Towards a Shared Integrated Grid in New England's Energy Water Nexus

Steffi Muhanji[1], Clifton Belows [2], Tad Montgomery [3] and Amro M. Farid[4]

***Abstract*— The electric power system is rapidly decarbonizing with variable renewable energy resources (VREs) to mitigate rising climate change concerns. There are, however, fundamental VRE penetration limits that can only be lifted with the complementary integration of flexible demand-side resources. A recent study has shown that flexible energy-water resources can serve such a role, provide much needed operating reserves and cost-effectively reduce power system imbalances. The implementation of such demand-side resources necessitates a "shared integrated grid" that is characterized by: 1) integral social engagement from individual electricity consumers 2.) the digitization of energy resources through the energy internet of things (eIoT), and 3) community level coordination. This paper discusses the efforts of Dartmouth College and the City of Lebanon, NH to develop such a shared integrated grid. It leverages the newly passed New Hampshire municipal aggregation bill to develop a prototype transactive energy (TE) market that enables Lebanon residents to trade carbon-free electricity products and services amongst themselves.**

I. Introduction

The electric power system is rapidly decarbonizing to mitigate rising climate change concerns. This evolution to a carbon-free grid has been characterized by a widespread adoption of variable renewable energy resources (VREs) such as solar and wind throughout the electricity supply chain. In the meantime, VRE adoption has been driven by a combination of technology improvements, favourable legislation and lower costs. While much VRE integration has been in the form of utility-scale developments, more recent integration, particularly roof-top solar has been at the consumer level, behind-the-meter, as distributed generation (DG).

VREs, however, pose fundamental challenges to the technical and economic control of the power grid. First, these resources are highly variable and erode the dispatchable nature of the generation fleet [1]. Second, both solar and wind power profiles are influenced by external factors such as wind-speed and solar irradiance that are challenging to predict and leverage in grid operations. Grid operators must rely on forecasted VRE power profiles in order to dispatch generation so as to meet demand in real-time. Such forecasts are error-prone and, therefore, impede system operators' ability to exactly match generation and demand. Third, the eroded dispatchability of the generation fleet impedes its ability to track the net load. Whereby "net load" is defined as the difference between the aggregated system load and the total generation produced by VREs, tieline imports/exports, and any transmission and distribution losses. Fig. 1 represents a phenomenon commonly referred to as the "duck curve". The black line represents the net load. With each gigawatt (GW) of solar added, the "belly" of the net load curve grows. As the sun rises over the course of the day, an increasing number of dispatchable generators are taken offline. As the sun sets, these same generators must start up and ramp up quickly to replace the waning solar generation [1], [2]. Incidentally, this ramp also happens to coincide with the evening electricity demand peak. These challenges greatly limit the extent to which VREs can be adopted within the current electricity grid set up.

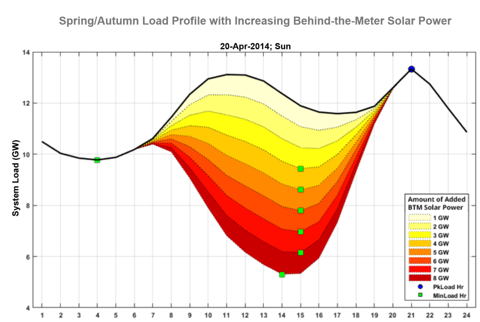


Fig. 1: The duck curve. [2]

Indeed, dozens of renewable integration studies across varied geographies have come to the following consensus conclusions [1]–[6]:

1) VREs require greater quantities of normal operating reserves.
2) Both the variability and forecast errors of VREs contribute towards system imbalances.
3) VREs present dynamics that span multiple time scales and layers of power system control.

[1]Steffi Muhanji (*corresponding author*), is with the Thayer School of Engineering, Dartmouth College, Hanover, NH 03755, USA [1]Steffi.O.Muhanji.TH@dartmouth.edu

[2] Clifton Below is a City Councillor at the Lebanon City Council,NH. [2]Clifton.Below@lebanonnh.gov

[3] Tad Montgomery is a Chief Energy and Facilities Manager with the City of Lebanon, NH.[3]Montgomery@lebanonnh.gov

[4]Amro M. Farid is with the Faculty of Thayer School of Engineering, Dartmouth College, Hanover, NH 03755, USA Amro.M.Farid@dartmouth.edu

4) Operators are forced to take corrective manual actions to deal with real-time variability.
5) VRE forecast errors can impede real-time energy markets from clearing. The associated optimization models result in infeasible solutions.
6) Operating a system with high amounts of VREs requires even greater quantities of ancillary services.

These conclusions not only call for holistic and integrated solutions but also the need to significantly increase available grid services [7].

Engaging the demand-side has been proposed as a key control lever towards effective VRE integration [1], [8]. Firstly, the grid periphery is increasingly activated by "smart-home" distributed energy resources (DERs); be they in the form of rooftop solar, electric vehicles (EVs), or battery energy storage. Secondly, electricity consumers are becoming more conscious of the cost and sustainability of their consumption patterns [1], [8], [9]. Thirdly, the deregulation of electric power systems has steadily disbanded traditional generation monopolies and opened the way for increasing consumer choice in electricity service. Finally, the rise of the energy Internet of Things (eIoT) and its associated data-driven services have modernized the electricity demand-side, incentivized new types of grid actors (e.g demand aggregators), and inspired new retail services [1], [8], [9]. When these seemingly independent developments converge to maturation, they form transactive energy (TE) market places that cost-effectively transact electricity "products" amongst everyday grid "prosumers", reliably secure the physical power grid, and seamlessly inter-operate with wholesale (bulk) electricity markets. Coupled with favourable local legislation, American communities are now able to take control over their electricity needs through various community energy aggregation schemes. These factors allow consumer choice of energy provider, foster the development of local renewable energy and facilitate the formation of market structures in which local consumers exchange energy products and services both with their local neighbours and with the grid as a whole [1], [9].

A. Contribution

This paper seeks to tie the "macro-picture" of grid decarbonization and VRE integration into the "local-picture" of community efforts towards a ***shared integrated grid***. First, it draws on the lessons learned from the ISO New England's (ISO-NE) 2017 System Operational Analysis and Renewable Energy Integration Study (SOARES) to illustrate the fundamental limits to VRE integration. Specifically, in the absence of complementary demand-side initiatives, the electric power system develops a notable dependence on VRE curtailment as a key control lever. Second, this paper demonstrates that the needed control levers can come from the flexible operation of a modest percentage of New England's energy-water resources. Doing so would enhance the grid's balancing performance, CO_2 emissions, water withdrawals and consumption, and real-time/day-ahead market production costs. To achieve such a synergistic outcome, the paper presents a concept of a shared integrated grid that is characterized by: 1) integral social engagement from individual electricity consumers, 2) the digitization of energy resources with eIoT, and 3) community level coordination. The City of Lebanon NH and Dartmouth College are currently collaborating towards its implementation in the form of a Transactive Energy (TE) Blockchain prototype.

B. Outline

The rest of the paper is structured as follows. Section II, discusses the key findings and lessons learned in the SOARES. Section III presents the New England energy water nexus study results and conclusions. Section IV discusses ongoing efforts towards a shared integrated grid in NH. Finally, the paper concludes in Section V.

II. MOTIVATION — THE CURTAILMENT PROBLEM.

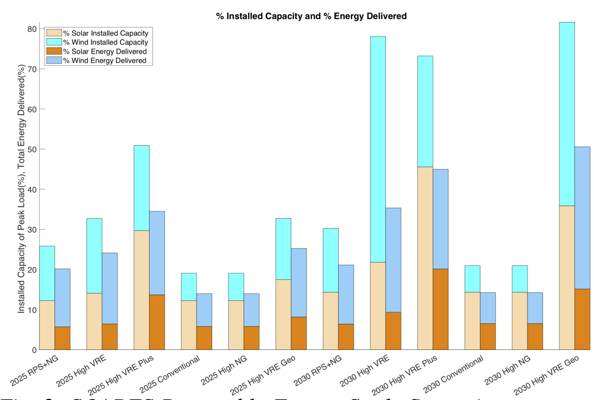


Fig. 2: SOARES Renewable Energy Study Scenarios as agreed by ISO-NE stakeholders [?].

A. Study Description

In 2017, ISO-NE commissioned the System Operational Analysis and Renewable Energy Integration Study (SOARES) to investigate the impact of varying penetrations of VREs on the operations of the ISO-NE system. This study looked into 12 predefined (by the New England Power Pool (NEPOOL)) scenarios with 6 in 2025 and 6 in 2030 [2]. These scenarios were distinguished by the capacity and diversity of dispatchable generation resources, solar, wind, and energy efficiency. Fig. 2 represents the installed capacity of and actual energy delivered by solar and wind for each of the 12 scenarios. The "2025/2030 Conventional" scenario reflects the

ISO-NE system if it were to evolve in a "business-as-usual" manner. Due to the high penetrations of solar and wind, most scenarios experienced a negative "net load" during low load periods in the Spring and Fall months. In addition, nuclear generation units were considered "must-run" resources and therefore, generated electricity at all times and at full capacity [2]..

B. *Highlights of Key Results*

The dispatched generation profile for the "2030 VRE Plus" scenario in mid-April is shown in Fig. 3. The majority of the generation is met by wind, solar, and nuclear power. At any one point in time, very few dispatchable generators are committed. Note that with such high amounts of VREs, the commitment of dispatchable generators is no longer a trivial issue but rather, one that is difficult to predict as it is highly influenced by both the non-linear dynamics of VREs and the statistics of the net load profile [2]. Such high VRE penetration levels significantly impact the system's ability to deal with net load variability and hence mitigate imbalances in real-time. For example, at midday, large amounts of solar result in low load conditions and test the system's ability to ramp downwards. The opposite is observed as the sun begins to set whereby the system must ramp upwards to compensate for the declining generation. As Fig. 3 shows, instead of the traditional "duck curve" (as in Fig. 1) an even more exaggerated profile (called here the "duck-dive curve") is observed for the "2030 VRE Plus" scenario. The sharper ramp in this Fig. 3 further illustrates the operational constraints presented by high penetrations of VREs.

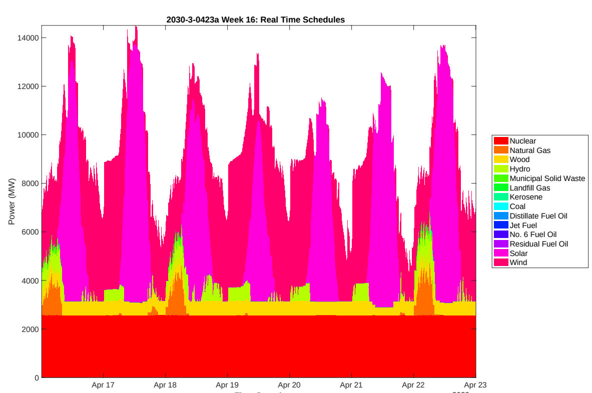


Fig. 3: Dispatched generation profile by fuel type for the month of April.

For the scenarios with a significant presence of VERs ("High VREs", "High VRE Plus" and "High VRE GEO"), the system is shown to entirely exhaust both its upward and downward load-following as well as ramping reserves [2]. Where load-following reserves represent the available capability by online generators to move up or down and ramping reserves is the ability of online generators to move up or down per unit time. Figures 4 and 5 illustrate load-following and ramping reserves for the "High VREs Plus" scenario. Both the load-following and ramping reserves go to zero in the Fall and Spring months. The minimum statistic of both reserve quantities is particularly important as it indicates the "safety margin" that the system has to ensure its security. As the third subplots of Figures 4 and 5 respectively illustrate, both types of reserves have a zero minimum. Incidentally, the exhaustion of these reserve quantities corresponds to even higher imbalances as the system is unable to respond to variability in the net-load in real-time. These results challenge the assumptions around the acquisition of these reserve quantities and motivate the need for better techniques to obtain them.

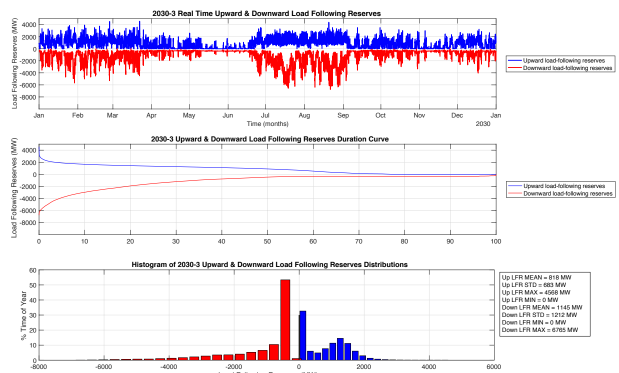


Fig. 4: Load-Following reserves profile for the "2030 VRE Plus" scenario [2].

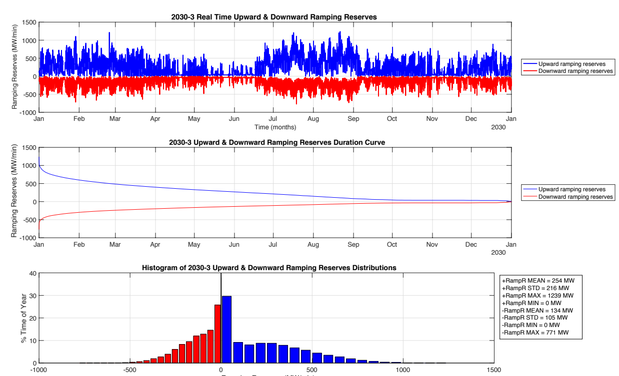


Fig. 5: Ramping reserves profile for the "2030 VRE Plus" scenario [2].

Perhaps the most insightful finding of this study is the reliance on curtailment to maintain the system's normal operating conditions. For all of the 12 scenarios, curtailment of VREs emerged as a key control lever in addition to the load-following and ramping reserves provided by dispatchable generators. Each scenario utilized curtailment as a balancing lever at least 98% of the time [2]. More interestingly, the total energy curtailed ranged from 2.72% of the total available VRE capacity for the conventional scenarios to 41.19% for scenarios with high penetrations of VREs [2]. While some of the curtailment was due to excessive VRE generation in the system, a small portion of this curtailment was caused by topological limitations of the system. Curtailment is especially vital when variable resources are situated in remote locations such as Northern Maine. In these cases, it can be the only available control lever [2].

Irrespective of the reason for curtailment, the extent to which curtailment was used in all these simulation scenarios is potentially concerning. Although increasing the line-carrying capacity would alleviate the need for curtailment in cases with topological constraints, building more transmission is not always an option in most regions. Furthermore, lower levels of curtailments are vital as they increase the overall amount of generation from renewable sources, and reduce the use of expensive dispatchable generation; which in turn cuts costs and CO_2 emissions. This study illustrates the indispensable role of curtailment in power system balancing performance.

Mathematically speaking, curtailment is not unlike load-following and ramping reserves. The curtailment signal used in this study moved the power levels of a given curtailable resource up or down within the real-time resource scheduling market time step of 10 minutes. This means that to curtail a VRE, this resource must ramp up/down from its current production level to the curtailed level within 10 minutes. The ramping of a VRE as it reduces its generation level could count towards the system ramping reserves and be compensated accordingly. Similarly, the total power available for curtailment from any given VRE could also count towards the system load-following reserves. Reconciling the definitions of operating reserves and curtailment and, therefore, their treatment in electricity markets would go a long way to provide the much needed flexibility in systems with high penetrations of VREs. Semi-dispatchable resources (i.e. resources whose supply can be curtailed) could provide load-following and ramping reserves. Similarly, a much faster curtailment signal can help develop regulation reserves.

III. Results from the New England Energy-Water Nexus Study

TABLE I: A summary of available flexible water resources in the system as percentage of the peak load.

	2040-1	2040-2	2040-3	2040-4	2040-5	2040-6
Hydro Run-of-River & Pond	1854MW (6.21%)	1788MW (5.99%)	1646MW (7.10%)	1782MW (5.97%)	1798MW (5.99%)	1784MW (5.97%)
Pumped Storage	1758MW (6.15%)	1758MW (6.15%)	1758MW (6.15%)	1758MW (6.15%)	1758MW (6.15%)	1758MW (6.15%)
Water Load	565MW (1.89%)	565MW (1.89%)	565MW (2.44%)	565MW (1.89%)	565MW (1.89%)	565MW (1.89%)
System Peak Load	28594 MW	28594 MW	22103MW	28594MW	28594 MW	28594 MW

The findings of the SOARES are significant in two main ways. First, they highlight the value of curtailment in balancing performance, and second, they show the need to engage more demand-side resources in market operations. With these conclusions in mind, the New England Energy-Water-Nexus study was conducted to analyze: 1) the value of curtailment in the provision of load-following, and ramping reserves, 2) the value demand response by energy-water resources of various types, 3) the fuel flows of thermal units and their associated CO_2 emissions, 4) water withdrawals and consumption by thermal units, and 5) the effect of flexible operation on the New England energy market production costs. This study combines the two main insights of the SOARES, by redefining the role of curtailment in power system operation and activating energy-water demand-side resources . The first goal is achieved by allowing curtailment to count towards the provision of both load-following and ramping reserves. The second is achieved by allowing energy-water resources to provide demand response through their load-shedding capabilities.

The New England Energy Water Nexus study considered 6 2040 scenarios for the ISO-NE system. The resource mixes for the six 2030 scenarios of the SOARES were evolved to 2040 scenarios using the Regional Energy Deployment System (ReEDS) optimization tool developed by the National Renewable Energy Lab (NREL). Table I summarizes the capacity mixes of all the energy-water resources used in this study. Two modes of operation were considered: flexible operation (with flexible energy-water resources) and conventional operation (without them). In the flexible mode, run-of-river and pond-hydro were curtailable at a cost of $\$4.5/MWh$ while demand from water and wastewater treatment facilities had a load-shedding capability. The opposite was true for the conventional operation mode. Pumped storage was treated as a dispatchable resource across all six scenarios in both operating modes.

The "flexibility value" of coordinated flexible operation of the New England energy-water nexus was assessed based on three main areas: 1) balancing performance (improvements in load-following, ramping and regulation reserves, curtailment, and system imbalances), 2) environmental impact (reductions in water withdrawals and consumption, and CO_2 emissions) and 3) overall production costs (day-ahead and real-time). Table II summarizes the range of improvements brought about by coordinated flexible operation of the New England Energy water nexus.

A. Balancing Performance

Flexible operation enhanced the mean upward and downward load-following reserves by 1.26%-12.66% across the six 2040 scenarios as illustrated in Table II. The study also showed that flexible operation significantly improves the minimum levels of load-following

TABLE II: Balanced Sustainability Scorecard: The range of **improvements** *caused by coordinated flexible operation of the energy-water nexus.*

Balancing Performance	**% Improvement**
Average Load Following Reserves	1.24–12.66%
Average Ramping Reserves	5.28–18.35%
Percent Time Curtailed	2.67–10.90%
Percent Time Exhausted Regulation Reserves	0%
Std. Dev. of Imbalances	3.874–6.484%
Environmental Performance	**% Improvement**
Total Water Withdrawals	0.65–25.58%
Total Water Consumption	1.03–5.30%
Total CO_2 Emissions	2.10–3.46%
Economic Performance	**% Improvement**
Total Day-Ahead Energy Market Production Cost	29.30–68.09M$
Total Real-Time Energy Market Production Cost	19.58–70.83M$

reserves across all six scenarios and in some cases by up to 82.96%. The results indicate that by adding a small amount of flexibility in the system (see Table I), the robustness of the system is improved in the worst case points and the overall operation during challenging periods.

Similarly, the mean downward and upward ramping reserves values were improved by 5.28%-18.25% with flexible operation as shown in Table II. The minimum statistic of ramping reserves improved across all six scenarios with up to 31.65% for downward ramping reserves and up to 47.32% for upward ramping reserves. These improvements were greater for systems with a high penetration of VREs. This result further illustrates the role of curtailment in improving the flexibility of the system if applied towards the provision of load-following and ramping reserves.

Although, flexible operation increased the amount of power available for curtailment, the results of the study showed that flexible operation reduced the percent of time VREs were curtailed by 2.67%–10.90%. Contrasted with the SOARES where curtailments occurred up to 98% of the time [2], flexible operation significantly improves the use of curtailment and, therefore, renewable energy in power system operations. Also, due to flexible operation, regulation reserves were exhausted for 0% of the time unlike the SOARES where they exhausted 0.14%–46.20% of the time. Finally, the standard deviations of imbalances decreased by 3.874%-6.484%. These results illustrate that by revising the role of curtailment in power system operation and engaging demand-side resources, the overall security of the system is improved through increased flexibility in balancing performance.

B. Environmental Impact

Flexible operation reduced the environment impact of the electric power grid by reducing the water withdrawals and consumption by thermal power plants by 0.65%–25.58% and 1.03%–5.30% respectively. Similarly, the overall CO_2 emissions were reduced by 2.10%–3.46%. These results indicate that an even bigger environment impact is likely with increased flexible operation and demand-side participation.

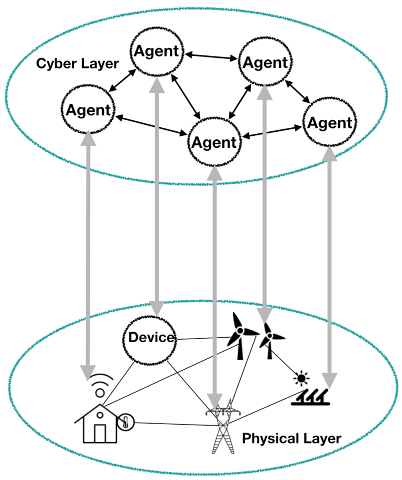
C. Economic Impact

Finally, flexible operation reduced the overall electricity production cost by 29.30–68.09M$ for the day-ahead market and 19.58–70.83M$ as compared to the conventional mode of operation. These results indicate that the flexible mode of operation allows for less constrained day-ahead and real-time optimization programs, that, in turn, result in reduced overall production costs.

IV. Discussion

The New England energy-water-nexus study showed that the introduction of small quantities of flexible energy-water demand-side resources could have far-reaching consequences on all aspects of power system performance. Nevertheless, there are many challenges to realizing the benefits of flexible energy-water demand side resources; be they water treatment plants, wastewater treatment plants, or even everyday household electric water heaters. First, they are owned and operated by individual electricity consumers; with their own objectives for their use. Second, many such devices lack the necessary instrumentation and control technology to become active grid resources. Third, they are both small and connected to the distribution system and consequently lack the ability to have noticeable impact on wholesale bulk power system operation. To overcome these challenges and achieve the synergistic outcomes of the New England energy-water nexus study, this paper presents the concept of a ***shared integrated grid*** that is characterized by: 1) integral social engagement from individual electricity consumers, 2) the digitization of energy resources with eIoT, and 3) community level coordination.

Fig. 6: Summary of available generation capacity as a percentage of total available capacity by fuel type for all six 2040 scenarios.



To that effect, and following on the recent enactment of NH Senate Bill 286, the City of Lebanon NH has launched Lebanon Community Power (LCP) as a municipal load aggregation initiative. The main objective of the initiative is to enable consumer choice in newly animated retail electricity markets so that smaller electricity consumers can benefit from the savings and rate alternatives that wholesale customers already enjoy. In so doing, the municipal aggregation gives access to real-time electricity prices that are on-average lower compared to the fixed retail rates. Furthermore, the local transactions of energy with Lebanon can serve to bolster renewable energy adoption, load reduction, and decarbonization as a whole. Furthermore, at the city level, the presence of municipal load aggregation can catalyze other initiatives like electric vehicle charging stations, smart street-lighting, and the deployment of other DERs like battery and thermal energy storage. A key component of the LCP initiative is to obtain granular meter data through collaborating with Liberty Utility to support research efforts to guide the deployment of DERs. This will involve meter upgrades to enable near-real time readings.

With these factors in mind, the Laboratory for Intelligent Integrated Networks of Engineering Systems (LIINES) at the Thayer School of Engineering at Dartmouth has teamed-up with LCP to develop a Transactive Energy (TE) Blockchain prototype to support the LCP initiative. The goal of the TE platform is to support real-time market transactions while ensuring that the Lebanon electric power system continues to function securely and reliably. Transactive energy (TE) is defined as "a system of economic and control mechanisms that allow the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter." Central to the development a TE prototype as the economic backbone of the LCP is the integration of power systems control engineering to secure grid's many operational and technical constraints. The technical development of the TE prototype draws on key lessons from the technical literature distributed control algorithms and multi-agent systems. Furthermore, the LIINES is collaborating with Liberty Utilities so the TE prototype addresses the specific complexities of the Lebanon distribution system.

In a TE context, each physical DER participates as a market agent in a cyber (or market) layer. As a design principle to minimize complexity and ensure privacy, each agent in the cyber layer only holds and exchanges information that is relevant to their specific participation in the market. It then carries out local and coordinated cost-minimization algorithm that simultaneously respects operational and physical constraints of the system. Given the magnitude of information exchange, Blockchain serve as a secure and distributed ledger to record and store transactions that each agent can ultimately access and verify.

V. Conclusion

In conclusion, the technical development of the transactive energy blockchain prototype coupled with the legislative enactment of SB 286 serve to enable the Lebanon Community Power initiative. While the LCP may be classified as a type of Community Choice Aggregator, this particular conception demonstrates several advanced features including: 1.) working with innovative private-sector partners to expand market access, 2.) working with utilities and technology developers to deploy the right IT infrastructure, and 3.) working with wide range of public and private stakeholders to ensure that the market structure continues to evolve and embraces new technologies — under a nimble, flexible mode of governance. These characteristics are integral to a truly "shared integrated grid" that through continued innovation in energy policy, markets, and technology platforms expands consumer choice, enables the flexible operation of demand-side resources, reduces electricity costs, facilitates greater adoption of renewable energy and ultimately accelerates the decarbonization of the electric power sector.

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