# Report to Natural Resources Canada Climate Change Adaptation – AP66

## Transactional Energy Framework for Net-Zero Energy Communities


Shivam Saxena, MASc, P. Eng
Chief Technical Officer
Hero Energy and Engineering

Aidan Brookson, MASc
Analyst
Toronto and Region Conservation Authority
Sustainable Technology Evaluation Program

Dr. Hany Farag, PhD, P. Eng
Associate Professor
Electrical Engineering and Computer Science
York University

Leigh St. Hilaire, B.A.Sc.
Project Manager
Toronto and Region Conservation Authority
Sustainable Technology Evaluation Program

Dr. Henry Kim, PhD
Associate Professor
Schulich School of Business
York University

## THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency program, led by the Toronto and Region Conservation Authority (TRCA). The program helps to provide the data and analytical tools necessary to support broader implementation of sustainable technologies and practices within a Canadian context. The main program objectives are to:

- monitor and evaluate clean water, air and energy technologies;
- assess barriers and opportunities to implementing technologies;
- develop tools, guidelines and policies, and
- promote broader use of effective technologies through research, education and advocacy.

Technologies evaluated under STEP are not limited to physical products or devices; they may also include preventative measures, alternative urban site designs, and other innovative practices that help create more sustainable and livable communities.

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- Blockchain Based Transactive Energy Frameworks
- Internet of Things Based Distributed Voltage Regulation
- Utility Control Software Dashboard over IEC 61850

## ACKNOWLEDGEMENTS

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# EXECUTIVE SUMMARY


Climate change adaption within the energy sector is defined as a collection of strategies, tools, and actions to improve the sector's resilience to the impacts of climate change [1]. A reactionary adaptation strategy is to reduce the greenhouse gas emissions produced by the energy and transportation sectors by increasing the uptake of distributed energy resources (DERs) such as solar distributed generation, battery energy storage systems, electric vehicles, and smart thermostats. However, this strategy places excessive stress on the electric distribution system infrastructure and requires the upgrading of all residential distribution transformers, resulting in capital expenditure (CAPEX) that would exceed $51 B [2].

Clearly, such massive upgrades to the distribution system are not feasible and will slow the adoption of DERs, thereby continuing to expose the population to financial, economic, and social risks associated with climate change. As such, **anticipatory** adaptation strategies are needed to reduce the impact of these risks. To that end, this project investigates the impact of transactive energy frameworks (TEFs) on the load profile an all-electric, 8 home, residential community. A TEF is a combination of incentive-based control techniques to improve grid resiliency and efficiency [12]. The deployment of a TEF within a residential community is conceptualized as a peer to peer (P2P) energy trading marketplace, where homeowners may place energy bids for each of their owned DERs. Creating a residential energy marketplace has the potential to settle power mismatches and reduce peak load by coordinating the charging cycles of battery energy storage systems and electric vehicles to increase the self-consumption of local renewable energy. Further, the TEF is implemented using blockchain technology to automate the bidding, validation, and dispatching of individual DERs within the marketplace. The utilization of blockchain technology removes trust issues between market participants by using a shared distributed ledger that enables all transactions to be validated and audited in consensus by all participants.

Simulated experiments on the 8 home residential community are conducted on three case studies, including: P2P energy trading, congestion relief, as well as power outage prevention. The TEF-based P2P energy trading marketplace reduces a community summer peak load from 109.96 kW to 52.29 kW (reduction of 52%), while the local renewable energy utilization increases from 69% to 93%. The reduction of the peak load reduces the size of the upgrades needed to the distribution system, resulting in an average of $56.8M (or 31.6%) of CAPEX savings for a sample size of distribution utilities. Further savings are enabled with the second study of congestion relief by adding demand caps on the community load, which reduces the peak load to 41.71 kW and increases CAPEX savings to $102.5M (or 57.1%). Results for the third case study demonstrate the ability of BESSs to provide voltage support to the distribution grid to prevent sustained undervoltage events during brownouts, resulting in annual community payments of $1440.

Lastly, a real-world, blockchain-based TEF is implemented using Hyperledger Fabric and deployed to a microgrid in Vaughan, Ontario. The TEF facilitates a marketplace that enables the microgrid DERs to bid and trade for energy. Real work experiments show the ability of the TEF to automate the bidding and dispatch process of the DERs, as well as to respond to demand caps set by the utility to force zero grid consumption from the microgrid during times of congestion.

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# 1.0 INTRODUCTION

## 1.1 Motivation

According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas emissions (GHGs) produced by human actions are causing significant levels of climate change [1]. Given that 73% of Canada's GHGs are produced by the energy and transportation sector [4], current research is devoted towards finding low-carbon solutions for these sectors, such as: a) increasing the uptake of renewable distributed energy resources (DERs) such as photovoltaic panels (PV) and battery energy storage systems (BESS); and b) electrifying transportation and heating/cooling systems via electric vehicles (EVs) and smart thermostats, respectively. However, uncontrolled operation of these DERs lead to negative consequences that include: destabilizing voltage swings due to the intermittency of sunlight, as well as power surges due to coincidental EV charging [5]. These consequences place the infrastructure of electric distribution systems under a great deal of stress, which limits the penetration of DERs and increases the overall impact of climate change.

To highlight the impact of DER penetration on distribution system infrastructure, an hourly summer electric load profile of a contemporary home is plotted with the profile of an all-electric home in Figure 1. In addition to standard electric loads, the all-electric home is assumed to have a 5 kW PV, 6 kW/25kWh BESS, a 6 kW/45kWh EV, as well as a smart thermostat. As seen in the figure, the load profile of the all-electric home is starkly different from the profile of the contemporary home, including the creation of a new mini-peak between the hours of 0:00-3:00, negative loading between 7:00-15:00, as well as a 4.4x increase in peak demand during 19:00-21:00. The peaks are primarily caused by the charging of the BESS and EV during off-peak pricing hours, while the negative loading is caused by excess PV production during the afternoon. In executing simulations for an all-electric community of 8 homes, the peak community load is found to be **110 kW.** This is well over the 50 kVA (45 kW with 0.9 power factor) capacity of the average distribution transformer that serves a typical 8-home community [5].

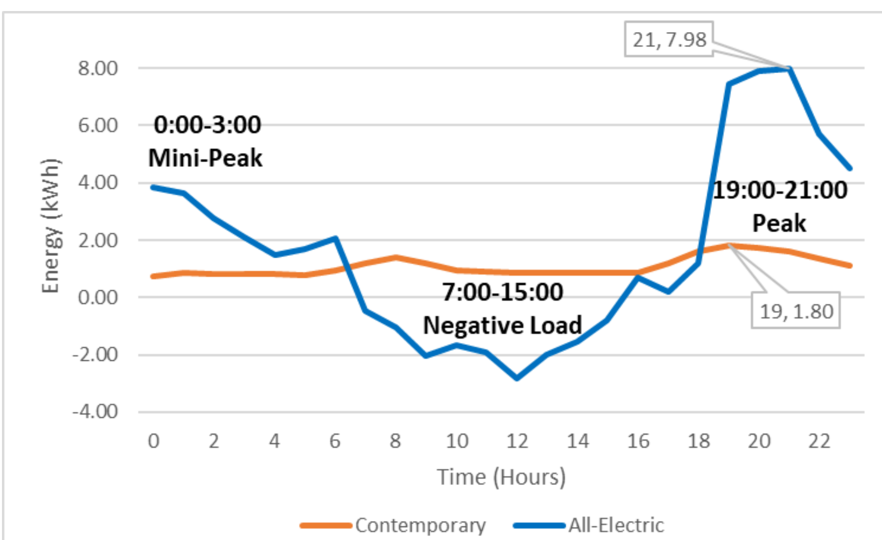


***Figure 1 - Comparison of load profile of contemporary home to all-electric home.***

***Table 1 - Average CAPEX for Ontario utilities for replacement of distribution transformers.***

| Utility | Customers | Residential Ratio (%) | Distribution Transformers | CAPEX ($) |
|---|---|---|---|---|
| Alectra Utilities | 987,000 | 90.0 | 113,622 | 756.5 M |
| Toronto Hydro | 771,890 | 89.3 | 60,560 | 400.1 M |
| Hydro Ottawa | 331,777 | 91 | 46,536 | 313.3 M |
| London Hydro | 159,040 | 91 | 14,873 | 100.1 M |
| Kitchener-Wilmot Hydro | 91,169 | 90.4 | 10,600 | 58.6 M |
| Waterloo North Power | 56,196 | 88.6 | 8,300 | 54.4 M |
| EnWin Utilities | 160,000 | 89.0 | 6,700 | 44.1 M |
| Halton Hills Hydro | 22,000 | 90.0 | 4,024 | 22.1 M |
| Essex Powerlines | 33,151 | 90 | 3,082 | 20.5 M |
| Lakefront Utilities | 10,300 | 92 | 1,200 | 8.1 M |

To adapt to this increase in peak demand, electric utilities must upgrade their 50 kVA transformers to a minimum of 125 kVA, resulting in an additional capital expenditure (CAPEX) of $7398 per transformer [7]. The unit cost of the transformer is computed with the assumption that the original 50 kVA transformers would be replaced exactly once during their lifetime, and thus, the price of a 50 kVA transformer is subtracted from the price of a 125 kVA transformer to find the additional CAPEX per transformer. Consequently, the expected additional CAPEX of distribution transformer replacement for a handful of utilities in Ontario is provided in Table 1 below. It should be noted that the projected costs in Table 1 do not include upgrades to electrical substations, which will likely require significant additional CAPEX [6].

As such, it is clear that anticipatory adaptation activities must be planned and executed to lower financial, economic, and social risks associated with the impact of climate change on the energy sector. In particular, the penetration level of DERs must be maximized while keeping the CAPEX requirement of utilities to a minimum. To that end, recent research has proposed the concept of transactive energy frameworks (TEFs), which is a combination of incentive-based control techniques to improve grid resiliency and efficiency [12]. In a TEF, energy producers are directly linked to neighboring energy consumers via peer to peer (P2P) energy trading schemes, thereby increasing the local utilization of renewable energy. The deployment of a TEF as a virtual marketplace within residential communities could therefore settle power mismatches caused by the intermittency of solar power, increase the efficiency and resiliency of the overall grid by coordinating the charging cycles of BESSs and EVs, and lower CAPEX requirements by reducing the community peak demand.

A specific requirement of the TEF is that it must maintain non-discriminatory participation of all participants, while also maintaining auditable interfaces to track and validate all energy transactions [12]. These requirements address the notion of ***trust***, where all TEF participants must be guaranteed that their transactions are valid, executed properly, and that the incentive received for the transaction is calculated fairly. The issue of trust within TEFs is critical, particularly when considering that the distribution utility is significantly dependent on consumer owned DERs to reduce peak demand in response to incentive signals that the utility may offer via the marketplace.

An emerging technology that is built to address these trust issues is known as blockchain, which is a distributed ledger that is used to keep a record of all transactions and data exchanges between participants. Blockchains utilize software applications known as smart contracts to automate the process of executing the transactions on the ledger, where smart contracts contain business logic that must be satisfied before the transaction is complete. Therefore, a blockchain-based TEF would enable a utility to negotiate a smart contract with a community to reduce their peak demand at a specific time for a certain incentive, and the smart contract would automatically execute after validating that the peak demand requirement was obeyed by checking the data on the ledger.

Motivated by the above discussion, this project seeks to design and deploy a blockchain-based TEF for residential communities with the major objectives of reducing peak demand and increasing local renewable energy utilization. The TEF is analogous to a virtual marketplace, where homes within a community can place energy bids to buy/sell energy based on their real-time energy requirements. Three case studies are investigated to determine how the marketplace can accomplish these objectives. The first case study investigates the impact of coordinated P2P energy trading within a single residential community, where a residential community is defined as a community of 8 all-electric homes. The second case study investigates congestion relief on the distribution transformer by adding a utility enforced demand cap on the residential community. Finally, the third case study considers the TEF can utilize DERs within the marketplace to provide voltage support to the distribution grid during sustained periods of low voltage, thereby preventing brownouts.

The experimental results for these case studies are generated by both simulated and real-world experiments. For the simulated results, simulations are executed for two data sets in the summer (July 20-July 26) and winter (Feb 1-Feb 7), respectively. The real-world experiments are conducted at the Kortright Centre Microgrid (KCM), which is a research facility located in Vaughan, Ontario. The KCM is equipped with over 50 kW of renewable power capacity, 100 kWh of energy storage, 3 EV charging stations, as well as 2 smart homes that are equipped with smart thermostats. It should be noted that the simulation results cover all three case studies, while the real-world experiments cover only the first two case studies. Brownouts, and by extension, undervoltage events could not be generated due to excess renewable power production at the KCM that keeps the system voltage within normal levels.

## 1.2 Report Organization

The organization of the report is as follows. Section 2 provides an overview of blockchain-based TEFs by providing a brief review of energy markets, formulating bidding strategies for the DERs, and introducing the design architecture of the proposed system. Section 3 presents experimental results from both simulations and real-world experiments. Section 4 discusses the potential barriers to adoption for TEFs, while Section 5 discusses the benefits of the project. Finally, Section 6 concludes the report by summarizing the major findings.

# 2.0 OVERVIEW OF ENERGY MARKETS AND BLOCKCHAINS

## 2.1 Review of Electricity Markets

The main objectives of electricity markets are to: a) ensure that the supply and demand of electricity throughout the grid is balanced; b) the cost of electricity is secured at a competitive price; and c) to ensure that there are enough reserves to stabilize the grid in case of contingencies. As such, several sub-markets are often defined within electricity markets, which include energy, capacity, and ancillary markets. Energy markets are executed to set the price of electricity competitively by arranging an energy auction between generators and loads during discrete time intervals (usually 5 minutes). Capacity and ancillary markets secure the provision of grid support services, such as demand response, voltage/frequency regulation, and black start through a competitive auction.

Energy markets, whether executed at the transmission (wholesale) level, or at a residential level (as within this project), rely on the principles of supply and demand. The market is executed as a bid-based auction that enables generators and loads to submit energy bids as a function of quantity (kWh) and price ($) within discrete market intervals to an auctioneer. The auctioneer typically employs a double auction method to arrange generator bids in ascending order of price and the load bids in descending order, as seen in Figure 2. Note that all critical loads, which are defined as uncontrollable loads that require power, are slotted at the highest price on the load curve. The intersection of the generation and load bid curves is set as the market clearing price (MCP), which is where the supply of energy meets the demand. Generator bids that are below and to the left of the MCP are granted, while load bids that are above and to the left of the MCP are granted. Bids to the right of the MCP are not granted, and do not generate/consume power for the duration of the market interval. This process results in the merit-order effect, where the highest bids of energy demand are satisfied by the most inexpensive generators.

An example bidding process is illustrated in Figure 2, where the MCP is shown for a system with limited (MCP1) and high levels of DER penetration (MCP2), respectively. It can be seen that in the second scenario, the merit order effect is greatly enhanced due to the greater deployment of inexpensive DER generation, resulting in a lower MCP ($0.07 versus $0.11) and greater system demand being able to be serviced (1.8 kWh versus 0.8 kWh).

To alleviate concerns of congestion when the demand of energy is far greater than the supply, a bid from the distribution utility can be used as a virtual demand cap to reduce the overall demand that is needed to be served by the grid. These bids are defined as *grid bids*. As shown in Figure 3, the grid bid is placed as a vertical bid at the specific quantity of energy that the grid can deliver at that point of time, resulting in loads 3-5 not being granted.

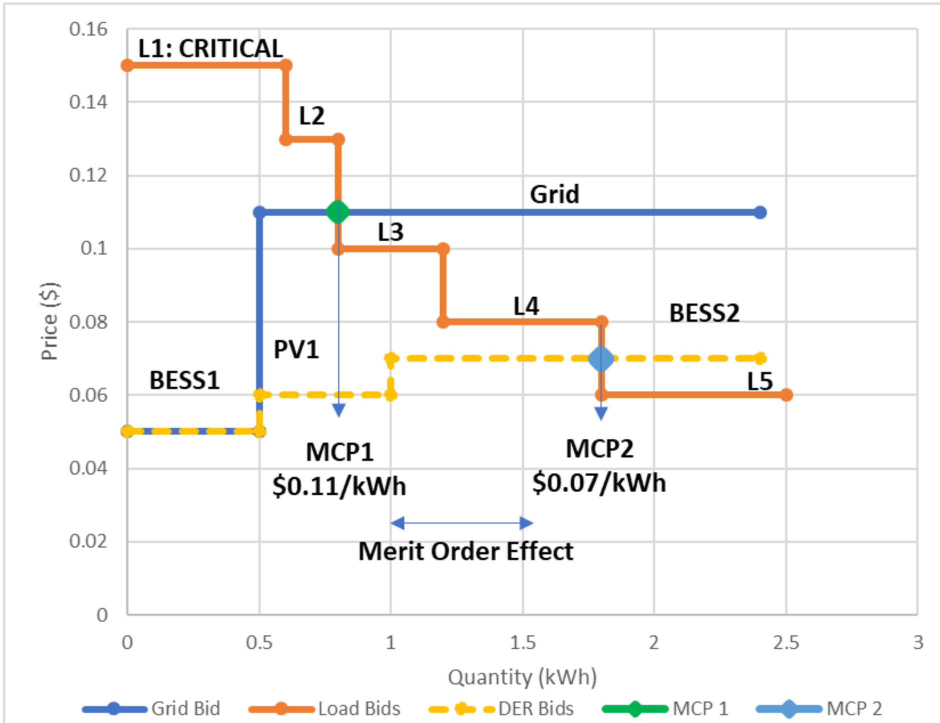


***Figure 2 - Example of market clearing price procedure within energy market.***

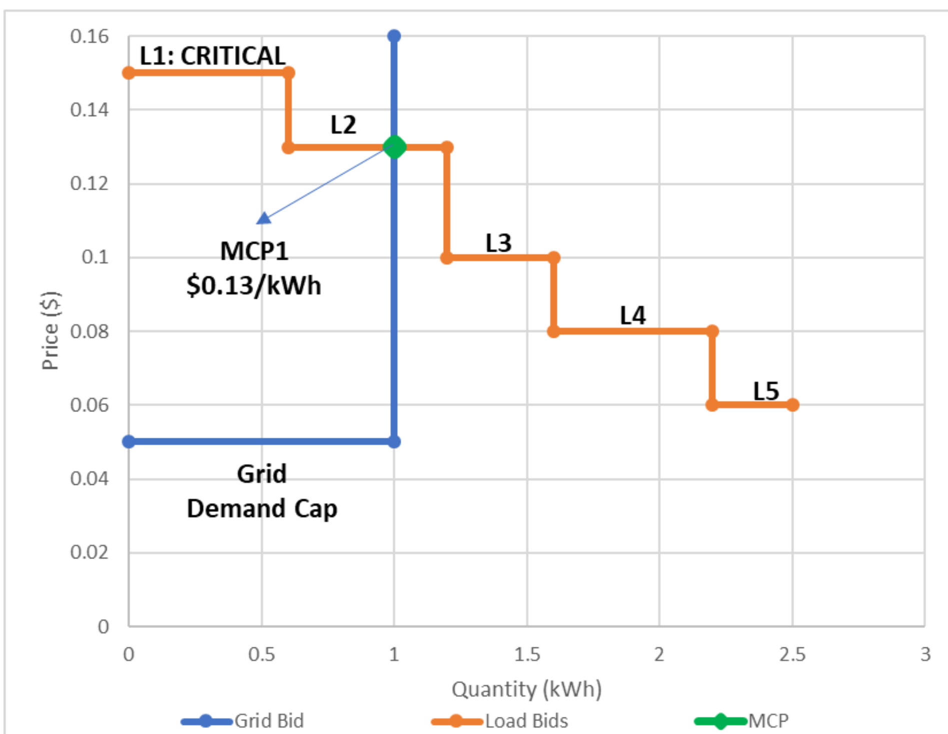


***Figure 3 - Vertical grid demand cap limits grid energy supply for the system.***

It should be noted that capacity and ancillary markets are typically not executed using the double auction method. Conventional auction methods have recently been used to secure services for demand response and ancillary services such as frequency regulation [13]. The method of payment also differs from energy markets, where providers of the service are paid a commitment fee for available reserve capacity, as well as a per-unit rate for the provision of the service.

Within this project, the residential energy market will be executed in intervals of 5 minutes, where each homeowner may bid for energy using all available DERs. Grid bids may be used by the distribution utility within any market interval. The ancillary market (for voltage regulation services) will be assumed to have been contracted to the residents of the community ahead of time.

## 2.2 Classification of Bidding Strategies

Within this project, bidding strategies are defined for the controllable DERs, which are smart thermostats (STs), BESSs, and EVs. PVs are assumed to have static bids as shown in Figure 2.

In general, an energy bid is a reflection of the value that a market participant places on their generation or consumption of energy. Within the context of residential energy markets, energy bids reflect how much a DER owner is willing to pay for the sacrifice of something that holds value, which can be modeled by using bidding curves. In the case of STs, the item of value is the flexibility of thermal comfort, whereas for EVs, the item of value is the flexibility of the desired state of charge (SoC) that is dictated by its arrival and departure times. BESSs, by virtue of being able to both consume and generate energy, are able to formulate their strategy based on their desire to maximize self-consumption, or to generate revenue depending on the MCP.

Generalizing the above, two bidding strategies are defined in this project as *selfish* and *helpful*, where a selfish bidding strategy tends to produce inflexible bid curves, and a helpful bidding strategy tends to produce less steep and flexible bid curves. The more selfish a bid curve is for a particular DER, the higher its energy demand and cost is for the homeowner, and the less impact the DER can have in participating in initiatives to reduce peak demand. For example, two ST bid curves are depicted in Figure 4, where the bid curve symbolizes the incremental price a ST is willing to pay as the deviation from the desired setpoint increases. Typical distribution system energy prices (time of use - TOU), along with a sample PV bid are also depicted in the figure, where the intersection of the ST bid curve with each supply curve represents the price that the ST is willing to pay per unit of temperature deviation from the setpoint. Although both bid curves become steeper as the temperature deviation increases, it can be seen that bid curve 1 is more selfish because it reaches its maximum threshold at 0.5°C, whereas bid curve 2 reaches its maximum threshold at 1.5°C. In this case, the maximum threshold is the point where the ST will pay any price for the cooling energy it requires.

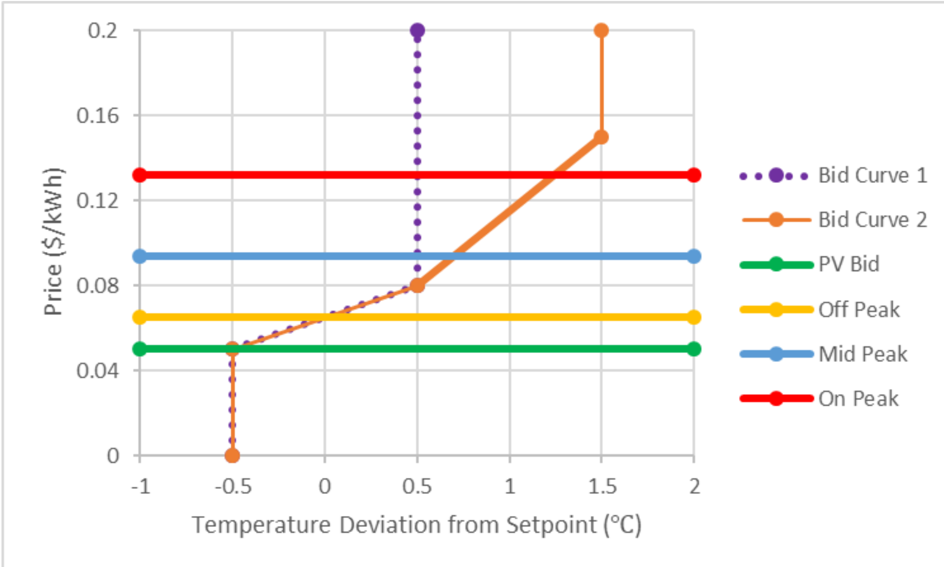


***Figure 4 - Example bid curves of smart thermostats.***

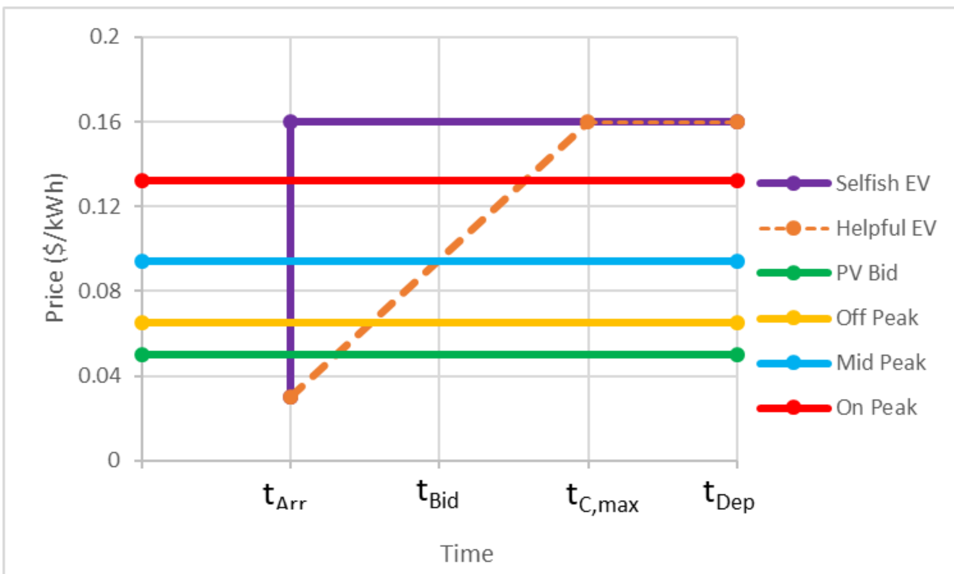


***Figure 5 - Example bid curves of selfish and helpful EVs.***

An example of selfish/helpful bidding strategies for EVs is shown in Figure 5, where relevant parameters of time are defined as $t_{Arr}$ (the home arrival time of the EV), $t_{Bid}$ (the time at which the EV places a bid), $t_{C,max}$ (the maximum time the EV can wait before it must charge at full power to reach a desired SoC based on the time of departure), and $t_{Dep}$ (the departure time of the EV). The selfish EV bid curve shows that it will have the EV charge instantaneously upon $t_{Arr}$ and is willing to pay any electricity rate to charge. On the other hand, the helpful EV bid curve is more flexible, willing to bid in the market by ramping its energy demand until $t_{C,max}$. At this point, the two bid curves converge because maximum power is needed to reach the desired SoC before $t_{Dep}$.

The selfish/helpful bids for BESS revolve around financial incentive and consumption strategy. As such, a selfish BESS will charge only in off-peak periods or when there is excess PV energy available and attempt to discharge at on-peak periods to gain maximum revenue. On the other hand, a helpful BESS will look to charge only when there is excess PV energy available, and discharge when its local load exceeds its local demand.

## 2.3 Overview of Blockchains

A blockchain is a type of distributed ledger, where each peer maintains a local copy of the ledger and participates in a consensus process to verify all transactions made by all peers. In the context of this project, each peer is analogous to a homeowner within a residential community. Transactions submitted to the blockchain during a given time period are first encrypted to hide the identity of peers associated with the transaction, collected in a discrete block of data, verified by peers against a set of rules that the network is governed by, and then chained together at the end of the ledger in a tamper-proof fashion. Transactions are generated and verified by smart contracts, which are software applications that are deployed to the blockchain and auto-execute based on the state of the ledger.

A depiction of a blockchain-based TEF is shown in Figure 6, where peers are analogous to home owners, and examples of transactions are energy bids from each DER for each discrete market interval, as well as power measurements from each DER that has submitted a bid. The business logic for each smart contract follows the logic to calculate the MCP of a time period, as well performing the validation that each DER responded correctly to the MCP by checking the energy measurements on the ledger.

There are several advantages in utilizing blockchain technology as the transactive layer for TEFs. First, the architecture of blockchains is fundamentally distributed, since each peer is responsible for storing and maintaining a copy of the ledger. This means that the system is not vulnerable to a single point of failure. Second, the fact that transactions are auditable and tamper-proof ensures that there is transparency among all peers in the framework, which is crucial for all market participants to trust that the calculation of the MCP is fair. Last, the utilization of automated smart contracts obviates the need for a central intermediary to facilitate/verify all transactions, thereby reducing trust issues among peers. This is particularly important for a utility that depends on a residential community to reduce its energy demand based on a congestion signal. In such a case, the smart contract would be able to broadcast the correct MCP, which would automatically trigger the contracted DERs with the correct control signals in response to the congestion signal. The smart contract would also be able to validate the control actions of the DER by checking the energy measurements on the ledger ***before*** payment is issued to the DER owners.

A major drawback of using blockchains is its scalability. Due to the restriction of needing a number of peers to maintain the ledger collectively, the required amount of computational resources increases, while the transaction speed degrades over time. For example, the energy consumed from validating transactions on the popular Bitcoin blockchain platform in the year 2017 was equivalent to the annual energy consumption of Ireland, which is in excess of 30 TWh [11]. As such, this project uses a class of blockchains known as permissioned blockchains, which a)

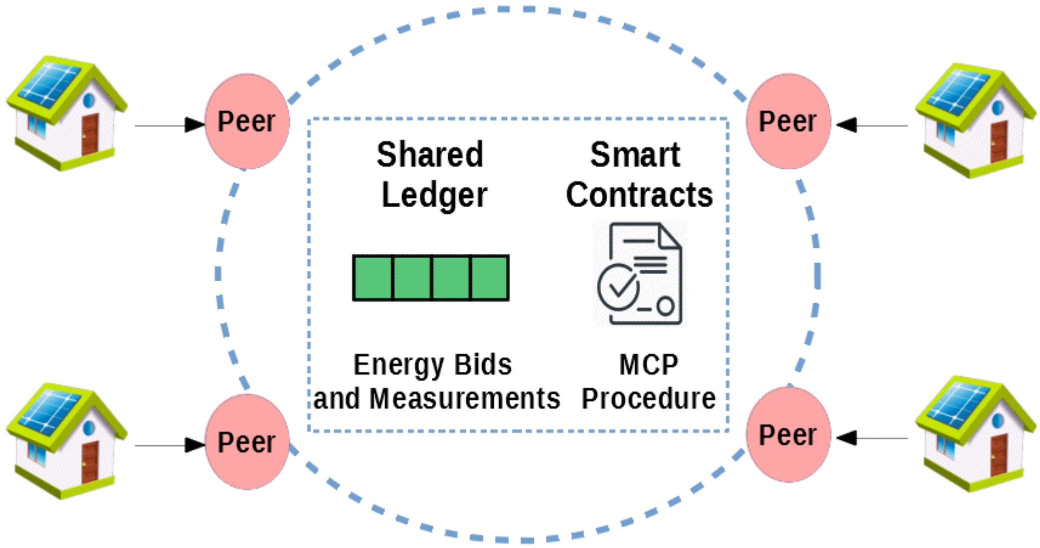


***Figure 6 - A prototypical blockchain-based Transactive Energy Framework.***

requires an authenticated invitation to join the network, and b) require only a subset of peers to validate the transactions. Both these reasons greatly reduce the communication and storage requirements for running a blockchain network. Recent benchmarks show that the permissioned blockchain platform (Hyperledger Fabric) is capable of 3000 transactions per second [15], while Bitcoin can reach only 27 transactions per second [16].

To that end, the proposed system is implemented using Hyperledger Fabric (HLF), which is an enterprise-grade permissioned blockchain framework. HLF allows the overall system to be segmented into private channels, where peers may conduct transactions that are hidden from other channels. Each channel is designated its own ledger, in which the peers are responsible for maintaining the ledger state. Segmentation allows for better scalability and abstraction, since all peers are not required to validate all transactions throughout the entire system. A high-level architectural block diagram of the proposed system is illustrated in
Figure ***7***, where communities are segregated into their own channel, each self-governed by the peer nodes of the homes in the channel. A description of the system components is given below:

- **Peer Node**: A node on the blockchain network that retains a copy of the ledger and participates in the consensus/verification process. A node within the energy trading platform would be an instance of a home participating in the TEF marketplace.
- **DApp**: The front-end application that allows a home to interact with the blockchain, including placing bids, monitoring bid status, submitted energy measurements, and facilitating automated control of DERs.
- **Ledger**: Decentralized database that stores shared system data, including all energy measurements and energy bids for all smart homes.
- **Smart Contract**: Set of functions that auto-execute based on ledger data. The functions include opening a new market interval, facilitating energy bids, and executing the MCP procedure.

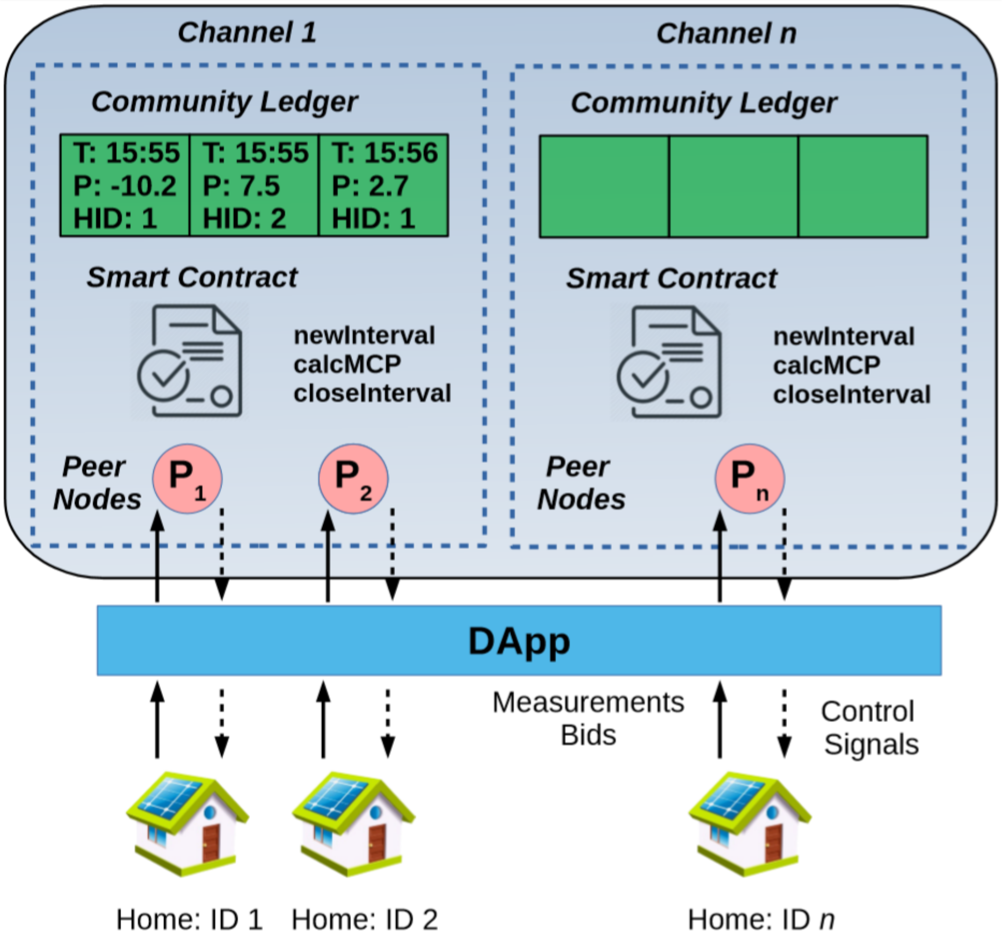


***Figure 7 - Architecture of blockchain-based TEF.***

As such, a smart contract is triggered every time a new market interval starts and begins to accept energy bids and measurements from the homes during this period. All bids are cross-verified by the peer nodes, and submitted to the ledger, where the smart contract finds the MCP of the current bid. The smart contract then broadcasts the MCP back to each DER that submitted a bid, where each DER dispatches accordingly.

It is worthwhile to mention that the design architecture proposed in Figure 7 requires a slight modification when simultaneously supporting a market for voltage support services (case study 3 in this report). Modern DERs, such as PVs and BESSs, have the ability to boost voltage levels within the grid via the injection of reactive power (measured in VAR–VoltAmpere reactive). Unlike the MCP process, reactive power injections occur dynamically and without the need of communication signals from the utility. As such, a VoltVAR curve is pre-loaded within the memory of the BESS, which specifies the precise amount of VAR to inject per unit of voltage deviation from the setpoint. When an undervoltage event is measured by the BESS, it dynamically injects the requisite amount of reactive power according to the VoltVAR curve. Therefore, the ledger must additionally store the VoltVAR curve of every DER under contract, as well as ongoing measurements of reactive power. Smart contracts would then be able to check the ledger to determine the contribution of every DER's reactive power injection during undervoltage events.

# 3.0 EXPERIMENTAL RESULTS

## 3.1 Experimental Variables

For this project, both simulated and real-world experiments are conducted. The simulated experiments revolve around the modeling, simulation, and control of an 8 home, all-electric residential community. The nameplate settings for the DERs of each home are provided in Table 2. Simulations are conducted on two independent sets of weather data, which include one week of data for the summer (July 20-26, 2016) and winter (Feb 1-Feb 7, 2016). Measurements for the typical critical loads for the home, such as lighting, dishwasher, fridge are obtained from historical data at the KCM.

***Table 2 – Experimental variables for DERs used in simulated and real-world experiments.***

| | Experimental Variables | |
|---|---|---|
| DER | Simulated Experiment | Real-World |
| PV | 5 kW | SolarEdge 6000H, 2x 6kW |
| BESS | 6 kW, 25kWh, 3 kVAR, 6 kVA | Schneider Xantrax-6780 6 kW, 75 kWh |
| EV | 6 kW, 45 kWh | Nissan Leaf 6 kW, 45 kWh |
| ST | 2 kW | 6 kW (electric heater) |

Real-world experiments were executed at the KCM. A single line diagram of the microgrid is provided in Figure 8, along with nameplate ratings of the microgrid DERs in Table 2. There are 4 individual buildings at the KCM, which are the solar hut, wind hut, as well as Smart Homes A and B. The solar hut is equipped with 30 kW of PV, although only 12 kW were connected at the time of the experiment. The wind hut contains 20 kW of wind power capacity, a 75 kWh BESS, as well as a 6 kW electric load (E-Load). Downstream of solar and wind hut, smart home A has a Level 2 charging station used for charging an on-premises EV (Nissan Leaf), while smart home B has a 5 kW PV array. Each building is equipped with a gateway device (either a Raspberry Pi or Windows desktop machine), that communicates with the blockchain network via a REST API. The API is used to submit bids and measurements to the blockchain ledger, as well as to monitor the result of the MCP calculation. Once the smart contract finds the MCP, a notification is received by the gateway device of the building, and the relevant DER is dispatched accordingly.

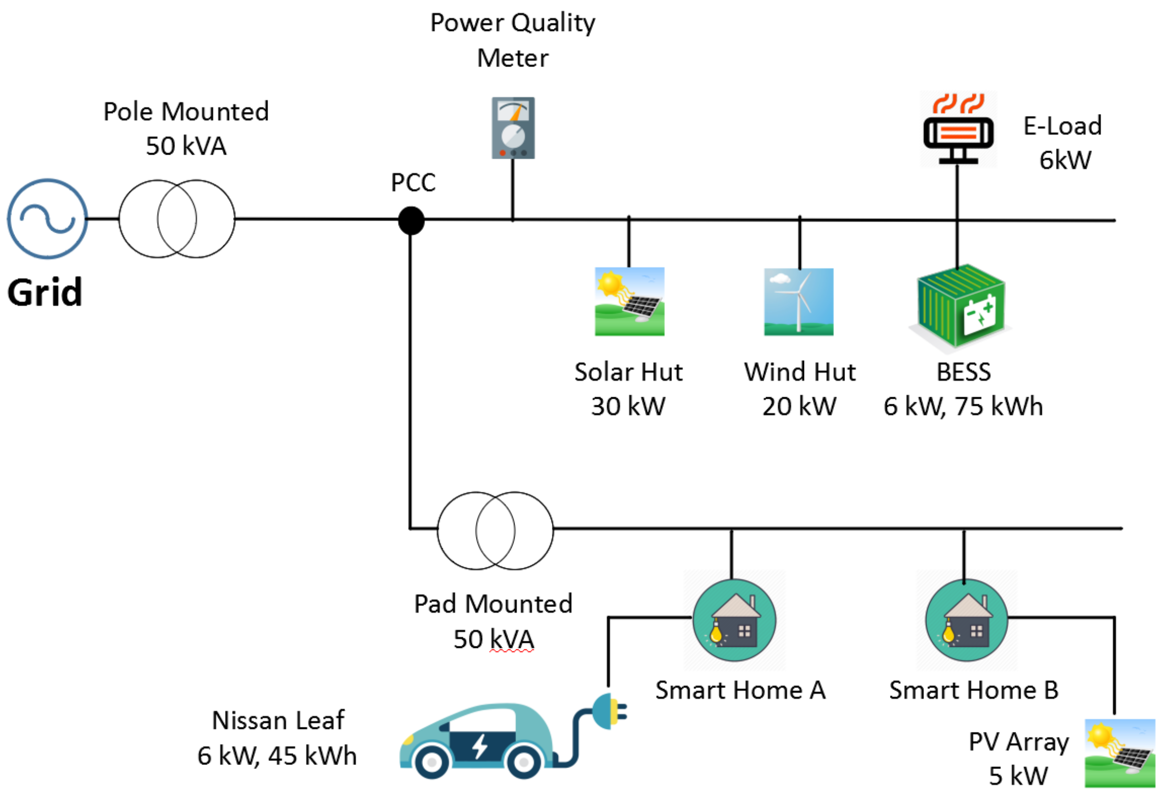


***Figure 8 - Single line diagram of Kortright Centre Microgrid.***

In terms of the bidding prices, the following list identifies the specific values used by each market participant:

- Grid: TOU prices of 2018, plus regulatory and delivery charges. Off-peak bids at \$0.09435/kWh, mid-peak bids at \$0.1259/kWh, and on-peak bids at \$0.1673/kWh
- PV: Static bidding at \$0.05/kWh
- ST: Maximum bidding price of \$0.1673/kWh, curve based on following configurations:
  - High flexibility: Between 0°C and 4°C setpoint deviation allowed.
  - Medium flexibility: Between 0°C and 2.5°C setpoint deviation allowed.
  - Low flexibility: Between 0°C and 1°C setpoint deviation allowed.
- EV: Maximum bidding price of \$0.1673/kWh, curve based on following configurations:
  - Helpful: Bidding ranges between \$0.05/kWh - \$0.09435/kWh (arrival to departure)
  - Selfish: Bidding ranges between \$0.05/kWh - \$0.1673/kWh (arrival to departure)
- BESS: Maximum bidding price of \$0.12/kWh, curve based on following configurations:
  - Helpful: Charging at \$0.06/kWh, Discharging at \$0.08/kWh
  - Selfish: Charging at \$0.10/kWh, Discharging at \$0.12/kWh

## 3.2 Case Study 1: Peer to Peer Energy Trading

The objective of this case study is to demonstrate how the homeowners may engage in P2P energy trading within a coordinated residential electricity marketplace. In particular, a sensitivity analysis is carried out to find the impact of selfish/helpful DER bidding on the peak reduction of the community. For the sake of comparison, a baseline load profile is generated for an 8 home, all-electric residential community without any marketplace for bidding. The BESSs and EVs within the baseline load profile are configured to react to typical TOU pricing, and essentially operate as per a selfish bidding curve. The sensitivity analysis is used to generate different load profiles of a community operating a TEF by varying the amount of selfish/helpful EVs and BESSs within the community.

The results of the sensitivity analysis are provided in Figures Figure 9-Figure 11 as well as Table 3. As seen in Figure 9 and Figure 10, increasing the amount of helpful BESS units has a direct correlation on reducing the community peak load, as well as the community cost. The peak load reduces from a baseline of 109.96 kW to 55.18 kW (a decrease of 49.8%), while the overall community cost decreases from $251.81 to $236.27 (reduction of 6.1%). When adding EVs to the sensitivity analysis, it is found that the optimal bidding configuration is 8 helpful BESSs, and a combination of 4 helpful and 4 selfish EVs. A bidding strategy of 8 helpful EVs with identical bidding curves creates a peak during the off-peak hours of the night and distributing the loading impact of the EVs by varying their bidding profiles helps to reduce this peak. Using the optimal bidding configuration, the peak load of the community reduces from 55.18 kW to 52.29 kW, for a total reduction of 52% as compared to the baseline peak.

The impact of the optimal bidding configuration on the load profile of the community can be seen in Figure 11, where the peak load is visibly reduced every day. Further load metrics are provided in Table 3, which indicate a significant increase in load factor (from 14% to 27%), and renewable energy utilization (69% to 93%). These increase are primarily due to the presence of the 8 helpful BESSs that seek to primarily charge with any excess renewable power available during the mid-afternoon day.

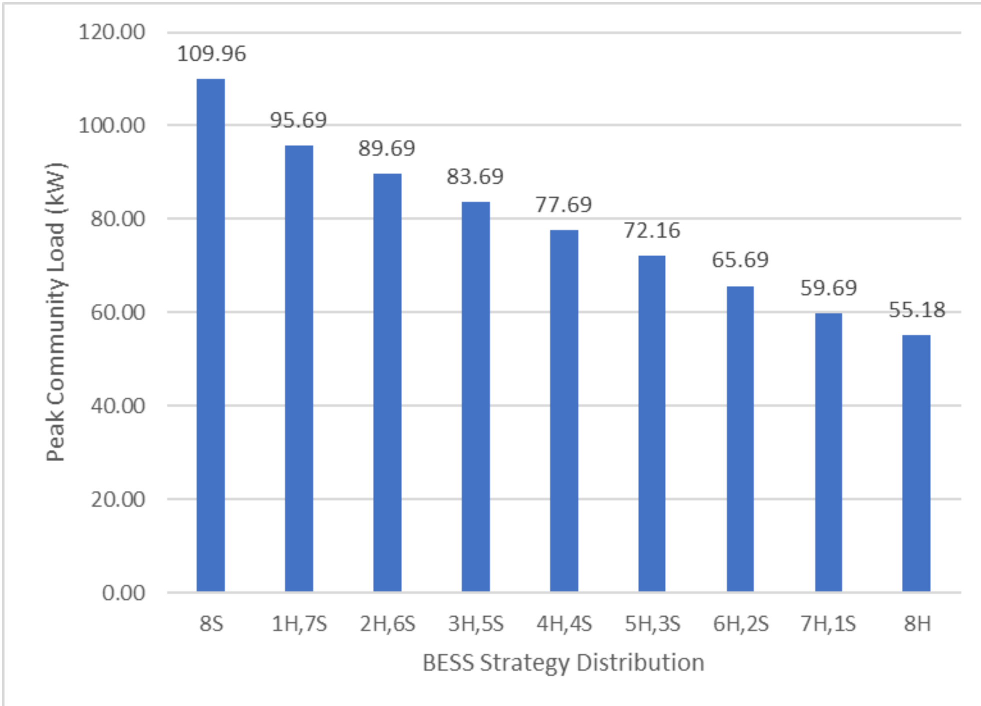


***Figure 9 - Impact of selfish BESS bidding on community peak load.***

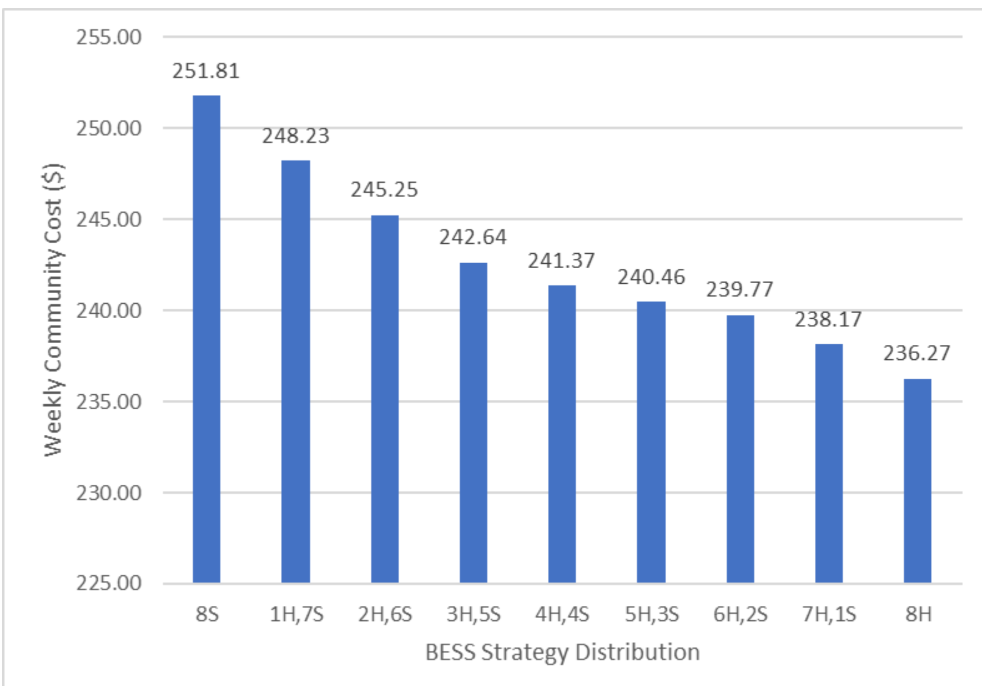


***Figure 10 - Impact of selfish bidding on community cost.***

*Table 3 - Comparison of baseline and TEF on loading metrics for summer dataset.*

| Metric | Baseline | TEF |
|---|---|---|
| Weekly Energy Consumption (kWh) | 2410.98 | 2356.13 |
| Peak Load (kW) | 109.96 | 52.29 |
| Load Factor (%) | 14 | 27 |
| Renewable Energy Utilization (%) | 69 | 93 |

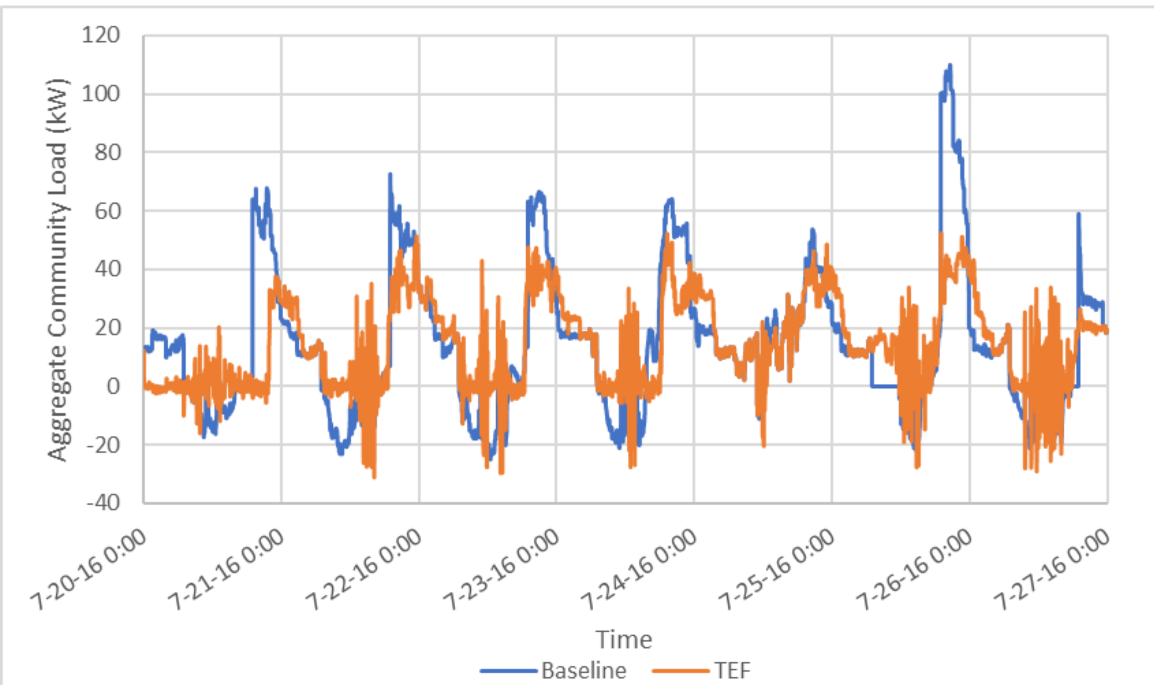


***Figure 11 - Average community load peak reduction for summer dataset.***

It is worthwhile to mention that the STs also have a role to play in the reduction of the peak load. By closely following the MCP, STs are able to pre-cool their homes when the MCP is lower and reduce their consumption by adjusting their cooling needs when the MCP is high. This can be seen in Figure 12, where the MCP hovers around the $0.05/kWh mark from the period of 8:00 to 16:00. The MCP is driven to this mark because of the excess generation of inexpensive PV energy during the day. During this time frame, the STs increase their electrical consumption to pre-cool their homes. On the other hand, the spiking of the MCP to $0.12/kWh after 17:00 causes the STs to decrease their electrical consumption.

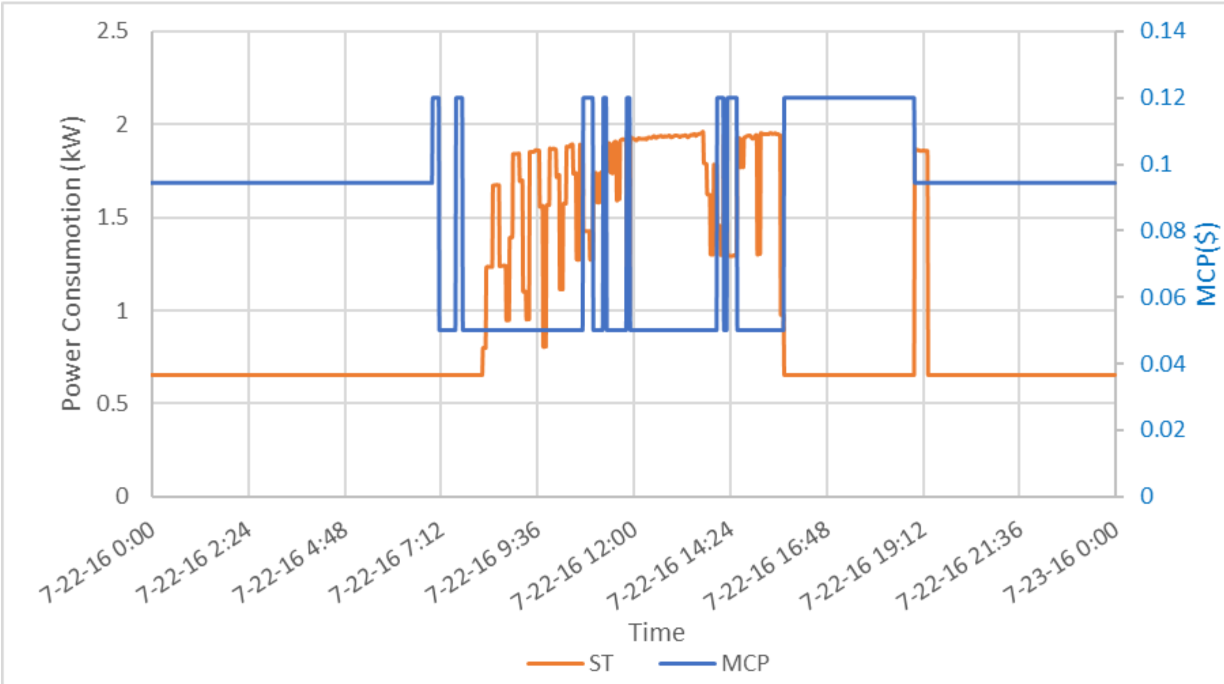

***Figure 12 - Bidding behavior of smart thermostats based on MCP.***

The sensitivity analysis is repeated for the winter dataset, with the weekly load profile comparison presented in Figure 13, and the load metric comparison presented in Table 4. When the TEF is deployed, the community peak reduces from 114.42 kW to 62.5 kW (45% reduction), while the load factor increases from 25% to 41% (64% increase). There is negligible improvement in the renewable energy utilization, primarily because the utilization is already quite high (93%).

Recalling the peak demand reduction from the summer dataset (52%), it can be observed that the TEF does not perform as well in the winter as it does in the summer. This can be explained by the fact that there is much less PV energy available in the winter when compared to the summer, and as such, helpful BESSs are not able to charge completely during the daytime. This means that the helpful BESSs cannot discharge as effectively during the evening when the peak loading occurs.

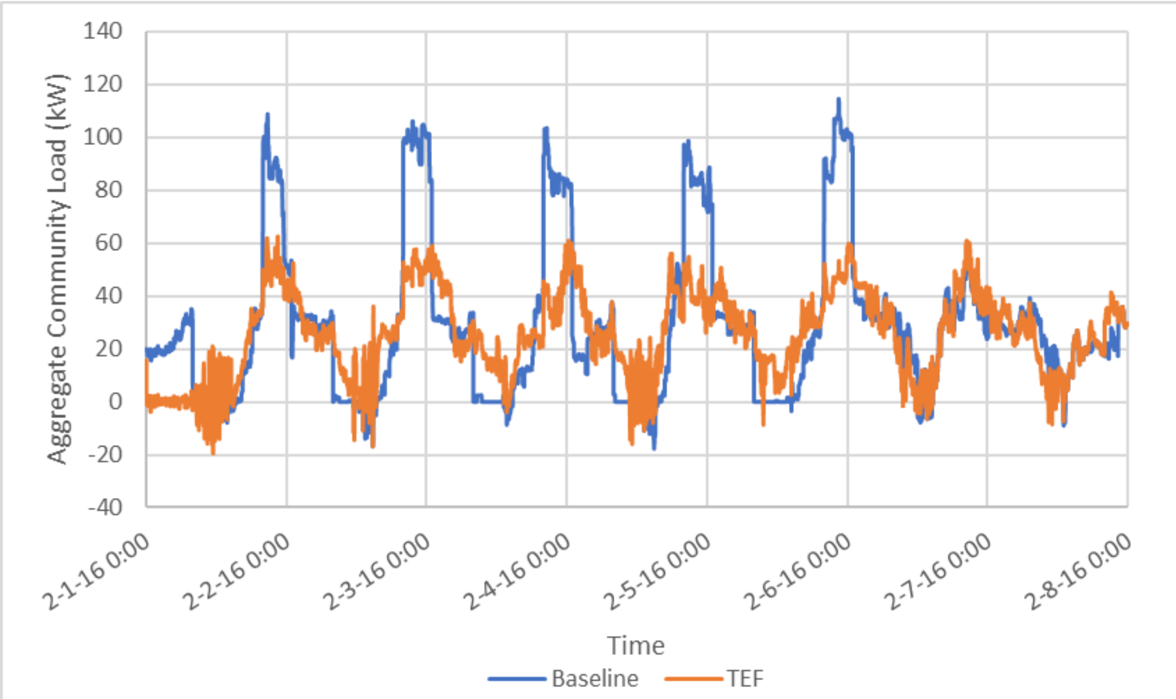


***Figure 13 - Average community load peak reduction for winter dataset.***

***Table 4 - Comparison of baseline and TEF on loading metrics for winter dataset.***

| | Baseline | Optimal TEF |
|---|---|---|
| Weekly Energy Consumption (kWh) | 4820.32 | 4258.7 |
| Peak Load (kW) | 114.42 | 62.5 |
| Load Factor (%) | 25 | 41 |
| Renewable Energy Utilization (%) | 93 | 95 |

Taking the maximum of the summer and winter peaks, a winter peak of 62.5 kW would translate into a peak load of 69.4 kVA, assuming a power factor of 0.9. This means that electric utilities would need to replace all 50 kVA distribution transformers with 75 kVA transformers instead of the original projection of using 125 kVA transformers. This would result in an average CAPEX savings for $2,340 per transformer for all utilities. Thus, the resultant CAPEX savings for each utility mentioned in Section 1 is provided in Table 5. The TEF is able to provide an average of $56.8M (or 31.6%) of CAPEX savings for the 10 utilities under study.

***Table 5 - CAPEX Savings with TEF for utility transformer replacement.***

| Utility | Transformer Replacements | CAPEX Without TEF ($) | CAPEX With TEF ($) | CAPEX Saved ($) | CAPEX Saved (%) |
|---|---|---|---|---|---|
| Alectra Utilities | 102,260 | 756.5 M | 517.2 M | **239.3 M** | **31.6** |
| Toronto Hydro | 54,081 | 400.1 M | 273.5 M | **126.6 M** | |
| Hydro Ottawa | 42,348 | 313.3 M | 214.2 M | **99.1 M** | |
| London Hydro | 13,535 | 100.1 M | 68.5 M | **31.7 M** | |
| Kitchener-Wilmot | 9.583 | 70.9 M | 48.5 M | **22.4 M** | |
| Waterloo North | 7,354 | 54.4 M | 37.2 M | **17.2 M** | |
| EnWin Utilities | 5,963 | 44.1 M | 30.2 M | **13.9 M** | |
| Halton Hills Hydro | 3,622 | 26.8 M | 18.3 M | **8.5 M** | |
| Essex Powerlines | 2,774 | 20.5 M | 14.0 M | **6.5 M** | |
| Lakefront Utilities | 1,104 | 8.2 M | 5.6 M | **2.6 M** | |
| Averages | 24,262 | 179.5 M | 122.7 M | **56.8 M** | |

## 3.3 Case Study 2: Congestion Relief via Demand Caps

As discussed in Section 2, a utility can attempt to enforce a demand cap on a residential community if the distribution system is under congestion. In this case study, a 40 kW demand cap is placed on the residential community studied in Case Study 1 to determine the impact on overall peak demand. The optimal strategy from the previous case study is compared to the load profile of a residential community under two types of caps: quantity (Q-cap) and price (P-Cap). For the Q-cap, the bid of the grid is capped at a maximum of 40 kW, and the price is set to the TOU price for every market interval during the simulation. For the P-Cap, the bid is capped at 40 kW, but the price is 2x of the TOU price.

The impact of demand caps can be seen in Figure 14, while relevant load metrics are provided in Table 6. As seen in the figure, although both the Q-Cap and P-Cap are able to reduce the peak demand on all days of the week, their maximum peak is still above 40 kW (49.59 kW for the Q-Cap, 41.71 kW for the P-Cap). Several reasons cause this behaviour. First, critical loads represent 17 kW, or 42.8% of the P-Cap peak load, and these critical loads must be served regardless of high the MCP is. Second, there is a limit to how helpful the DERs can be with respect to the theoretical limits of their bidding curves. To illustrate this, a plot of the SoC of the EVs is presented for all three scenarios in Figure 15. As seen in the figure, there is little difference between the charging behaviour of EVs for the baseline TEF and the Q-Cap, and the SoC is fully replenished to the maximum of 45 kWh on each day. However, the plot of the P-Cap shows that the EV never gains a full charge during the week because of the doubling of the MCP. This is not a scenario that is desirable for any TEF participant and underlines the fact that incentive structures are needed to compensate TEF participants for any loss of convenience. This is particularly true in the case of the P-Cap, since the weekly energy costs rise from $231.43 to $299.72 (an increase of 22.7%).

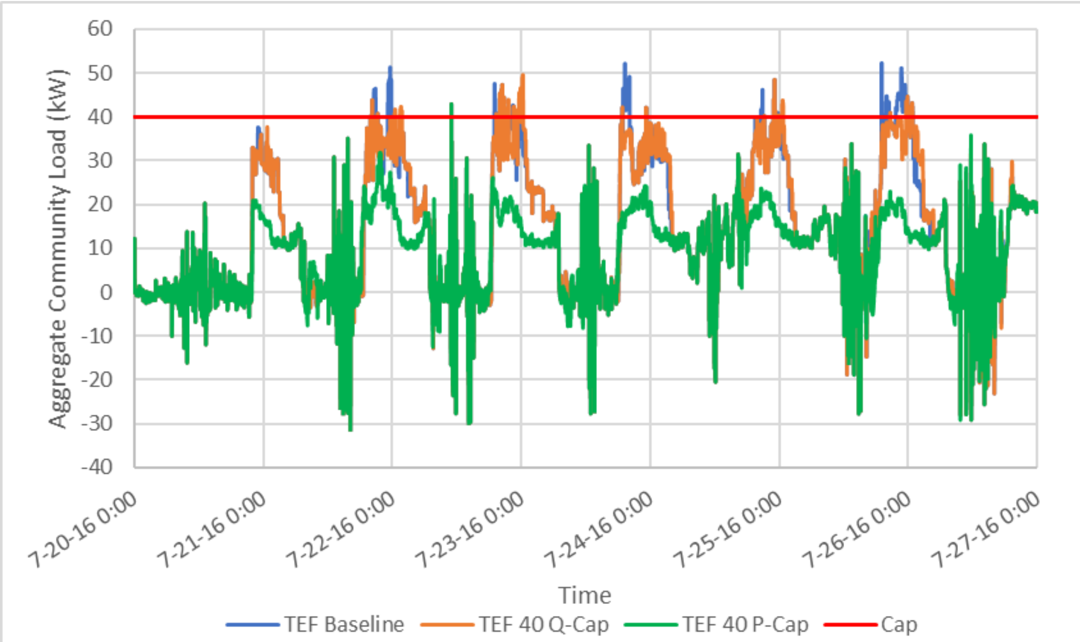


***Figure 14 - Results of peak reduction after demand cap is enforced for summer dataset.***

***Table 6 - Comparison of load metrics for demand cap enforcement for summer dataset.***

| | TEF Baseline | TEF 40 Q-Cap | TEF 40 P-Cap |
|---|---|---|---|
| Weekly Energy Consumption (kWh) | 2356.13 | 2356.13 | 1493.92 |
| Peak Load (kW) | 52.29 | 49.59 | 41.71 |
| Load Factor (%) | 27 | 28 | 21 |
| Renewable Energy Utilization (%) | 93 | 93 | 93 |
| Community Cost ($) | 231.43 | 231.43 | **299.72** |

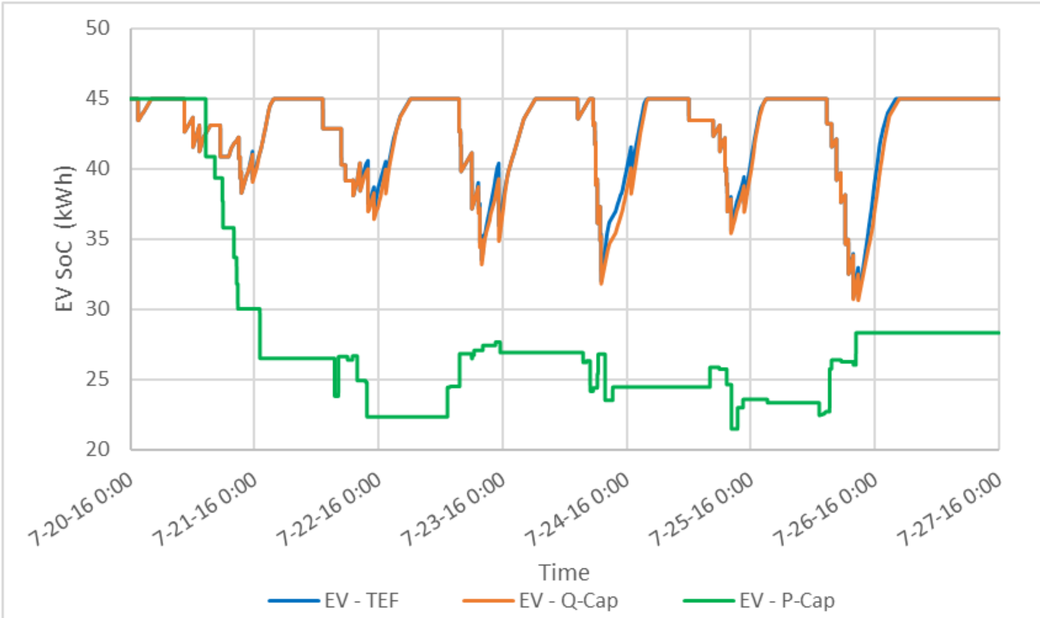


***Figure 15 - SoC of EVs when demand cap is enforced.***

For the sake of completion, a similar analysis is done for the winter dataset. The weekly load profile is provided in Figure 16, while the accompanying load metrics are provided in Table 7. In this case, the P-Cap is able to reduce the community peak load from 62.5 kW to 35.1 kW, which is a reduction of 43.8%. However, the community cost also rises from $462.58 to $529.7, which is an increase of 12.7%.

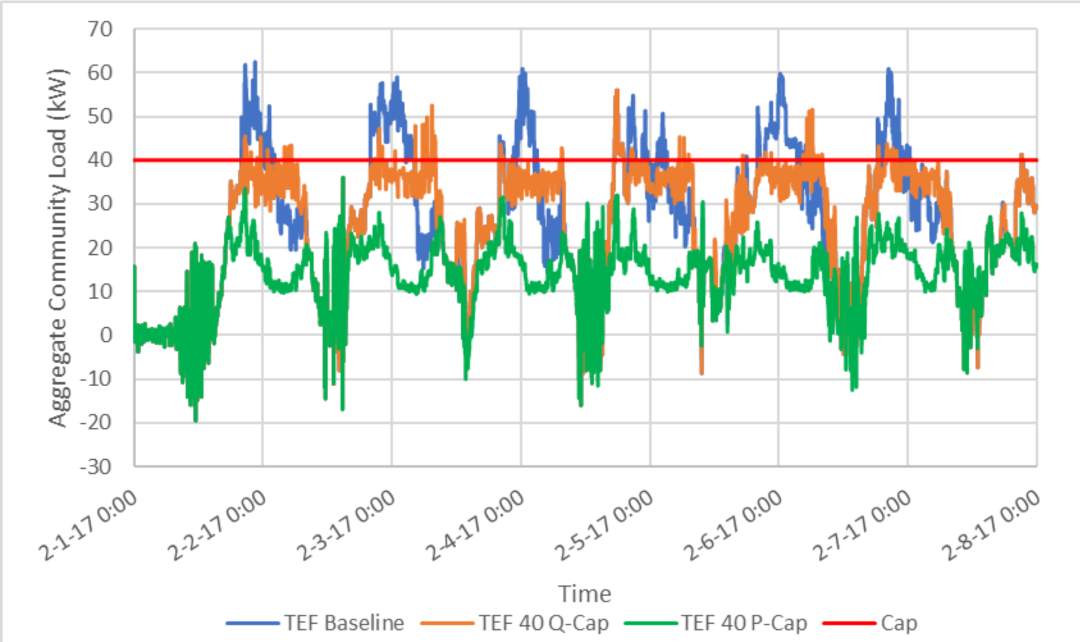


***Figure 16 - Results of peak reduction after demand cap is enforced for winter dataset.***

***Table 7 - Comparison of load metrics for demand cap enforcement for winter dataset.***

| | TEF Optimal | TEF 40 CAP | TEF 40 CAP MCP |
|---|---|---|---|
| Weekly Energy Consumption (kWh) | 4258.87 | 4192.59 | 2303.6 |
| Peak Load (kW) | 62.5 | 56.01 | 35.1 |
| Load Factor (%) | 41 | 45 | 39 |
| Renewable Energy Utilization (%) | 95 | 95 | 94 |
| Community Cost ($) | 462.58 | 457.21 | **529.7** |

Taking the maximum of the summer and winter peaks, a summer peak of 41.71 kW would translate into a peak load of 46.3 kVA, assuming a power factor of 0.9. This means that electric utilities would not need to upgrade their existing 50 kVA distribution transformers in residential neighborhoods. Deducting the cost of replacing the 50 kVA transformers once during their expected lifetime, the computed CAPEX saving is $7398 per transformer. Therefore, the TEF is able to provide an average of $102.5 M (or 57.1%) of CAPEX savings for the utilities under study.

***Table 8 - CAPEX Savings with TEF-DR for utility transformer replacement***

| Utility | Transformer Replacements | CAPEX Without TEF-DR ($) | CAPEX With TEF-DR ($) | CAPEX Saved ($) | CAPEX Saved (%) |
|---|---|---|---|---|---|
| Alectra Utilities | 102,260 | 756.5 M | 324.4 M | **432.1 M** | **57.1** |
| Toronto Hydro | 54,081 | 400.1 M | 171.2 M | **228.5 M** | |
| Hydro Ottawa | 42,348 | 313.3 M | 134.3 M | **179.0 M** | |
| London Hydro | 13,535 | 100.1 M | 42.9 M | **57.2 M** | |
| Kitchener-Wilmot | 9.583 | 70.9 M | 30.4 M | **40.5 M** | |
| Waterloo North | 7,354 | 54.4 M | 23.3 M | **31.1 M** | |
| EnWin Utilities | 5,963 | 44.1 M | 18.9 M | **25.2 M** | |
| Halton Hills Hydro | 3,622 | 26.8 M | 11.5 M | **15.3 M** | |
| Essex Powerlines | 2,774 | 20.5 M | 8.8 M | **11.7 M** | |
| Lakefront Utilities | 1,104 | 8.2 M | 3.5 M | **4.7 M** | |
| Averages | 24,262 | 179.5 M | 76.9 M | **102.5 M** | |

## 3.4 Case Study 3: Power Outage Prevention

For this case study, the impact of voltage regulation services provided by a residential community to the distribution system is investigated. The objective of this case study is to demonstrate how brownouts can be prevented by the TEF. Brownouts occur when there is a significant voltage drop within a power system, referred to as an undervoltage event. Electrical devices begin to malfunction and in some cases, may even fail to run properly. Traditionally, utilities have used reactive power compensation techniques to boost the voltage at a particular point within the grid via capacitor banks, line voltage regulators, and/or STATCOM devices. However, modern DERs such as PVs and BESSs are equipped with smart inverters that allow them to inject reactive power into the grid to stabilize the voltage during undervoltage events, thereby preventing a system collapse.

In this case study, the BESSs are assumed to have smart inverters with a physical limit of 3 kVAR reactive power output. A test distribution grid is modeled in MATLAB, where power flow equations in [17] are used to find the voltage at the point of common coupling (PCC) between the residential community and the distribution grid based on the summer baseline load profile of the community. The undervoltage event is simulated by increasing the load at a location upstream of the community. The event is then mitigated by the residential community by injecting all 24 kVAR of its rated capacity to the grid and boosting the voltage past the undervoltage threshold, which is set at 228V (-5% of the nominal 240 V).

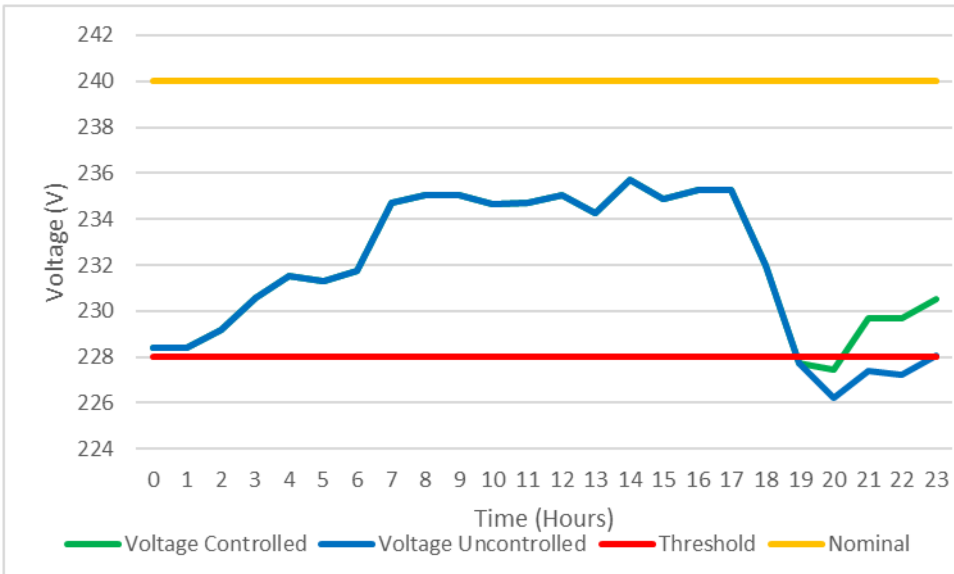


***Figure 17 - Undervoltage mitigation by residential community.***

The results can be seen in Figure 17. The voltage profile is relatively healthy in the middle of the day as it approaches the nominal 240 V mark. This increase in voltage is primarily due to the excess PV generation of the community. However, the voltage slips below the threshold at 20:00, when there is no solar irradiance and peak loading of the residential community begins. Without the voltage boost provided by the community, the community is in threat of a brownout from 20:00 to 23:00. However, the 24 kVAR reactive power injection provided by the community restores the voltage within the next timestep and prevents the brownout from occurring.

With respect to incentives for the voltage support service provided by the community, a provider of this service is typically paid for capacity (measured in kVAR-year), as well as an additional payment for the service provided during the voltage violation (measured in kVAR/hr). Electric utilities at the distribution level have only just begun to offer voltage regulation as a service for DERs, with mean capacity payments being $60 kVAR-year [18]. Using this mean value, and assuming that the BESSs reserve 3kVAR of reactive power ability for every hour of the year, this would result in an annual payment of $1440 from the utility to the community.

### 3.5 Real World Results

The execution of the real-world experiments involves the participation of the PV of the solar hut, the EV of House A, the E-Load of the wind hut, as well as the critical loads of House B. The first experiment is conducted to demonstrate P2P energy trading between the three DERs. Figures Figure 18-Figure 20 show the results of 3 consecutive bidding cycles, while Figure 21 shows the individual load profile of all three DERs, including measurements from the PCC of the microgrid to the main distribution grid. The sign of the PCC measurements indicates whether the microgrid is exporting (negative) or importing (positive) power from the main grid.

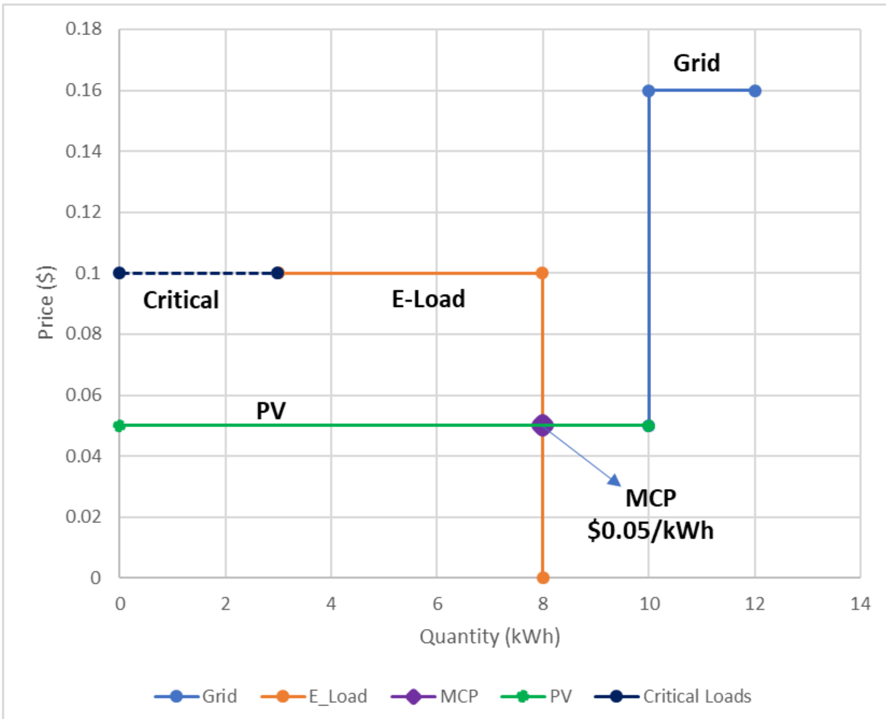


*Figure 18 - Bid #1: PV energy satisfies entire microgrid demand.*

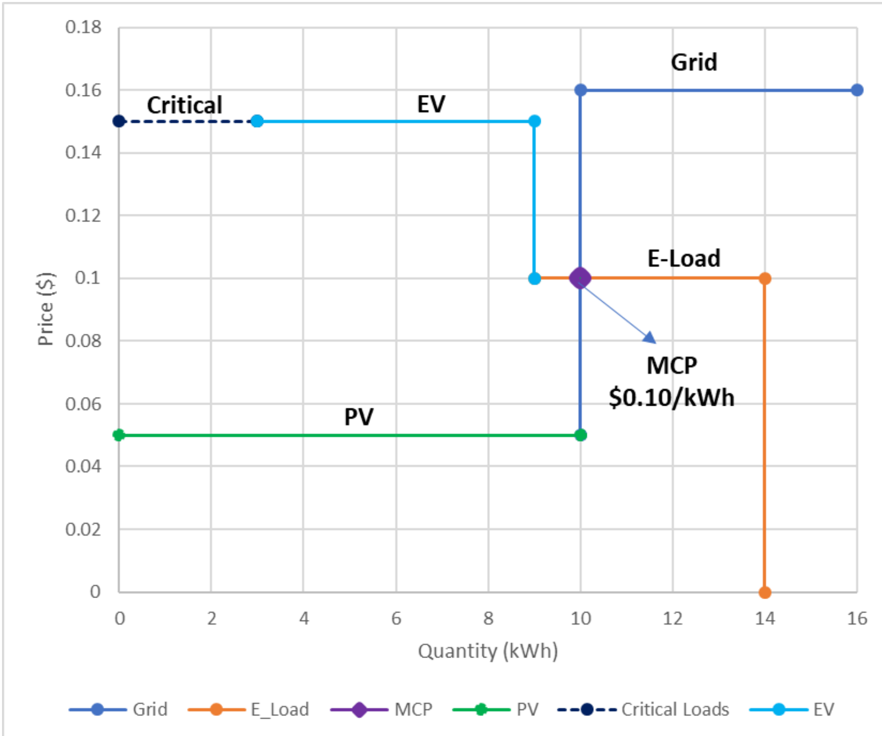


***Figure 19 - E-Load is turned off due to being outbid by the EV.***

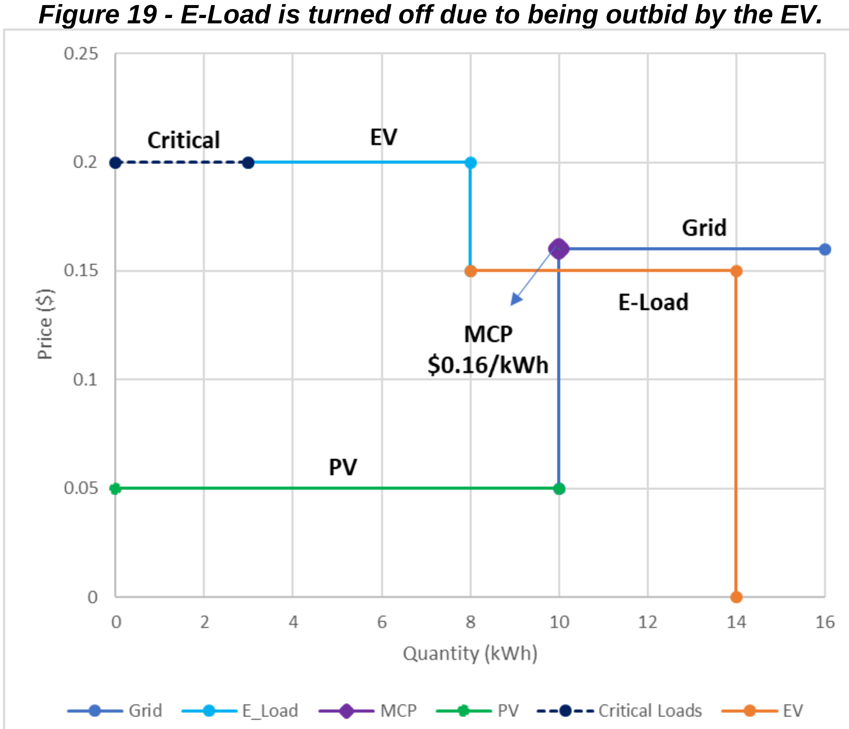


***Figure 20 – Bid #2: Microgrid requires grid import due to high bids from EV and E-Load.***

A description of all three bids is as follows:

- Bid #2 – 11:51:10 to 11:53:10:

- **Bid Details:** The E-Load bids at $0.10/5 kWh, while PV bids at $0.05/10 kWh. The EV is assumed to have just arrived home and is on standby power (1.4 kW) and is counted as a critical load. With the House B critical loads being roughly 1.6 kW, the resultant critical load bid is $0.1/3 kWh.
- **Result:** Critical load bids and E-Load bids are accepted at an MCP of $0.05/kWh.

- Bid #2 – 11:53:10 to 11:55:10:
    - **Bid Details:** The EV requires charging and bids at $0.15/5 kWh, which outbids the bid of the E-Load at $0.10/6 kWh. The critical load bid is unchanged.
    - **Result:** The microgrid, via its PV, cannot satisfy all three load bids. The MCP is calculated at $0.1/kWh, therefore granting the bids of critical loads and EV, while denying the E-Load.

- Bid #3 – 11:55:10 to 11:57:10:
    - **Bid Details:** The E-Load upgrades its bid to $0.20/6 kWh, while the critical load and EV bids are unchanged.
    - **Result:** The upgraded E-Load bid pushes the MCP upward to $0.16/kWh, which matches the TOU bid price of the grid. This results in the microgrid importing roughly 1 kWh to satisfy all three loads.

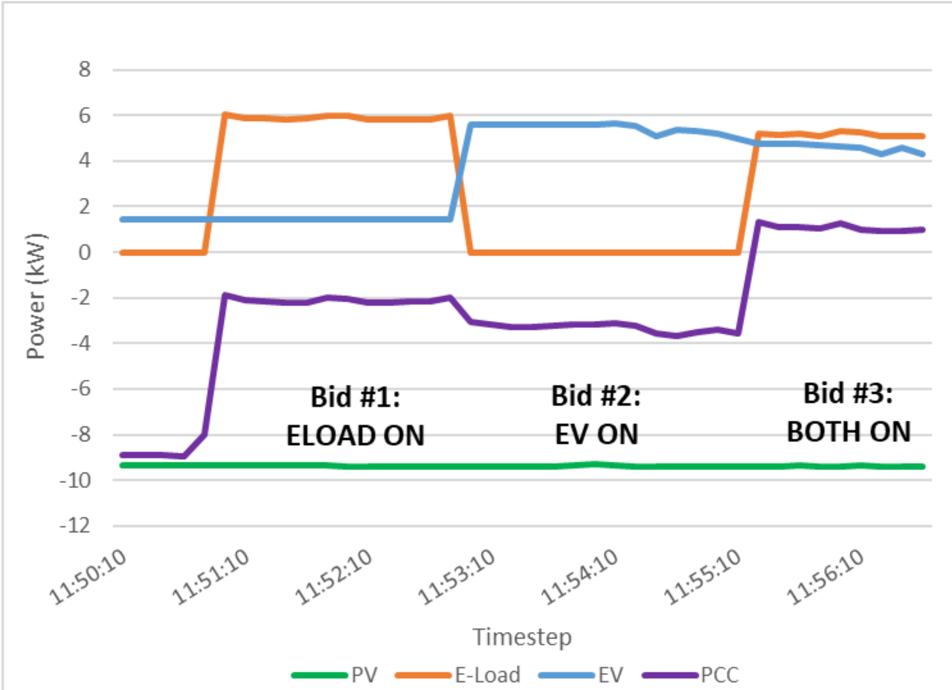


***Figure 21 – Bid #3: Load profile of DERs during all three bids.***

A time series graph of the experiment is provided in Figure 21, which reflects the load profile during all three bidding cycles. The PV output remains constant throughout the experiment, while the measurement at the PCC fluctuates as a result of the EV and E-Load being turned on and off. Within the first bidding cycle. The E-Load is on and drawing approximately 5 kW from the PV generation, while the EV is drawing 1.4 kW of standby power. The microgrid is still exporting approximately 1.5 kW of the PV generation, as indicated by its negative value in the figure. In the second bidding cycle, the EV turns on while the E-Load turns off, and the net export of the microgrid remains constant due to the minimal difference in loading of the two devices. In the third bidding cycle, both loads turn on, and the PCC plot shows a net import of 1 kW to satisfy the loading requirement.

In the second experiment, the validation of a demand response cap is demonstrated on the microgrid, where a time-series plot of the load profile of the microgrid can be seen in Figure 22. Note that the bidding plots are not shown to avoid redundancy with Figure 18- Figure 20. At the beginning of the experiment (14:35:30), both the EV and the E-Load are turned off. Both loads turn on at 14:36:00, and the loading of the microgrid peaks at 10 kW as a result. The first instance of a demand cap is signaled at 14:36:30, where the cap is set at a threshold of 5 kW. In this case, the EV outbids the E-Load, and the E-Load turns off, resulting in the microgrid net load being approximately 4 kW. The second instance of a demand cap demands a threshold of 0 kW, which results in the EV turning off to satisfy the cap. This results in the microgrid having a negative load.

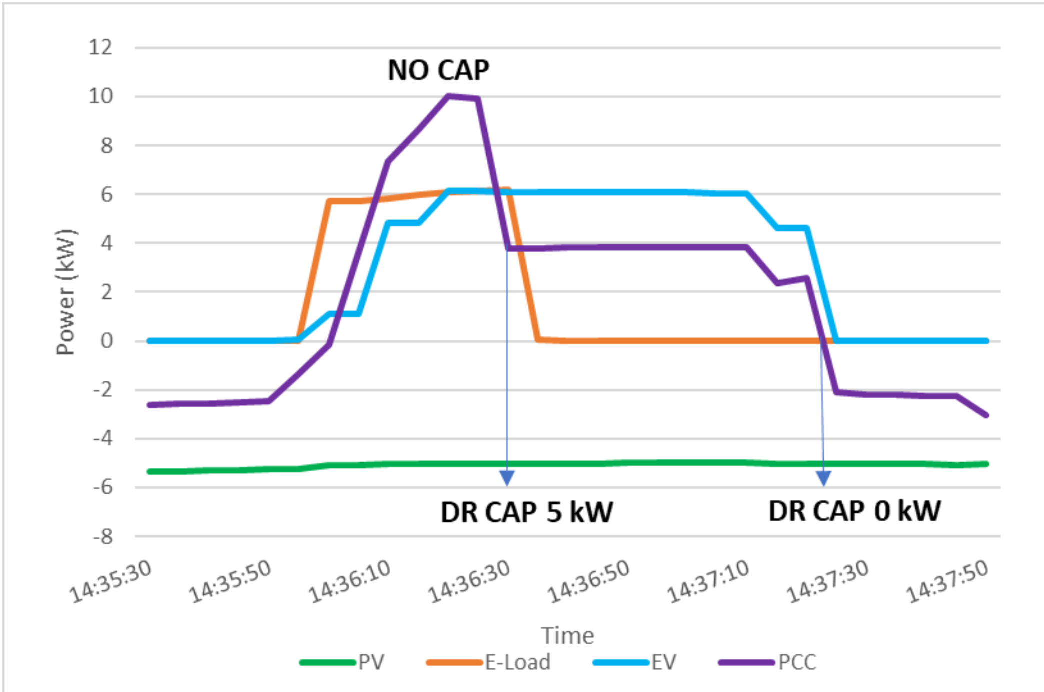


***Figure 22 - Plot of demand response caps altering load profile of microgrid.***

## 4.0 BARRIERS TO ADOPTION

1) **Lack of Customer Engagement**

Customer participation in utility-driven initiatives has traditionally been quite poor [19]. With transactive energy-based systems providing significantly more choices and complexity for the end customer, there are concerns over its adoption by the wider residential community. This project, for example, provides mathematical formulations for bidding curves for the homeowner, but does not address how to derive the bidding curves from an intuitive set of energy preferences. Thus, it is imperative that the residential/community owner be outfitted with a customizable, easy to use home energy management system (HEMS) that is capable of translating broad customer preferences into specific, quantifiable, and measurable system specifications.

2) **Regulatory Barriers**

In deregulated electricity markets, there is an entity that is responsible for the fair and equitable setting of wholesale rates of electricity. In Ontario, this is the Ontario Energy Board (OEB), which publishes an annual Regular Price Plan (RPP) that is subsequently followed by all electrical utilities. Other provincial energy regulators include British Columbia Utilities Commission (BCUC) and Alberta Energy Regulator (ARB), among others. As such, the buying/selling of electricity without regulation from the regulating entity is technically not permissible. However, a notable exception is if an entity chooses to be an energy retailer. The prices set by a retailer are *not* subject to regulation by the regulatory entity, although they must provide a text-based contract to their customers stating the price, contract length, and a price comparison of current regulated rates. The usage of the phrase “text-based” is open to interpretation, and no clarification is given as to if digital contracts are acceptable. In any case, it is highly unlikely that the transactive energy framework will consist solely of electricity retailers. A comprehensive restructuring of regulatory guidelines will be necessary to support the growth of TEFs.

3) **Resistance to Evolution from Utility to Distribution System Operator (DSO)?**

This project addresses the business case for utilities in terms of reduced CAPEX savings, however, it assumes that utilities would be fully cooperative in administering a distribution level marketplace as a DSO, mirroring what the Independent Electricity System Operator (IESO) performs at the transmission level. The project further assumes that utilities would be comfortable with blockchain-based implementation of TEFs, where their responsibilities of validating measurements and contracts from DERs would essentially be obviated via the usage of *smart contracts*, as explained in Section 2. These assumptions do not capture the initial resistance of utilities that are concerned that the growth of DERs will significantly lessen revenue streams and further reduce their rate-base. As such, it is imperative that utilities must investigate and identify new business models within the paradigm of TEFs that will allow them to further automate their operations while still remaining profitable. For example, in the case of this project, the utility may wish to charge a per-transaction premium for all communities within their jurisdiction.

4) **System Performance – Data, Response, Scalability**

The deployment of a TEF at the distribution level includes the ability for potentially thousands of end points to engage in a virtual marketplace. As such, TEF designers will face severe issues in designing highly scalable systems that can dynamically accommodate this growth. Special care must be taken to measure the amount of energy and expense being consumed to maintain the TEF to ensure that the overall system is operating efficiently. Furthermore, if a blockchain implementation is considered, the response time of the transaction becomes a crucial limiting factor because transaction speeds tend to reduce with the number of endpoints (nodes) on the network. Recent benchmarks show that the permissioned blockchain platform (Hyperledger Fabric) is capable of 3000 transactions per second [14], while Bitcoin can reach only 27 transactions per second [15]. However, recent innovative technology is challenging these limits. In 2018, a blockchain-company named Insolar launched an enterprise-grade blockchain platform capable of delivering upwards of 20,000 transactions per second [20].

## 5.0 PROJECT BENEFITS

The following bulleted list summarizes the project benefits.

- **Conceptualizes** the architecture of transactive energy frameworks in the form of P2P energy marketplaces.
- **Demonstrates** how residential energy markets help avoid significant capital expenditure.
- **Develops** bidding strategies that enable the modeling of different loading/generation profiles.
- **Demonstrates** how blockchain enables automated management of DERs.
- **Shares** technical learnings from a real-world implementation of a TEF within a microgrid based in Vaughan, Ontario.
- **Identifies** *how TEFs can help all stakeholders in the energy value chain adapt to the impacts of climate change.*

# 6.0 CONCLUSION

This project investigates the impact of a blockchain-based TEF on an 8 home residential community for the purposes of reducing peak demand, as well as increasing local renewable energy utilization. The project demonstrates the efficacy of the TEF by investigating three case studies, which are: P2P energy trading, congestion relief, and power outage prevention. Bidding strategies for DERs such as PVs, BESSs, and EVs are characterized as *selfish* and *helpful*, where selfish bidding strategies strive to maximize personal revenue, while helpful bidding strategies strive to increase self-consumption. Simulations are executed on summer and winter datasets to find the optimal bidding strategy for the community that would reduce peak demand and increase energy utilization. Further, a design architecture for the blockchain based implementation of the TEF is proposed within this project, which enables bidding strategies to be implemented and executed using the double auction procedure. The blockchain implementation of the TEF is tested by executing real-world experiments at a microgrid in Vaughan, Ontario, by using microgrid assets to bid within a P2P energy market.

The results of the simulated experiments indicate that the optimal bidding configuration of an 8 home residential community is 8 helpful BESSs, and a combination of 4 selfish and 4 helpful EVs. The presence of selfish EVs help to spread the distribution of EV charging throughout the off-peak periods. Using the optimal bidding strategy, the execution of a P2P energy market within the TEF paradigm reduces the summer peak load of the community from 109.96 kW to 52.29 kW, for a total reduction of 52%, while the local renewable energy utilization increases from 69% to 93%. For the winter simulations, the winter peak load is reduced from 114.42 kW to 62.5 kW (45% reduction), while the local renewable energy utilization increased from 93% to 95%. The reduction of peak load has a major impact on the CAPEX of distribution utilities, since the regular 50 kVA distribution transformers that serve residential communities can be replaced by 75 kVA transformers instead of 125 kVA transformers. As such, the TEF is able to provide an average of $99.2M (or 31.6%) of CAPEX savings for the utilities under study. Further savings are enabled with the utilization of demand caps on the community, which reduce the peak load to 41.71 kW in the summer, and 35.1 kW in the winter. This obviates the need for the utility to upgrade the transformer to 75 kVA, resulting in total average CAPEX savings of $179.2M (or 57.1%). Additionally, simulations are also executed to demonstrate the ability of BESSs to provide grid voltage support to prevent sustained undervoltage events during brownouts. By injecting 24 kVAR of reactive power to boost the system voltage during an undervoltage event, the residential community is able to earn $1440 in annual payments for the provision of this service.

Lastly, real-world experiments for the blockchain implementation of the TEF demonstrate the ability for individual DERs to bid for energy in discrete market intervals, monitor the calculated MCP of the market interval, and automatically dispatch based on if their bid was granted. A P2P energy trading experiment demonstrates the ability of the TEF to accommodate all critical loads of the microgrid with its on-site PV supply, while a demand cap experiment demonstrates that the TEF can force zero-consumption from the microgrid during times of congestion. The automation of the bidding process and execution of the MCP calculation, as well as the transparency of data on the ledger are found to be the major strengths of using a blockchain implementation.

## 7.0 REFERENCES


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