

Market-based Coordination for Integrated Electricity and Natural Gas Systems Under Uncertain Supply

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Abstract—The interdependence between electricity and natural gas systems has lately increased due to the wide deployment of gas-fired power plants (GFPPs). Moreover, weather-driven renewables introduce uncertainty in the operation of the integrated energy system, increasing the need for operational flexibility. Recently proposed stochastic dispatch models optimally use the available flexibility and minimize the total expected system cost. However, these models are incompatible with the current sequential market design. We propose a novel method to optimally define the available natural gas volume for power production scheduling, anticipating the real-time flexibility needs. Our model is formulated as a stochastic bilevel program aiming to enhance the inter-temporal coordination of scheduling and balancing operations, while remaining compatible with the sequential clearing of day-ahead and real-time markets. The proposed model accounts for the inherent flexibility of the natural gas system via the proper modeling of linepack properties and reduces the total expected system cost by the optimal definition of natural gas volume availability for GFPPs during the scheduling phase.

Index Terms—Bilevel programming, integrated electricity and natural gas systems, market-based coordination, uncertainty.

I. INTRODUCTION

The coupling between the electricity and natural gas systems has been substantially strengthened due to the increased utilization of gas-fired power plants (GFPPs) over the last decades and this trend is expected to continue in the foreseeable future [1]. In addition, renewable energy sources, such as wind and solar power, already comprise a significant share of the generation mix. The co-existence of these two types of power production plants serves as a promising combination for a smooth transition to a sustainable energy system that is flexible enough to accommodate high shares of renewables. To this end, the interdependence between these two energy systems will increase and the intermittency of renewable energy sources will eventually affect the operation of both systems. Hence, there is a compelling need to introduce mechanisms that treat these systems in an integrated manner.

The coordinated operation of electricity and natural gas systems has been extensively studied lately. The benefits of improved coordination between the two energy systems under high intraday variability of GFPPs' fuel consumption are indicated in [2]. In a similar context, the impact of natural gas supply uncertainty and price variability on the power system dispatch is analyzed in [3], showing that these parameters can

considerably alter the market outcomes. Moreover, authors in [4] highlight the benefit in terms of improved flexibility and reliability, when accounting for the ability to store natural gas in the pipelines, known as linepack. Therefore, both physical and economic links between electricity and natural gas systems have an eminent role in short-term operations and are highly essential in the presence of renewables. The effect of uncertain renewable power production to the coupled energy system is analyzed via a robust co-optimization framework in [5], while authors in [6] utilize stochastic programming to dispatch the power system with feasible fuel supply from the natural gas network. Moreover, authors in [7] consider a joint optimization framework that utilizes GFPPs to firm up uncertain power supply from renewables. Taking a market perspective, an equilibrium model for the interdependent electricity and natural gas markets that allows for short-term energy trading based on locational marginal prices is proposed in [8]. Similarly, we study the short-term coupled operation of electricity and natural gas systems in a market framework where the energy commodities are traded based on their marginal prices. Such an approach is highly attractive especially when the two systems are operated by the same entity, e.g. Energinet.dk in Denmark, that is both electricity and natural gas systems' operator [9].

Following the paradigm of the electricity sector, the volume of natural gas traded in the spot markets is continuously increasing [9]. Therefore, the short-term operation of electricity and natural gas systems should be modeled on the basis of a market-based framework. The short-term operation is mainly associated with two trading floors, namely the day-ahead and balancing markets that are cleared in a sequential manner. The day-ahead market is settled 12-36 hours ahead of the actual system operation and the balancing market deals with the necessary adjustments to keep the system balanced. However, this sequential arrangement is inefficient under high shares of stochastic renewable power production due to its deterministic view of the uncertain renewables' production. In the European context, the day-ahead market follows a zonal network representation, while a nodal network representation is considered during the real-time operation. Stochastic programming has been utilized to enhance the temporal coordination between these two trading floors by making use of a probabilistic description of stochastic renewable production [10], [11]. Despite that this approach provides the solution with the minimum expected system cost, it is not compatible with the current market design and in addition it suffers from some design flaws related to the violation of the least-cost merit-order principle [12], [13]. For this reason, several approaches have been proposed that aim at approximating the stochastic ideal solution, while maintaining the current market

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architecture. An improved dispatch model that minimizes system's expected cost and respects the merit-order principle by scheduling wind power in a value different than its expected production is proposed in [12], while cost recovery¹ of flexible producers is guaranteed for any realization of uncertainty. Additionally, authors in [14] develop a framework to set the available transfer capacity (ATC) in a cost-optimal manner and attain a solution closer to the stochastic one. Finally, a model that efficiently dispatches the power system with an optimal setting of allocation between energy and reserves on the inter-regional HVDC interconnections is proposed in [15]. In the aforementioned works, the system operator is able to properly tune these purely financial parameters, i.e. wind dispatch, ATCs, HVDC allocation, in order to communicate the missing information to the day-ahead stage and achieve a partial temporal coordination between the trading floors.

Following a similar approach, we propose a systematic method to define the optimal natural gas volume that is made available for power production at the day-ahead stage. We consider this natural gas availability as a parameter that can be controlled by the operator and we build a stochastic bilevel model to determine its optimal value, while anticipating the future balancing needs due to forecast errors from uncertain power supply. This mechanism aims to improve the temporal coordination between day-ahead and balancing trading floors and approximate the efficiency of the stochastic solution, while the existing market architecture is preserved. The natural gas availability only affects the day-ahead schedule of the integrated energy system and the real-time balancing takes into account the physical characteristics of the two networks. Regarding the natural gas system, we model the linepack capability to make optimal use of the available network flexibility. Our models achieve optimal operation in terms of total operating cost for the integrated energy system with detailed representation of the technical constraints for both components, i.e. electricity and natural gas networks. Thus, the proposed *volume-based* model optimally determines the natural gas volume offered to GFPPs and in turn provides an appropriate system dispatch to cope with the imbalances in real-time. Finally, we compare the *volume-based* approach with the *price-based* model proposed in [16], which introduces a stochastic bilevel program that generates proper flexibility price signals to adjust the natural gas price perceived by GFPPs in order to provide a more efficient market outcome.

The remaining of the paper is organized as follows. Section II outlines the main properties of each dispatch model for the integrated energy system, while the mathematical formulation is presented in Section III. The results are illustrated in Section IV, and Section V concludes the paper. Finally, additional material including some mathematical extensions, proofs and a detailed nomenclature are given in the online appendix [17].

II. MARKET-BASED COORDINATION

In this paper, we study four dispatch models for scheduling and balancing electricity and natural gas systems. These models achieve different degrees of temporal coordination for the

integrated energy system. This section describes their fundamental principles and provides a schematic representation to outline the main properties of each coordination scheme.

A. Sequential Dispatch of Integrated Energy System

The sequential dispatch of the integrated energy system (*Seq*) models a case of perfect inter-systems coordination between electricity and natural gas networks for both day-ahead and balancing markets, as shown in Fig. 1. However, these market floors are cleared in sequential and independent auctions, resulting to imperfect temporal coordination between the scheduling and balancing operations. Having as input a single-valued forecast of the stochastic power production, a common day-ahead market is cleared to obtain the initial operation schedule for both systems. Getting closer to actual operation, when the realization of stochastic production ω' is known, the balancing actions to compensate for potential forecast errors are jointly optimized for both systems through a common balancing market. Even though this sequential approach may be inefficient due to imperfect temporal coordination, it admits an important economic property that ensures cost recovery for flexible producers for any realization of stochastic production, as shown in the electronic companion [17]. Assuming a co-optimization process that minimizes the combined system cost at each market stage, this setup deviates from the current design since it does not respect the asynchronous timing and independent clearing of the respective markets [18]. However, this market model allows us to assess the net value of temporal coordination between the day-ahead and balancing markets of interdependent energy networks.

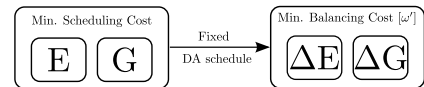


Fig. 1. Sequential dispatch of integrated energy system. DA: Day-ahead, E: Electricity, G: Natural gas, ΔE : Electricity adjustment, ΔG : Natural gas adjustment.

B. Stochastic Dispatch of Integrated Energy System

To improve the temporal coordination between the scheduling and balancing operations, we construct the stochastic coupled electricity and natural gas dispatch model (*Stoch*) illustrated in Fig. 2. Here, the day-ahead market co-optimizes the electricity and natural gas schedules based on a probabilistic description of uncertain supply, which allows to anticipate the cost of re-dispatch actions in real-time operation. Such probabilistic description is based on the available forecast at the day-ahead stage and may not cover the exact realization in real-time. However, given that the uncertainty modelling adequately captures the true characteristics of the stochastic processes involved, the potential realization will be represented via a set of scenarios Ω . This market setup is mathematically formulated as a two-stage stochastic programming problem that minimizes the total expected cost of the integrated energy system. The definition of this model provides an ideal reference solution that attains perfect inter-systems and temporal coordination, assuming that a realistic range and probability distribution of scenarios are considered. However, its real-life

¹Revenue of each market participant is greater than or equal to its operating costs.

implementation is restricted because cost recovery for market participants and revenue adequacy² for the system operator hold only in expectation [10]. Actually, these fundamental economic properties may be violated for some uncertainty realizations in scenario set Ω since this model does not respect the least-cost merit-order principle in the day-ahead market.

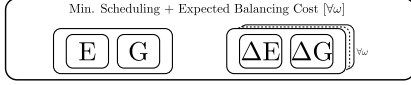


Fig. 2. Stochastic dispatch of integrated energy system.

C. Volume-based Coordination in Sequential Dispatch of Integrated Energy System

Aiming to address the caveat of imperfect temporal coordination of the *Seq* model, while sidestepping the design flaws of the *Stoch* model, we introduce a volume-based (*V-B*) coordination mechanism. This mechanism leverages the physical coupling of electricity and natural gas systems through the GFPPs to implicitly coordinate the day-ahead and balancing markets. The system operator uses as coordination signal an amount χ^v of the natural gas volume that is available to GFPPs at the day-ahead stage, while the full capacity of the natural gas network is released during real-time operation. Note that volume χ^v affects only the fuel demand of GFPPs, while industrial/commercial natural gas loads have higher priority.

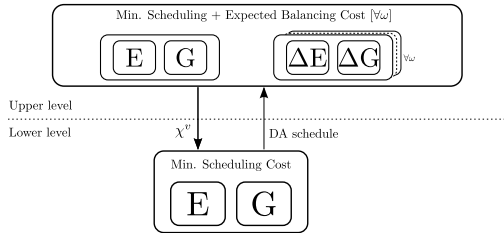


Fig. 3. Volume-based coordination in sequential dispatch of integrated energy system.

A systematic method for the definition of the optimal value of χ^v is mathematically formulated as the stochastic bilevel program presented schematically in Fig. 3. Similar to the *Stoch* model, the upper-level problem minimizes the expected cost of the integrated system, having χ^v as a non-negative decision variable. In turn, the lower-level problem reproduces the day-ahead clearing of the integrated market for a fixed value of χ^v that enters the lower level as a fixed parameter. This structure accounts for the independence of day-ahead and balancing markets, since the day-ahead schedule that is enforced by the lower-level problem has the exact same properties as its counterpart in the *Seq* model. Consequently, the re-dispatch actions are optimized individually for each uncertainty realization in the upper level. Essentially, the optimal value of χ^v is found by anticipating the day-ahead market outcome and the subsequent expected balancing cost.

This coordination mechanism resembles the “maximum gas burn” constraint recently introduced by California Independent System Operator (CAISO) to address reliability risks due

²Payments made to/received from market participants do not incur financial deficit to the operator.

to the limited operability of the Aliso Canyon natural gas storage facility. Using this constraint CAISO is able to limit the gas consumption of a group of generators in a defined area [19]. In the same vein, our volume signal χ^v can be applied to a whole control zone or be tailored to specific areas or GFPPs. Nonetheless, the proposed mechanism extends CAISO’s approach to consider primarily issues pertaining to forecast errors of stochastic power producers.

D. Price-based Coordination in Sequential Dispatch of Integrated Energy System

Apart from the physical interaction of electricity and natural gas networks, there is also an economic link that couples the operation of these systems through the natural gas price offered to GFPPs. Therefore, a coordination mechanism analogous to the volume-based approach outlined above, can be established using instead a price-based (*P-B*) signal χ^p applied to the natural gas prices. To define the optimal value of χ^p we employ the stochastic bilevel optimization model that is depicted schematically in Fig. 4 and presented in [16]. The construction of this model follows the same rationale as the volume-based coordination scheme and thus it also preserves the independent clearing of day-ahead and balancing markets that enforces per-se the merit-order principle.

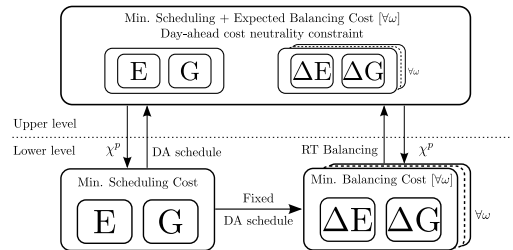


Fig. 4. Price-based coordination in sequential dispatch of integrated energy system. RT: Real-time.

This coordination mechanism allows GFPPs to utilize all available natural gas resources but can instead control (either increase or decrease) the natural gas price that is perceived by the GFPPs via the free in sign χ^p . In turn, this affects their short-term marginal costs and consequently their price offers on the electricity side of the integrated market in both day-ahead and balancing stages. Practically, these price signals reflect the scarcity value of flexible GFPPs for the system operator during real-time balancing. In order to ensure fairness and transparency for all counter-parties, this mechanism is designed on a cost-neutral basis such that the system operator is financially balanced at the day-ahead stage. Potential financial imbalances in the real-time settlements can be compensated using out-of-the-market payments as a supporting mechanism for the flexible producers, similar to the flexible capacity remuneration mechanisms that are currently discussed in the European electricity market context [20].

E. Features of Bilevel Models and Computational Tractability

Since the sequential arrangement between the trading floors is preserved with *V-B* and *P-B* models, cost recovery for flexible producers is guaranteed for each realization of stochastic

production. Moreover, it can be noticed that in V - B implementation only the day-ahead stage needs to be included in the lower-level problem since the natural gas volume availability χ^v only affects the natural gas volume that is announced at the day-ahead market stage and then the physical capacity of the natural gas network is made available in real-time. On the contrary, both the day-ahead and balancing markets must be included in the lower-level problem of P - B , since the price adjustment χ^p affects the marginal cost of GFPPs in the day-ahead market; however, the real-time price offers have to be altered in a consistent way to preserve the incentive for the provision of balancing services. Since the proposed dispatch models V - B and P - B are formulated in a bilevel structure, it is necessary to ensure that the lower-level problems are linear and convex in order to allow a single-level reformulation as a tractable mixed-integer linear program (MILP). Therefore, we study two variants of the balancing market in the following section. The first one directly permits the comparison between V - B and P - B since the balancing market is formulated as a linear program (LP). On the other hand, the second variant can be applied only to V - B as it has a detailed formulation for the gas flows in the real-time stage, which requires the introduction of binary variables that make the problem non-convex. Finally, model V - B results in a MILP with fewer binary variables than P - B as the balancing market is not included in the lower level. Note that since the balancing market is not included in the lower level of V - B model, this formulation is less computationally expensive as the number of binary variables is independent of the number of scenarios.

III. MODEL FORMULATION

Before presenting the mathematical formulation of the dispatch models, we introduce a set of assumptions utilized in this study. A holistic view of the energy systems is followed, where the electricity and natural gas markets are considered coupled, hence the market clearing is a single optimization problem. Uncertain supply from stochastic producers is modeled via a finite set of scenarios Ω , accounting for temporal and spatial correlations of the forecast errors. We assume that electricity and natural gas demands are inelastic and exactly known, hence we take the operator's perspective that minimizes system's cost. The physical link between the electricity and natural gas systems is provided by GFPPs, where their fuel consumption has a lower priority than industrial/commercial natural gas demands. The cost structure for electricity and natural gas producers is assumed to have the form of linear functions, while stochastic producers bid with zero marginal cost. We focus on the two trading floors of day-ahead and balancing markets, where a pool-based approach, i.e. without network constraints, is used to clear the day-ahead market, while the balancing market is formulated under two different setups. The first setup is formulated as an LP under the assumption that the balancing market is cleared as a pool with additional fuel constraints for the GFPPs based on an *ex-ante* estimation of pipeline capacities, similarly to the approach in [3]. In the second setup, we introduce network constraints for both electricity and natural gas systems. For the power system, we adopt a DC power flow, while a model that approximates

gas flow dynamics via linepack consideration is used for the natural gas system [21], which leads to a MILP formulation.

A. Sequential Dispatch of Integrated Energy System

As illustrated in Fig. 1, the day-ahead and balancing markets are cleared independently in the *Seq* model. Initially, the day-ahead market is formulated in (1) as follows,

$$\text{Min.}_{\Theta^D} \sum_{t \in T} \left(\sum_{i_c \in I_c} C_{i_c} p_{i_c, t} + \sum_{k \in K} C_k g_{k, t} \right) \quad (1a)$$

subject to

$$0 \leq p_{i, t} \leq P_i^{\max}, \quad \forall i, t, \quad (1b)$$

$$0 \leq w_{j, t} \leq \widehat{W}_{j, t}, \quad \forall j, t, \quad (1c)$$

$$0 \leq g_{k, t} \leq G_k^{\max}, \quad \forall k, t, \quad (1d)$$

$$\sum_{i \in I} p_{i, t} + \sum_{j \in J} w_{j, t} - \sum_{r_e \in R_e} D_{r_e, t}^E = 0 : \hat{\lambda}_t^E, \quad \forall t, \quad (1e)$$

$$\sum_{k \in K} g_{k, t} - \sum_{r_g \in R_g} D_{r_g, t}^G - \sum_{i_g \in I_g} \phi_{i_g} p_{i_g, t} = 0 : \hat{\lambda}_t^G, \quad \forall t, \quad (1f)$$

$$0 \leq \sum_{t \in T} \sum_{i_g \in A_{\psi}^{I_g}} \phi_{i_g} p_{i_g, t} \leq |T| \sum_{k \in K} G_k^{\max} - \sum_{t \in T} \sum_{r_g \in R_g} D_{r_g, t}^G, \quad (1g)$$

$$0 \leq \sum_{i_g \in A_{\psi}^{I_g}} \phi_{i_g} p_{i_g, t} \leq F_{\psi, t}^{\max} - \sum_{r_g \in A_{\psi}^{R_g}} D_{r_g, t}^G, \quad \forall \psi, t, \quad (1h)$$

where $\Theta^D = \{p_{i, t}, \forall i, t; w_{j, t}, \forall j, t; g_{k, t}, \forall k, t\}$ is the set of optimization variables. The objective function (1a) to be minimized determines the day-ahead cost of the integrated electricity and natural gas system, including thermal electricity producers i_c , GFPPs i_g and natural gas producers k . Parameters C_i and C_k are production costs, and t is the index for time periods. We have excluded the electricity cost of GFPPs since this is already accounted through the cost of their natural gas consumption. Power production $p_{i, t}$ of power plant i (either thermal or GFPP) is constrained by their generation capacity P_i^{\max} in (1b), while power dispatch $w_{j, t}$ of stochastic (e.g. wind) electricity producer j is bounded by its expected production $\widehat{W}_{j, t}$ in (1c). Moreover, natural gas production $g_{k, t}$ is constrained by capacity G_k^{\max} in (1d) for each producer. The balance in power and natural gas systems is enforced through (1e) and (1f), whose dual variables $\hat{\lambda}_t^E$ and $\hat{\lambda}_t^G$ reflect the market price for electricity and natural gas, respectively. Note that r_e and r_g are indices for electricity and natural gas demands, and their loads are denoted by parameters $D_{r_e, t}^E$ and $D_{r_g, t}^G$. In addition, parameter ϕ_{i_g} refers to the power conversion factor for each GFPP. The marginal cost of each GFPP can be endogenously calculated by the multiplication of the natural gas price and the power conversion factor. Constraints (1g) limit the daily natural gas use of GFPPs up to the available natural gas volume at the day-ahead stage, which is determined by subtracting the commercial/industrial natural gas demand from the total daily available capacity. We introduce a specific set to group GFPPs indexed by ψ , which may comprise GFPPs in a specific area of the natural gas system or even only a particular GFPP. Set $A_{\psi}^{I_g}$ denotes a subset of GFPPs belonging to the specific area ψ , while similar notation for sets A is used in all formulations. The hourly fuel constraints are imposed in

(1h), where $F_{\psi,t}^{\max}$ denotes the maximum natural gas availability for the specific group of GFPPs. For the sake of conciseness, we denote the power adjustment provided by each power plant as $\Delta p_{i,\omega',t} = p_{i,\omega',t}^+ - p_{i,\omega',t}^-$ with $p_{i,\omega',t}^+, p_{i,\omega',t}^- \geq 0$ and the natural gas adjustment for each gas producer as $\Delta g_{k,\omega',t} = g_{k,\omega',t}^+ - g_{k,\omega',t}^-$ with $g_{k,\omega',t}^+, g_{k,\omega',t}^- \geq 0$. The day-ahead schedule is a fixed input (denoted with superscript ‘*’) to the balancing market and model (2) simulates the balancing market to compensate for potential imbalances due to the stochastic power realization $W_{j,\omega',t}$:

$$\begin{aligned} \text{Min.}_{\Theta^R} \quad & \sum_{t \in T} \left(\sum_{k \in K} (C_k^+ g_{k,\omega',t}^+ - C_k^- g_{k,\omega',t}^-) + \sum_{r_e \in R_e} C^{sh,E} l_{r_e,\omega',t}^{sh,E} \right. \\ & \left. + \sum_{i_c \in I_c} (C_{i_c}^+ p_{i_c,\omega',t}^+ - C_{i_c}^- p_{i_c,\omega',t}^-) + \sum_{r_g \in R_g} C^{sh,G} l_{r_g,\omega',t}^{sh,G} \right) \end{aligned} \quad (2a)$$

subject to

$$-P_i^* \leq \Delta p_{i,\omega',t} \leq P_i^{\max} - p_{i,t}^*, \quad \forall i, t, \quad (2b)$$

$$-P_i^- \leq \Delta p_{i,\omega',t} \leq P_i^+, \quad \forall i, t, \quad (2c)$$

$$0 \leq w_{j,\omega',t}^{sp} \leq W_{j,\omega',t}, \quad \forall j, t, \quad (2d)$$

$$0 \leq l_{r_e,\omega',t}^{sh,E} \leq D_{r_e,t}^E, \quad \forall r_e, t, \quad (2e)$$

$$\begin{aligned} & \sum_{i \in I} \Delta p_{i,\omega',t} + \sum_{r_e \in R_e} l_{r_e,\omega',t}^{sh,E} \\ & + \sum_{j \in J} (W_{j,\omega',t} - w_{j,\omega',t}^{sp} - w_{j,t}^*) = 0 : \tilde{\lambda}_{\omega',t}^E, \quad \forall t, \end{aligned} \quad (2f)$$

$$-g_{k,t}^* \leq \Delta g_{k,\omega',t} \leq G_k^{\max} - g_{k,t}^*, \quad \forall k, t, \quad (2g)$$

$$-G_k^- \leq \Delta g_{k,\omega',t} \leq G_k^+, \quad \forall k, t, \quad (2h)$$

$$0 \leq l_{r_g,\omega',t}^{sh,G} \leq D_{r_g,t}^G, \quad \forall r_g, t, \quad (2i)$$

$$\sum_{k \in K} \Delta g_{k,\omega',t} + \sum_{r_g \in R_g} l_{r_g,\omega',t}^{sh,G} = \sum_{i_g \in I_g} \phi_{i_g} \Delta p_{i_g,\omega',t} : \tilde{\lambda}_{\omega',t}^G, \quad \forall t, \quad (2j)$$

$$0 \leq \sum_{t \in T} \sum_{i_g \in A_z^{I_g}} \phi_{i_g} (p_{i_g,t}^* + \Delta p_{i_g,\omega',t}) \leq F_z^A, \quad \forall z, \quad (2k)$$

$$0 \leq \sum_{i_g \in A_z^{I_g}} \phi_{i_g} (p_{i_g,t}^* + \Delta p_{i_g,\omega',t}) \leq F_z^M, \quad \forall z, t, \quad (2l)$$

where $\Theta^R = \{p_{i,\omega',t}^{+/-}, \forall i, t; l_{r_e,\omega',t}^{sh,E}, \forall r_e, t; l_{r_g,\omega',t}^{sh,G}, \forall r_g, t; g_{k,\omega',t}^{+/-}, \forall k, t; w_{j,\omega',t}^{sp}, \forall j, t\}$ is the set of optimization variables. The cost of re-dispatch actions is minimized in objective function (2a). Balancing offer prices $C^+ > C$ and $C^- < C$ denote the adjustment costs for thermal power plants i_c and natural gas producers k , while $C^{sh,E}$ and $C^{sh,G}$ are costs for load shedding in the two systems. The bounds of power adjustments are defined in (2b) considering the day-ahead dispatch of the power plants. Constraints (2c) limit power adjustments to the maximum capability P_i^+ and P_i^- of each power plant. Power spillage $w_{j,\omega',t}^{sp}$ and electricity load shedding $l_{r_e,\omega',t}^{sh,E}$ are constrained by the realized power production of stochastic producers $W_{j,\omega',t}$ and electricity demand through (2d) and (2e), respectively. Constraint (2f) represents the power balance in real-time operation. The adjustment of natural gas production is limited by (2g), where day-ahead schedules are taken into account. Additionally, constraints (2h) impose the maximum capability G_k^+ and G_k^- of natural gas adjustments. Natural gas load shedding $l_{r_g,\omega',t}^{sh,G}$ is limited by the natural gas demand in

(2i). Moreover, constraint (2j) imposes real-time natural gas balance. The daily natural gas volume limit F_z^A for pipeline z is imposed by (2k), while the real-time physical pipeline capacity $F_{z,t}^M$ is enforced by (2l). The upper bounds of (2k) and (2l) are calculated based on an *ex-ante* analysis, where the industrial/commercial natural gas demand is subtracted by the maximum physical capacity of the pipeline and thus no explicit description of natural gas system dynamics is included.

In the remainder of the section, we present a more detailed setup for the balancing market where the network flows in electricity and natural gas systems are taken into account. At the electricity side, a DC power flow is considered with the following set of constraints,

$$\begin{aligned} & \sum_{i \in A_n^I} (p_{i,t}^* + \Delta p_{i,\omega',t}) + \sum_{r_e \in A_n^{R_e}} l_{r_e,\omega',t}^{sh,E} + \sum_{j \in A_n^J} (W_{j,\omega',t} - w_{j,\omega',t}^{sp}) \\ & - \sum_{r:(n,r) \in L} B_{n,r} (\delta_{n,\omega',t} - \delta_{r,\omega',t}) = \sum_{r_e \in A_n^{R_e}} D_{r_e,t}^E : \tilde{\lambda}_{n,\omega',t}^E, \quad \forall n, t, \end{aligned} \quad (3a)$$

$$B_{n,r} (\delta_{n,\omega',t} - \delta_{r,\omega',t}) \leq F_{n,r}^{\max}, \quad \forall (n,r) \in L, t, \quad (3b)$$

$$\delta_{n,\omega',t} \text{ free}, \quad \forall n/n : \text{ref}, \quad \delta_{n,\omega',t} = 0, \quad n : \text{ref}, \quad \forall t. \quad (3c)$$

More specifically, the real-time balancing is imposed for each node of the power system, hence (3a) replaces (2f). Moreover, constraints (3b) determine the power flow between nodes n and r , where $\delta_{n,\omega',t}$ is the voltage angle defined in (3c). The transmission capacity limits $F_{n,r}^{\max}$ are enforced by (3b).

At the gas side, an isothermal natural gas flow $q_{m,u}$ in horizontal pipelines is assumed [22]. Then, the Weymouth equation is used to describe the natural gas flow from node m to u with the dependency at the pressure pr_m of adjacent nodes,

$$q_{m,u} = K_{m,u}^f \sqrt{pr_m^2 - pr_u^2}, \quad \forall (m,u) \in Z, \quad (4)$$

where $K_{m,u}^f$ is the Weymouth constant that depends on the physical characteristics of each pipeline Z . Since (4) is non-linear, we use an outer approximation by deriving the Taylor series expansion around fixed pressure points $(PR_{m,v}, PR_{u,v}) \in V$ to obtain a linear expression [23], [24]. Consequently, we replace equality constraints (4) by the following set of linear inequalities,

$$q_{m,u} \leq K_{m,u}^f \left(\frac{PR_{m,v}}{\sqrt{PR_{m,v}^2 - PR_{u,v}^2}} pr_m - \frac{PR_{u,v}}{\sqrt{PR_{m,v}^2 - PR_{u,v}^2}} pr_u \right). \quad (5)$$

$\forall (m,u) \in Z, \forall v \in V.$

To ensure an efficient approximation of the non-linear equation (4), we use a large number of fixed pressure points $v \in V$ [25]. Thus, we achieve an outer approximation by the constructed planes in (5) that are tangent to the surface defined by (4) which results in approximating the gas flow by the linear constraint in (5) that is binding [23]. An advanced natural gas system with linepack is modeled using the following constraints:

$$PR_m^{\min} \leq pr_{m,\omega',t} \leq PR_m^{\max}, \quad \forall m, t, \quad (6a)$$

$$pr_{u,\omega',t} \leq \Gamma_z \cdot pr_{m,\omega',t}, \quad \forall (m,u) \in Z, t, \quad (6b)$$

$$q_{m,u,\omega',t} = q_{m,u,\omega',t}^+ - q_{m,u,\omega',t}^-, \quad \forall (m,u) \in Z, t, \quad (6c)$$

$$0 \leq q_{m,u,\omega',t}^+ \leq \tilde{M} y_{m,u,\omega',t}, \quad \forall (m,u) \in Z, t, \quad (6d)$$

$$0 \leq q_{m,u,\omega',t}^- \leq \tilde{M}(1 - y_{m,u,\omega',t}), \quad \forall (m,u) \in Z, t, \quad (6e)$$

$$y_{m,u,\omega',t} + y_{u,m,\omega',t} = 1, \quad \forall (m,u) \in Z, t, \quad (6f)$$

$$y_{m,u,\omega',t} \in \{0, 1\}, \quad \forall (m,u) \in Z, t, \quad (6g)$$

$$q_{m,u,\omega',t}^+ \leq KI_{m,u,v}^+ pr_{m,\omega',t} - KO_{m,u,v}^+ pr_{u,\omega',t} + \tilde{M}(1 - y_{m,u,\omega',t}), \quad \forall \{(m,u) \in Z | m < u\}, \forall v, t, \quad (6h)$$

$$q_{m,u,\omega',t}^- \leq KI_{m,u,v}^- pr_{u,\omega',t} - KO_{m,u,v}^- pr_{m,\omega',t} + \tilde{M} y_{m,u,\omega',t}, \quad \forall \{(m,u) \in Z | m < u\}, \forall v, t, \quad (6i)$$

$$q_{u,m,\omega',t}^- \leq KI_{m,u,v}^+ pr_{m,\omega',t} - KO_{m,u,v}^+ pr_{u,\omega',t} + \tilde{M} y_{u,m,\omega',t}, \quad \forall \{(m,u) \in Z | m < u\}, \forall v, t, \quad (6j)$$

$$q_{u,m,\omega',t}^+ \leq KI_{m,u,v}^- pr_{u,\omega',t} - KO_{m,u,v}^- pr_{m,\omega',t} + \tilde{M}(1 - y_{u,m,\omega',t}), \quad \forall \{(m,u) \in Z | m < u\}, \forall v, t, \quad (6k)$$

$$q_{m,u,\omega',t}^+ = \frac{q_{m,u,\omega',t}^{\text{in}} + q_{m,u,\omega',t}^{\text{out}}}{2}, \quad \forall (m,u) \in Z, t, \quad (6l)$$

$$q_{m,u,\omega',t}^- = \frac{q_{u,m,\omega',t}^{\text{in}} + q_{u,m,\omega',t}^{\text{out}}}{2}, \quad \forall (m,u) \in Z, t, \quad (6m)$$

$$h_{m,u,\omega',t} = K_{m,u}^h \frac{pr_{m,\omega',t} + pr_{u,\omega',t}}{2}, \quad \forall (m,u) \in Z, t, \quad (6n)$$

$$h_{m,u,\omega',t} = h_{m,u,\omega',t-1} + q_{m,u,\omega',t}^{\text{in}} - q_{m,u,\omega',t}^{\text{out}}, \quad \forall (m,u) \in Z, t, \quad (6o)$$

$$\sum_{k \in A_m^K} (g_{k,t}^* + \Delta g_{k,\omega',t}) + \sum_{r_g \in A_m^{Rg}} l_{r_g,\omega',t}^{\text{sh,G}} - \sum_{i_g \in A_m^{Ig}} \phi_{i_g} (p_{i_g,t}^* + \Delta p_{i_g,\omega',t}) - \sum_{u:(m,u) \in Z} (q_{m,u,\omega',t}^{\text{in}} - q_{u,m,\omega',t}^{\text{out}}) = \sum_{r_g \in A_m^{Rg}} D_{r_g,t}^G : \tilde{\lambda}_{m,\omega',t}^G, \quad \forall m, t. \quad (6p)$$

The bounds of pressure at each node of the system PR_m^{min} and PR_m^{max} are given by (6a), while the active pipelines are modeled by the relation of pressures between the two adjacent nodes via a compression factor Γ_z in (6b) [4]. More specifically, the outlet pressure at node u is greater than the inlet pressure at node m , when the gas flow is from m to u for the active branches. The natural gas flow $q_{m,u,\omega',t}$ is defined in (6c)-(6g) by two non-negative variables $q_{m,u,\omega',t}^+, q_{m,u,\omega',t}^- \geq 0$, where the direction of flow is defined by binary variable $y_{u,m,\omega',t}$. Note that parameter \tilde{M} is a sufficient large constant. The physical characteristics of gas flow are introduced in (6h)-(6k) that are derived by (5) with

$$\left\{ KI_{m,u,v}^+ = \frac{K_{m,u}^f PR_{m,v}}{\sqrt{PR_{m,v}^2 - PR_{u,v}^2}}, KO_{m,u,v}^+ = \frac{K_{m,u}^f PR_{u,v}}{\sqrt{PR_{m,v}^2 - PR_{u,v}^2}}, \right. \\ \left. KI_{m,u,v}^- = \frac{K_{m,u}^f PR_{u,v}}{\sqrt{PR_{u,v}^2 - PR_{m,v}^2}}, KO_{m,u,v}^- = \frac{K_{m,u}^f PR_{m,v}}{\sqrt{PR_{u,v}^2 - PR_{m,v}^2}} \right\}, \quad (7) \\ \forall \{(m,u) \in Z | m < u\}, \forall v.$$

Finally, two additional non-negative variables for the inflow and outflow of each pipeline $q_{u,m,\omega',t}^{\text{in}}, q_{u,m,\omega',t}^{\text{out}} \geq 0$ are introduced to model linepack flexibility. Constraints (6l) and (6m) define the flow of each pipeline as the average of inflow and outflow [4]. The average mass $h_{m,u,\omega',t}$ in each pipeline is given by (6n), where $K_{m,u}^h$ is a constant dependent on pipeline characteristics. The mass conservation at each pipeline is enforced by (6o). The natural gas balancing in the real-time is enforced by (6p) that replaces (2j). The presented model approximates the dynamics of the natural gas system and is

described in detail in [21]. We refer the reader to [26] for a steady-state modeling of the natural gas system with geometric programming and to [27] for a transient model that closely describes the physical behaviour of the natural gas flow.

The pool-based balancing market is formulated with the set of constraints (2b)-(2l). A different set of constraints is used for the network constrained balancing market that consists of {(2b)-(2e),(2g)-(2i),(3a)-(3c),(6a)-(6p)}. In both cases, the objective function is (2a). We use “ N ” to determine the use of network constrained balancing market, hence models *Seq* and *Seq-N* are formulated. Moreover, the set of primary variables Θ^R is extended with $\Theta^{\text{EX}} = \{\delta_{n,\omega',t}, \forall n, t; pr_{m,\omega',t}, \forall m, t; q_{m,u,\omega',t}^{\text{in/out}}, q_{m,u,\omega',t}^{\text{+/-}}, h_{m,u,\omega',t}, y_{u,m,\omega',t}, \forall (m,u) \in Z, t\}$ in *Seq-N*. In *Seq-N*, the prices are calculated after having fixed binary variables related to the natural gas flow direction. The expected balancing cost over a scenario set Ω is given as the sum of the balancing cost for each scenario ω weighed by its probability of occurrence π_ω .

B. Stochastic Dispatch of Integrated Energy System

As presented in Fig. 2, the *Stoch* model optimizes jointly the day-ahead and balancing stages of the integrated electric power and natural gas systems. The problem is formulated as a two-stage stochastic program aiming to minimize the total expected cost and writes as follows:

$$\text{Min.}_{\Theta^{\text{SC}}} \sum_{t \in T} \left[\sum_{i_c \in I_c} C_{i_c} p_{i_c,t} + \sum_{k \in K} C_k g_{k,t} + \sum_{\omega \in \Omega} \pi_\omega \left(\sum_{k \in K} (C_k^+ g_{k,\omega,t}^+ - C_k^- g_{k,\omega,t}^-) + \sum_{i_c \in I_c} (C_{i_c}^+ p_{i_c,\omega,t}^+ - C_{i_c}^- p_{i_c,\omega,t}^-) + \sum_{r_e \in R_e} C_{r_e}^{\text{sh,E}} l_{r_e,\omega,t}^{\text{sh,E}} + \sum_{r_g \in R_g} C_{r_g}^{\text{sh,G}} l_{r_g,\omega,t}^{\text{sh,G}} \right) \right] \quad (8a)$$

subject to

$$\text{constraints (1b), (1d) – (1h),} \quad (8b)$$

$$0 \leq w_{j,t} \leq \bar{W}_j, \quad \forall j, t, \quad (8c)$$

$$\text{constraints (2b) – (2l),} \quad \forall \omega, \quad (8d)$$

where $\Theta^{\text{SC}} = \{\Theta^{\text{D}}; \Theta_\omega^{\text{R}}, \forall \omega\}$ is the set of optimization variables. In this model, the temporal coordination of the two trading floors is achieved through the real-time constraints (8d) for all scenarios $\omega \in \Omega$. When network constrains {(2b)-(2e),(2g)-(2i),(3a)-(3c),(6a)-(6p)} are introduced to replace (8d), the model is named *Stoch-N*. Note that in model (8), the day-ahead dispatch of stochastic producers is restricted by the installed capacity \bar{W}_j , according to (8c), instead of the expected power generation and day-ahead dispatch decisions are treated as variables.

C. Volume-based Coordination in Sequential Dispatch of Integrated Energy System

According to Fig. 3, the *V-B* dispatch model that aims at minimizing the expected cost of the integrated energy system and defining the optimal natural gas volume availability writes as follows:

$$\text{Min.}_{\Theta^{\text{VUL}}} \quad (8a) \quad (9a)$$

subject to

$$(2b) - (2l), \quad \forall \omega, \quad (9b)$$

$$0 \leq \bar{\chi}_{\psi}^v \leq |T| \sum_{k \in K} G_k^{\max} - \sum_{t \in T} \sum_{r_g \in R_g} D_{r_g,t}^G, \quad \forall \psi, \quad (9c)$$

$$0 \leq \chi_{\psi,t}^v \leq F_{\psi,t}^{\max} - \sum_{r_g \in A_{\psi}^{R_g}} D_{r_g,t}^G, \quad \forall \psi, t, \quad (9d)$$

$$(p_{i,t}, w_{j,t}, g_{k,t}) \in \arg \left\{ \begin{array}{l} \text{Min.}_{\Theta^{\text{VLL}}} \sum_{t \in T} \left(\sum_{i_c \in I_c} C_{i_c} p_{i_c,t} + \sum_{k \in K} C_k g_{k,t} \right) \end{array} \right\} \quad (9e)$$

subject to

$$\text{constraints (1b) - (1f)}, \quad (9f)$$

$$0 \leq \sum_{t \in T} \sum_{i_g \in A_{\psi}^{I_g}} \phi_{i_g} p_{i_g,t} \leq \bar{\chi}_{\psi}^v, \quad \forall \psi, \quad (9g)$$

$$0 \leq \sum_{i_g \in A_{\psi}^{I_g}} \phi_{i_g} p_{i_g,t} \leq \chi_{\psi,t}^v, \quad \forall \psi, t, \quad (9h)$$

where $\Theta^{\text{VUL}} = \{\bar{\chi}_{\psi}^v, \forall \psi; \chi_{\psi,t}^v, \forall \psi, t; \Theta_{\omega}^R, \forall \omega\}$ is the set of optimization variables of the upper-level problem. Additionally, $\Theta^{\text{VLL}} = \Theta^D$ is the set of optimization variables of the lower-level problem. The objective function of model (9) is the same as in (8). Thus, the upper-level problem minimizes the expected cost of operating the integrated energy system by deciding the optimal value of $\bar{\chi}_{\psi}^v$ and $\chi_{\psi,t}^v$. Variable $\bar{\chi}_{\psi}^v$ limits the total daily natural gas consumption of GFPPs according to (9g), while $\chi_{\psi,t}^v$ defines their hourly fuel limit in (9h). We define fuel availability $\bar{\chi}_{\psi}^v$ and $\chi_{\psi,t}^v$ under different setups, ranging from a single value for the whole market to individual values for specific areas or GFPPs. Therefore, these two variables are indexed by $\psi \in \Psi$ that defines the GFPPs that are grouped together in each setup. The lower-level problem reproduces the day-ahead coupled electricity and natural gas market. Under this setup the sequential clearing of day-ahead and balancing markets is practically emulated, since the day-ahead decisions are fixed to the sequential dispatch though (9e)-(9h) and the balancing market is simulated for each independent scenario by imposing constraints (9b) for all $\omega \in \Omega$. The system operator has the ability to decide the natural gas volume that will be made available for power production at the day-ahead stage within specified limits, defined by (9c) and (9d). The upper-level variables $\bar{\chi}_{\psi}^v$ and $\chi_{\psi,t}^v$ have an impact on the decisions of the lower-level problem as the total fuel availability for GFPPs affects the day-ahead schedule for power production. Moreover, the lower-level decision variables affect the total expected cost of the integrated system. Owing to the this structure, model (9) finds an appropriate dispatch that minimizes expected system cost by revealing flexibility from GFPPs, while ensuring that the least-cost merit-order principle is respected. The different effects of these approaches are illustrated in the numerical study. Similarly, the model is named *V-B-N* with the introduction of network constrains $\{(2b)-(2e), (2g)-(2i), (3a)-(3c), (6a)-(6p)\}$ to replace (9b). The bilevel problem (9) can be reformulated as a Mathematical Program with Equilibrium Constraints (MPEC) by replacing

the linear, and thus convex, lower-level problems by their Karush-Kuhn-Tucker (KKT) conditions as presented in [17].

D. Overview of Dispatch Models

Before proceeding to the numerical results, we provide an overview of the dispatch models and their features in Table I.

TABLE I
DISPATCH MODELS' CHARACTERISTICS

Fuel / Network constraints	Seq / Seq-N	Stoch / Stoch-N	V-B / V-B-N	P-B / P-B-N
Temporal coordination	Imperfect	Perfect	Partial	Partial
Coordination mechanism	Non-existing	Explicit	Implicit via χ^v *	Implicit via χ^p

* The value of χ^v can be defined for the whole market, specific areas or GFPPs.

The dispatch models are classified based on the networks' representation in the balancing market, as well as the temporal coordination achieved and the mechanism utilized.

IV. NUMERICAL RESULTS

In this section, we first demonstrate the features of the four dispatch models presented in Section II in a tailored case study. Then, we compare the performance of volume-based variants on a more realistic case study.

A. Tailored Case-Study

1) *1-hour Simulation Results*: To allow a fair comparison between *P-B* and *V-B* models, the balancing market in this illustrative example is modeled as a pool with fuel constraints for GFPPs. Moreover, we assume a single type of uncertain supply that is wind power. Here, we consider a system which comprises three thermal power plants (I_1 , I_2 and I_5), two GFPPs (I_3 and I_4) that acquire their fuel from the natural gas market, one wind farm (WP) and two natural gas producers (K_1 and K_2). Table II collects the data for the producers in both markets. Wind power is characterized by two equiprobable scenarios ω_1 (166 MW) and ω_2 (86 MW). The offer prices for upward and downward regulation are equal to 1.1 and 0.9 of the day-ahead offer prices. In *P-B*, we limit the natural gas price adjustment to \$1.35/kcf. Moreover, we consider a pipeline capacity of 6,000 kcf. The cost of electricity and natural gas load shedding is \$1,200/MWh and \$600/kcf, while wind spillage is cost-free. The peak electricity and natural gas demand for industrial/commercial loads are equal to 430 MW and 3,600 kcf/h, respectively.

TABLE II
ELECTRIC POWER AND NATURAL GAS SYSTEM DATA

Unit i	I_1	I_2	I_3	I_4	I_5	Unit k	K_1	K_2
P_i^{\max} (MW)	80	110	50	100	100	G_k^{\max} (kcf)	10,000	6,000
P_i^+ (MW)	10	0	30	25	20	G_k^+ (kcf)	2,500	1,000
P_i^- (MW)	10	0	30	25	20	G_k^- (kcf)	2,500	1,000
C_i (\$/MWh)	30	10	-	-	60	C_k (\$/kcf)	2	3
ϕ_{i_g} (kcf/MWh)	-	-	12	18	-			

We solve all dispatch models for 24-hours and provide detailed results for a specific time period. Two variants of (9), where natural gas volume availability is determined for the whole market (*V-B*) and for each individual GFPP (*V-B gen*), are studied. In this instance, natural gas is produced only by unit K_1 , hence the natural gas price is \$2/kcf and the marginal costs of GFPPs I_3 and I_4 are \$24/MWh and \$36/MWh.

TABLE III
EXPECTED SYSTEM COST AND ITS BREAKDOWN IN \$ WHEN TOTAL POWER LOAD IS 387 MW

	Total	Day-ahead	Balancing	Up regulation	Down regulation
<i>Seq</i> / <i>V-B</i>	10,400	9,982	418	990	-572
<i>Stoch</i>	10,234	10,222	12	660	-648
<i>P-B</i>	10,273	10,042	231	825	-594
<i>V-B gen</i>	10,261	10,162	99	693	-594

The action of adjusting the natural gas price or volume availability becomes beneficial when the day-ahead dispatch is altered with regards to *Seq* to allow more cost-effective power plants to provide the required regulation in the balancing market. This results in an increase of the day-ahead cost and a decrease of expected balancing cost that yields a reduction of total expected cost.

Initially, we demonstrate the performance of all dispatch models in Table III, when the total electricity demand is equal to 387 MW. It can be observed that *Stoch* returns the lowest expected system cost and *Seq* the highest one due to imperfect temporal coordination between day-ahead and balancing markets. Models *P-B*, *V-B* and *V-B gen* attain an expected cost that is in between the ideal solution of *Stoch* and the one of *Seq*. Thus, a reduction of expected system cost can be accomplished, while the system is still dispatched based on the merit-order principle.

The detailed system dispatch is illustrated in Table IV for an electricity demand of 387 MW. Regarding *P-B*, the marginal cost of all GFPPs is affected by adjusting the natural gas price with $\chi_{I_1}^p = -\$0.333/\text{kcf}$. The decreased natural gas price of $\$1.666/\text{kcf}$ results in a lower marginal cost for GFPP I_4 equal to $\$30/\text{MWh}$, which equals the one of unit I_1 . Therefore, unit I_1 is dispatched to 70 MW and GFPP I_4 to 31 MW without breaking the merit order. Model *V-B* returns the same results with *Seq*, as a change of total natural gas volume availability would not decrease the total expected cost. On the contrary, *V-B gen* has a better performance due to its ability to influence the dispatch of both GFPPs I_3 and I_4 . Note that GFPPs I_3 and I_4 produce a total of 71 MW in both *Seq* and *V-B gen* at the day-ahead stage. However, the allocation between the two GFPPs is different and more efficient under *V-B gen*. More specifically, the total natural gas volume bought by GFPPs in *Seq* is 987 kcf, where 600 kcf are consumed by GFPP I_3 and the remaining 387 kcf by GFPP I_4 . In *V-B gen*, the natural gas volume made available for GFPP I_3 is 420 kcf, while GFPP I_4 consumes 648 kcf. The adjustment of natural gas volume availability has a direct impact on the day-ahead dispatch which in turn reduces the total expected cost compared to *Seq*. The day-ahead cost increases but this increase is counterbalanced by a greater decrease of balancing cost. In particular, the up-regulation cost is decreased because unit I_5 is not activated and the need for up-regulation is covered by the cheaper GFPP I_3 . Moreover, a greater portion of the total 40 MW needed for down-regulation is provided by GFPP I_4 that is more cost-effective than GFPP I_3 .

The *Stoch* and *Seq* models provide the two extreme solutions in terms of expected cost for all time periods of the scheduling horizon and serve as upper and lower bounds, respectively, for the expected costs of *P-B*, *V-B* and *V-B gen* models. We perform an analogous analysis for the case with a total power

TABLE IV
POWER SYSTEM SCHEDULE IN MW WHEN TOTAL POWER LOAD IS 387 MW (VARIATION FROM *Seq* DAY-AHEAD (DA) SCHEDULE IN BOLD)

Unit	<i>Seq</i>			<i>P-B</i>			<i>V-B</i>			<i>V-B gen</i>		
	DA	ω_1	ω_2	DA	ω_1	ω_2	DA	ω_1	ω_2	DA	ω_1	ω_2
I_1	80	-10	0	70	-10	+10	80	-10	0	80	-10	0
I_2	110	0	0	110	0	0	110	0	0	110	0	0
I_3	50	-9	0	50	-5	0	50	-9	0	35	-5	+15
I_4	21	-21	+25	31	-25	+25	21	-21	+25	36	-25	+25
I_5	0	0	+15	0	0	+5	0	0	+15	0	0	0
WP	126	+40	-40	126	+40	-40	126	+40	-40	126	+40	-40

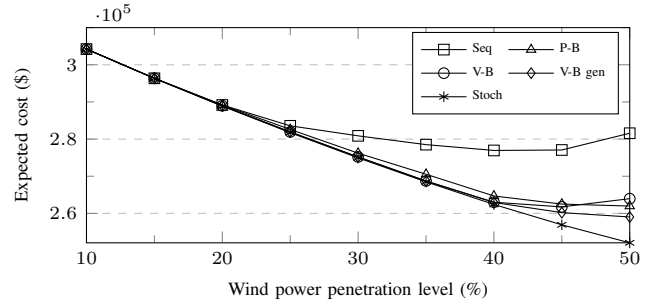


Fig. 5. Impact of wind power penetration level on the expected system cost.

load of 344 MW where χ^p gets a positive value and all three improved sequential models achieve the same expected cost with *Stoch*. This fact illustrates that it is possible in specific cases to have an efficient sequential dispatch if the future balancing costs are communicated into the day-ahead market through the operator-defined parameters χ . The additional results are presented in the electronic companion [17].

2) *24-hour Simulation Results*: Additionally, we provide the following results for the whole 24-hour scheduling horizon, where 20 equiprobable wind power scenarios are utilized (available at [28]). Fig. 5 presents the expected cost of the integrated energy system as a function of wind power penetration level, defined as the share of wind power capacity on total system's electricity demand.

The expected cost of *Stoch* is decreasing with an increase of wind power penetration and achieves the lowest expected cost in all cases. On the other hand, model *Seq* becomes inefficient for a wind power penetration level above 25%, while even an increase of the expected cost is observed when this level is greater than 40%. The *V-B* and *V-B gen* models manage to approximate efficiently the solution of *Stoch* model up to a share of 40%, where they start diverging with an increasing tendency. Note that the expected cost of *V-B gen* is lower than *V-B*, confirming its higher flexibility to provide an improved day-ahead dispatch. Similarly, *P-B* attains an expected cost close to the one obtained by *Stoch*.

We now highlight the main features of the proposed dispatch models. All three *P-B*, *V-B* and *V-B gen* demonstrate a considerable ability to bridge the gap between *Seq* and *Stoch* models. They manage to return an expected system cost closer to the stochastic ideal solution, while still dispatch the system based on the merit-order principle and keep the economic properties of *Seq*. Moreover, they can affect the system dispatch regardless of the type of marginal producer, i.e. GFPP or power plant using another fuel. In models *V-B* and *V-B gen* at least one GFPP would have to be scheduled in order to be able to improve the dispatch of the system, while this restriction does not apply to *P-B*. Additionally,

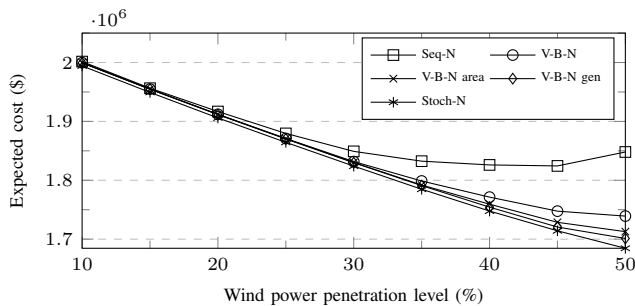


Fig. 6. Impact of wind power penetration level on the expected system cost.

model *V-B* is able to alter the dispatch of the GFPP with the higher conversion factor. In case the natural gas availability is defined individually for specific areas of the system, the GFPP affected is the one with the greater conversion factor in the specific area. Finally, *V-B gen* is more flexible than *V-B* as it can change the dispatch of each individual GFPP. More specifically, the portion of the day-ahead power to be produced by GFPPs can be split under different shares in order to reveal more cost-effective regulation in the balancing market.

B. Realistic Case-Study

A more realistic case study is considered to assess the performance of the proposed dispatch model *V-B-N* when network constraints are included for the real-time operation of the energy system. The integrated energy system consists of the IEEE 24-bus Reliability Test System (RTS) [29] and a 12-node natural gas system based on [5]. More specifically, there exist 12 conventional power plants, out of which 4 are GFPPs, 2 wind farms and 3 natural gas suppliers. Wind power production is modeled by a set of 25 equiprobable scenarios. The data and network topology are provided in the online appendix available in [17]. Moreover, we introduce a new variant of (9) that defines the natural gas volume availability for specific areas of the integrated energy system, namely *V-B area*. Two areas are determined in this study including two GFPPs in each one of them. More specifically, GFPP 1 and GFPP 5 are included in area *I*, while GFPP 7 and GFPP 11 in area *II*. Similarly to Section IV-A, we also examine *V-B-N* and *V-B-N gen*. We optimize over a 24-hour scheduling horizon and we set the level of linepack at the end of the day equal to the one at the beginning of the day that is 448,000 kcf.

The expected system cost for different wind power penetration levels is illustrated in Fig. 6. All models reduce the expected cost compared to *Seq-N* and this reduction is more significant for higher shares of wind power penetration. Moreover, it can be observed that allowing more degrees of freedom to define natural gas availability allows to capture more efficiently the benefits of *Stoch-N*.

Additionally, we quantify the benefits of modeling the linepack in the natural gas system by comparing the outcome of the dispatch models when a purely steady-state operation is followed. In this case, the pipelines are not able to store natural gas, hence the inflow and outflow is equal for each time period. Fig. 7 illustrates the relative increase in expected cost when neglecting linepack in comparison with the expected cost presented in Fig. 6. An increase in expected cost is observed for all dispatch models, when the additional flexibility

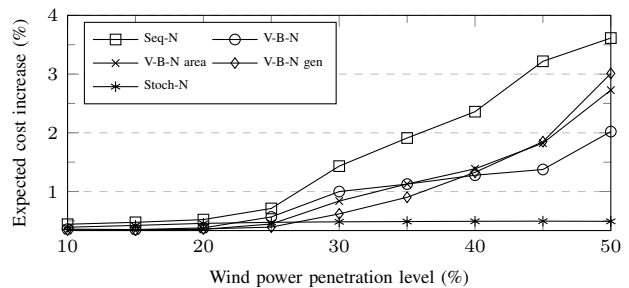


Fig. 7. Impact of wind power penetration level on the expected system cost increase when neglecting linepack modeling.

TABLE V
DAILY PROFITS OF THERMAL UNIT I_3 IN CASE WIND PENETRATION IS 50%

	<i>Seq-N</i>	<i>Stoch-N</i>	<i>V-B-N</i>	<i>V-B-N area</i>	<i>V-B-N gen</i>
Expected profit (\$)	239,062	4,618	73,895	52,649	47,487
Probability of negative profits* (%)	0	4	0	0	0
Average losses (\$)	0	-46.7	0	0	0

* Based on the available scenario set Ω .

introduced by linepack is not considered. Model *Stoch-N* is the most advanced one and accomplishes a consistent decrease of expected cost in both cases, which is only slightly affected by wind power penetration level. On the other hand, *Seq-N* is the most inefficient and has the greatest increase when linepack is ignored that results in about 3.5% for a wind power share of 50%. Regarding the proposed volume-based dispatch models, two trends are noticed. Initially, we observe that the more flexible the procedure to define natural gas volume availability, the less the outcome is altered up to a 30% wind power penetration level. Then, the difference in expected cost is higher for *V-B-N gen* at higher penetration levels. This difference though mainly stems from the efficiency of *V-B-N gen* to exploit the linepack flexibility and significantly reduce the expected cost in this case, while still having an adequate performance when linepack is neglected.

Finally, we illustrate that it is possible for flexible producers to face losses in *Stoch-N* as cost recovery is only guaranteed in expectation and not for each wind power scenario. On the contrary, models *Seq-N*, *V-B-N*, *V-B-N area* and *V-B-N gen* respect the merit-order and thus cost recovery is ensured for each scenario. Table V presents the daily profits for the flexible power plant I_3 for wind power penetration level equal to 50%. For *Stoch-N*, the average losses and the probability of facing a negative profit is shown. Note that the expected profit is significantly higher in *Seq-N* due to the payments to flexible producers under the very costly balancing actions (e.g. load shedding). Such balancing actions are less often under *V-B-N*, *V-B-N area* and *V-B-N gen*; hence, the expected profits are decreased for power plant I_3 .

The optimization problems were solved using CPLEX 12.6.2 under GAMS on a stationary computer with Intel i7 4-core processor clocking at 3.4 GHz and 8 GB of RAM. The average solution time is presented in Table VI for both case studies. It can be noticed that *P-B* has significantly higher solution time. This is due to the greater number of binary variables required for the linearization of complementarity constraints in the KKT conditions, since the balancing market is also included in the lower-level problem of the bilevel formulation. Moreover, the time-coupling constraint that ensures

TABLE VI
AVERAGE SOLUTION TIME IN SECONDS

Model	Seq	Stoch	V-B	V-B gen	P-B
Tailored Case-Study	0.3	0.6	1.5	1.5	520
Model	Seq-N	Stoch-N	V-B-N	V-B-N area	V-B-N gen
Realistic Case-Study	48	1,100	2,920	1,409	1,034

cost neutrality for the system operator at the day-ahead stage also increases the complexity of the problem.

V. CONCLUSION

This paper proposed a framework to optimally define the natural gas volume availability for power production in an integrated electricity and natural gas system under high shares of stochastic renewables. Releasing in the day-ahead market a proper amount of natural gas to be consumed by the GFPPs allows us to increase the efficiency of the sequential market design via creating an implicit link between the day-ahead and balancing markets. The current sequential market structures are highly challenged from the increased uncertainty and variability introduced by renewables since the description of uncertain parameters is performed in a deterministic way. Using the stochastic dispatch model as an ideal benchmark, the proposed volume-based model is utilized to bridge the efficiency gap between the sequential and stochastic dispatch models. The optimal setting of natural gas availability is achieved through a stochastic bilevel program that anticipates balancing costs, while its outcome can be directly incorporated in the current market structure. In order to fully exploit the flexibility of the integrated energy system and to enhance the overall system efficiency, we approximate the natural gas system dynamics by modeling linepack that plays an important role in short-term operations. Moreover, a comparison with the price-based model that alters the natural gas price perceived by GFPPs to achieve an implicit temporal link is performed.

Our analysis illustrated that the efficiency of the sequential dispatch model through the intelligent adjustment of the natural gas volume or price significantly improves and approximates the stochastic ideal solution. The utilization of such decision-support tools facilitates the integration of renewables and captures the benefits of the stochastic dispatch model, while respecting the least-cost merit-order principle and its economic properties. For future work, more detailed models for the electricity and natural gas systems can be considered, as the utilization of AC power flow and the incorporation of compressors' fuel consumption in the natural gas system. Moreover, potential computational challenges can be tackled by the use of decomposition techniques.

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