Demand-Side Management for Balancing Supply and Demand in Renewable-Dominant Energy Systems

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Abstract

The transition to decarbonized energy systems depends on renewable energy sources. Their variability and intermittency introduce various challenges, including curtailment. This article examines Demand-Side Management strategies that can effectively balance supply and demand to mitigate renewable energy curtailment, while considering key opportunities for policy planning.

Energy System Transition

The global energy system requires a deep transformation of the supply (power) and demand (residential, commercial, industry, transport, and agriculture) sectors to achieve full decarbonization. This was one of the main outcomes of the Paris Agreement, in which parties agreed to implement the appropriate measures to limit the rise in global temperature to < 2 °C, with efforts to further constrain it to < 1.5°C [1]. In this context, renewable energy has been identified as one of the key solutions, where its share in global annual electricity generation will need to increase from 29.1% (2022) to 86% (2050) [1][2]. Applications of renewable energy have also been emphasized by the Sustainable Development Goals (SDGs), particularly SDG7 that seeks access to affordable, reliable, sustainable, and modern energy by 2030 [3].

In conventional energy systems, electricity is generated when demanded and supply is always matched with variable demand. In contrast, renewable-dominant energy systems generate electricity when the resource is available and not necessarily when needed, creating a supply and demand gap. With more intermittent renewable energy sources, available supply capacity has become dynamic, fluctuating over time based on factors such as solar and wind intensity. This shift has transformed energy systems from “matching fixed supply to dynamic demand” to “matching dynamic supply with dynamic demand”. These changes introduce several challenges including balancing variable supply with variable demand and capacity redundancy, leading to low plant load factors which reduce the economic viability of power plants [4].

These challenges can be addressed through two forms of energy management [4][5]. The first is supply-side management (SSM) which optimizes supply resources through generation expansion planning, plant utilization, resource scheduling, and operational planning [4][5]. With the growing market penetration of renewable energy, supply-side measures alone are insufficient for maintaining system stability. Nearly every action taken on the generation side has an equivalent demand-side countermeasure [6]. Solutions on the demand-side have become essential for managing fluctuations in supply and demand across short-, medium-, and long-term horizons [4]. Demand-side management (DSM) is one planning technique that ensures smooth system operation by strategically moderating demand variations to follow variations in generation patterns [4][5]. Its functions by promoting off-peak electricity usage, scheduling demand to higher generation periods, reducing peak-hour usage to avoid supply shortages, and minimizing redundant capacity for resource management. Implementing DSM optimizes power efficiency, resource allocation, and environmental sustainability. Therefore, this article aims to:

1. *Identify demand-side interventions that can effectively manage the variability and intermittency introduced by renewable energy.*
2. *Explore key opportunities for policy planning to advance DSM strategies for improved renewable energy integration in energy systems.*

Renewable Energy Curtailment

Renewable energy generation is inherently uncertain as output depends on meteorological conditions. At times, generation exceeds storage capacity of existing facilities, forcing utility companies to halt power production to maintain the real-time balance between supply and demand [7], as electric generation cannot be economically stored on a large-scale [8]. The energy generated from renewables must be limited to less than the maximum energy that the system can produce, a practice known as curtailment [7]. Renewable energy curtailment (REC) refers to the enforced reduction of electricity generation from renewable sources compared to the ideal capacity of the generating unit. This occurs when the system cannot accommodate the full generation output, leading to wasted green energy that could otherwise be used and revenue loss [9]. Primary causes of REC are largely technical and system balancing constraints including equipment failures, lack of flexible generation and demand-side flexibility, incorrect protection settings, defective control systems, grid congestion, and lack of coordination among dispatch centers [8][10][11].

Energy curtailment is a growing challenge in power sector management [7]. System operators assess curtailment causes to determine compensable losses and compensate generators accordingly [10]. The lack of accurate and real-time data further complicate the process of claiming compensation, justify unmet targets, and manage asset efficiency. Also, transmission infrastructure development has lagged behind the rapid expansion of renewable energy production. In many regions, grid capacity remains insufficient to handle production peaks leading to frequent curtailment. For example, wind farms are generally quicker to construct than transmission networks, resulting in some instances where power plants are built in advance of the necessary infrastructure to deliver the energy to load centers [10]. The absence of policy frameworks exacerbates the frequency of REC and hinders efforts to mitigate its impact. The extent of REC can affect grid planning, infrastructure development, operational management, dispatching, and emissions reduction [8]. Identifying effective strategies to minimize or utilize REC requires enhancing system flexibility [6][7]. Key approaches include advancing DSM to improve supply and demand balance [12].

Demand Side Management

A. Common Strategies

DSM (initially known as load management [13]) offers the flexibility to balance electricity generation and demand, which is crucial for integrating variable renewable energy sources. It is a flexible system management strategy involving planning, evaluation, implementation, and monitoring of various strategies to optimize electricity consumption [9][12][14] across various sectors notably, residential, commercial, and industry, each with distinct characteristics and requirements[6][15]. The first step in selecting DSM alternatives is defining the overall objectives to be achieved following a hierarchical framework[16]:

i. **Strategic Objectives**: Broad goals for utility long-range planning such as improving cash flow, increasing earnings, and enhancing customer and employee relations.
ii. **Tactical/Operational Objectives**: More specific actions for guiding utility management.
iii. **Load Shape Objectives**: Operational goals translated into targeted demand patterns following six generic load shapes between on-peak and off-peak duration [5], [17]–[21]:
   - *Peak Clipping/Shaving:* A direct load control technique that reduces demand during peak hours, particularly useful when investment in new generation units is limited.
   - *Valley Filling:* Encourages increased electricity consumption during off-peak hours by offering lower prices to end-users during that time.
   - *Load Shifting:* Shifts demand from peak to off-peak hours through time-based pricing incentives, benefiting both utilities and consumers by paying cheaper tariffs during off-peak hours.
   - *Strategic Conservation/Load Reduction:* Lowers overall electricity demand by promoting energy-efficient appliances, helping reduce peak loads and contributing to energy conservation.
   - *Strategic Load Growth:* Encourages controlled increases in electricity consumption with a certain limit to optimize power system capacity and ensure smooth grid operation.
   - *Flexible Load Shape:* Redistributes loads across different time slots by identifying consumers willing to adjust their consumption in exchange for incentives.

The broad range of DSM strategies to influence the patterns and magnitude of end-use electricity consumption can be categorized as reducing (peak clipping/shaving, conservation), increasing (valley filling, load growth), or rescheduling energy demand (load shifting) [6].

Table 1 presents a taxonomy of DSM implementation strategies, categorizing them into program types, and providing operational examples commonly reported in the literature [14], [17], [18], [20]–[25].

DSM strategies are typically classified into two main types: Energy Efficiency (EE) and Demand Response (DR) [13]–[15][18][22][23][26]. EE refers to enhancements in appliances and processes to reduce demand as a long-term energy conservation strategy [15][14][18]. These include a combination of technical and behavioral measures. Technical measures include the adoption of LED lighting instead of incandescent bulbs, variable-speed air conditioning, and smart meters for real-time energy monitoring and feedback [18]. Behavioral measures include changing consumer habits and decision-making to reduce consumption such as shifting electricity usage to off-peak hours, turning off unused appliances, optimizing thermostat settings, and utilizing natural lighting. Meanwhile, DR refers to intentional shifts in electricity demand to suit supply availability or infrastructure constraints for short-term load manipulation [14][15][18]. DR is classified into price-based and incentive-based programs based on consumer participation [13], [15], [17], [18], [22]–[24]. Price-based DR, also known as time-based, adjusts demand through time-varying electricity rates, while incentive-based DR offers bill reductions or direct payments for demand adjustments [15]. Price-based DR is most common for residential and commercial users, while industrial users typically engage in incentive-based DR [15]. Examples of DR applications across relevant sectors are presented in Table 2 [15].

Applications of DSM strategies and corresponding programs have been tested across a variety of case study applications with recent examples including the United Kingdom (2017) [27], Lleida-Spain (2018) [28], Finland (2018) [29], Portugal (2019) [30], Germany (2020) [31], Karnataka-India (2023) [32], sub-Saharan Africa (2023) [33], Pakistan (2024) [34], Trabzon-Türkiye (2024) [35], Dübendorf-Switzerland (2024) [36], Liaoning-China (2024) [37], and Arunachal Pradesh-India (2024) [38].

Table 1: Taxonomy of Demand Side Management (DSM) strategies

Strategy	Program Type		Operational Examples
Energy Efficiency (EE)	– Efficiency – Conservation		– Fuel economy standards – Appliance and equipment standards – Energy star program – Weatherization – Improving routine maintenance of electrical equipment by recovering waste heat – Enhancing maintenance procedures – Using modern equipment with optimum designs – Practicing cogeneration – Distributed generation – Advanced control systems for voltage regulation, power factor correction and data acquisition systems – Low–loss transformers – Gas installation substations – Smart metering – High–transmission voltages – Promotion/communication/education/awareness–raising campaigns – Energy consciousness and willingness of users/consumers – Award/recognition programs
Demand Response (DR)	– Price–based (time–based) program, Non–dispatchable		– Time of Use (ToU) pricing – Critical peak pricing (CPP) – Real–time pricing (RTP) – Critical–peak rebates (CPR) – Peak time rebate (PTR) – Inclined block rate (IBR)
	– Incentive–based program, Dispatchable	– Classical-based programs	– Direct load control – Curtailable/interruptible load – Spinning/responsive reserves – Non–spinning reserves – Regulation service
		– Market-based programs	– Emergency demand response – Demand bidding/Buyback – Capacity market – Ancillary services market

B. Potential Opportunities

DSM improves sustainability indicators, including reliability, quality, security, and stability, in modern power systems. A key advantage is reducing the generation margin, as DSM can serve as an alternative to installing additional new generation units that would only be used occasionally resulting in unnecessary capital cost [25][39]. Instead of building costly standby plants, DSM enables demand reduction during peak periods, providing a cost-effective reserve solution particularly valuable in renewable-dominated systems. DSM also optimizes transmission grid investment and operational efficiency by reducing congestion and enabling a shift from preventive to corrective control approaches. At the distribution level, DSM helps relieve voltage constraints, manage substation congestion, and improve outage management, resulting in increased network resilience, better asset utilization, and carbon reduction [25]. DSM's value in balancing fluctuating intermittent renewable generation depends on the flexibility of the existing generation mix, making it a critical tool in systems with high shares of inflexible generation [25]. It plays a key role in distributed power systems, particularly in decentralized energy networks with small- and medium-scale Combined Heat and Power (CHP) plants and renewable energy sources. By utilizing waste heat effectively and supporting local generation-balancing mechanisms, DSM can enhance overall efficiency and reduce reliance on large-scale power plants [25]. The shift towards distributed generation, combined with DSM-enabled demand flexibility, can accelerate the transition to low-carbon energy systems.

As a result of implementing DSM strategies, blackouts and outages are reduced as DSM helps balance supply and demand more effectively. By enabling the use of a diverse power generation portfolio, including renewables and distributed energy resources, DSM contributes to a more resilient energy system while also reducing price volatility and lowering unit electricity costs for consumers. Customers benefit further from incentivized payments, bill reductions, and greater flexibility in managing their energy consumption. From a utility perspective, DSM supports the expansion of generation capacity and reserves, defers costly infrastructure upgrades, and reduces operating costs by optimizing existing resources. It decreases

Table 2: Selected examples of DR applications across sectors of the energy system

<table>
<tr><th>Sector</th><th>Relevant Sub–sectors</th><th>Demand Response (DR) Applications</th></tr>
<tr><td>Residential</td><td>– Home, Apartment, etc.</td><td rowspan="2">– Appliances: Dishwashers, washing machines, dryers, computers, televisions, smart controllers
– Lighting: LED and smart lighting systems, daylight harvesting
– Cooking: Smart ovens and electric stoves/appliances
– Space heating/cooling: HVAC systems with smart thermostats
– Refrigeration: Smart refrigerators and freezers
– Water heating: Electric hot water cylinders with demand control
– Storage: Thermal storage, electric vehicle batteries, fleet charging, hydrogen storage
– Building envelope: Enhanced thermal insulation and smart windows</td></tr>
<tr><td>Commercial</td><td>– Office buildings, Supermarkets, etc.</td></tr>
<tr><td>Industrial</td><td>– Pulp and paper, Metal, Storage warehouses, Cement, Electrolysis plants, Textile factories</td><td>– Mechanical Processes: Milling, mixing, grinding, electric motors with storage, inventory buffers
– Variable Speed Drives: Energy–efficient motor control for industrial machinery
– Heating and Cooling Processes: Thermal storage for electric furnaces, large refrigeration systems
– Metal Refining: Demand–response strategies for electrolysis and smelting processes
– Energy–Intensive Processes: Smart demand control in cement, steel, and chemical industries</td></tr>
</table>

load losses, improves system efficiency, and enhances voltage stability, ensuring a more reliable power supply. DSM also helps in relieving transmission congestion and facilitating optimal power flow by efficiently allocating demand-side resources, ultimately leading to a more flexible and cost-effective grid. Furthermore, DSM plays a crucial role in reducing power plant emissions, supporting clean energy transitions and broader climate goals [14][24].

C. Policy Planning

Despite promising opportunities, DSM adoption remains relatively slow due to various associated challenges. Limited ICT infrastructure hinders advanced metering, communication, and control systems, requiring significant investments in integrated energy networks. Also, the lack of clear methodologies for quantifying costs and benefits makes it difficult to build a strong business case [25]. For example, the lack of standardized test data and daily load profiles limits DSM validation and real-world implementation particularly for time-sensitive operations [18][24]. DSM solutions also struggle to compete with traditional network and generation expansion, often due to being perceived as more complex and less cost-effective. DSM increases operational complexity when compared with traditional approaches, requiring corrective control strategies that add challenges to system management [25]. Consumer and prosumer preferences further hinder adoption, as many end-users are either unaware of DSM programs or unconcerned with their benefits, leading to low participation rates [18][24]. Effective DR implementation requires a sector-specific approach rather than a one-size-fits-all strategy. While commercial and industrial sectors are more adaptable to DSM due to their structured energy usage and controllable loads, the residential sector presents greater challenges due to diverse appliance usage patterns, dispersed consumers, and varying preferences [18]. Furthermore, inappropriate market structures and lack of incentives pose barriers, as DSM benefits are spread across multiple stakeholders, making it difficult to establish a viable business model [25]. Unlocking DSM's full potential requires targeted pilot schemes, regulatory support, standardized data, and clear cost-benefit feasibility, among others, for seamless integration into modern power systems. Government and policymakers' commitment are crucial for advancing DSM adoption at scale. Examples of potential policy instruments, categorized into four main types, include [22][26][40]:

i. **Regulatory:** Setting clear performance standards for appliances, equipment, and buildings, along with enforcing energy audits to ensure efficiency and demand flexibility. Mandatory labeling programs can be used to inform consumers of energy-efficient products. Additionally, stringent utility obligations can reinforce active DSM participation, requiring energy providers to integrate solutions such as advanced monitoring, real-time data analytics, and predictive maintenance into operations and investment planning, particularly in ancillary service markets and capacity provision schemes.

ii. **Market-oriented:** Reforming electricity market structures to facilitate DSM through certificate trading schemes including Energy Savings Certificates (ESC), Energy Efficiency Credits (EEC), or White Tags to incentivize efficiency investments. Market transformation programs can promote DSM-friendly grid operations and demand response tariffs to encourage load shifting and peak demand reduction. Additionally, infrastructure upgrades, such as advanced metering, real-time communication, and automated control systems, should be prioritized to enhance grid responsiveness.

iii. **Financial:** Reducing investment risks and attracting private sector participation through low-interest loans, direct subsidies, tax exemptions, and dedicated research and development funding. Performance-based financial incentives, such as Energy Performance Contracts (EPCs), can reward utilities and businesses implementing successful DSM programs, ensuring investments yield tangible energy savings and system efficiency improvements.

iv. **Voluntary:** Strengthening consumer engagement and knowledge through public education and awareness campaigns, real-time energy feedback, and behavioral incentives to encourage households, businesses, and industries to adopt DSM strategies proactively. Regular program assessment with feedback loops will ensure continuous improvement and alignment with evolving energy market needs.

By implementing a well-balanced mix of policies, DSM can transition from an auxiliary strategy to a mainstream pillar of energy management. An effective policy framework will not only support DSM implementation but also contribute towards achieving the broader objectives of approaching global agendas for the Sustainable Development Goals (2030) and the Paris Agreement Net-Zero Emissions target (2050).

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