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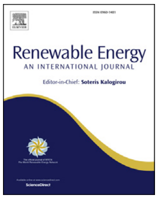

Harnessing households to mitigate renewables intermittency in the smart grid

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ABSTRACT

This paper presents and evaluates a novel demand response method for households, designed for mitigating intermittency in smart grids with a high share of renewables. The method, named Dynamic-Active Demand Response (DADR), is based on an innovative paradigm of offering multiple electricity service levels and a dynamic-active demand response scheme. It provides the grid operator with the ability to influence consumption patterns in real time, so that responding to renewables intermittency is more effective in terms of reliability, predictability and response time.

DADR's performance is evaluated using a Monte Carlo simulation model, which assesses the method's intermittency mitigation potential and estimates the expected economic value of implementing it in the Israeli residential sector. Major components of the model are based on a survey, conducted among Israeli households. The survey results indicate that, given a sufficiently attractive economic incentive, participation rates can reach as high as 85–90%. The Monte Carlo simulation results reveal that DADR can make a significant contribution to mitigating renewables intermittency, with energy savings of hundreds to thousands of MWh a day and a positive net economic benefit.

1. Introduction

Power intermittency, inherent in generating electricity from Renewable Energy Sources (RES) - wind and solar in particular - has become one of the central problems in the transition to renewable energy [1].[1] It stems from the nature of power grids - at all times supply must equal demand in order to balance frequencies, where storing electricity cannot be done yet economically at the desired scale [2].[2] This problem is expected to be prevalent in future power systems which will be characterized by a diverse, decentralized and dispersed portfolio of power generators, with a high share of RES [3].

Aside from hydroelectric facilities, the leading RES technologies - solar and wind - are variable in nature [4]. Their power output is influenced by seasonal, diurnal and synoptic weather patterns which are largely irregular and only partially predictable [5]. For this reason, solar and wind power generation, together with a few other generation technologies, are labeled “Variable Energy Resources” (VERs) [6].

The additional operating reserve required in a power grid with a high share of VERs is viewed as one of the primary sources of potential cost increases associated with the transition to VERs [6]. At low levels of penetration, VERs can be accommodated without modifications to the grid. As the share of VERs increases, the traditional approach for ensuring grid stability runs into difficulties. If the operating reserve is provided by conventional plants, costs of additional start-ups and shut-downs are incurred and the plant operation is distant from the optimal fuel efficiency and emission control points [6]. In addition, the recurrent start-ups, shut-downs and ramping increase mechanical stress and result in higher maintenance costs and shorter life [6,7].

The magnitude of the challenges of integrating VERs into a power grid and the associated costs depend both on the VER's

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[1] In this paper, intermittency refers to the stochastic behavior of power output generated by wind and solar energy sources, which is characterized by both variability and intermittency.

[2] It should be noted that in some countries pumped-storage hydroelectricity is a viable solution for storing electricity on a large scale, but the extent of its development has geographical limitations [35].

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List of abbreviations:

ACDL	Aggregate Controllable Dynamic Load
CHA	Controllable Household Appliance
DADR	Dynamic-Active Demand Response
HH	Household
ISP	Independent Service Provider
VERs	Variable Energy Resources

characteristics and the grid's ability to accommodate intermittency [8]. Demand Response (DR) can be one of the important measures for expanding the operating reserve and serve as a key enabling technology for integrating VERs [9]. DR offers an emission-free and potentially lower-cost alternative to using conventional plants for providing the required operating reserve [10]. It can render the demand load an active element of the system and provide the grid operator with additional capabilities for power system control [11].

DR can also contribute to neutralizing market power in deregulated electricity markets, by rendering the demand responsive to the availability of power supply [12]. Unchangeable demand allows power producers to exercise market power by artificially reducing capacity, which leads prices in the wholesale market to artificially go up [13]; [14]. The motivation for exercising market power tends to be higher in grids with photovoltaic (PV) energy sources whose time profile is more predictable than that of wind power [15].

Various DR programs are proposed in the literature for the smart grid, with the objective to harness the grid's advanced capabilities in order to engage residential consumers in the electricity market and provide them with tools to respond to changing grid conditions. Reviews of these programs can be found in Aghaei and Alizadeh [2]; Jalali and Kazemi [16]; Shariatzadeh et al. [17]; Siano [18] and Zehir et al. [19]. Reference to significant studies, recently conducted on the implementation of DR and modeling their role in balancing power supply and demand in the presence of renewables, can be found in Aghajani et al. [20].

Residential DR programs that rely on real-time pricing seem to have good potential for mitigating VERs intermittency, where the underlying premise is that the market forces of supply and demand can lead towards balancing the grid. However, a deeper examination reveals considerable difficulties and limitations. First, a major obstacle stems from uncertainty about consumers' response to dynamically changing rates [21]. This leads to incompatibility between the economic model and the management and control processes of operating the grid [22]. Grid operators need resources that can be utilized - at all times with almost absolute certainty - to change the power supply (or demand) in order to ensure the stability and reliability of the grid [22]. They need to be certain of the expected load response level when a price signal is sent to consumers [5]. Hence, the natural tendency of grid operators is to reject the approach of matching supply and demand by varying the rates [22].

Second, the elasticity of demand for electricity in developed countries is relatively low [23]. As expenditures on electricity account on average for only 2–3% of total household expenditures, there is a continuing debate as to how responsive residential consumers are to price signals [6].

Third, since non-flat tariffs carry some risk with respect to the eventual charges, residential consumers tend to prefer flat tariffs, even if it implies paying a premium [24]. This leads to relatively low consumer participation rates in DR programs that are based on real-time pricing.

Forth, real-time pricing requires consumers to make a large number of optimization decisions daily, which renders the approach less suitable for households. Moreover, to allow consumers to plan the use of appliances, the expected rates have to be signaled ahead of time, and therefore don't reflect the current state of the grid. Consumers' difficulties in making the required optimization decisions and the VERs intermittency requirement for immediate response and high frequency of variations suggest the need to base DR programs on automation and control technology [5,25]. Although integrating VERs and DR has been an area of focus in recent studies, one of the main limitations is developing automation technology with minimum consumer intervention, which is required for obtaining high consumer participation rates [17]. Relying on fully automated home energy management systems suffers from the following shortcomings:

- The ability to influence consumer habits and daily routines to meet the VERs intermittency mitigation objectives is fairly limited as the system tends to adapt itself to the preferences of individual consumers.
- The appliances' load curves reflect the preferences of (and is optimized for) individual consumers. This implies that the resulting operating reserve is statistical in nature, lacking the degree of certainty required by grid operators.
- A system that retains full control over appliances may be perceived by consumers as problematic, with implications on participation rates [5].
- Developing algorithms that reflect individuals' comfort and convenience and their trade-off with electricity costs, which function well under all circumstances and are suitable for the public at large, is a highly complex endeavor.

2. Study aims and method

The aims of this study are to develop a residential DR paradigm that can be employed to mitigate VERs intermittency, evaluate its intermittency mitigation potential and assess its economic viability.

In order to address both the societal and consumer perspectives and properly model the performance of the proposed paradigm, the adopted method is comprised of the following four steps:

1. Develop a DR paradigm that is effective for mitigating VERs intermittency, simple to operate and suitable for the public at large (this new approach has been given the name: "DADR-*Dynamic-Active Demand Response*").
2. Conduct a consumer survey to test the market acceptance of DADR and gather the required data for evaluating its expected performance (the survey was conducted among Israeli households, which consume about a third of the country's electricity).
3. Develop a Monte Carlo simulation model for assessing DADR's functional and economic performance, where the simulation of household loads and the determinants of consumer participation rely on data gathered in the consumer survey.
4. Evaluate the intermittency mitigation potential and the expected net economic benefit under different scenarios.

The rest of the paper is organized as follows. Section 3 presents the operating principles and use cases of DADR. Section 4 reviews and discusses the consumer survey results. The Monte Carlo model is described in Section 5 and the simulation results are presented in Section 6. In section 7 we provide a conclusion, discuss the findings and consider the implications for policy makers.