Optimal and Collaborative Operations of Demand Response Programs in Power Systems

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Wichita State University

59th ranked Engineering Graduate Program in US

- US News
- *1st in Kansas*

Dr. Ward Jewell,
Professor Emeritus

Renewable Energy
Power quality
Demand site management

Dr. Visvakumar Aravinthan
Associate Professor
Chair of Dept. of ECE

Reliability
Distribution system
Operation and control
Cyber-physical systems

Dr. Chengzong Pang
Associate Professor
Site Director PSERC

Systems
Protection
Demand Response
Renewable Integration

Dr. Perlekar Tamtam
Associate Teaching Professor

Power systems

Photo Courtesy: https://www.wichita.edu/

NSF EPSCoR RII Track-1, #2148878 (2022-2027)

- ARISE: Adaptive and Resilient Infrastructures driven by Social Equity;
- This statewide initiative seeks to advance the resilience of infrastructures that all Kansans depend on—such as water, *energy*, and transportation systems—by creating tools that ensure support for our most vulnerable communities in both rural and urban areas. The project will also create a pipeline of community leaders and decision-makers who will transform how a community invests in and manages its human and physical infrastructure;
    - Theme 1 - Socially Equitable Interdependent Infrastructure for Resilience Analysis;
    - Theme 2 - Scalable holistic resilience evaluation;
    - Theme 3 - Infrastructure Enhancement and Decision Levers: Case Studies
    - Theme 4 – Decision-Support Structure
- Dr. Aravinthan is leading research efforts at Wichita State University.

Smart Grid Initiative

Smart Energy

- Renewable energy integration
- Energy storage devices
- Energy markets
- System dynamics
- Green house Gasses
- Optimize spinning reserves

Smart Grid

- Sensors
- Data Analytics
- Distribution automation
- Synchro-Phasors
- Component reliability
- Demand response

Smart User

- Energy management
- Smart meters
- Electric vehicles
- Reliable power
- Real time pricing
- Price response

Center for Energy Research; Power Quality Lab; Evergy Energy Lab; Power System Protection and Simulation Lab, etc….

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Outline

- Introduction
- Applications of demand response programs
  - Part 1: Active smart home management system
  - Part 2: Transmission congestion management
  - Part 3: Reliability improvement in Microgrids
- Conclusions

Dr. Amin Mohsenzadeh

Dr. Lin Yang

Ms. Nimanthi Nandasir

PSERC

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Demand Side Management in Power Grid

Volatile Energy Costs

Growing Electricity Demand

Intermittent and Uncertain Resources

Inefficient and Old Infrastructure

Demand Side Management (DSM) is introduced to tackle the energy dilemma

Photo Courtesy: https://www.power-technology.com/analysis/smart-cities-redefining-urban-energy/
Infrastructure upgrade such as smart LED street lighting can significantly reduce a city’s energy demand. Credit: Jerry Ferguson

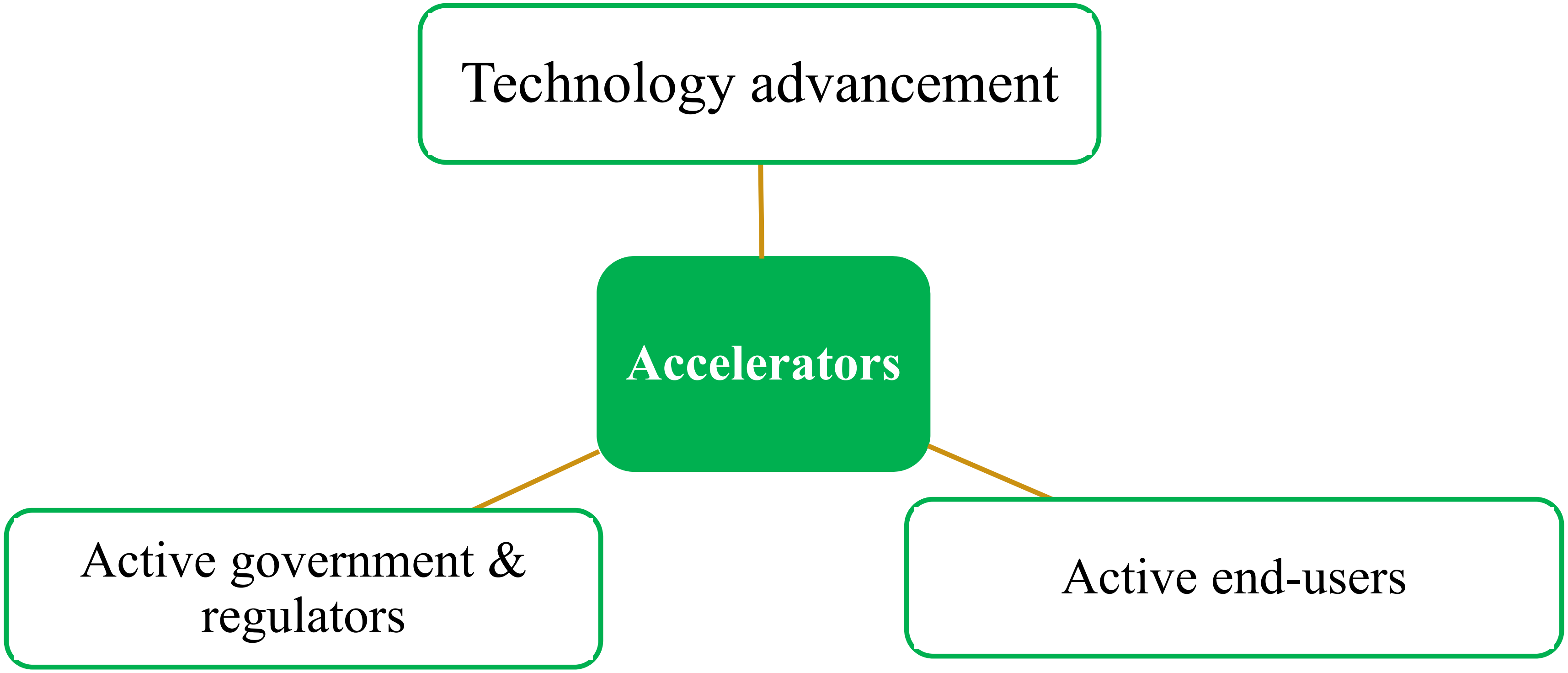
Demand Response Definition

The Federal Energy Regulatory Commission (FERC) defines demand response as:

“*Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*”.

Source: https://www.ferc.gov/industries-data/electric/power-sales-and-markets/demand-response/reports-demand-response-and

Demand Side Management



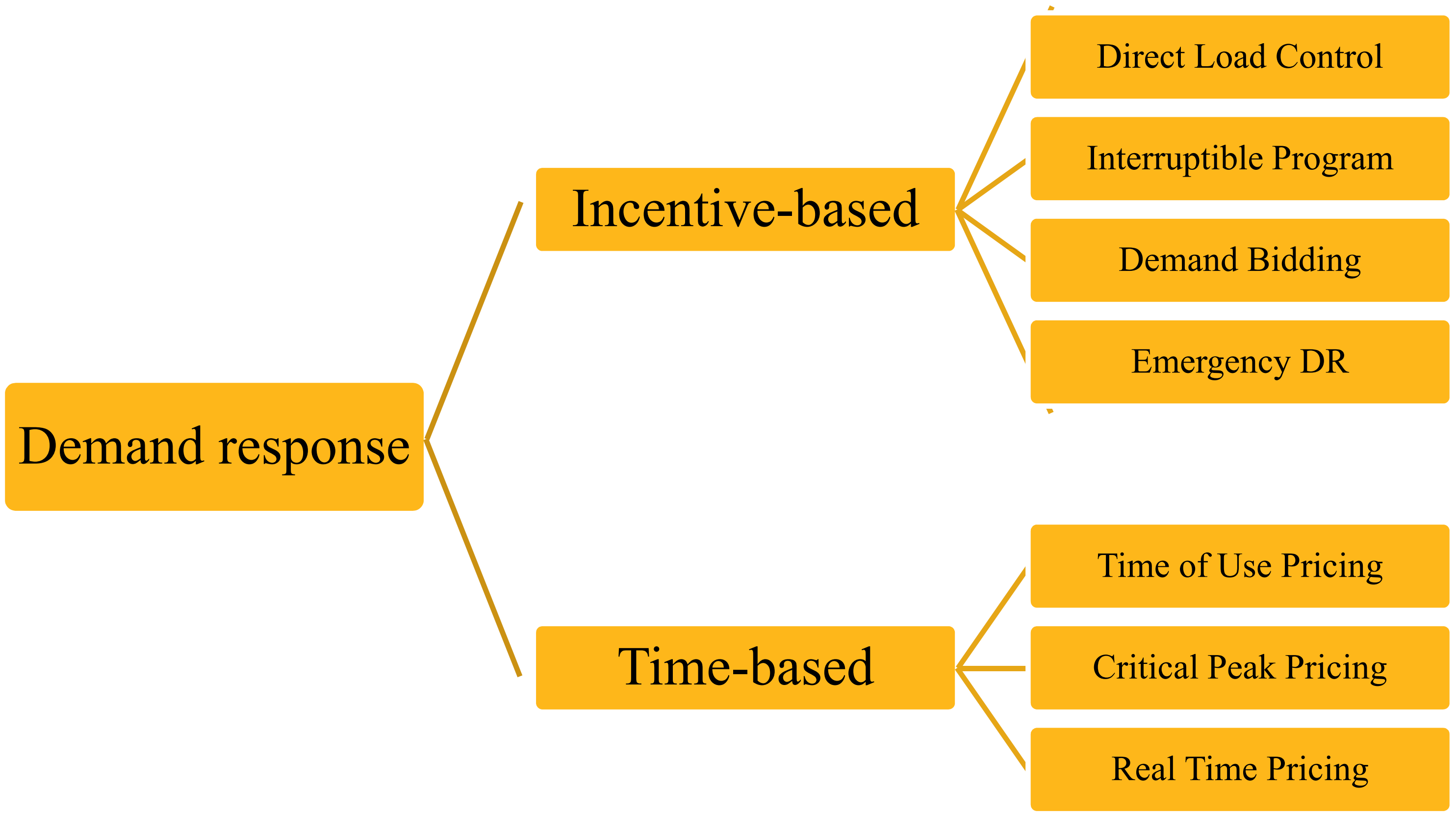
Technology advancement

Accelerators

Active government & regulators

Active end-users

Demand Response Programs Categories



- Demand response
  - Incentive-based
    - Direct Load Control
    - Interruptible Program
    - Demand Bidding
    - Emergency DR
  - Time-based
    - Time of Use Pricing
    - Critical Peak Pricing
    - Real Time Pricing

Y. Liu, S. Hu, H. Huang, R. Ranjan, A. Y. Zomaya and L. Wang, "Game-Theoretic Market-Driven Smart Home Scheduling Considering Energy Balancing," in *IEEE Systems Journal*, vol. 11, no. 2, pp. 910-921, June 2017.

Potential Benefits of Demand Response

Economic

- Lower electricity prices
- Defer new capacity investments

System Operation

- Maintain the reliability
- Provide ancillary services

Environmental

- Integration of renewable resources
- Displacement of fossil fuel resources

Customer Benefits

- Satisfy electricity demands
- Reduce / stabilize costs
- Improve value of service
- Maintain/improve lifestyle

Utility Benefits

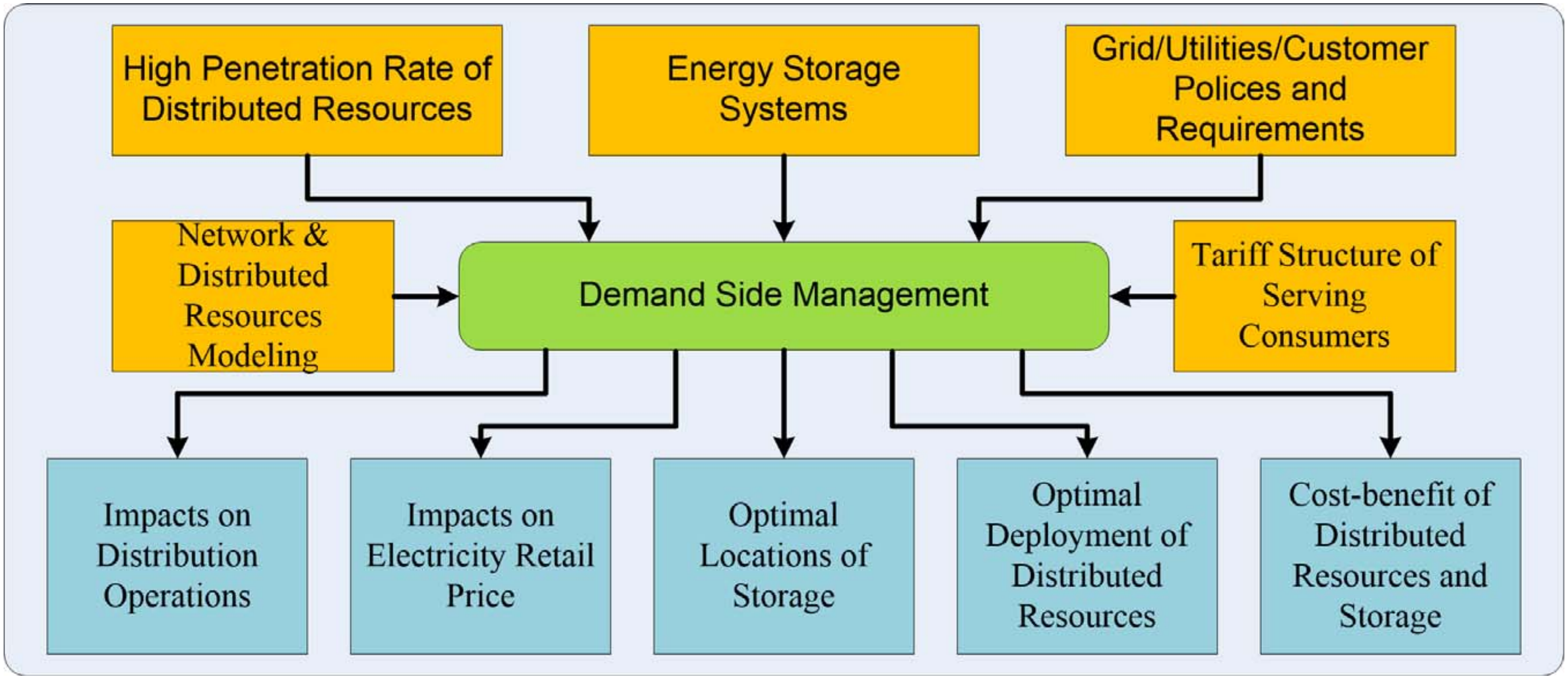
- Lower cost of service
- Improved operating efficiency,
- Flexibility of operation
- Reduce capital needs

Societal Benefits

- Reduce environmental degradation
- Conserve resources
- Protect global environment
- Maximize customer welfare

A. Basit, G. A. S. Sidhu, A. Mahmood and F. Gao, "Efficient and Autonomous Energy Management Techniques for the Future Smart Homes," in *IEEE Transactions on Smart Grid*, vol. 8, no. 2, pp. 917-926, March 2017.
IIEC, "Demand side management best practices guidebook or pacific island power utilities," *International Institute for Energy Conservation*, July 2006

Demand Side Management: Move Forward



High Penetration Rate of Distributed Resources

Energy Storage Systems

Grid/Utilities/Customer Polices and Requirements

Network & Distributed Resources Modeling

Demand Side Management

Tariff Structure of Serving Consumers

Impacts on Distribution Operations

Impacts on Electricity Retail Price

Optimal Locations of Storage

Optimal Deployment of Distributed Resources

Cost-benefit of Distributed Resources and Storage

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Active Smart Home Management Systems

- Residential sector accounts for the largest share of the energy used in U.S.
- Recent advances in smart metering technology enable bidirectional communication between the operator and the end-users
- Smart homes are currently the best option to perform DR in distribution networks

Typical Smart Home

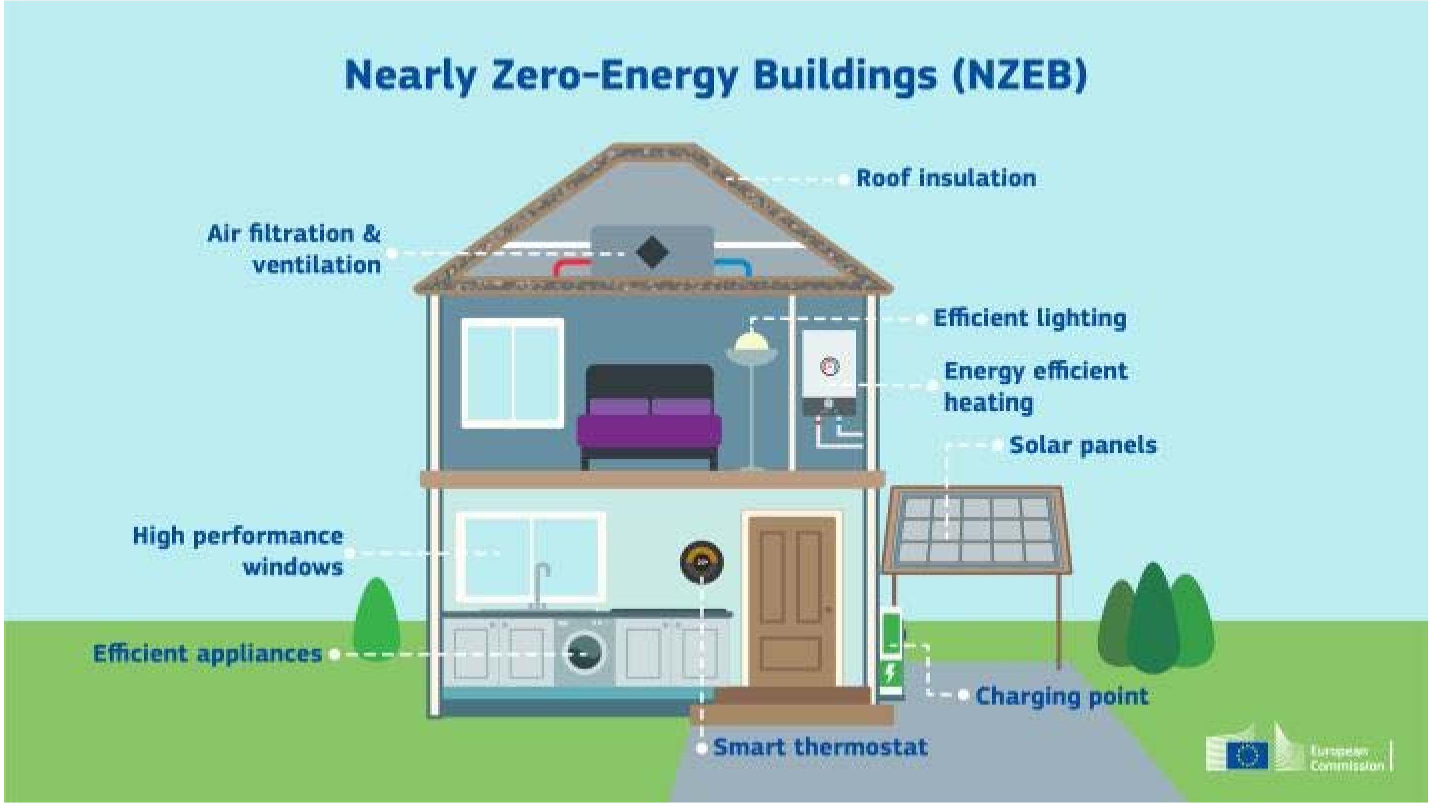
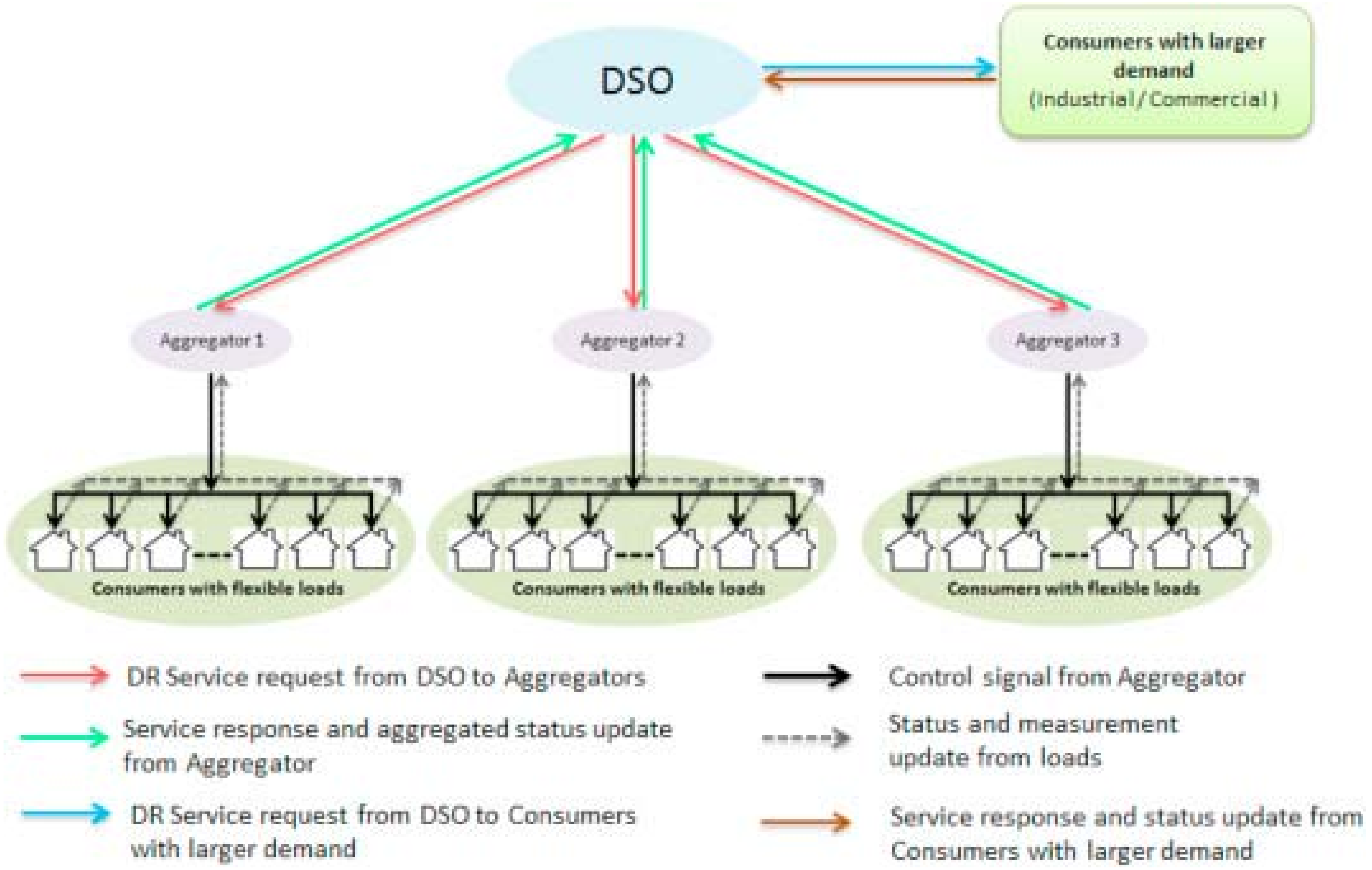


Photo Courtesy: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en

Demand Response Aggregators

- Residential DR can be more useful if a large number of scattered DR resources can provide a coordinated response to its requirements
- The aggregator mainly acts as an intermediary between end-users, and the distribution system operators.
- The aggregators sell DR services to the operators and provide compensation to customers to modify their consumption pattern

Interactions among DSO, Aggregators, and End-users

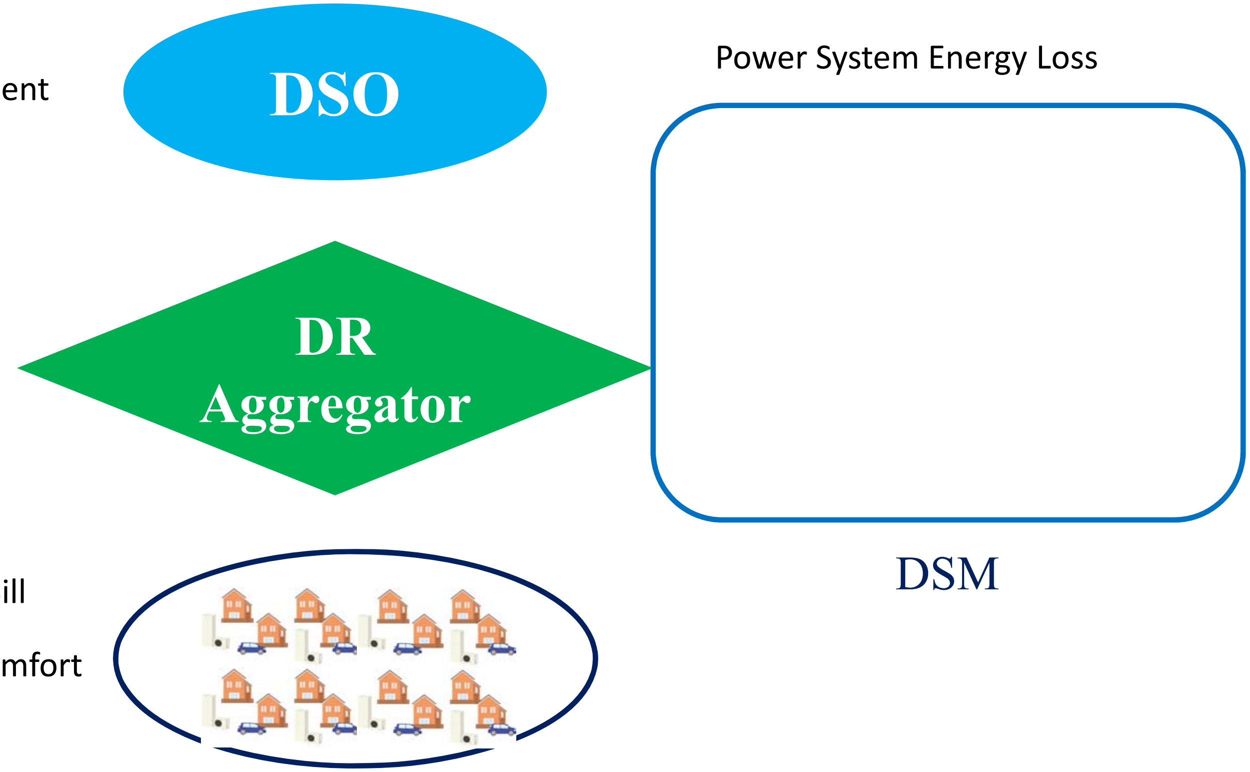


- → DR Service request from DSO to Aggregators
- → Service response and aggregated status update from Aggregator
- → DR Service request from DSO to Consumers with larger demand
- → Control signal from Aggregator
- ⇢ Status and measurement update from loads
- → Service response and status update from Consumers with larger demand

Demand Response Aggregators

- Scheduling residential customers to minimize energy bill
- Bill reduction for customers, and improve the customer comfort
- Minimizing energy bill, satisfying home power demand and PEV charging requirements
- Implementing incentive-based DR strategy for load reduction and voltage improvement
- Managing smart home appliances considering the lifetime of a distribution transformer and energy bill of customers

Optimal and Collaborative Operations of Demand Response Programs



Transmission Congestion

Power System Asset Management

DSO

Power System Energy Loss

DR Aggregator

DSM

Energy Bill

Customer Comfort

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Impact of different variables on the transformer's aging

- Transformers represent the largest portion of capital investment in distribution networks
- Joint effect of loading, cooling characteristics, ambient temperature, and oil time constant on transformer's aging

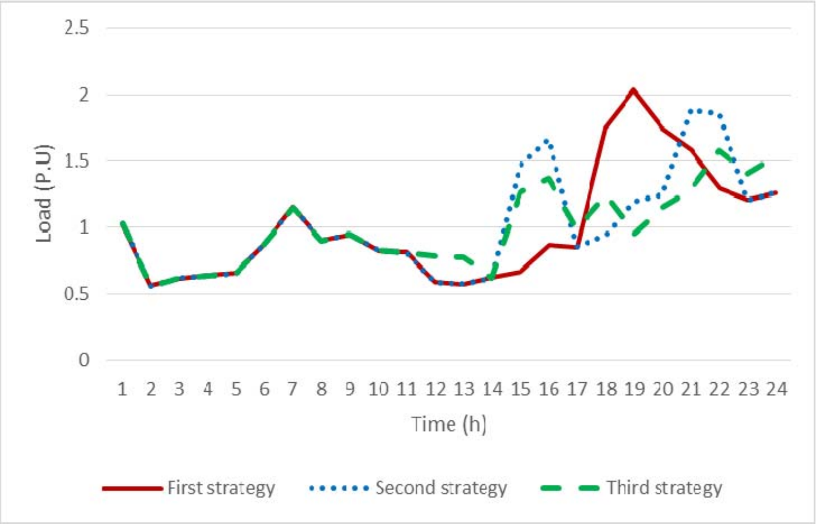
Factor		**Level**	
Transformer Load profile	**A**	0	Level 1
		1	Level 2
Ambient Temperature	**B**	0	20 ºC
		1	40 ºC
Cooling Characteristic	**C**	0	ONAN
		1	ODAF
Oil Time Constant	**D**	0	100
		1	300

Term	**Contribution (%)**
A-Loading	60.44
B-Ambient	2.55
C-Cooling	31.02
D-OTC	0.22
AB	5.080E-003
AC	5.75
AD	2.306E-003
BC	3.688E-003
BD	4.011E-005
CD	1.345E-003

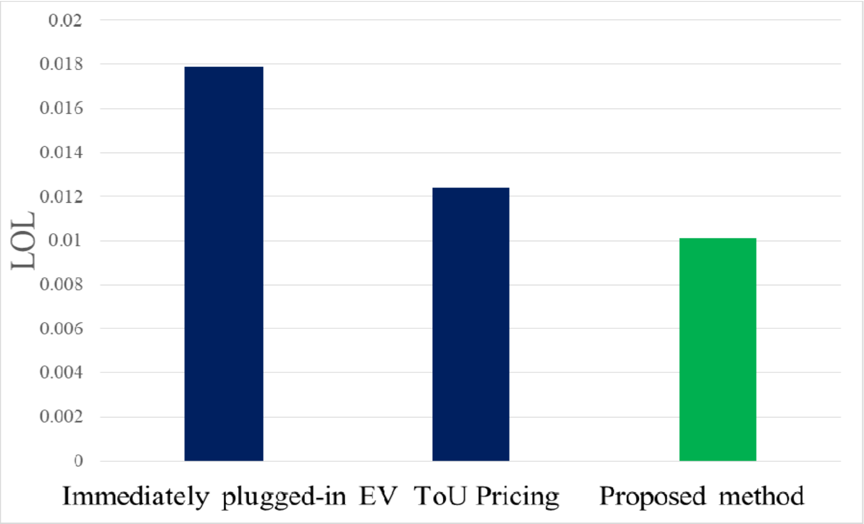
A. Mohsenzadeh, M. H. Kapourchali, C. Pang and V. Aravinthan, "Impact of smart home management strategies on expected lifetime of transformer," 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D), 2016, pp. 1-5.

Model Development

1. Customer Comfort
2. Customer Comfort and Electricity Price
3. Customer Comfort, Electricity Price , and Aging of Transformers



Loading pattern of the distribution transformer



'LoL of transformers

Comprehensive Model

- EV and ESS Modeling:

$$P_t^{EV,Ch} = P_t^{EV,CHRate} u_t^{EV}$$

$$P_t^{EV,Dis} = P_t^{EV,DisRate} (1 - u_t^{EV})$$

$$SOC_t^{EV} = SOC_{t-1}^{EV} + \frac{P_t^{EV,Ch}}{BC^{EV}} - \frac{P_t^{EV,DisCh}}{BC^{EV}}$$

$$SOC^{EV,Min} \le SOC_t^{EV} \le SOC^{EV,Max}$$

$$\boxed{SOC_t^{EV} = SOC^{EV,Desired} \quad , if \quad t = T^d}$$

- Small Scale PV:

$$T_{Cell} = T_{amb} + S . \frac{T_{Nom} - 20}{0.8}$$

$$I = S.[I_{sc} + k_c (T_C - 25)]$$

$$V = V_{oc} + k_v T_C$$

$$FF = \frac{V_{MPP} . I_{MPP}}{V_{oc} . I_{sc}}$$

$$P_t^{Solar} = N \cdot FF.V.I$$

S. Pazouki, A. Mohsenzadeh, S. Ardalan and M. R. Haghifam, “Optimal place, size, and operation of combined heat and power in multi carrier energy networks considering network reliability, power loss, and voltage profile” IET Generation, Transmission & Distribution ,Volume 10, Issue 7, 05 May 2016, p. 1615 – 1621,

Comprehensive Model

- Appliances:
  - Non-controllable appliances:

$$f_N(load) = \frac{1}{\sqrt{2\pi .\delta}} e^{-(1-\mu)^2/2\delta^2}$$

  - Controllable appliances:

Household Appliances Characteristics

Device	Rated Power(kW)	Duration Time (Hours)	Desired Start Time (Hours)
Dishwasher	1.5	1	21-24
Washer machine	2	2	18-22
Dryer machine	1.5	1	18-22

Talari, Saber, Mohsen Yazdaninejad, and Mahmoud-Reza Haghifam. "Stochastic-based scheduling of the microgrid operation including wind turbines, photovoltaic cells, energy storages and responsive loads." IET Generation, Transmission & Distribution 9.12 (2015): 1498-1509.,

Comprehensive Model

- Appliances:
  - Thermal appliances - HVAC:

$$P_t^{Thermal} = Q_l + mC\,(\theta_2^t - \theta_1^t)$$

$$Q_l = k_l A_l (\theta_{out}^t - \theta_{in}^t) \qquad l \in w, c, f$$

$$\frac{1}{k_l} = \frac{1}{h_1} + \frac{1}{h_2} + \frac{e_1}{z_1} + \frac{e_2}{z_2} \qquad l \in w, c, f$$

N. Lu and D. P. Chassin, "A state-queueing model of thermostatically controlled appliances," Power Systems, IEEE Transactions on, vol. 19, pp. 1666-1673, 2004.

Comprehensive Model

- In order to complete the proposed method, the energy loss reduction needs to be added as an objective to the model.
- Distribution Locational Marginal Pricing (DLMP) is introduced as a signal price to charge end users.

$$I(jj) = \sum_{k=1}^{N(jj)} \left[\frac{P\{ie(jj,k)\} + jQ\{ie(jj,k)\}}{V\{ie(jj,k)\}} \right]^*$$

$$PLOSS(jj) = \mathrm{Re}\{(V_i - V_j) * I(jj)\}$$

$$PLOSS(jj) = \mathrm{Re}\left((V_i - V_j) * \sum_{k=1}^{N(jj)} \left[\frac{P\{ie(jj,k)\} + jQ\{ie(jj,k)\}}{V\{ie(jj,k)\}} \right]^* \right) \rightarrow \left[\frac{V_i - V_j}{V\{ie(jj,k)\}} \right]^* = \alpha\{ie(jj,k)\} + j\beta\{ie(jj,k)\}$$

$$PLOSS(jj) = \sum_{k=1}^{N(jj)} \alpha\{ie(jj,k)\}P\{ie(jj,k)\} + \beta\{ie(jj,k)\}Q\{ie(jj,k)\}$$

$$Tplossi(l) = \sum_{jj=1}^{NB-1} ploss(jj,l) \qquad for\ \ l = 2,3,\ldots,NB.$$

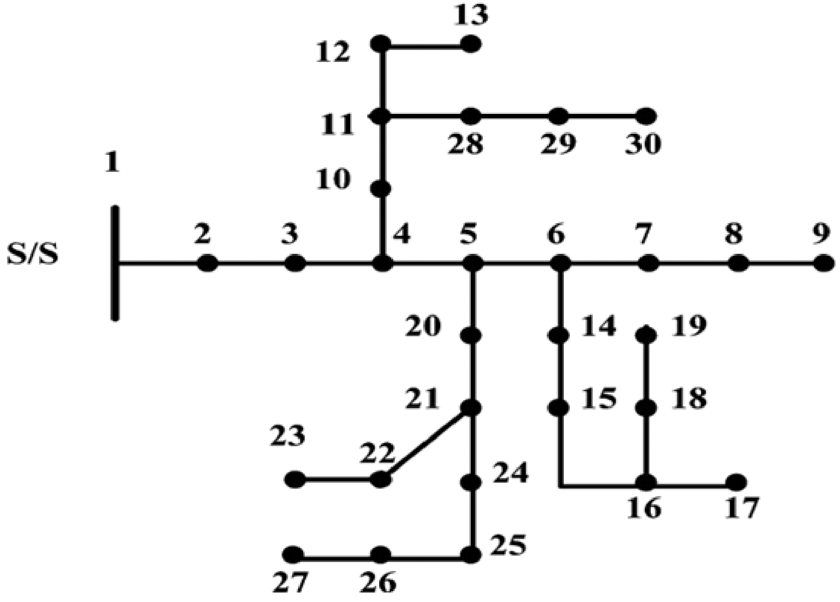
Comprehensive Model

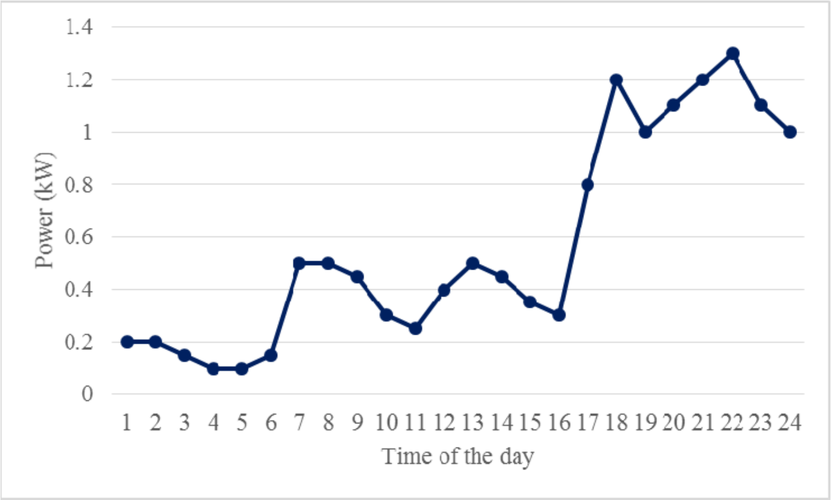
- The DLMP of a node consists of energy cost and allocated power loss to the node.

$$\mathrm{DLMPi} = LMP\left(1 + \frac{Tplossi}{PLOSS}\right)$$

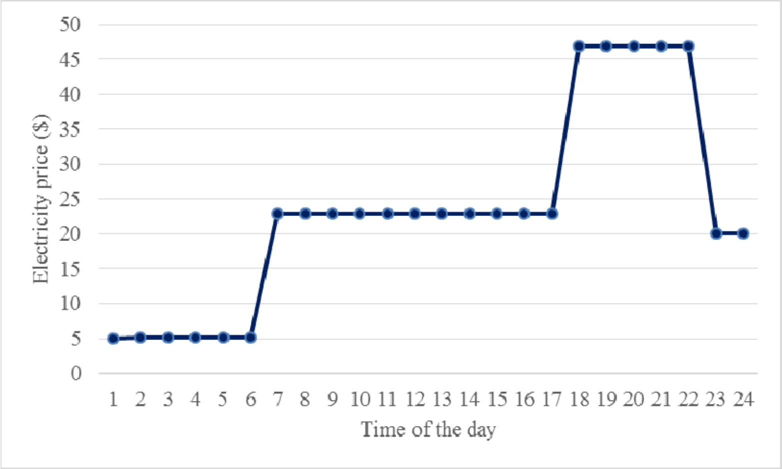
- The comprehensive optimization model is applied to obtain optimal operation of household appliances, thermal devices , ESS, rooftop PV, and EV considering electricity price, customer comfort, aging of transformers, and energy loss

Sensitivity Analysis



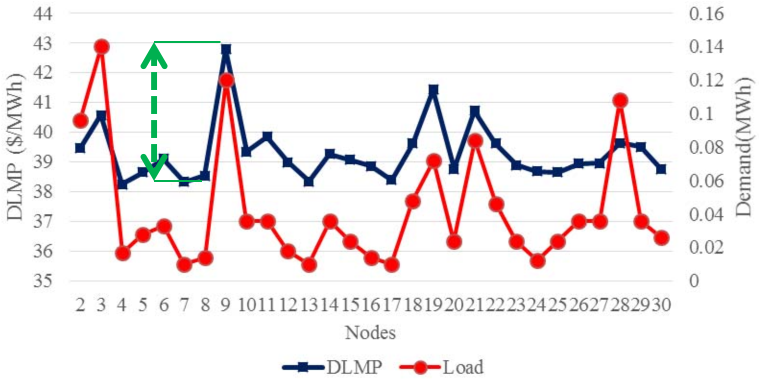


The real-time measured load demand of a smart home

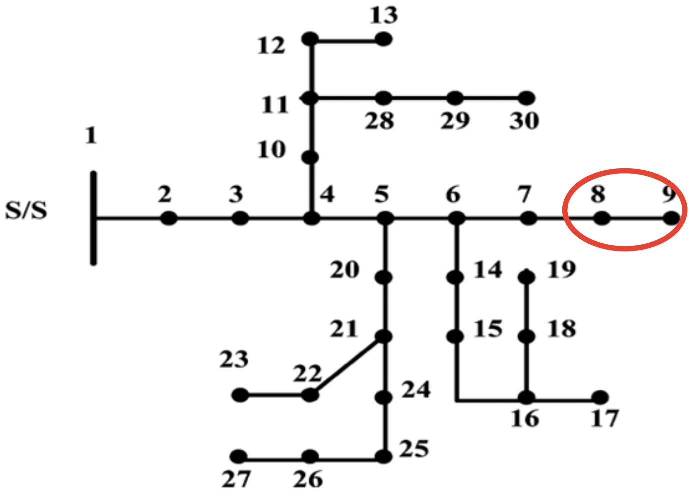


TOU electricity price

Sensitivity Analysis

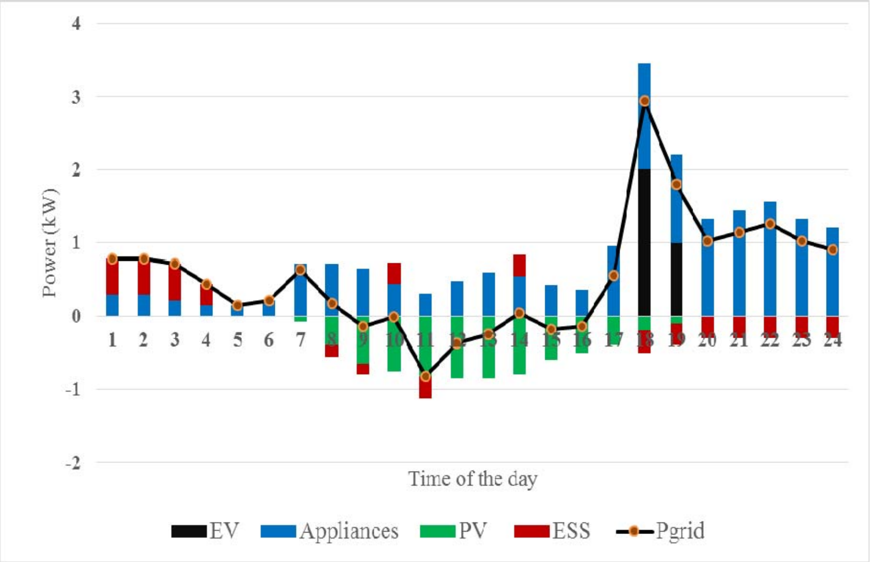


Correlation between demand and DLMP in power distribution system

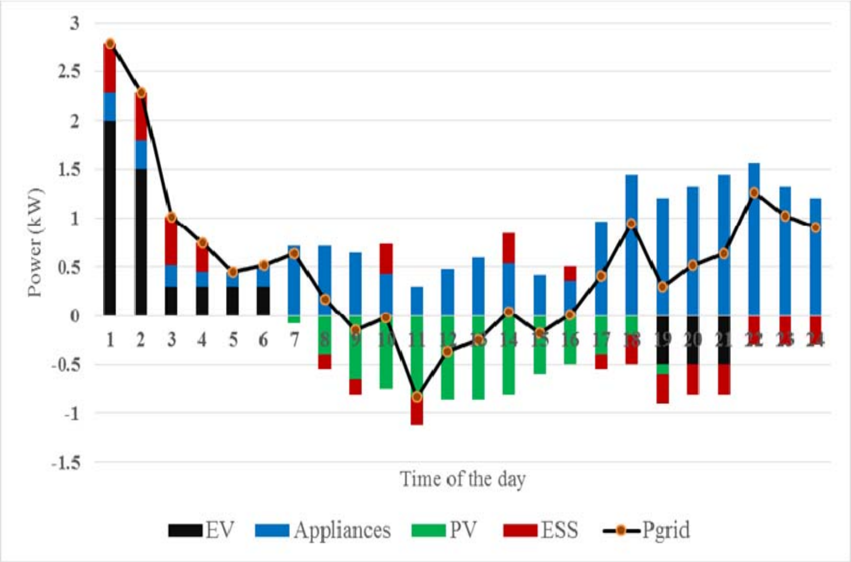


Verifying the impact of Load on DLMP

Numerical Results

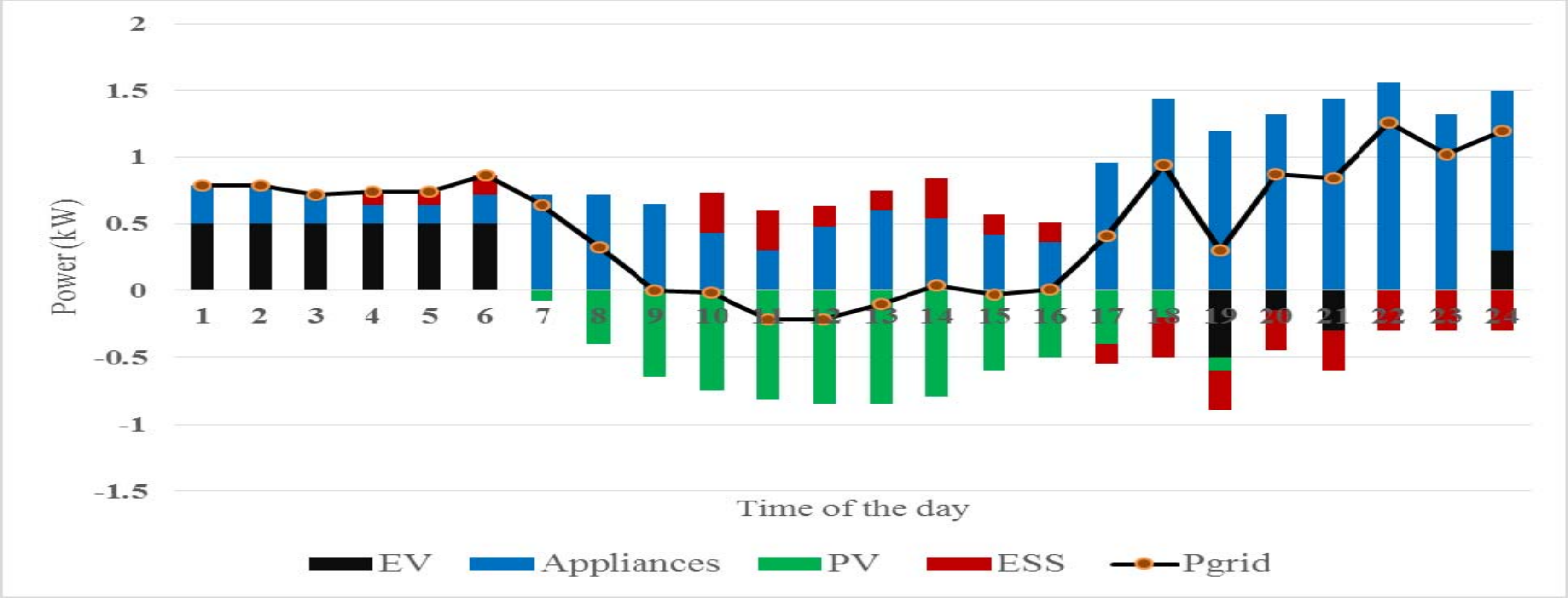


Total household power demand for consumers willing to charge their EV immediately



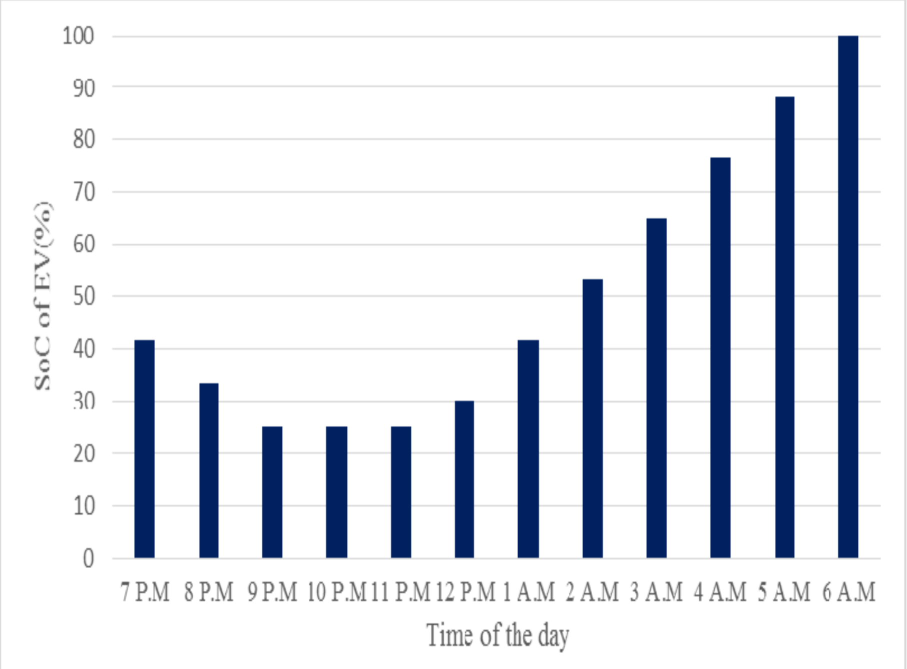
Total household power demand for consumers willing to charge their EV with lower prices

Numerical Results

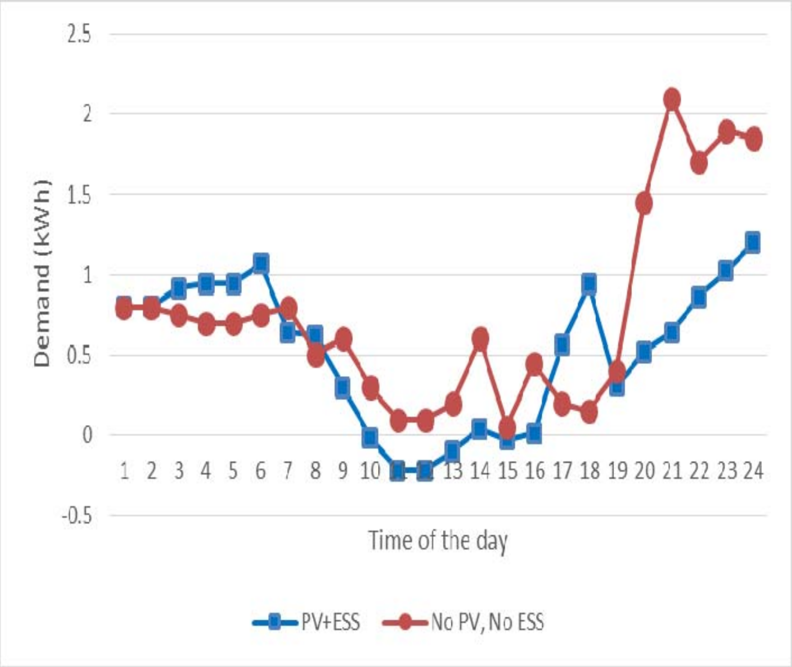


Decomposition of smart house demand via the proposed method

Numerical Results

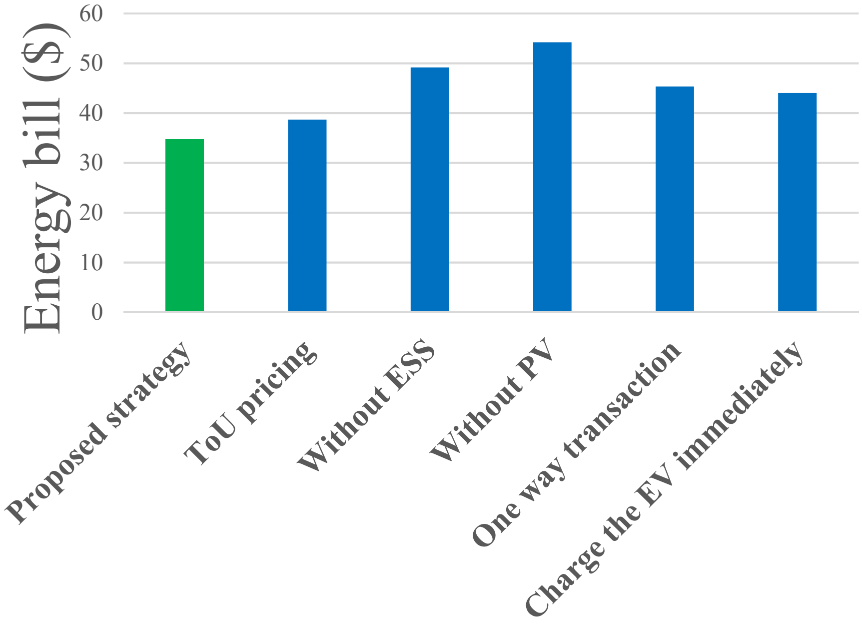


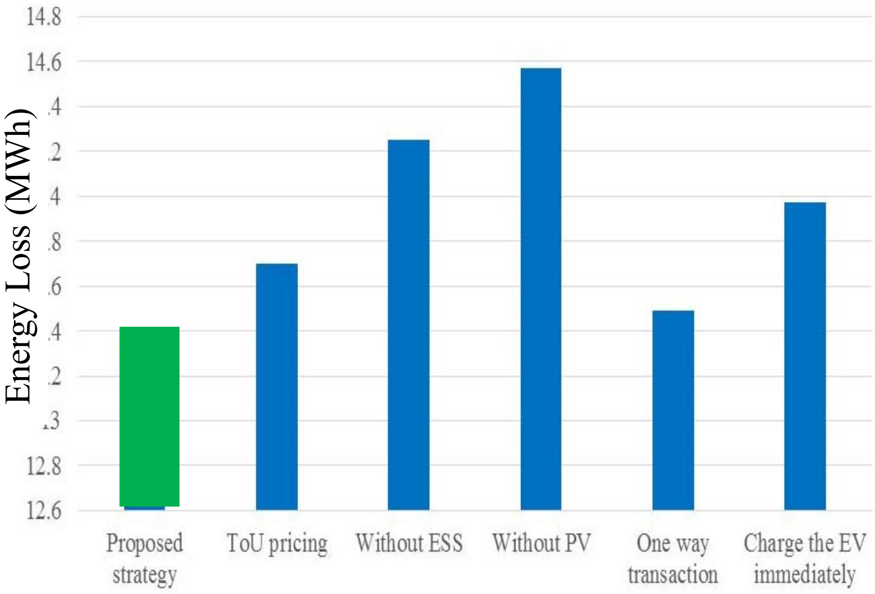
EV battery SoC variation for consumers willing to charge their EV under proposed method with EV V2H option



The consumption pattern of a smart house without energy resources

Numerical Results





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Transmission Congestion Management

- Congestion takes place when the transmission lines are not sufficient to transfer the power according to market desires.

- Transmission congestion may induce higher costs for consumers, because operators must rely on higher-cost generation sources

Current Methods

- Rescheduling the committed generators
- Using FACTS devices
- Performing DR programs
- Operating DERs in power distribution networks
- etc.

Proposed Model

DR aggregator has two options to relieve the transmission congestion

(1) Performing residential DR programs

(2) Operating the small-scale distributed generations (DERs or V2Bs)

- Objective : Minimizing the total energy cost
- Constrains: capacity of transmission lines, voltage boundaries, load curtailment limitations, and etc.

Locational Marginal Pricing – Example

$$\lambda_i = \lambda_{Energy,i} + \lambda_{Loss,i} + \lambda_{Congestion,i}$$

$$\lambda_{Congestion,i} = -\sum_{k}^{NC} \mu_k SF_{j,k}$$

Objective Function

μ: how much more money we can make by increasing the capacity of feeder i

SF: measures the sensitivity of the transmission line flow to the load changes of a bus

$$Min \quad \left[\sum_{t=1}^{T} \sum_{i=1}^{nbus} (P_{net,i} \lambda_i) + \sum_{t=1}^{T} \sum_{j=1}^{n} P_{DG,j}^{t} \; Cost_{DG,j} + P_{jDR,i}^{t} \; Inc_{EDRP,j} \right]$$

A. Mohsenzadeh, C. Pang & L. Yang (2021) Transmission congestion management considering EV parking lots and demand response programes, *International Journal of Ambient Energy*, 42:15, 1727-1731

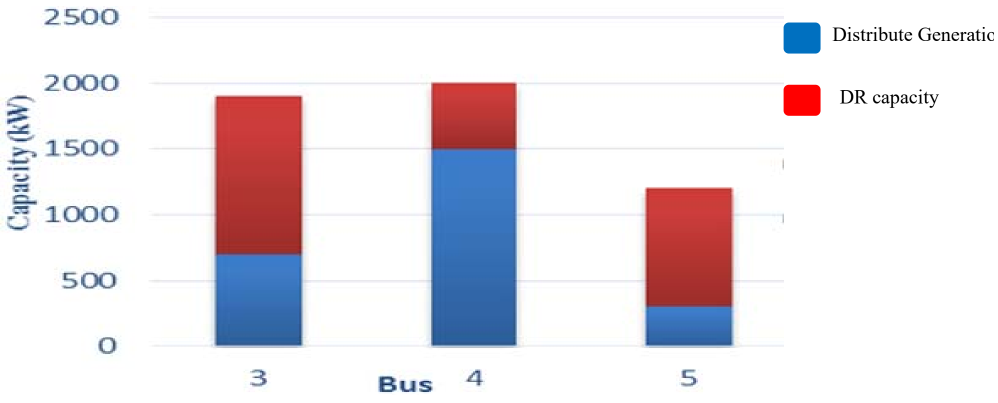
Numerical Results

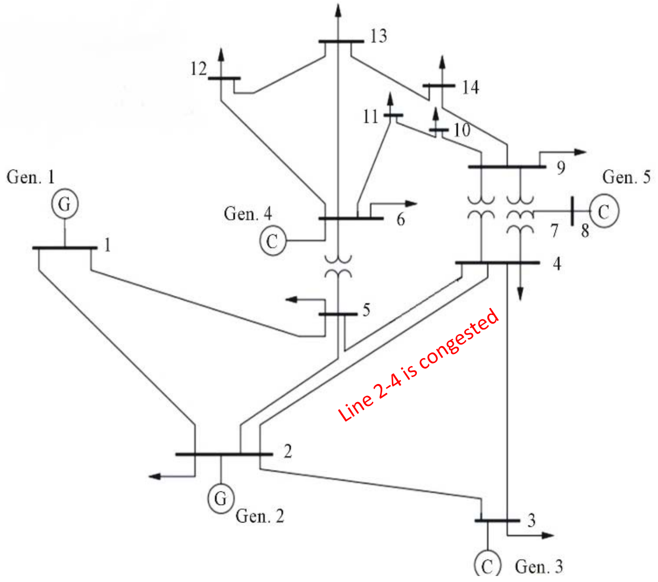
SHIFT FACTOR

Bus	2	3	4	5
SF	0.005	0.021	0.035	0.026

LMP OF THE SYSTEM DURING THE CONGESTION

Bus	3	4	5
LMP($/MWh)	1846	2805	2098





Line 2-4 is congested

The LMP has been **decreased** to 14.67 $/MW.

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Reliability Evaluation

- The duration and frequency of interruptions determine the reliability of power distribution network .
- Sustained and momentary interruptions impose negative impacts on systems safety, utilities' profits, and customers satisfaction
- Power system utilities try to design a reliable, and resilient system to reduce outage costs.

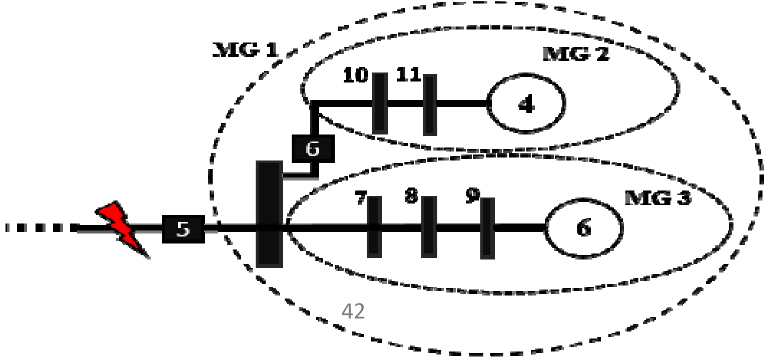
Common Approaches for Reliability Improvement

1. Reducing the frequency of interruptions
    - Performing preventive maintenance at regular intervals
    - Undergrounding cables

2. Reducing the duration of interruptions
    - Fault Location
    - Fault Isolation
    - Fault Restoration

Microgrid

- **Microgrids** consist of DERs (including demand management, storage, and generation) and loads and they are able to operate in parallel with, or independently from, the main **power** grid.
- Determining the most efficient boundaries of microgrids under contingencies is one of the main challenges of utilities from safety and security points of view;
- Most researches have been focused on the pre-defined boundary or static microgrids;
- Compared to current approaches, boundaries of the proposed flexible microgrids can be extended or shrunk based on generation and demand levels, technical constraints, and customer comfort.



Reliability Index

- Reliability indices are used to evaluate the performance of outage management system in utilities.
- Energy Not Supplied Cost and Average System Interruption Duration Index (ASIDI) are used to determine the interruption duration and outage cost of the system

$$ECOST = \sum_{i=1}^{N} r_i \, L_{avg,i} \, CDF_i$$

$$ASIDI = \frac{\sum r_i \, L_i}{L_T}$$

Objective function

Install remote switches

Minimizing Outage Costs

Sizing and sitting of DGs

Utilizing DR

A. Mohsenzadeh, C. Pang and M. -R. Haghifam, "Determining Optimal Forming of Flexible Microgrids in the Presence of Demand Response in Smart Distribution Systems," in *IEEE Systems Journal*, vol. 12, no. 4, pp. 3315-3323, Dec. 2018.

Problem Formulation

$$Min \quad \sum_{i=1}^{nload}\left[(L_i \cdot t \cdot CDF) + (A_i)\right] + P_{DG}.Cost_{DG} + N_{Switch}.Cost_{Switch}$$

← Number of candidate places for switches →← Number of candidate places for DGs →

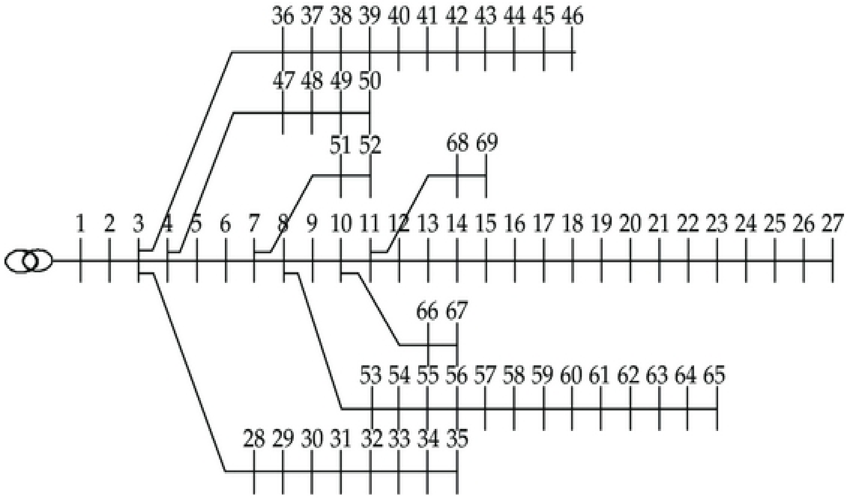
1	0	……….	1	1	3	0	……….	2	1

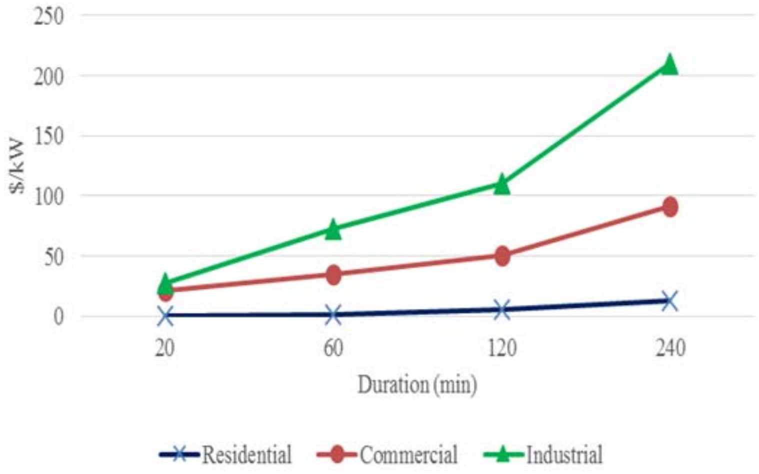
The first part, represents the location of switches

The second part, represents the location and size (50, 100, 150, and 200 kW) of DGs

Numerical Results

- IEEE 69-bus distribution system is selected as the test system.
- Capital cost of a switch: $3,000/Switch





Numerical results

Location of switches and reliability indices of static microgrids

Location of Switch	3, 4, 7,8, 11, 17,22,30,33, 38, 40,44, 55, 61
ASIDI(hour)	1.0552
ENS (kWh)	86086
Final Cost ($)	254010

Sizing and sitting of DGs

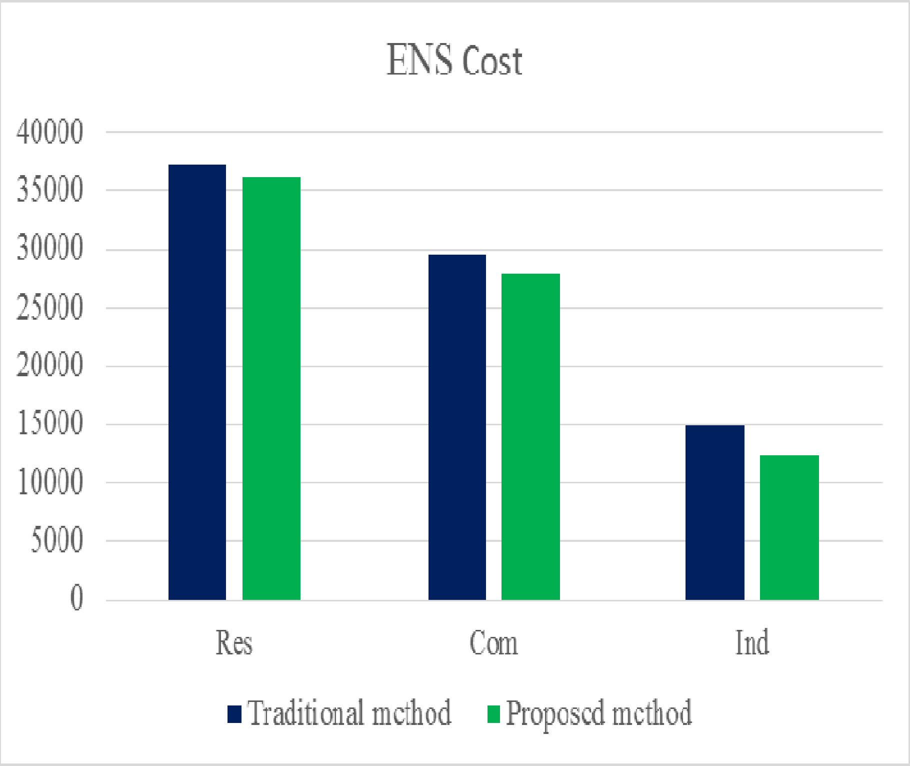
BUS NUM	40	44	47	69	21	66	64	31	35
CAPACITY	150	200	50	150	200	100	50	150	150

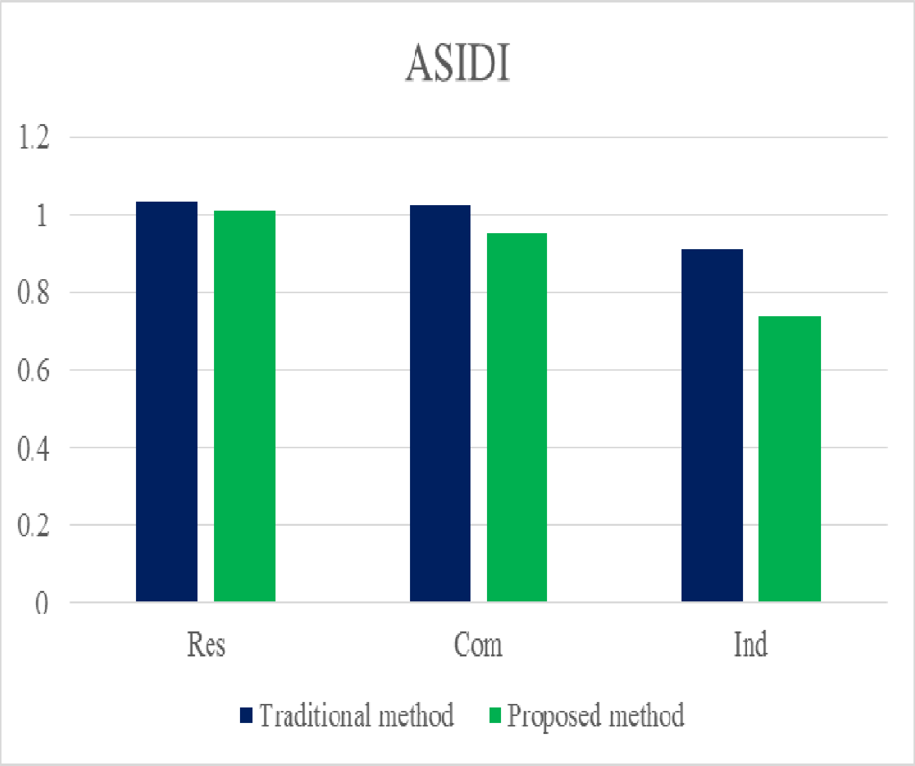
Numerical results

Location of switches and reliability indices of flexible microgrids

Location of Switches	3, 4, 7, 8, 11, 17, 22, 32, 38, 43, 59
ASIDI(hour)	0.9456
ENS (kWh)	78829
Final Cost ($)	226310

Numerical results





Outline

- Introduction
- Applications of demand response programs
  - Part 1: Active smart home management system
  - Part 2: Transmission congestion management
  - Part 3: Reliability improvement in Microgrids
- Conclusions

Conclusions

- A new analytical model was proposed to analyze the impact of demand response programs on asset management and energy loss;
- The optimal scheduling of household appliances and DERs were determined to minimize the sum of customer bills and utilities' costs;
- An optimal strategy for DR participants in order to relieve the power transmission congestion is also discussed;
- The proposed approach gives insight on how to design and operate flexible microgrids in order to improve reliability and reduce the energy not supplied costs.

Future works:

- Policy and protocol about optimal strategy for DR aggregators in wholesale electricity markets;
- Data analytics and a decision-making tool;
- Stochastic optimization models.

Questions?

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