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# Optimal use of energy storage systems with renewable energy sources ☆

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ABSTRACT

This article proposes a multi-period optimization to study the technical and economic effects of the placement and use of Renewable Energy Sources (RES) and Energy Storage Systems (ESS) in an electrical network. As the RES penetrations increase, their inherent variability affects the actual amounts of energy dispatched, their contribution to decrease emissions of pollutants and greenhouse gases, and the overall welfare effects they may have. Moreover, to better harness the energy from renewable sources, both new methodologies and technologies need to be adopted, counteracting the variability and uncertainty of these sources. A possible solution to the challenges of RES adoption is the coupling to energy storage sources, either as dedicated facilities on the supply side, or supporting the accommodation of loads to the available generation on the demand side. This paper suggests an algorithm for network dispatch, aimed at answering some of fundamental changes in the way the system is managed and discusses analytical characteristics of the optimal solution.

The proposed methodology is applied to a case study. Four scenarios are analyzed in their dispatches, estimating the welfare effects on the participants in the wholesale market for a modified IEEE 30-bus network with wind energy as the RES in penetrations close to 15%. The policy implications from the results obtained prove that, first, ESS can decrease the ramping necessary for load following, but not necessarily increase the amount of wind energy used, and second, congestion patterns in the electrical network play a crucial role in the final effectiveness of the RES and ESS. These are important insights into an ongoing debate on how to direct storage and renewable energy investments for a low carbon economy.



## 1. Introduction

The windy shores of Lake Erie will have one of the first demonstration projects of a new technology that may become ubiquitous. A 32 MW Vanadium Redox battery will be placed in the city of Painesville, OH, in a symbiotic role with an existing coal plant. This pilot joins projects being conducted in the US and in other countries to better understand the role and placement of Vanadium Redox and other Energy Storage Systems (ESS) and technologies to manage the electricity network [1,2].

To maintain Operating Reliability (e.g. [3]), system operators are required to adopt practices that use new available technologies. The interest in storage technologies and ESS for electricity network operations stems from fundamental changes occurring in the way these complex systems are managed. In different countries, the amount of energy from renewable sources is increasing, either by market forces or voluntary quotas, like Renewable Portfolio Standards in the US [4]. The system operation needs to better accommodate the power delivered by stochastic sources, without compromising the security of the system, as has been well documented (e.g. [5,6]).

As new Energy Storage Systems (ESS) technologies like the Vanadium Redox flow battery are developed, their active participation in future power systems are likely to witness a significant increase [7–9]. This is driven by different forces, like cost reducing technology advancements and the expected forthcoming of electrified transportation in urban centers. While dedicated ESS capacity is already in use for certain systems (e.g. Sodium sulfur, [10]), its prohibitive cost has not allowed widespread coupling with intermittent generation sources. The electrification of transportation on the other hand provides an opportunity to develop compensating mechanisms that encourage vehicle owners to participate in the energy and ancillary services markets, providing further ESS capacity from the car's chemical storage [11–13].

This paper suggests a formulation for a multi-period Alternating Current Optimal Power Flow (AC-OPF) to analyze the interaction between Renewable Energy Sources (RES) and ESS optimal usage.

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The analytical model is illustrated with a case study focusing on the effects of location and geographic distribution of both resources.

The paper is structured as follows: Section 2 synthesizes the antecedents to this work and presents the analytical framework. Sections 3 and 4 summarize the specifications of a case study that considers the effects of location for RES, specifically wind, and for ESS in an electrical network. Section 5 analyzes the obtained results and the conclusions are summarized in Section 6.

## 2. Literature and problem formulation

The antecedents to the engineering network problem in this article can trace its roots back to the seminal economic dispatch and Optimal Power Flow (OPF) contributions by [14]. Later research has extended this model to include welfare considerations that allow for optimal load shedding, in the framework of support for ramping service provision [15]. The issue of proper provision of ancillary products is discussed in [16], with special attention paid to the necessity of a clear remuneration structure to ensure adequate quality of service in the Australian New Electricity Market (NEM). Part of the philosophy of NEM is cost causality.[1]

The adoption of RES in the system, specifically wind, is studied in [17] with a wind model that assesses the reliability contribution of a wind farm. The methodology is comprehensive, while recognizing the high level of data requirements for proper calculation. Such high data input requirements are a generalized issue that can limit the usability of agents with constrained data.[2] The study of the capacity contribution of RES such as wind is a subject of continued debate. In general terms, the support provided by wind generation is dependent on the characterization of the resource, and its relation to the demand in the system [19].

Ref. [20] study a single node problem with heterogeneous consumers that could be curtailed in their demand, according to assumed price-sensitivity preferences assigned using a scaling factor. Their question is planning-oriented, finding the optimal level of investment to cover the electricity demand, and establishing the outputs and price schedules expected. Their results provide a stylized benchmark to compare regulatory schemes.

The aim of this model is to provide an engineering-economic framework to evaluate the use of storage resources as optimized by a social planner, in the context of high penetrations of Renewable Energy Sources (RES) in the electricity system. The uncertainty in the system, coming from RES is modeled as a gaussian noise in each period that affects the availability of RES available [21].

The main contribution of this work is to suggest a method that includes specific restrictions reflecting the technical (engineering) characteristics of the electricity network, and endogenously solves the optimized dispatches for ESS, for all generating units and for dispatchable demands, taking into account the economic and dynamic characteristics of each element. Such considerations are necessary to reflect the true benefits (and costs) faced by a System Operator, the congestion that can lead up to the formation of load pockets [22], and the effects that adoption of RES has in the system. I derive optimality conditions for the trade-offs between conventional generators and ESS resources for the case in which the commitment decisions are set [23]. To the best of my knowledge this is the first paper to include a complex model of the attributes of the network and the analytical derivation of inter-temporal tradeoffs of using an ESS unit. The implementation uses Matpower's extensible architecture [24], with a case study to illustrate the use of the methodology.

### 2.1. Multiperiod AC-OPF

Consider a social planner (a System Operator-SO), maximizing the total welfare in the system of providing energy subject to reliability economic criteria and the non-linear constraints of an OPF AC system [14,25]. In addition to the OPF variables, the SO is faced with the decision of which units to commit in advance, the "unit commitment" (UC) problem [26]. The general form for this combined problem is as follows:

$$\min_{\mathbf{x},\mathbf{p},\mathbf{e},I} f(\mathbf{x},\mathbf{p}) + C(\mathbf{p},I) + f_u(\mathbf{x},\mathbf{p},\mathbf{e}) \tag{1}$$

subject to

$$g(\mathbf{x},\mathbf{p},\mathbf{e}) = 0 \tag{2}$$

$$h(\mathbf{x},\mathbf{p},\mathbf{e}) \leqslant 0 \tag{3}$$

$$\mathbf{x}_{\min} \leqslant \mathbf{x} \leqslant \mathbf{x}_{\max} \tag{4}$$

$$0 \leqslant \mathbf{p} \leqslant \mathbf{p}^c_{\max} \tag{5}$$

$$\mathbf{e}_{\min} \leqslant \mathbf{e} \leqslant \mathbf{e}_{\max} \tag{6}$$

$$l \leqslant A \begin{bmatrix} \mathbf{x} \\ \mathbf{p} \\ \mathbf{e} \end{bmatrix} \leqslant u \tag{7}$$

The variables for this problem are shown in Table 1.

The cost $f(\cdot)$ is assumed to be separable over units, so the cost of running one unit does not affect the cost of running another one [27]. The cost per generator, $C(\mathbf{p}, I)$, is a function of the units committed to the system.

Each one of the constraints can be summarized as follows:

1. The equality constraints (2) consist of the set of non linear power balance equations for real and reactive power for each generator, and ESS constraints, among others.
$$g_P(\Theta, V, P) = 0 \tag{8}$$
$$g_Q(\Theta, V, Q) = 0 \tag{9}$$
2. The inequality constraints (3) consist of the set of branch flow limits as non-linear functions of the bus voltage angles and magnitudes, among others.
$$h_f(\Theta, V) \leqslant 0 \tag{10}$$
$$h_t(\Theta, V) \leqslant 0 \tag{11}$$
3. The unit limit constraints, (4)–(6) indicate e.g., the upper and lower limits for voltage magnitudes, bus angles and real and reactive generator injections for the committed units. The limits are given by e.g., the physical characteristics of the generators and the operational limits for voltage magnitudes and angles. Note that the negative sign for $e_i^t$ in the case of energy storage units would add to the load to be served.
4. Eq. (7) includes additional inequality constraints to (3). They reflect the ramping constraints, e.g. (15) and (16), and the charging and discharging restrictions for ESS units, (17)–(21), among others.
5. Integer variables are used for implementing minimum up and down times for a linearized version of the problem (Direct Current, or DC-OPF). The constraints are:
$$s_{i,t} - h_{i,t} = u_{i,t} - u_{i,t-1} \tag{12}$$
$$\sum_{y=t-\tau_i^+}^{t} s_{i,y} \leqslant u_{i,t} \tag{13}$$
$$\sum_{y=t-\tau_i^-}^{t} h_{i,y} \leqslant 1 - u_{i,t} \tag{14}$$

[1] Participants in energy markets should be paid for providing, and pay for the energy services they use.

[2] System Operators generally have such information; but in such a case, the relevant question is the proper market design to elicit the necessary information [18].