructure type, installation area, number of infrastructures, loads-block, and to a planning horizon stage, respectively.

$S, B, T$ Index corresponding to the total number of areas, loads-blocks, and planning horizon intervals, respectively.

### Superscripts

$SP$ Symbol of gas supply systems.

$GP$ Symbol of gas pipelines.

$GS$ Symbol of gas storage systems.

$CO$ Symbol of gas compressors.

$GPG$ Symbol of gas-fired power plants.

$TL$ Symbol of transmission lines.

$RE$ Symbol of renewable-based generation units.

### Constants/Parameters

$C_{inv}$ Investment cost.

$C_{O\&M}$ Fixed operation and maintenance cost.

$C_{opr}$ Variable operation cost.

$C_{inc}$ Renewables' incentive-based support scheme cost.

$\mu, \lambda$ Injection and withdrawal cost of gas storage systems, respectively.

$\overline{v}, \underline{v}$ Maximum and minimum bounds of gas storage systems, respectively.

$\overline{v}^{inj}, \underline{v}^{inj}$ Maximum and minimum injection bounds of gas storage systems, respectively.

$\overline{v}^{with}, \underline{v}^{with}$ Maximum and minimum withdrawal bounds of gas storage systems, respectively.

$\overline{p}, \underline{p}$ Maximum and minimum power generation capacity, respectively.

$\overline{g}, \underline{g}$ Maximum and minimum gas production capacity of gas supply systems, respectively.

$\overline{h}, \underline{h}$ Maximum and minimum heat power generation capacity, respectively.

$\delta$ Renewable-based distributed generation capacity factor multiplied by 8760.

$\text{g}$ Electricity-to-gas conversion factor.

$\overline{N}$ Maximum number of an infrastructure that can be installed during the planning horizon.

$\overline{f}_g$ Maximum flow capacity of a pipeline.

$\tau$ Seasonal storage factor.

$r$ Discount year.

$\rho^{out}, \rho^{in}$ Outlet, inlet pressures of a gas compressor, respectively.

$\varphi$ Polytrophic exponent of the empirical equation of gas compressors' consumed power.

$hp$ Horsepower of gas compressors.

$\xi$ Natural gas thermal value.

$\xi_g$ Natural gas emission factor.

$\eta$ Efficiency of an infrastructure.

$Pc$ Electrical power consumed by a compressor.

$Gc$ Gas consumed by a compressor.

$B^{tot}$ Total available budget in the base year.

$\overline{EENS}$ Allowed amount of not served energy.

$VOLL$ Value of lost load.

$\Phi^E, \Phi^H$ Duration of electrical and heat loads, respectively.

$\Omega^G, \Phi^G$ The amount and duration of gas demand, respectively.

$\Phi^G, \Phi^{\overline{G}}$ Duration of total gas demand in equivalent gas and heat demand curve.

$\Omega^E, \Omega^{\overline{G}}$ Electricity and total gas demand (including gas demand of heat loads), respectively.

#### Variable

$p$ Generated power ($MWh$).

$g$ Produced gas ($MM^3/h$).

$x$ Binary decision variable.

$v^{inj}, v^{with}$ Injection and withdrawal of gas storage systems ($MM^3/h$), respectively.

$f_g$ Natural gas flow in a gas pipeline ($MM^3/h$).

$f_e$ Electric flow in a transmission line ($MWh$).

$EENS$ Expected energy not served ($MWh$).

$CR$ Curtailed electricity load ($MW$).

#### Sets

$I$ Set of candidate types corresponding to each infrastructure.

$I_{N\&E}$ Set of new-added and existent types of each infrastructure.

## 1. INTRODUCTION

### A. Motivation and paper description

Following increasing human dependencies on energy carriers, the challenges faced by energy systems (ESs), as well as the need for more optimal solutions to address them, are more felt. In this context, a realization of the sustainable development, gas and electricity energy systems (G&ES), and the coordinated/integrated approach can be treated as the most important challenges, the largest energy systems, and as the newest ESs' planning approach, respectively.

Despite multifarious challenges derived from energy systems (ESs), energy is steel at the heart of most critical economic, environmental and developmental issues facing the world today. Clean, efficient, affordable and reliable energy services are indispensable for global prosperity. In this regard, the need for developing countries for more access to reliable and modern energy services to increase productivity, enhancing competitiveness and promoting economic growth, indeed, has made the need for the continuous expansion of ESs inevitable. In parallel with this fact, the impacts of the energy sector on environmental issues have made many developed countries worried about probable future threats, resulting in moving towards more clean and compatible energy sources as well as more optimal planning methodologies. Among these ESs, power systems, as the largest energy system, have a prominent role in socio-economic development of countries, and meanwhile, in an acceleration of climate changes, which has posed a huge threat to human welfare [1]. In this context, the complete awakening of world societies about the importance of environmental issues has enforced different political institutions in the governments for decision making about the ways of decreasing the dependencies on fossil fuels in different sectors, promoting renewable energy sources (RES), decelerating the growth of energy demand, and so on. Regarding the electricity generation sector share on greenhouse gases (GHG) emission, nowadays, consideration of environmental issues in all power systems planning areas seems inevitable. In this context, RES diffusion plays a substantial role in GHG mitigation with respect to the incremental electricity demand growth and inevitable nature of its consumption [2].

Following the world's response to climate change in terms of adoption of the United Nations Framework Convention on Climate Change (UNFCCC), the need to apply emission restrictions to the generation sectors has propelled different countries to use energy sources characterized by lower emission. Accordingly, natural gas (NG) will have the main role among fossil fuels in the future of conventional energy systems (ESs). However, the rotation of visions to NG energy is not only derived from climate change. Factors have tightened the correlation of G&ES during the recent decade can be enumerated as follows:

- The need for increasing the capacity of fast-response generation units in parallel with the fast penetration of renewable energy sources (RES) as non-dispatchable and inherently uncertain energy sources.
- Lower NG price compared with other fossil fuels.
- Generation companies' inclination to invest in NG-fired units having lower investment costs and shorter installation time compared with other types of power plants.
- Redundancy and better geographical distribution of natural sources of the gas carrier.
- Advances in extraction of NG from unconventional sources in terms of shale gas.
- Technological progress in multi-generation units.
- The advent of new storage/conversion technologies such as power-to-gas units.

Increasing rate of energy demand and the need for more generation/supply capacity, under environmental and economic restrictions from one hand, and increases in the correlation of G&ES from the other hand, has made employment of more optimal and cleaner methodologies for planning the energy systems (ESs) infrastructures inevitable, in particular in developing countries coping with aforementioned challenges.

As a developing country with a high level of energy demand and large-scale G&ES, Iran also faces a variety of energy-related challenges to be addressed. From the viewpoint of energy department of Iran, planned measures and enacted policies to cope with the challenges can be generally regarded from two main perspectives: economical, and environmental. Like other developing and even developed countries, such as China, in Iran, development schemes for each sector of society, such as energy, agriculture, industry, and etc., are updated every five years and are announced in term of Five-Year Plan (FYP). The FYPs indeed is a blueprint containing decisions made by the governments on social, economic, and political issues. Through the last, i.e., 6th, FYP of Iran, the most important included macro measures and policies are as follows:

i . Reducing 4% of GHG emissions by 2030 following the obtained treaty from the 21st conference of UNFCCC parties in 2015.

ii . Replacing current fuel of power plants with NG and supplying all outlying NG demands in response to that treaty and being low the level of energy efficiency in ESs.

iii . Promoting RES-based units via incentive mechanisms regarding the large RES potential neglected.

Obviously, economic restrictions derived from large capital costs of G&ES infrastructures expansion schemes, in particular in developing countries, can threaten to reach these goals. Under this circumstance, the need to employ a comprehensive planning approach encompassing all pursued linchpins in the last FYP of Iran is felt, as adopted measures tie the future of G&ES to each other in this country more than before. This is the main motivation of the present research work to propose a comprehensive planning model for co-expansion of the Iranian G&ES with respect to the most important factors, such as the role of RES generators, gas storage systems, and budget constraint.

### B. Literature survey

In this subsection, a multitude of researches accomplished in the field of expansion planning of integrated energy systems is categorized in two different groups. The classification is based upon the energy systems sectors incorporated into the planning problem. Meanwhile, the content of these works are assessed. Accordingly, two considered categories are:

i . Integrated expansion planning of power and NG systems.

ii . Expansion co-planning of transmission lines and NG pipelines without considering the generation sector.

#### B.1. Expansion planning of the electricity generation sector amalgamated with gas and/or electricity transmission networks

During the recent decade, numerous studies have been carried out on the simultaneous expansion planning of G&ES, as one of the most attractive planning fields [3–11]. The accuracy of modeling, optimization methodologies, and various integrated planning areas, including both operation and expansion fields, can be regarded as the main distinctions between aforementioned research works. In this regard, Unsihuay-Vila et al. suggest a novel and detailed model to plan NG networks expansion in a long-term horizon and incorporates it into another model aimed at jointly computing the long-term, multi-regional expansion plan of G&ES [4]. The built framework concentrates on jointly the NG value chain (i.e., the gas supply from the NG wells, its transportation through NG pipelines, and the storage systems) and the electricity value chain (i.e., power generation and transmission). This study indeed plans an expansion of integrated G&ES infrastructures with respect to their simplified value chains affected by the RES and emission restrictions. The model is formulated as a mixed-integer linear programming problem aiming to minimize both operation and expansion costs. Analysis of the findings demonstrates the effectiveness of the proposed framework compared to the separated planning of simulated G&ES. This topic has also been outlined in [12].

In today's world economic situation in which efforts at economic development continue ceaselessly, incorporation of gas and electricity distribution systems can be treated as a new business opportunity to supply growing demand through less investment budget. This subject has encouraged responsible authorities to more invest in NG-based DG units in electricity distribution networks as NG is more eco-friendly compared to other fossil fuels and generally has lower extraction, transmission and distribution cost [13, 14]. In this context, reference [15] proposes a novel cost-based model for integrated gas and electricity distribution networks with a high penetration of gas-fired DG units. Aiming to minimize expansion costs, the planning problem is first simulated and then obtained results are compared with the results of the traditional situation in which the understudy gas and electricity networks are separately considered in expansion scenarios. From comparison results, it is inferred that expansion cost of both understudy systems is reduced because NG-based DG is an endogenous variable in the integrated approach, whereas it is an exogenous variable (power injection of gas demand) in the traditional approach. Further, the results reveal that the proposed framework, in practice, can be convenient for countries having vertically integrated structures in their energy systems, while a reduction in investment cost in power systems brings about remarkable benefits for end-users. Integrated planning of gas and electricity distribution networks in the presence of gas-fired DG units is also addressed in [7, 16]. These units have been scrutinized from the emission point of view in [8, 17].

In the context of low-carbon economy, how NG-based units affect the traditional interactions between G&ES in an integrated expansion planning framework is addressed in [6] with respect to the reliability and environmental aspects along with economic ones. In this work, indeed, simultaneous expansion planning of power transmission network, NG pipelines, and only NG-based power generation units is modeled with the aim of maximizing the benefit/cost ratio comprising benefits in operation reduction, carbon emission reduction and reliability improvement against augmentation investment costs. Compared to other carried out studies on the expansion planning of G&ES, the proposed framework in [6] is a little different. The aforementioned study also presents a simulation platform for both gas and electricity markets, trying to remove the G&ES market timeline mismatch with respect to the line-pack effect and risks derived from the market uncertainties, demand growth as well as fuel prices. Analysis of the findings reveals that the simulated framework could provide a better demonstration of present G&ES infrastructure weakness in order to supply growing demand, techno-economic interactions between G&ES, and social welfare enhancement in the context of G&ES integration.

Amalgamated planning of G&ES has also been addressed in

[7]. In this work, in order to adapt the developed model to large-scale systems, first, a three-stage heuristic method is developed for transmission expansion planning of understudy system, i.e., the Iranian power system. A new approach for NG load flow is also proposed to decrease the computation time of the load flow in large-scale systems. Thereafter, an integrated model to identify the optimal co-expansion plan of G&ES is presented. The place and capacity of new generation technologies to be added to the generation mix of the planning horizon base-year, the place and capacity of new transmission lines and the place of new gas pipelines are involved in the main optimization variables of the problem. In this study, similar to the research done in [6], some aspects such as type of newly added generation technologies and DG units in terms of candidate units for investing have been neglected. The simulation results confirm the applicability of the proposed method for large-scale real-world systems and multi-period modeling.

With an emphasis on the effectiveness of expansion co-planning of G&ES infrastructures in reducing investment costs compared with the traditional separate expansion planning, Zhang et al. propose a suitable co-optimization model for long-term planning of incorporated G&ES [18]. Subjected to a variety of NG grid and electricity constraints, simulated framework aims to identify the least-cost planning schedule of candidate generating units, transmission lines, and natural gas pipelines. Compared to the above-reviewed studies, the authors in [18] present a more detailed model for the NG system, including suppliers, pipeline transportation, and end users. The obtained results from this study show that expansion planning of G&ES in a coordinated manner decreases investment costs for both systems. Further, consideration of fuel transportation constraints can fundamentally affect the long-term expansion decisions of power systems.

In a new and competitive framework, how promotion of gas-fired units can affect expansion co-planning problems of power transmission girds and gas transportation networks is addressed in [10, 11]. Faced by the independent system operator, the models proposed in these works are formulated as a mixed-integer linear programming problem and aim to minimize the costs of investments plus operation. The congestion of transmission lines, reliability, prices in purchase gas and electricity contracts, and the balance between demand and supply are also modeled as constraints. Verifying the effectiveness of the proposed models, simulated case studies reveal that co-planning of G&ES can provide energy network planners with thorough information on the physical and economic interactions between G&ES. Through an almost similar framework, Qiu et al. develop a novel co-expansion planning model to address the strategic contemplation of the interactions of G&ES [19]. The place, type, installation time period of new added gas-fired units, NG network pipelines, and newly added power transmission lines are included the variables of optimization problem aiming to identify the optimal expansion strategy in terms of social welfare. The obtained results from these studies [10, 11, 19] all emphasize the importance and necessity of G&ES expansion planning in an amalgamated manner as a consequence of the factors outlined below:

- Better identification of strengths and weaknesses of G&ES infrastructures in order to better response to demand in long term.
- Deeper perception of techno-economic interactions between G&ES as well as the relationship between corresponding decision making systems in expansion and operation areas.
- Improving energy systems' asset management and energy efficiency levels because of amalgamated operation/expansion planning.
- Reaching a higher level of social welfare.

As a newly invented storage system, the power-to-gas technology (P2G) will play a significant role in coming energy systems, as it can directly link electricity systems being saturated with non-dispatchable RES with NG networks. In this context, Zeng et al. investigate the impacts of P2G units' penetration in energy systems on intermittencies and volatilities associated with non-dispatchable RES-based units as well as investment strategies of G&ES [3]. In doing so, they propose a multi-stage expansion co-planning model in an integrated G&ES. Regarding the timeline mismatch between G&ES in terms of daily line-pack variation, observations demonstrate that equipping electricity systems with P2G fundamentally changes optimal operation strategies of integrated G&ES and results in much lower operational cost, gas supply, and wind curtailment. Furthermore, the results show that more conversion capacities of P2G should be installed to accommodate the increasingly high penetration levels of wind power in power systems, while the coal-fired units are gradually replaced with gas-fired ones having low emission levels and fast ramp rates. Similar frameworks have been built in [20–22], proposing a multi-stage contingency-constrained co-planning model for electricity-gas systems interconnected with gas-fired units and P2G plants considering the uncertainties of load demand and wind power.

As can be seen, over the recent decade, the viewpoints of power system planners on NG systems and on its incorporation into PSP studies have fundamentally changed and consideration of the interactions between G&ES in operation/expansion planning problems has been imperative.

#### B.2. Transmission expansion planning of gas and electricity energy carriers

Through a simpler and more accurate framework, the second category of studies carried out on the energy systems' expansion planning focuses only on how energy transmission networks should be expanded in parallel with the growing demand. In this regard, by proposing a comprehensive multi-objective cost-based model, reference [9] aims to concentrate on an expansion co-planning framework for integrated gas and power transmission grids. In this framework, the well-known N-1 criterion is used for reliability assessment purposes in the presence of wind farms uncertainties and correlations. The obtained results, determining which and where natural gas pipes, gas compressors and power transmission lines should be expanded, show that amalgamated expansion planning of transmission infrastructures of G&ES improves not only whole system reliability but also enhances social welfare as a consequence of reduced costs. Further, from the results, it can be inferred that increases in wind farms capacity can increase generation (load meeting) costs if there is no enough fast-response capacity to address wind farms uncertainties. In this context, an almost similar framework is also built in [23]. Regarding the role of gas-fired units in connection of gas and power systems infrastructures, this study tries to determine the optimal place and installation time of new gas pipelines, gas compressors, gas storage equipment, and new transmission lines, during the planning horizon, as it assumes that the understudy system has sufficient electricity generation capacity. The results obtained from two different simulated scenarios, i.e. base case and low-carbon scenarios, show that the demand for NG rapidly grows in response to rigid environmental restrictions, and this, in turn, leads to the need for more investment in NG grids. In addition, findings reveal that achieving the possible most cost-efficient expansion strategies is crucially contingent upon the integration of G&ES in the expansion planning problem.

From reviewing studies addressing the problem of expansion planning NG system infrastructure, it can be seen that there are a few works in which this subject has been addressed regardless of electricity systems. In this context, a computational model for operation and expansion planning of NG systems infrastructures has been presented in [24] regardless of the competitive environment of gas companies. In contrast, researches accomplished in [25–28] addresses the expansion problem of NG infrastructures restricted by operation constraints in a competitive framework related to the NG markets of the Europa and the North of the United States. Introduced as a multidisciplinary problem that requires various engineering knowledge, optimal designing and developing of NG transmission pipeline networks in a long-term planning horizon are also explored in [23]. The proposed model formulated as a nonlinear mixed-integer programming problem and aims to identify the best place and scheduling for installation of new equipment as well as the type of them so that both operation and investment costs are minimized. In this regard, Hamedi et al. provide an overview of the optimization methodologies applied to the NG systems planning problem [24]. Techno-economic evaluation of five-year expansion projects related to the U.S. NG network infrastructures is also presented in [25], providing some useful insights into the aspects of NG systems to be considered in reality."

Despite the diversity of pursued aims and proposed structures of the studies available in the literature, focusing on a real case study is contingent upon incorporation of the most relevant effective factors into the model. As a matter of course, the more complete cognition of under-study G&ES, the more realistic the model. Accordingly, to propose a comprehensive planning model, it has been tried to incorporate the most important factors that can influence under-study G&ES expansion strategies. Of these factors:

- Renewable generators in terms of independent power producers in the semi-deregulated environment of the Iranian power system.
- Energy policies enacted for diffusion of renewable energy sources.
- Strengthened correlation between gas and electricity systems in response to the gasification of electricity generation mix, lagged extraction process of gas carrier from the common gas field, RES penetration, etc.
- International treaties on reducing the emission level of greenhouse gases.
- The possibility of employing the depleted fields or salt caverns in terms of gas storage systems.

### C. Paper contribution

Regarding the available literature, consideration of multifarious energy forms together with the electrical energy in power system planning studies in an integrated framework can be treated as one of the hottest topics that have been regarded in the field of energy systems' planning so far. As a matter of course, today's world energy-related challenges, ranging from anthropogenic climate change to continuous growth of demand and economic constraints, have enforced energy systems' planners to concentrate on more optimal and eco-friendly operation and expansion planning methodologies. In line with the collaborative efforts for cleaner and more optimal planning of power systems, increased interdependency of gas and electricity systems and tremendous improvement in capability of computers as well as soft computing science, realizing the optimization of hyper-complex mathematical models, have led to amalgamated planning of gas and electricity energy systems infrastructures.

Investigated through a wide range of energy-related researches under different titles from various viewpoints, the integrated approach will provide a great revolution in power system planning methodologies if it is realized in practice. This is the main motivation of the present article to propose a comprehensive framework for studying integrated expansion schemes of the Iranian gas and electricity energy systems in dealing with today's basic challenges faced by G&ES of developing countries characterized by semi-deregulated environments.

To the best of authors' knowledge, none of the previous research works has investigated the impacts of upcoming and unavoidable energy-related challenges of developing countries on the expansion studies of energy systems. As one of those countries, Iran has large gas and electricity energy systems faced by a variety of challenges, ranging from socio-economic restrictions to the incremental rate of demand growth, providing the need for more optimal and cleaner expansion planning approaches. Of these challenges, obligation to reduce GHG emission, low penetration rate of RES, lagged process of natural gas extraction from common gas fields, and above all, budget constraint that directly affects the capacity expansion of energy systems. To cope with these challenges and analyze the derived solutions in the Iranian energy systems, the model of the G&ES expansion planning problem has to consider the following issues:

- Renewable-based independent power producers in the semi-deregulated environment of the Iranian power system.
- Feed-in-tariff system for supporting renewable energy generators.
- Increased interactions between gas and electricity systems affected by the efforts to increase the natural gas share in the fuel basket of power plants.
- International treaties on reducing the emission level of greenhouse gases.
- The possibility of employing the depleted fields or salt caverns in terms of gas storage systems to postponing the need for capacity expansion of gas sector infrastructures.

Motivated by the aforementioned facts, this paper endeavors to outline an optimization and modeling framework for integrated expansion planning of Iranian G&ES. In doing so, first, a comprehensive coordinated planning model is proposed. Formulated as a mixed-integer linear programming problem, the model aims to identify the least-cost planning schedule of candidate generating units, transmission lines, gas pipelines, gas supply systems, gas compressor stations, and underground gas storage systems. Then, two different planning scenarios are conducted to clarify how integrated approach can affect the future G&ES expansion schemes of Iran compared with the traditional separate planning methods.

Based on the above discussions, the main contributions drawn out of this work can be enumerated as follows:

- Proposing a comprehensive co-expansion planning model compatible with the G&ES of Iran.
- Providing an in-depth discussion on the advantages of employing integrated planning approach compared with separate one in determining expansion schemes of G&ES.
- Clarifying how existing depleted fields and/or salt caverns can affect the future of expansion strategies of gas systems.
- Analyzing the interactions between RES incentive-based support schemes, the amount of expected energy not served, and the electricity sector expenditures.

### D. Paper organization

To present the pursued linchpin, the rest of this paper is organized as follows. Construction of the proposed model and optimization framework are allocated to section 2. Section 3 deals with the numerical analysis where the pursued framework is implemented on the test systems. Eventually, the drawn conclusion is provided in section 4.

## 2. THE PROPOSED CO-EXPANSION PLANNING MODEL

Energy (electricity) industries, in some countries, in particular in developing countries like Iran, have not completely transformed from the monopoly to the competitive structure. Actually, the power industry in these countries has passed the possible first step toward the introduction of competition and has only a partially deregulated structure in the generation sector. Under this circumstance, the traditional utility no longer owns all the generation capacity and independent power producers (IPPs) are connected to the grid and sell their generation to the utility acting as a purchasing agent. In this structure of the power industry, the ESs' expansion planning problem is often addressed as a cost-minimizing problem from the utility point of view, while all different objectives are lumped into one using different economic criteria. Accordingly, In this section, a multistage, multiregional, cost-based single-objective model is proposed to plan expansion strategies of G&ES simultaneously, so that all capital and operation costs are minimized and meanwhile, the required techno-economic constraints are satisfied. Formulated in terms of a MILP problem, the model is tailored for a semi-deregulated environment to incorporate the role of RES-based IPPs into the model. Gas supply systems (set of gas wells and refineries), GSSs, gas pipelines, GPGs, and transmission lines are the main infrastructures regarded in generation and transmission sectors. Different parts of the proposed model are presented in the following.

### A. Objective function

The objective function (OF) is comprised of the net present value (NPV) of all G&ES costs to be minimized. As can be seen in (1), the OF has 20 cost terms in (M$) defined by (2) and (3) corresponding to the gas and electricity infrastructures, respectively. For instance, in the case of gas energy system, the first term, i.e. $\Gamma_1^G$, depicts investment cost of $n^{th}$ gas supply system from type $i$ in region $s$ and $t^{th}$ stage of the planning horizon. Investment costs of gas pipelines installed between regions $s$ and $k$, $n^{th}$ GSS from type $i$ in the relevant region and planning stage, gas furnaces, and gas compressors, are regarded by second to fourth terms of (2), respectively. Variable operation cost of GSSs, comprising injection and withdrawal costs, the relevant fixed operation and maintenance (O&M) costs, the O&M cost of gas supply systems, their variable operation costs, and the variable operation costs of gas compressors are depicted by last five terms of the aforementioned equation, respectively. Similar to Eq. (2), Eq. (3) represents the costs associated with the expansion of the NG-based electricity generation and transmission systems. The first two terms show the capital costs of GPG units and transmission lines, respectively. The costs derived from the considered incentive measure, i.e., feed-in-tariff (FIT), to encourage IPPs to investment on RES-based units and from expected energy not supplied (EENS) during each planning stage is modeled by third and fourth terms of Eq. (3), respectively. And, ultimately, operation costs of GPG units are considered by the last term of the aforementioned equation.

$$\text{Min}: OF = \sum_{t=1}^{T}\sum_{s=1}^{S}(1+r)^{1-t}\left[\underbrace{\left(\Gamma_1^G+\Gamma_2^G+\cdots+\Gamma_9^G\right)}_{\Gamma^G}+\underbrace{\left(\Gamma_1^E+\Gamma_2^E+\cdots+\Gamma_{11}^E\right)}_{\Gamma^E}\right] \tag{1}$$

$$\begin{aligned}\Gamma^G = &\sum_{i\in I^{SP}(s)}\sum_{n=1}^{n^{SP}(i)}\begin{pmatrix} C_{inv}^{SP}(i,s,n,t)\cdot \\ x^{SP}(i,s,n,t)\end{pmatrix} + \sum_{k=1,k\neq s}^{S}\sum_{i\in I^{GP}}\sum_{n=1}^{n^{GP}(i)}\begin{pmatrix} 0.5C_{inv}^{GP}(i,s,k,n,t)\cdot \\ x^{GP}(i,s,k,n,t)\end{pmatrix}\\
&+\sum_{i\in I^{GS}(s)}\sum_{n=1}^{n^{GS}(i)}\begin{pmatrix} C_{inv}^{GS}(i,s,n,t)\cdot \\ x^{GS}(i,s,n,t)\end{pmatrix} + \sum_{i\in I^{CO}(s)}\sum_{n=1}^{n^{CO}(i)}\begin{pmatrix} C_{inv}^{CO}(i,s,n,t)\cdot \\ x^{CO}(i,s,n,t)\end{pmatrix}\\
&+\sum_{i\in I_{N\&E}^{GS}(s,t)}\sum_{n=1}^{n_{IO}^{GS}(i,s,t)}\sum_{b=1}^{B}\begin{pmatrix} \mu(i,s,n,t)\cdot v^{inj}(i,s,n,b,t) \\ +\lambda(i,s,n,t)\cdot v^{with}(i,s,n,b,t)\end{pmatrix}\cdot\Phi^{\overline{G}}(s,b,t)\\
&+\sum_{i\in I_{N\&E}^{GS}(s,t)}\sum_{n=1}^{n_{IO}^{GS}(i,s,t)} C_{O\&M}^{GS}(i,s,n,t)\cdot\overline{v}(i) + \sum_{i\in I_{N\&E}^{SP}(s,t)}\sum_{n=1}^{n_{IO}^{SP}(i,s,t)}\begin{pmatrix} C_{O\&M}^{SP}(i,s,n,t)\cdot \\ \overline{g}^{SP}(i,s,n,t)\end{pmatrix}\\
&+\sum_{i\in I_{N\&E}^{SP}(s,t)}\sum_{n=1}^{n_{IO}^{SP}(i,s,t)}\sum_{b=1}^{B} C_{opr}^{SP}(i,s,n,t)\cdot g^{SP}(i,s,n,b,t)\cdot\Phi^{\overline{G}}(s,b,t)\\
&+\sum_{i\in I_{N\&E}^{CO}(s,t)}\sum_{n=1}^{n_{IO}^{CO}(i,s,t)}\sum_{b=1}^{B} C_{opr}^{CO}(i,s,n,t)\cdot Gc(i,s,n,b,t)\cdot\Phi^{\overline{G}}(s,b,t)\end{aligned} \tag{2}$$

$$\begin{aligned}\Gamma^E = &\sum_{i\in I^{GPG}(s)}\sum_{n=1}^{n^{GPG}(i)}\begin{pmatrix} C_{inv}^{GPG}(i,s,n,t)\cdot \\ x^{GPG}(i,s,n,t)\end{pmatrix} + \sum_{k=1,k\neq s}^{S}\sum_{n=1}^{n_{s-k}^{TL}}\begin{pmatrix} 0.5C_{inv}^{TL}(s,k,n,t)\cdot \\ x^{TL}(s,k,n,t)\end{pmatrix}\\
&+\sum_{i\in I_{N\&E}^{GPG}(s,t)}\sum_{n=1}^{n_{IO}^{GPG}(i,s,t)}\begin{pmatrix} C_{O\&M}^{GPG}(i,s,n,t)\cdot \\ \overline{p}^{GPG}(i,s,n,t)\end{pmatrix}\\
&+\sum_{i\in I^{RE}(s)}\sum_{n=1}^{n^{RE}(i)}\begin{pmatrix} C_{inc}^{RE}(i,s,n,t)\cdot\overline{p}^{RE}(i,s,n,t)\cdot \\ \delta(i,s)\cdot x^{RE}(i,s,n,t)\end{pmatrix}\\
&+\sum_{b=1}^{B}\begin{pmatrix} VOLL(s,b,t)\cdot \\ EENS(s,b,t)\end{pmatrix}\cdot\Phi^{E}(s,b,t)\\
&+\sum_{i\in I_{N\&E}^{GPG}(s,t)}\sum_{n=1}^{n_{IO}^{GPG}(i,s,t)}\sum_{b=1}^{B} C_{opr}^{GPG}(i,s,n,t)\cdot p^{GPG}(i,s,n,b,t)\cdot\Phi^{E}(s,b,t)\end{aligned} \tag{3}$$

### B. Demand modeling

As shown in Fig. 1 for NG load, demand behavior for the other under-study carries in each regain is modeled as the discretized load duration curve (LDC). The LDC provides a suitable yearly summary of hourly fluctuations in demand typically divided into base-load, medium-load, and peak-load durations.

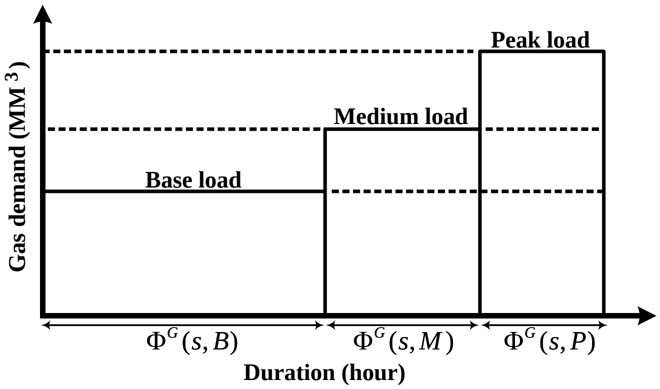


**Fig. 1.** The discretized NG load duration curve.

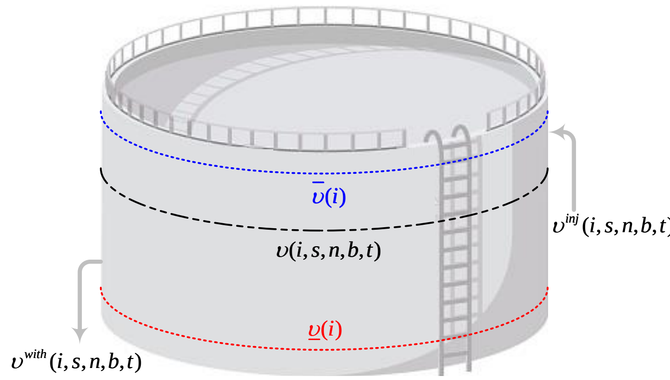


**Fig. 2.** Schematic of a gas storage system.

### C. NG system constraint

Regarding the terms of OF, the cost associated with adding and operating each infrastructure is taken into account when the state of relevant binary variable changes to 1 and this state of each binary variable is not changeable till the end of the planning horizon unless the infrastructure is decommissioned because of the lifetime constraint, if considered. The capital cost of each infrastructure is assumed to be added to the OF at the beginning of the relevant operation period. Furthermore, to compute operation costs in each stage, the number of in-operation infrastructures should be updated. The binary variables are defined by (4) and (5); and, for the set of considered NG system infrastructures, constraints on the state of binary variables and updating the number of infrastructures are formulated by (6)-(7) and (8)-(9), respectively. Apart from the number of infrastructures, the sets encompassing technology types of each infrastructure should also be upgraded, as formulated by (10)-(11).

$$x^{infra}(i,s,n,t) \in \{0,1\}\,;\, t=1,..,T; s=1,..,S; \\ n=1,..,n_{IO}^{infra}(i,s,t); \forall i \in I_{N\&E}^{infra}(s,t); \forall infra \in \{SP,GS,CO\}. \tag{4}$$

$$x^{GP}(i,s,k,n,t) \in \{0,1\}\,;\, t=1,..,T; s=1,..,S; \\ k=1,..,S, k\neq s; n=1,..,n_{IO}^{GP}(i,s,k,t); \forall i \in I_{N\&E}^{GP}(s,k,t). \tag{5}$$

$$x^{infra}(i,s,n,t) \le x^{infra}(i,s,n,t+1); t=1,..,T; s=1,..,S; \\ n=1,..,n_{IO}^{infra}(i,s,t); \forall i \in I_{N\&E}^{infra}(s,t); \forall infra \in \{SP,GS,CO\}. \tag{6}$$

$$x^{GP}(i,s,k,n,t) \le x^{GP}(i,s,k,n,t+1); t=1,..,T; \\ s=1,..,S; k=1,..,S; n=1,..,n_{IO}^{GP}(i,s,k,t); \forall i \in I_{N\&E}^{GP}(s,k,t). \tag{7}$$

$$n_{IO}^{infra}(i,s,t+1) = n_{IO}^{infra}(i,s,t) + \sum_n x^{infra}(i,s,n,t); \\ t=1,...,T; s=1,...,S; \forall i \in I_{N\&E}^{infra}(s,t); \forall infra \in \{SP,GS,CO\}; \tag{8}$$

$$n_{IO}^{GP}(i,s,k,t+1) = n_{IO}^{GP}(i,s,k,t) + \sum_n x^{GP}(i,s,k,n,t); \\ t=1,...,T; s=1,...,S; k=1,....S; k\neq s;\ \forall i \in I_{N\&E}^{GP}(s,k,t).; \tag{9}$$

$$I_{N\&E}^{infra}(s,t+1) = I_{N\&E}^{infra}(s,t) \cup \{i\}\,, \forall i \in I^{infra}(s), \text{if } x^{infra}(i,s,n,t)=1; \\ n=1,..,n^{infra}(i); t=1,..,T;\ s=1,..,S; \forall infra \in \{SP,GS,CO\}. \tag{10}$$

$$I_{N\&E}^{GP}(s,k,t+1) = I_{N\&E}^{GP}(s,k,t) \cup \{i\}\,, \forall i \in I^{GP}(s,k), \text{if } x^{GP}(i,s,k,n,t)=1; \\ n=1,..,n^{GP}(i); t=1,..,T;\ s=1,..,S;\ k=1,..,S; k\neq s. \tag{11}$$

The restrictions on installation time of each infrastructure of the NG system are incorporated into the model as follows.

$$\sum_{n=1}^{n_{IO}^{infra}(i,s,t)} x^{infra}(i,s,n,t) \le \overline{N}^{infra}(i,s,t); t=1,..,T; s=1,..,S;\ i \in I^{infra}(s); \\ t=1,..,T; s=1,..,S;\ i \in I^{infra}(s); \forall infra \in \{SP,GS,CO\}. \tag{12}$$

$$\sum_{n=1}^{n_{IO}^{GP}(i,s,k,t)} x^{GP}(i,s,k,n,t) \le \overline{N}^{GP}(i,s,k,t); \\ t=1,..,T; s=1,..,S; k=1,..,S,\ k\neq s; i \in I^{GP}.; \tag{13}$$

Gas storage systems, in particular, under-ground storage (UGS) ones, play a prominent role in load meeting during the cold periods of years and in postponing investment costs of NG systems expansion capacity. The operation of GSSs is modeled with respect to their storage volume limit as well as the limitations of NG injection and withdrawal values. A typical representation of an above-ground NG reservoir is illustrated in Fig. 2. As can be seen from this figure, a GSS characterized by a fixed volume in specific pressure has a minimum ($\underline{\upsilon}(i)$) and maximum ($\overline{\upsilon}(i)$ ) capacity storage as well as a limit injection ($\upsilon^{inj}$) and withdrawal ($\upsilon^{with}$ ) volumes per hour. The volume of each GSS in load block $b$ can be expressed as (14) [4]. The constraints on storage capacity and injection/withdrawal processes are also considered by (15)-(17).

$$\upsilon(i,s,n,b,t) = \\ \upsilon(i,s,n,b-1,t) + \left(\upsilon^{inj}(i,s,n,b,t) - \upsilon^{with}(i,s,n,b,t)\right).\Phi^{\overline{G}}(s,b,t); \\ s=1,..,S; b=1,..,B; t=1,..,T; n=1,..,n_{IO}^{GS}(i,s,t); \forall i \in I_{N\&E}^{GS}(s,t). \tag{14}$$

$$\upsilon(i,s,n,b,t) \le \overline{\upsilon}(i); \& \upsilon(i,s,n,b,t)\ \ge \underline{\upsilon}(i) \\ s=1,..,S; b=1,....,B; t=1,..,T; n=1,..,n_{IO}^{GS}(i,s,t); \forall i \in I_{N\&E}^{GS}(s,t). \tag{15}$$

$$\upsilon^{inj}(i,s,n,b,t) \le \overline{\upsilon}^{inj}(i); \& \upsilon^{inj}(i,s,n,b,t) \ge \underline{\upsilon}^{inj}(i); \\ s=1,..,S; b=1,....,B; t=1,..,T; n=1,..,n_{IO}^{GS}(i,s,t); \forall i \in I_{N\&E}^{GS}(s,t). \tag{16}$$

$$\upsilon^{with}(i,s,n,b,t) \le \overline{\upsilon}^{with}(i); \& \upsilon^{with}(i,s,n,b,t) \ge \underline{\upsilon}^{with}(i); \\ s=1,..,S; b=1,....,B; t=1,..,T; n=1,..,n_{IO}^{GS}(i,s,t); \forall i \in I_{N\&E}^{GS}(s,t). \tag{17}$$

Completely modeling the performance of GSSs is contingent upon the consideration of GSSs' storing capability during base and medium load periods in each stage. In doing so, it $v^{GS}(s,b,t)$ depicts the volume of stored NG in region s during the load block $b$, the difference between NG supply capacity plus received volume and the total of transmitted plus consumed capacities, can be stored in the GSS, as follows:

$$v^{GS}(s,b,t) = v^{GS}(s,b-1,t) + \left( \sum_{i \in I^{GS}_{N\&E}(s,t)} \sum_{n=1}^{n^{GS}_{IO}(i,s,t)} \left( v^{inj}(i,s,n,b,t) - v^{with}(i,s,n,b,t) \right) \right) .\Phi^{\overline{G}}(s,b,t); \quad s = 1,..,S; b = 1,..,B; t = 1,..,T. \tag{18}$$

$$v^{GS}(s,b,t) \geq \tau(b).\overline{v}^{GS}(s,t); \quad \text{if} \sum_{i \in I^{SP}_{N\&E}(s,t)} \sum_{n=1}^{n^{SP}_{IO}(i,s,t)} \overline{g}^{SP}(i,n) + P^{inj}_{g}(s,b,t) \geq \Omega^{\overline{G}}(s,b,t); \quad s = 1,...,S;\ b = 1,...,b^{peak};\ t = 1,...,T. \tag{19}$$

$$\frac{\underline{v}^{GS}(s,t)}{\overline{v}^{GS}(s,t)} \leq \tau(b) \leq 1; s = 1,...,S;\ b = 1,...,b^{peak};\ t = 1,...,T. \tag{20}$$

Where $P^{inj}_{g}(s,b,t)$ represents total hourly NG volume injected to region $s$; $\tau(b)$ is the charge coefficient with a positive slope which causes that the GSS is charged during the base and medium-load periods, if the capacity restriction of the relevant gas supply system and the pipeline allows. As a matter of course, increase in the aforementioned coefficient results in the variation of the injection variable, i.e. $v^{inj}(i,s,n,b,t)$, in the defined range with respect to the load fluctuations (demands and stations consumption values) of all other regions that along with the region s are jointly supplied by the relevant gas supply system. Accordingly, from the beginning of base-load period, i.e., *b=1*, to the beginning of peak-load period, i.e., $b = b^{peak}$ in each stage, $\tau(b)$ will vary in direct proportion to the gas demands and increase the volume of stored gas to the highest possible level.

The capacity constraints of gas supply systems, pipelines, and gas compressors are taken into account by (21)-(23):

$$g^{SP}(i,s,n,b,t) \leq \overline{g}^{SP}(i); \& g^{SP}(i,s,n,b,t) \geq \underline{g}^{SP}(i); s = 1,..,S; \quad b = 1,..,B; t = 1,..,T; n = 1,..,n^{SP}_{IO}(i,s,t); \forall i \in I^{SP}_{N\&E}(s,t). \tag{21}$$

$$\left| f_g(i,s,k,n,b,t) \right| \leq \overline{f_g}(i); s = 1,..,S;\ k = 1,..,S; \quad k \neq s; b = 1,..,B; t = 1,..,T; n = 1,..,n^{GP}_{IO}(i,s,k,t); i \in I^{GP}. \tag{22}$$

$$\underbrace{\sum_{i \in I^{GP}_{N\&E}(s,k,t)} \sum_{n=1}^{n^{GP}_{IO}(i,s,k,t)} f^{+}_{g}(i,s,k,n,b,t)}_{\widetilde{F_g}(s,k,b,t)} \leq \sum_{i \in I^{CO}_{N\&E}(s,t)} \sum_{n=1}^{n^{CO}_{IO}(i,s,t)} \overline{g}^{CO}(i,s,k,n,t); \quad s = 1,..,S; k = 1,..,S; k \neq s; b = 1,..,B;\ t = 1,..,T. \tag{23}$$

where $\widetilde{F_g}(s,k,b,t)$ is total transmitted NG volume from the region $s$ to $k$, and $f_g(i,s,k,n,b,t)$ is the pipeline gas flow variable which can take positive or negative values with regard to the flow direction [4].

In gas stations, the required electricity for gas compressors is usually supplied by located DG units consuming around 3%-5% of the transmitted gas depending upon the compressor horsepower, which in turn is a function of flow rate and the ratio of input-output gas pressures, as shown in an empirical 24 [6] as:

$$Pc(i,s,k,n,b,t) = \frac{\widetilde{F_g}(s,k,b,t) \cdot \beta(i,s,n,t) \cdot \varphi}{\eta^{CO}(i) \cdot (\varphi - 1)} \left[ \left( \frac{\rho^{out}(i,s,n,b,t)}{\rho^{in}(i,s,n,b,t)} \right)^{\frac{(\varphi-1)}{\varphi}} - 1 \right]; \quad s = 1,..,S;\ t = 1,..,T; b = 1,..,B; n = 1,..,n^{CO}_{IO}(i,s,t); \forall i \in I^{CO}_{N\&E}(s,t). \tag{24}$$

$$\sum_{n=1}^{n^{GP}_{IO}(i,s,k,t)} x^{GP}(i,s,k,n,t) \leq \overline{N}^{GP}(i,s,k,t); \quad t = 1,..,T; s = 1,..,S; k = 1,..,S,\ k \neq s; i \in I^{GP}. \tag{25}$$

Where $\beta(i,s,k,n,t)$ is the participation factor of compressors in boosting the pressure of gas flow transmitted from area $s$ to $k$. Consequently, the NG volume consumed by each station is:

$$Gc(i,s,k,n,b,t) = \frac{3.412 \times Pc(i,s,k,n,b,t)}{\eta^{DG}(i).\zeta(s)}; s = 1,..,S;\ k = 1,..,S; k \neq s; \quad t = 1,..,T; b = 1,..,B; n = 1,..,n^{CO}_{IO}(i,s,t); \forall i \in I^{CO}_{N\&E}(s,t). \tag{26}$$

Where $\eta^{DG}(i)$ is the efficiency of GDG located at the station. Note that at given pipelines' physical characteristics, the parameters $\rho^{in}$, and $\varphi$ can be estimated. And, here, they are incorporated into the model as constants to keep the linearity [6].

### D. Electricity system constraint

Regarding the enumerated factors about NG importance, enacted policies about this carrier, and the pursued linchpin, only NG-based generation technologies are considered here as the generation sector of the electricity system. In doing so, among all conventional generation technology options on the generation side, gas-fired power plants, in terms of combined and open-cycle gas turbine (CCGT and OCGT) units, are only considered to meet the projected demand. Investing in RES, in terms of wind and solar units, is another load meeting option incorporated into the model as an opportunity for IPPs supported by the FIT system. In the following, the constraints derived from investing and operating procedures of these generation options are modeled.

In the case of the electricity sector infrastructures, definition of the binary variables along with the relevant constraints as well as updating the number of infrastructures and upgrading the sets related to the type of technologies in operation will be like (4)-(11). Accordingly, here, transmission lines and the other electricity system infrastructures (*infra*), defined as the set of $\{GPG, RE\}$, correspond to gas pipelines and the set of NG infrastructures, i.e., $\{SP, GS, CO\}$, respectively. The bounds on installation time of the electricity infrastructures are also modeled in a way similar to the relevant constraints of the NG sector, and hence, it is avoided writing them here. The capacity bound of infrastructures is regarded as follows.

$$p^{GPG}(i,s,n,b,t) \leq \overline{p}^{GPG}(i); \& p^{GPG}(i,s,n,b,t) \geq \underline{p}^{GPG}(i); \quad s = 1,..,S; b = 1,..,B; t = 1,..,T; n = 1,..,n^{GPG}_{IO}(i,s,t); \forall i \in I^{GPG}_{N\&E}(s,t). \tag{27}$$

$$\left| f_e(s,k,n,b,t) \right| \cdot x^{TL}(s,k,n,t) \leq \overline{f_e}; s = 1,..,S; \quad k = 1,..,S; k \neq s; b = 1,..,B; t = 1,..,T; n = 1,..,n^{TL}_{s-k}. \tag{28}$$

As the basic distinction between the power industries of different countries, the restructuring has resulted in transforming planning models. In a semi-deregulated structure, the IPPs sell their generation to the utility acting as a government-dependent purchasing agent. Here, to realistically incorporate the role of RES generators into the model, they are considered as IPPs supported by the FIT mechanism being implemented in some developing countries such as Iran. From an IPP point of view, investing in RES-based units is contingent upon the profitability of the project, which in turn, depends on associated capital costs, the estimated capacity factor taking into consideration the geographical features of the region, and the amount of FIT premiums. To model the guarantee on the IPPs' investment profitability, we have:

$$C_{inc}^{RE}(i,s,n,t)\cdot\overline{p}^{RE}(i,s,n,t)\cdot\delta(i,s)\geq (1+\%\alpha)\cdot\left[\frac{r\cdot C_{inv}^{RE}(i,s,n,t)}{1-(1+r)^{T^{Cont}}}+C_{opr}^{RE}(i,s,n,t)\right]; \quad s=1,..,S;b=1,..,B;t=1,..,T;n=1,...,n_{IO}^{RE}(i,s,t);\forall i\in I_{N\&E}^{RE}(s,t). \tag{29}$$

$$\underline{C_{inc}^{RE}}(i,s,t)\leq C_{inc}^{RE}(i,s,n,t)\leq\overline{C_{inc}^{RE}}(i,s,t); \quad s=1,..,S;\ t=1,..,T;n=1,...,n_{IO}^{RE}(i,s,t)\forall i\in I_{N\&E}^{RE}(s,t). \tag{30}$$

Accordingly, IPPs' income from FIT premiums, i.e., the left side of (30), in each planning stage should be greater than the total costs imposed on IPPs. This is done by $\alpha$, which indeed is a constant between $r$ and 1. The RES capital costs are computed in the equivalent annualized form, while the RES projects are mostly funded by (governmental) banks. Furthermore, to provide a trade-off between IPPs profit and paid subsidies by the planning authority threatened by over funding risk, the incentives are considered flexibly, as Eq. (31). The average amount of delivered power by IPPs in region $s$, planning stage $t$, and load block $b$ can be computed as follows.

$$p^{RE}(s,b,t)=\left(\sum_{i\in I_{N\&E}^{RE}(s,t)}\sum_{n=1}^{n_{IO}^{RE}(i,s,t)}\overline{p}^{RE}(i,s,n,t)\cdot\delta(i,s)/8760\right); \quad s=1,..,S;b=1,..,B;t=1,..,T. \tag{31}$$

Of other main factors affecting expansion plans are budget constraints [29]. Here, to plan expansion strategies as realistic as possible, the constraint on budget is given as follows.

$$Inv(t)\leq B(t); \quad t=1,...,T. \tag{32}$$

$$B(t)=(1+r)\,B(t-1)-Inv(t); \quad B(0)=B^{tot};t=1,..,T. \tag{33}$$

$$Inv(t)=\sum_{j=1}^{6}\Gamma_j^H+\sum_{q=1}^{4}\Gamma_q^E; \quad t=1,...,T. \tag{34}$$

Regarding the eighth term of Eq. (3), it is required that the total amount of EENS at each stage, computed by Eq.(35), is limited to a certain value, as Eq. (36). Note that since the values of lost loads in different regions may differ from one another, different EENS caps can be allocated to them by Eq. (36).

$$\sum_{b=1}^{B}EENS(s,b,t)\leq\overline{EENS}(s,t); \quad s=1,..,S;t=1,..,T. \tag{35}$$

$$\sum_{s=1}^{S}\sum_{b=1}^{B}EENS(s,b,t)\leq\overline{\overline{EENS}}(t); \quad t=1,..,T. \tag{36}$$

## 3. SIMULATIONS AND NUMERICAL STUDIES

In this section, the simulation results obtained from two different scenarios, conducted on a real large-scale case study, are presented and discussed. The defined scenarios, i.e., S1 and S2, are defined as follows; S1: separated expansion planning; S2: co-expansion planning. In S1, indeed, optimal expansion strategy of each under-study energy system is determined separately with regard to the projected demand and defined constraints for each system. In S2, expansion of G&ES is simultaneously planned. Eventually, the interactions between participation rate of IPPs, the FIT systems and the amounts of VOLL in the proposed framework are evaluated in terms of a sensitivity analysis.

### A. Description of the case study, input data, and assumptions

To investigate the adequacy of co-planning approach in the long-term large-scale ESs' expansion problem, the proposed framework is applied to the Iranian electricity and gas systems, shown in Figs. 3 and 4, respectively. As can be seen from Fig. 4, all energy demands are divided between 33 regions. Regardless of energy distribution networks, demands in each node/region are considered as a load point. The exchange rate of energy between the regions can increase by enhancing the capacity of existing transmission infrastructures and/or by implementing new transmission corridors projects.

In order to incorporate the importance of those gas supply systems fed by common gas fields into the problem, the expansion capacities of gas supply systems related to the uncommon ones are assumed to be restricted. Here, the gas refineries located in the region 29 are considered as the supply systems fed by common gas fields. Demand growth data for each region predicted based on the demand behaviors in recent decades, and capacity factors related to the considered RES-based generation options are also adopted from references [7, 29, 30]. According to the base topology of each under-study ESs, candidate transmission corridors, i.e., new transmission lines and/or pipelines, are also depicted in the figure. More clarifications in this context are also presented in Fig. 3.

The more load blocks the LDC of each carrier has, the more precise models for demands behavior are reached. Hence, each planning stage (year) has been considered here in term of three load periods, i.e., base, medium, and peak, and each period, in turn, are divided into four monthly load blocks, resulting in twelves blocks. The forecasted amounts of demand for each carrier, at each node, during each load block of the year 2020, as the base year of planning horizon, i.e., 2021-2030, together with the electrical load shedding price, i.e., VOLL, corresponding to each region, can be found in [18]. The techno-economic data of candidate infrastructures are itemized in Table 1. Note that in this table, an identification code (ID) is allocated to each technology type of infrastructure in order to facilitate the illustration of simulation results. The investment cost of new electricity transmission corridor projects and any additional path for existing topology are also assumed to be 0.24 $M\$/km$ and 0.15 $M\$/km$, respectively [7].

Generally, the expansion planning problem of energy systems' infrastructures has a constrained non-linear discrete dynamic and stochastic nature. As a matter of course, the complexity of ESs expansion planning problems are derived from discrete nature of the variables denoting infrastructures size and allocation, the set of non-linear constraints, high-dimensionality originated from the number of variables, long-term nature, and uncertainties related to the demand, fuel price, and/or RES-based generating units. The solution of the problems determines the capacity addition schedule (siting, timing, sizing, and technology of new infrastructures additions) that satisfies forecasted load demand within the given budget, reliability, emission criteria over a planning horizon of typically 10–30 years. Thus, the determination of the proven optimal solution would require the investigation of every possible combination of candidate options over the planning horizon. The enormous calculation

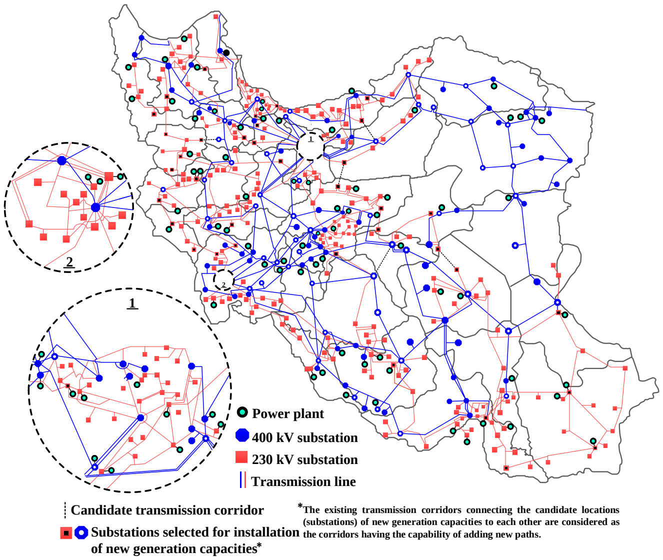


**Fig. 3.** The power system topology of Iran.

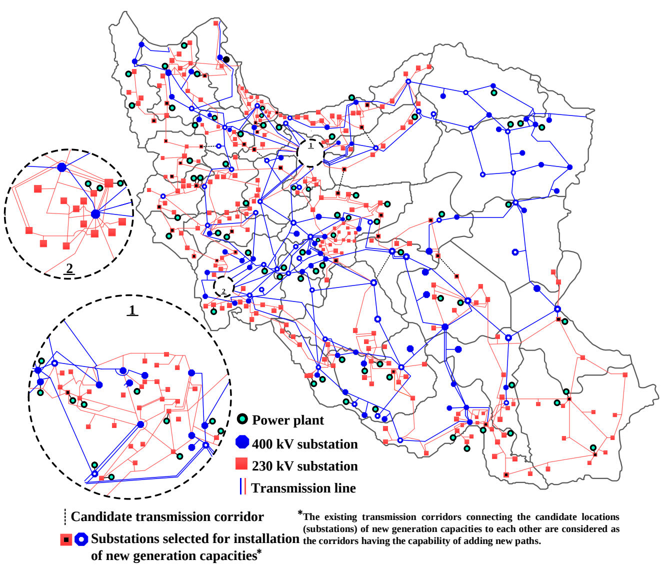


**Fig. 4.** A sketch of Iranian NG system.

overhead of such an approach has forced planners to employ simplifications of the models using linearization techniques and solve them via more reliable optimization packages during the past decades. As one of the most popular optimization tools, the GAMS package has proven its capability to handle various types of mathematical models, in particular, MILP ones [30–35].

Formulated in term of MILP problems, the model proposed here have been coded using the GAMS software and optimized via the CPLEX 11.2.0 solver. In the case of MILP-based models, the CPLEX solver has proven its own capability to find the optimal global solutions through a multitude of research works done in the field of ESs expansion planning problem. CPLEX, in fact, solves linear programming (LP) problems using several alternative algorithms. The majority of LP problems solve best using CPLEX's state of the art dual simplex algorithm. Certain types of problems benefit from using the primal simplex algorithm, the network optimizer, the barrier algorithm, or the sifting algorithm. The concurrent option will allow solving with different algorithms in parallel. The solution is returned by the first to finish. Note that CPLEX is a mathematical-based solver and unlike heuristic methods, it can guarantee the optimality of the solutions. Here, the simulations have been run using a PC powered by a core i3 processor and 3 GB of RAM. The optimal results have been obtained within a relative optimality gap of 0.00001.

Having assumed a cap on the investment budget, i.e., $B^{tot} = 90000M\$$ and a 5% discount rate, the solution results of the conducted scenarios are discussed in the following.

**Table 1.** Techno-economic data of candidate infrastructures for the gas and electricity energy systems

| Gas pipeline | ID | GP1 | GP2 | GP3 | GP4 | GP5 | GP6 |
|---|---|---|---|---|---|---|---|
| Diameter (inch) | | 20 | 24 | 30 | 36 | 42 | 48 |
| Cinv ($M\$/km$) | Steel | 2.1 | 2.9 | 4.8 | 6.7 | 9.4 | 12.2 |
| | Polyeth. | 1.7 | 2.24 | 3.6 | 5 | 7 | 8.5 |
| Max capacity ($km^3/h$) | Steel | 9.8 | 15.7 | 28.2 | 41.1 | 53.7 | 69.8 |
| | Polyeth. | 7.7 | 12.3 | 21.5 | 31.7 | 42.2 | 51.3 |
| **NG supply systems** | **ID** | **SP1** | **SP2** | **SP3** | | **SP4** | |
| Capacity ($Mm^3/day$) | | 125 | 60 | 20 | | 10 | |
| $C_{inv}$ ($M\$/Mm^3/day$) | | 156.95 | 160.23 | 164.61 | | 169.73 | |
| $C_{opr}$ ($\$/Mm^3/h$) | | 57.56 | 58.35 | 61.28 | | 63.48 | |
| $C_{O\&M}$ ($\$/Mm^3/h$) | | 51.67 | 43.75 | 30 | | 12.5 | |
| **Gas reservoirs** | **ID** | **GS1*** | **GS2**** | **GS3**** | | **GS4**** | |
| Capacity ($Mm^3$) | | 0.015 | 300 | 100 | | 1000 | |
| $C_{inv}$ ($M\$/Mm^3$) | | 1.03 | 0.781 | 0.923 | | 0.628 | |
| $\mu\&\lambda$ ($\$/Mm^3/h$) | | 1200 | 5000 | 5000 | | 5000 | |
| $C_{O\&M}$ ($\$/Mm^3/h$) | | 250 | 1150 | 1000 | | 830 | |
| Gas compressors | ID | CO1 | CO2 | CO3 | | CO4 | |
| Capacity (MW) | | 25 | 50 | 75 | | 100 | |
| Trans. rate ($Mm^3/h$) | | 1.24 | 2.92 | 4.58 | | 5.83 | |
| $C_{inv}$ (M \$/MW) | | 2 | 3.91 | 3.86 | | 3.81 | |
| $C_{opr}$ ($\$/Mm^3/h$) | | 41 | 39.7 | 38.2 | | 36.6 | |
| **GPG unit** | **ID** | **GPG1*** | **GPG2*** | **GPG3*** | **GPG4**** | **GPG5**** | |
| Capacity (MW) | | 80 | 120 | 160 | 160 | 200 | |
| $C_{inv}$ (M \$/MW) | | 1 | 0.98 | 0.96 | 0.83 | 0.81 | |
| $C_{opr}$ (\$/MWh) | | 16.1 | 15.3 | 14.5 | 21.6 | 21.6 | |
| $C_{O\&M}$ (\$/MWh) | | 43 | 41 | 38 | 159 | 156 | |
| Effic. (%) | | 55 | 58 | 61 | 41 | 41 | |

Note: Polyeth.*: Polyethylene type of gas pipelines are specified by GP1*-GP6*; GS1*: Above-ground (spherical tank) NG storage system; GS2**-GS4**: UGS systems based on aquifer, salt cavern, depleted field, respectively; Copr*: operation cost including O&M cost; GPG1*-GPG3*: CCGT; GPG4** & GPG5**: OCGT.

### B. Separated expansion planning results and analyses

As can be seen from the available literature, up to now, diverse analytical frameworks have built to assess the efficiency and efficacy of integrated planning methods of ESs compared with uncoordinated/separate planning methods. Nevertheless, in a multitude of these works, comparison results have been well analyzed only from some perspectives, such as reliability [36], [18], environmental issues [37], [6], and even mathematics and optimization process [7]. And how achieving the optimal expansion strategy for both ESs may less cost in integrated planning method compared with the separate planning one, has not been sufficiently scrutinized. On the other hand, achieving a rational economic comparison of aforementioned planning methods requires incorporating NG demand fluctuations affected by new NG-based electricity generation mixes into the model of two planning methods. This point has been less noticed until now. Since the neglect of new generation mix impact on the NG demand in separate expansion planning mode of G&ES results in a poor and unfair judgment on S1 expenditures in comparison with the expansion costs of S2, it is required that the impact of new-added NG-based electricity generation capacities on the NG system expansion strategy is considered. Accordingly, here, the scenario S1 is simulated based on the best real-world possible state. In doing so, among the gas and electricity sectors, first, how electricity sector should be expanded to meet the projected demand is addressed; regarding the optimal place, type, and entering time of new capacities, NG demands of the regions are updated; and then, the expansion strategy of NG sector is planned.

As S1 results summarized in Table 2 demonstrate, the total amount of capacity added to the initial generation mix is 4880 MW. The NPV of the total cost associated with the added capacities along with installed transmission lines, is 4205.14 M$. Table 3 demonstrates the details of IPPs contribution and the amounts of regions' EENS during the planning horizon. The NPV of total incentives allocated to the RES-based generators granted a FIT of 105 $/MWh and 122.5 $/MWh for wind and solar types [30], respectively, is 201.87 M$. In this context, referring to [7] and [30], the regions characterized by lower electricity demand growth and higher $\delta$ are more attractive options for attracting IPPs' contribution. Nevertheless, the share of RES in meeting the growing demand is negligible which may be derived from being low the VOLL or incentives paid to the renewable generators. It is noteworthy that in the proposed model, the uncertainties associated with the operation of the RES-based units are addressed by assuming reasonable values for their utilization hours per year, i.e., 1700 and 1400 hour/year, corresponding to the wind and solar technologies, respectively [38]. Through the S1, the total amount of EENS and the NPV of corresponding VOLLs in S1 are 32575.16 MWh and 229.703 M$, respectively. The differences between the amounts of EENS in different regions are derived from the location of GPG units, the profitability of RES-based units for the IPPs, the characteristics of transmission lines, and above all, defined prices for the shed loads.

From the viewpoint of location, newly added GPG units should be arranged in such manner that the total length of transmission lines required for supplying the projected demand is minimized, whereas this arrangement of GPG units may bring about remarkable expansion costs for the NG sector. The planned generation mix increases the projected NG demand in the relevant regions and planning stages. From the details of the NG system expansion strategy, summarized in Table 2, it can be seen that meeting the forecasted NG demand requires enhancing the capacity of existing paths as well as implementing new pipeline projects. Obviously, more factors affect EENS values if conditions of the NG system are taken into account in the planning process of the electricity sector. To evaluate the performance of GSS added to the under-study gas system in region 11, it is required that the NG load profile of this region together with the gas flow rate of new gas pipeline(s), feeding the relevant NG demand, are assessed. In this regard, the NG load profile of region 11, the performance of GSS added to the aforementioned region, as well as the gas flow rate of 11-16 pipeline, as the only corridor covering NG demand growth of region 11 is shown in Fig. 5.

Regarding the arrangement of expanded gas pipelines, presented in Table 2, it is simply found that the aforementioned feeding pipeline is originated from the gas supply systems in

**Table 2.** The details of S1 expansion results

| Symbol / ID of infrastructures | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SP, GS, GPG, & CO | | | | GP & TL | | | | |
| i | s | n | T | i | s | k | n | t |
| SP2 | 29 | 1,1 | 1,5 | GP1 | 1 | 2 | 1 | 1 |
| SP3 | 24 | 1 | 4 | | **10** | **16** | **1** | **1** |
| SP4 | 13 | 1,1,1 | 1,5,7 | | 20 | 21 | 1 | 1 |
| | 20 | 1 | 1 | | **27** | **28** | **1** | **1** |
| | 24 | 1 | 1 | GP1* | 3 | 4 | 1 | 1 |
| | 29 | 1,1,1 | 4,7,10 | | 7 | 13 | 1 | 1 |
| GS3 | 11 | 1 | 10 | | 8 | 15 | 1 | 1 |
| GPG1 | 4 | 1 | 3 | | **9** | **15** | **1** | **1** |
| | 10 | 1,1,1 | 1,4,6 | | **13** | **18** | **1** | **1** |
| | 12 | 1,1 | 1,6 | | 13 | 19 | 1 | 1 |
| | 13 | 1 | 1 | | **14** | **15** | **1** | **1** |
| | 14 | 1,1 | 1,8 | | 24 | 25 | 1 | 1 |
| | 15 | 1 | 1 | | **32** | **33** | **1** | **1** |
| | 17 | 1 | 1 | GP2 | 4 | 5 | 1 | 1 |
| | 26 | 1 | 1 | | 15 | 21 | 1 | 1 |
| | 28 | 1,1 | 1,5 | | 16 | 24 | 1 | 1 |
| | 29 | 1 | 1 | | 21 | 24 | 1 | 5 |
| GPG2 | 11 | 2 | 4 | | 27 | 31 | 1 | 1 |
| | 21 | 1 | 1 | | 30 | 31 | 1 | 1 |
| | 23 | 1,1 | 1,6 | GP2* | 5 | 6 | 1,1 | 1,6 |
| | 25 | 1 | 2 | | 23 | 26 | 1 | 1 |
| | 26 | 1 | 4 | GP3 | 12 | 17 | 1 | 1 |
| | 27 | 1 | 3 | GP3* | 2 | 16 | 1 | 1 |
| | 29 | 1 | 4 | GP4* | 6 | 12 | 1 | 1 |
| GPG3 | 1 | 1 | 1 | | 12 | 26 | 1 | 6 |
| | 2 | 1,1 | 1,5 | GP6 | 11 | 16 | 1 | 1 |
| | 11 | 1,1,1,1 | 1,2,5,6 | | 16 | 17 | 1 | 1 |
| | 13 | 1 | 4 | | 17 | 22 | 1 | 1 |
| | 17 | 1,1 | 2,8 | | 22 | 29 | 1 | 1 |
| | 24 | 1,1,1 | 1,4,6 | | 26 | 29 | 1 | 1 |
| | 33 | 1,1 | 1,6 | TL | 6 | 12 | 1 | 1 |
| GPG5 | 11 | 1 | 9 | | 7 | 12 | 1 | 1 |
| CO1 | 21 | 1 | 1 | | 8 | 14 | 1 | 1 |
| | 15 | 1 | 1 | | 9 | 10 | 1 | 1 |
| | 5 | 1 | 1 | | 10 | 16 | 1 | 2 |
| | 6 | 1 | 1 | | 13 | 19 | 1 | 1 |
| | 26 | 1 | 1 | | 14 | 20 | 1 | 1 |
| | 16 | 1 | 1 | | 14 | 15 | 1 | 8 |
| | 2 | 1 | 1 | | 17 | 18 | 1 | 1 |
| | 24 | 1 | 1 | | 22 | 25 | 1 | 2 |
| | 27 | 1 | 1 | | 24 | 25 | 1 | 1 |
| | 31 | 1 | 1 | | 29 | 30 | 1 | 1 |
| CO2 | 16 | 1 | 1 | The NPV of total inv. cost (M$) | | | | |
| | 17 | 1 | 1 | NG system | | | Elec. system | |
| | 26 | 1 | 6 | 82125 | | | 4205.14 | |
| | 12 | 1 | 1 | | | | | |
| Note: Highlighted rows: New GP and TL projects | | | | | | | | |

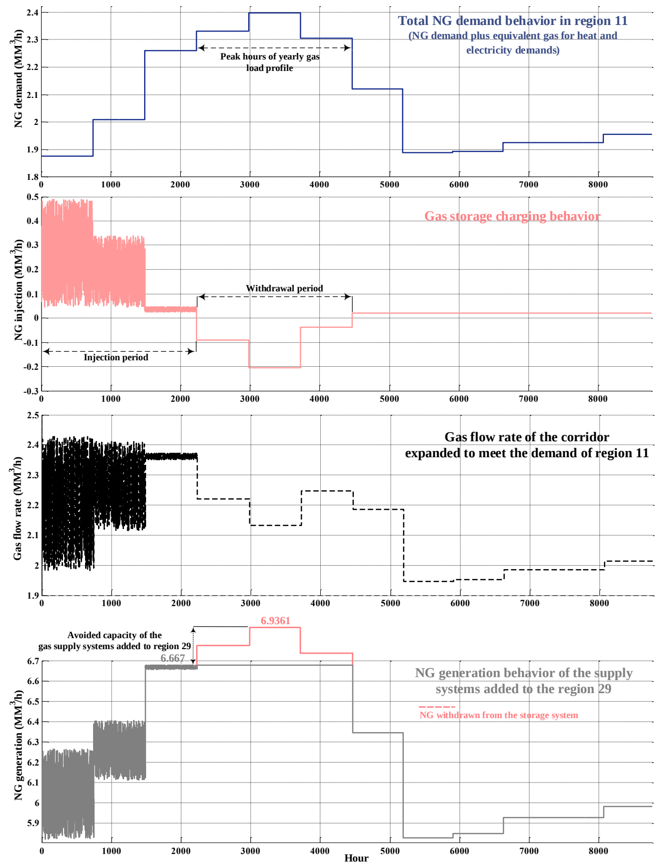


**Fig. 5.** A Charge behavior of the added GSS and its impact onto the gas supply systems.

**Table 3.** IPPs share and the amount of EENS in S1

| s | EENS | | IPPs | | | |
|---|---|---|---|---|---|---|
| | t | MWh | i | n | t | MW |
| 4 | 10 | 6140.2 | - | 0 | - | 0 |
| 7 | 10 | 7164.7 | - | 0 | - | 0 |
| 19 | 8 | 200.8 | Wind | 1 | 6 | 20 |
| 19 | 9 | 47.62 | Wind | 1 | 9 | 10 |
| 19 | 10 | 550.6 | - | 0 | - | 0 |
| 22 | 1 | 15044.6 | - | 0 | - | 0 |
| 27 | 1 | 1101.12 | Solar | 1 | 1 | 50 |
| 27 | 2 | 2298.96 | Solar | 1 | 2 | 50 |
| 32 | 9 | 27.08 | - | 0 | - | 0 |
| Total | | 32575.16 | - | 4 | - | 130 |

region 29 (follow the path of 29-22, 22-17, and 17-16 pipelines in Fig. 4. Hence, the generation behavior of the gas supply systems during the operation period of the added GSS is also demonstrated in Fig. 5 to scrutinize the impact that the GSS may have on the gas supply systems. From Fig. 5, the participation of added GSS in meeting the NG demand of the densest load point, i.e., region 11, during the peak period is apparent, as it fluctuates almost in an inverse proportion to the demand variations. As can be seen, during three first load blocks (months), the GSS acts as a load and is charged. This behavior causes that the hourly gas flow rate of the feeding pipeline is more than the total hourly NG demand during these load blocks. During the peak period (second three load blocks), negative charge profile of the GSS indeed shows the contribution of GSS in meeting the NG demand of the region.

The key point relates to the operation cost of the systems. The operation cost of GSS in comparison with the operation cost of NG supply systems is very high, and this means that during the operation period of GSS, there has not been enough capacity in the relevant gas transmission or supply sectors to meet the demand. The generation behavior of the gas supply systems added to region 29 can become more clear the effectiveness of the GSS role. During the peak period, as can be seen, the gas supply units of region 29 have bound to their maximum generation cap, i.e., $6.667 MM^3/h$; and this means that the GSS could result in avoiding more investment on expansion of generation capacities in region 29, as unrestricted NG node.

### C. Integrated expansion planning results and analyses

To better highlight the superiority of ESs' co-expansion planning approach compared with the separate planning one, the results of the second conducted scenario, summarized in Table 4, are discussed here.

Regarding the summarized results, the NPV of expansion costs of under-study gas and electricity systems, corresponding to the summarized results in Table 4, are 77896.96 M$ and 4463.91 M$, respectively. And this means that the co-expansion planning method in S2 would reduce the total expansion costs by 4.92% compared with those in S1. Note that in the second scenario, the operation cost of new-added GPG units is not taken into account; this cost indeed here lies in the operation cost of gas supply systems. The cost reduction can be treated as a reflection of utilization efficiency improvement of ESs' infrastructures, which in turn is the reflection of incorporating the interactions existing between G&ES into the planning. This can be better understood by evaluation of the impacts that electricity expansion plans can have on the NG sector in each scenario, while the electricity sector can be treated as one of the main NG consumers. As a matter of course, the new capacities added to the generation mix in S1, are only translated to a part of the projected NG demand with a predefined and fixed location for the NG sector. Whereas in S2, being variable, the location and capacity of NG-based generation options makes a level of flexibility for the NG sector and so a compromise between expansion of gas and electricity networks, resulting in achieving more optimal expansion strategies. Accordingly, GPG units, like support put under a rod, can make an optimal balance between the lengths of pipelines and transmission lines.

From S2 expansion costs, the share of IPPs at the end of the planning horizon has been 155 MW M$ showing a 12%-decrease compared with that in S1. This decrease in purchasing electricity is probably originated from the endeavor of optimization process to reach a better trade-off between expansion costs, EENS, and power purchasing from IPPs. The NPV of total incentives allocated to the RES-based generators in S2 is 60.687 M$. In this context, to clarify how the factors such as the VOLL and the amount of FIT premiums ca affect the participation level of IPPs in load meeting, the sensitivity of IPPs participation amount to aforementioned factors is analyzed through the next subsection.

By comparing the simulation results of S1 and S2, the increase in total installed electricity generation capacities, as well as the changes in their locations, is apparent. For instance, as the sum-

**Table 4.** The details of S2 expansion results

| Symbol / ID of infrastructures | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SP, GS, GPG, & CO | | | | GP & TL | | | | |
| i | s | N | t | i | S | k | n | t |
| SP2 | 24 | 1 | 4 | GP1 | **2** | **9** | **1** | **1** |
| | 29 | 1 | 4 | | 3 | 4 | 1 | 1 |
| SP3 | 13 | 1 | 1 | | **3** | **9** | **1** | **1** |
| | 20 | 1 | 1 | | 6 | 12 | 1 | 1 |
| | 24 | 1 | 1 | | 12 | 17 | 1 | 1 |
| | 29 | 2,1 | 1,1,6 | GP1* | 1 | 2 | 1 | 1 |
| SP4 | 13 | 1 | 7 | | 5 | 6 | 1 | 1 |
| | 20 | 1 | 7 | | 7 | 13 | 1 | 1 |
| | 29 | 1,1,1,2 | 4,6,8,9,9 | | 8 | 15 | 1 | 1 |
| | 30 | 1,1 | 1,6 | | **10** | **16** | **1** | **1** |
| | 33 | 1,1 | 1,5 | | **13** | **18** | **1** | **1** |
| GS2 | 2 | 1 | 8 | | 13 | 19 | 1 | 1 |
| GPG1 | 3 | 1 | 1 | | 14 | 15 | 1 | 1 |
| | 7 | 1 | 1 | | 24 | 25 | 1 | 1 |
| | 8 | 1 | 1 | | 27 | 31 | 1 | 1 |
| | 11 | 1 | 1 | | **27** | **28** | **1** | **1** |
| | 13 | 1,1,1 | 1,5,8 | | 30 | 31 | 1 | 1 |
| | 16 | 1,1 | 2,5 | | 32 | 33 | 1 | 1 |
| | 18 | 1 | 1 | GP2 | 11 | 16 | 1 | 1 |
| | 19 | 1 | 1 | GP3 | 17 | 23 | 1 | 1 |
| | 23 | 1,1 | 4,9 | GP3* | 21 | 24 | 1 | 1 |
| | 24 | 1,2,1 | 1,3,3,9 | GP4* | 20 | 21 | 1 | 1 |
| | 25 | 1 | 1 | GP5 | **9** | **15** | **1** | **1** |
| | 30 | 1,1,1,1 | 1,4,6,8 | GP6 | 16 | 22 | 1 | 1 |
| | 32 | 1 | 1 | | 22 | 29 | 1 | 1 |
| | 33 | 1 | 4 | | 23 | 26 | 1 | 1 |
| GPG2 | 9 | 1,1,1 | 4,6,8 | | 26 | 29 | 1 | 1 |
| | 16 | 1,1,1,1 | 1,5,6,9 | | 15 | 21 | 1 | 1 |
| | 23 | 1,1 | 5,6 | TL | 1 | 2 | 1 | 1 |
| | 24 | 1,1,1 | 1,7,8 | | 2 | 9 | 1 | 1 |
| | 29 | 1 | 1 | | 4 | 9 | 1 | 1 |
| | 33 | 1,1 | 1,6 | | **5** | **12** | **1** | **1** |
| GPG3 | 3 | 1 | 1 | | 6 | 12 | 1 | 1 |
| | 29 | 1 | 4 | | 6 | 7 | 1 | 6 |
| GPG5 | 16 | 1,1 | 3,7 | | 9 | 10 | 1 | 1 |
| | 23 | 1,1 | 1,7 | | 11 | 16 | 1,1 | 1,5 |
| | 24 | 1 | 5 | | **12** | **17** | **1** | **1** |
| CO1 | 17 | 1 | 1 | | 14 | 20 | 1 | 1 |
| | 3 | 1 | 1 | | 15 | 21 | 1 | 1 |
| | 12 | 1 | 1 | | 16 | 17 | 1 | 1 |
| | 6 | 1 | 1 | | 17 | 22 | 1 | 1 |
| | 2 | 1 | 1 | | 17 | 23 | 1 | 1 |
| | 13 | 2 | 1,1 | | 20 | 24 | 1 | 1 |
| | 15 | 1 | 1 | | 20 | 21 | 1 | 1 |
| | 31 | 1 | 1 | | 22 | 25 | 1 | 1 |
| | 27 | 1 | 1 | | 26 | 29 | 1 | 1 |
| CO2 | 21 | 1 | 1 | | 27 | 30 | 1 | 1 |
| | 26 | 1 | 1 | | 27 | 31 | 1 | 1 |
| | 23 | 1 | 1 | | 28 | 31 | 1 | 1 |
| | 16 | 1 | 1 | Total NPV of inv. cost (M$) | | | | |
| | 15 | 1 | 1 | The NG system | | The Elec. system | | |
| | 22 | 1 | 1 | | | | | |
| | 9 | 1 | 1 | 79896.9 | | 4463.91 | | |

marized results in Table 2 show, in region 11, a remarkable share of the relevant electricity demand is supplied by the generation capacities added to this region through the separated expansion planning scenario. And, this has brought about the need for implementation of high-diameter gas pipeline projects in longer distances (GP6 16-11). Whereas, as the summarized results of generation mix in Table 4 demonstrate, through the co-expansion planning approach, the electricity load of the aforementioned region is met via the new transmission lines, TL 16-11, and generation capacities added to the neighbor regions (16), resulting in less investment on gas pipeline projects. Through the S2, the total generation capacities added to the base generation mix is 5040 MW. And the NPV of the lost load through S2 is 67.072 M$, corresponding to 68601 MWh as total EENS. Noteworthy in this comparison is the reduction in the whole of expenditures (for both G&ES). As can be seen, despite that more generation capacities are added to the base generation mix through S2 in comparison with S1, the sum of above-mentioned cost terms together with the cost of energy purchasing from the IPPs through the second scenario is less than the sum of same costs in the first scenario. And, as mentioned, this cost saving demonstrates the superiority of co-expansion planning scheme compared with the traditional separated expansion planning approach. Apart from above-discussed distinctions, the effectiveness of operating GSSs in S2 is similar to S1.

### D. IPPs participation sensitivity analysis

In this subsection, how the amount of IPPs participation can be affected by the level of incentives in the FIT system and the amounts of VOLL in different regions is explored. In doing so, the base VOLL amounts of all regions, as well as the base amounts of incentives allocated to the renewable generators, i.e., the IPPs, are considered in three different levels. They indeed are multiplied by three coefficients, i.e., 0.8, 1.2, and 1.2. Accordingly, the changes in IPPs participation level in response to the changed base amounts of VOLL and the incentives are shown in Figs. 6 and 7, respectively. As can be observed from Fig. 6, the decrease in VOLL causes that the amount of EENS increases; and meanwhile, the motivation for purchasing green electricity from the IPPs has been decreased. All these changes decline the planning costs compared to the summarized results of the S2 in Table 4. By contrast, as Fig. 6 demonstrates, increases in the VOLL amounts increases the motivation for purchasing green electricity form the supported IPPs, resulting in decreasing the amount of EENS. And, this, in turn, increases the planning cost of the electricity sector. It should be noted that, as the effect of emission restrictions on RES promotion, the impact of VOLL amounts on the IPPs participation can be treated as a secondary (or indirect) effect.

Despite the fact that the premiums of the FIT system directly affect the RES penetration rate, as apparent from Fig. 7, the changes in the IPPs participation in response to the changes of the FIT premiums are less than the changes derived from changes in the VOLL amounts. As a matter of course, in the built framework, the sensitivity of IPPs presence in the electricity generation mix to the VOLL amounts is more than the amounts of FIT incentives. From Fig. 7, it can also be seen that decreasing the profit margin considered for the IPPs affected by decreased incentives (see Eq. 29) results in increasing the motivation for purchasing green electricity from the IPPs. Obviously, the amount of power purchased from the IPPs is decreased, if the investment cost of RES is decreased. The technological maturity of RES, in fact, decreases the amount of incentives required

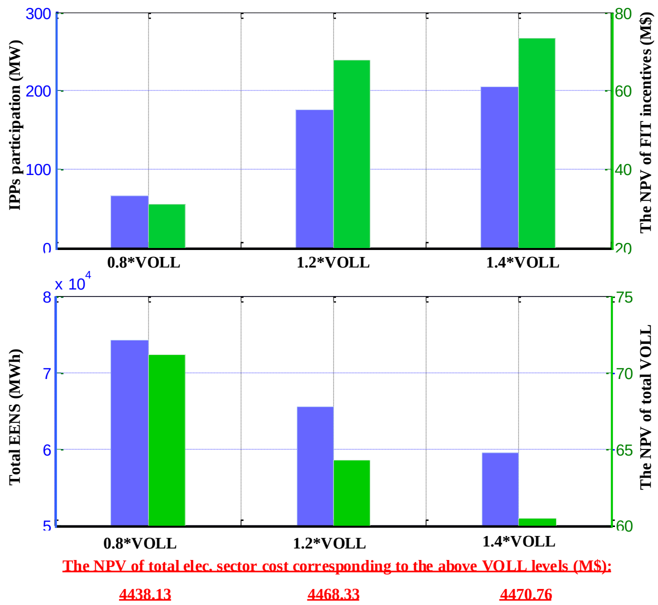


**Fig. 6.** The sensitivity of IPPs participation to the VOLL.

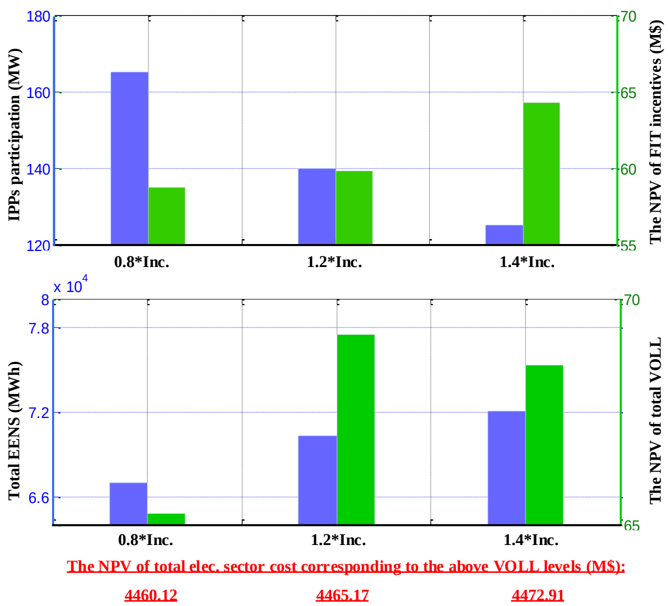


**Fig. 7.** The sensitivity of IPPs participation to the FIT premiums.

for encouraging the IPPs. And, this, in turn, can decline the amounts of loads shed. Regarding the above discussion, it can be said that in developing countries such as Iran having the semi-deregulated structure, consideration of the VOLL amounts as well as different levels of incentives for different regions with respect to the corresponding RES potential in designing the energy policies can reach more optimal IPPs participation.

## 4. CONCLUSIONS

A comprehensive well-adapted co-planning model is developed to explore the optimal amalgamated expansion strategy of gas and electricity energy systems, which can effectively handle the expansion planning problem about which and where natural gas pipes, gas compressors and NG-based power generation options are expanded in the integrated NG and electricity networks. Formulated as a MILP problem, the proposed model is applied to a real large-scale energy system, i.e., Iranian gas and electricity systems through two different scenarios. The results show that the integrated gas and electricity expansion planning results in cheaper costs when compared to the disaggregated option. This validates the initial assumption that the aggregated vision seems more attractive. Furthermore, analysis of findings reveals that employing the integrated approach in expansion planning problems of energy systems provides the opportunity of better understanding the interactions between energy systems infrastructures, such as the interaction between gas and electricity networks length affected by the location of GPG units. Among the remaining challenges, one that deserves special consideration is to make use of the results of an indicative centralized plan in a market-oriented environment. Hence, Work in progress thereby aims at evaluating legal frameworks required for more gas and electricity systems trade-off, when the NG sector can participate to the demand response programs or provide an alternative for large electricity loads equipped to NG-based distributed generators when the price of electricity is high and the NG price is low.

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