Estimating the Impacts of Direct Load Control Programs Using GridPIQ, a Web-Based Screening Tool

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Abstract—**In direct load control (DLC) programs, utilities can curtail the demand of participating loads to contractually agreed-upon levels during periods of critical peak load, thereby reducing stress on the system, generation cost, and required transmission and generation capacity. There may be a shift of load proportional to the interrupted load to the times before or after a DLC event, resulting in a new load profile shape characteristic of each program. However, the significant and unintuitive repercussions of DLC programs extend far beyond changes to load profile shape. Tools that can quantify the impacts of DLC programs on the bulk power system, including emissions, fossil fuel costs and required ramping are currently lacking. The Grid Project Impact Quantification (GridPIQ) screening tool includes a Direct Load Control module, which takes into account project-specific inputs and customer behavior, along with the larger system context in order to quantify the impacts of a given DLC program. This allows users (utilities, researchers, etc.) to quickly specify DLC programs and compare their impacts, informing program design and justification.**

Index Terms – GridPIQ, power systems, direct load control, demand response, emissions, demand side management, peak load reduction, impact analysis.

I. Introduction

GridPIQ, formerly known as Emissions Quantification Tool (EQT), is a transparent, modular, and publicly available web-based screening tool that estimates the impacts of various smart grid project types and specifications, within the context of the geographical location, generation and load characteristics, etc. [1]. GridPIQ allows the rapid screening of different grid projects, which include "smart charging" (based on coordinated electric vehicle charging), conservation voltage reduction (CVR), solar photovoltaic (PV) generation, and energy storage (ES) [2], [3], [4], [5]. This paper discusses GridPIQ's new "Direct Load Control (DLC)" module, which prompts for specifications of the DLC program itself, customer behavior and system context to estimate the various impacts of the program on the peak load, energy use, ramping requirements, fuel costs and emissions (CO_2, SO_2 and NO_x) of the system. Estimating the combined impacts of all these different factors is not a trivial task, but GridPIQ's DLC module pulls together user inputs and relevant data from its database to quickly compute the unintuitive impacts of various DLC programs. Therefore, this tool can provide valuable insights to researchers, utilities or regulators regarding the impact of DLC programs.

DLC is a type of utility-sponsored demand side management program in which customers who are willing to have their loads curtailed during critical peak demand times are offered financial incentives to enter into a contractual agreement with the utilities [6], [7]. The peak shaving action of a DLC program during a high demand period enhances the system operation by de-stressing it, increases system reliability, and can help defer system upgrade requirements (*e.g.* new power plants, transmission and distribution infrastructure). DLC can lower system costs, since fossil fuel units used to meet peak demand are typically more expensive to operate than the generators which are used to meet base load. Because peaking plants sit idle most of the year, utilities face greater excess capacity (lower utilization rates) during off-peak times, and therefore higher system costs. Many U.S. systems have rising peak-to-average electricity demand ratios, particularly in New England where this value increased from 52% in 1993 to 78% in 2012 [8]. A well-designed and implemented DLC program is thought to be an effective method of reducing the peak demand.

Utilities often offer DLC programs that primarily target specific appliances, such as air conditioners, central electric heaters, electric water heaters, irrigation pumps, and swimming pool pumps [9], [10]. The customers agree to a specific level of consumption, known as firm service level (FSL), and their consumption is curtailed by the utility to that level in times of high demand [11]. Typically there is a limit to the total number of DLC events that an utility is allowed to execute in a calendar year, and the maximum duration of any event is specified to be between 2 and 8 hours. Advanced notification is provided to the participating customers minutes to hours before each event. It should be mentioned here that in case of some DLC programs, enrolled equipment is cycled off and on during DLC events, and impact estimation of such programs using GridPIQ is part of future work. A table summarizing most of the DLC programs offered by power companies across the US is provided in [12].

In return for participation, customers are typically paid fixed incentive payments in the form of capacity credits or reservation payments (expressed as \$/kW-month or \$/kW-year), and a one-time participation payment. Therefore, implementation of DLC programs leads to financial gains for customers as well.

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The payment calculation may depend on the load commitment level and the amount of notice required (e.g., number of hours or minutes). Because load reductions must be of firm resource quality, curtailment is often mandatory, and penalties can be charged for early opt out or event overrides [10], [13].

Although DLC is considered an effective measure for daily peak demand shaving, it has been shown to produce significant load shifts. Analysis of several pilot programs show that load curtailment during DLC events can lead to additional consumption when the appliances are reconnected after the event due to the so-called "snapback" or "rebound" effect [14], [15]. Utilities or customers may run appliances more aggressively (e.g., pre-cooling in case of an air-conditioning DLC) before they are disconnected, which can lead to an increase in energy consumption before each DLC event. This behavior is referred to as "preconditioning" here. Both rebound and preconditioning effects may result in shift of load peak instead of reduction, and may require higher generation ramping up or down capabilities as a result.

The authors of [15] state that each utility will observe similar load profiles on load control days, and the load shift and its impacts will depend on the customers being served. To increase the benefits of DLC programs, it is important to understand customer preferences, and accordingly structure the program [16]. Some of the existing work have proposed control approaches for air conditioners and water heaters participating in DLC programs in order to minimize customer discomfort while improving demand reduction [6], [17]. It is known that the results of DLC programs are difficult to measure and verify [18]. Matlab-based simulation tools have been proposed for determining the grid impacts when the pre-project load data and the control algorithm are provided [19], [20]. However, they do not incorporate context, and do not provide fuel or emission related impacts. Also, these tools require detailed load models and control algorithm knowledge for each of the connected loads, which may not be available.

In this paper, we show that even contextual factors (e.g. generation fuel mix) and the specifications of the DLC program influence the impacts. Given different contexts, the impacts of the same DLC program can be vastly different, even when the behavior of the customer base remains the same. Similarly, given different DLC specifications, the impacts can be vastly different, even when context and customer base are same. However, there is a lack of publicly available tools for analyzing how all these different factors individually or together influence the outcomes of implementing a DLC program. GridPIQ's transparent, modular and user-friendly design, along with its pre-loaded databases can be used to conveniently and quickly screen the various impacts of different DLC programs.

In this paper, Section II describes the methodology used in GridPIQ and talks about the influencing factors and impacts. Section III presents the study performed using the DLC module to illustrate the impacts of various DLC programs. Section IV concludes the paper.

II. Methodology

GridPIQ has a modular design and its different modules interact with each other to compute the impacts of different types of grid projects like DLC, ES, PV etc. Fig. 1 shows how DLC module and the other functions in GridPIQ are integrated to estimate the impacts of DLC programs. Curtailments and load shifts due to DLC occur at the end-use level, but utilities typically have data at the substation or generation level. Hence, a Line Loss Correction function translates the pre-project load data from the original level (generation or substation) to end-use level. Based on the load data at the end-use level, DLC module selects n days with the highest peaks in each calendar year of the analysis period, where n is the user-specified DLC frequency. On those selected days, DLC is executed during the peak demand hours of length equal to the DLC duration to compute the load curtailments and the resultant load shifts. The Load-Relevant Impact Quantification function is fed the pre-project load data and the post-project load data, both at the end-use level, for determining the impacts on the local load profile. The second Line Loss Correction function translates the post-project load data at the end-use level back to the original level before estimating the impacts on fuels and emissions. The Fossil Fuel Correction function determines the dispatch stack for the system under analysis using regional historical generation data from the U.S. Energy Information Administration EIA [21]. Finally, the Emissions Quantification and the Fossil Fuel Impact Quantification functions use the outputs from the Fossil Fuel Correction function to estimate the impacts on emissions (CO_2, NO_x, and SO_2) and fossil fuel consumption respectively [4].

In this section, the inputs required to carry out the estimation process and the estimated impacts are briefly summarized.

A. *Factors Influencing Outcomes of DLC Program*

Estimation of the impacts of DLC projects requires careful incorporation of relevant details. The following three categories of factors influence the impacts of implementing a DLC program and are accepted as inputs in GridPIQ's DLC module for performing the impact estimation:

1) **Context**: The contextual factors shape the impacts of most smart grid projects, not just DLC programs. The context-specific inputs listed below capture the crucial information about location, historical load patterns, generation fuel mix, etc. and are required from the user. GridPIQ provides real-world reference values for each of these inputs, to help give the user perspective, but allows custom parameters.
    - Analysis region: The analysis region accounts for important factors such as line losses, fossil fuel correction, and emissions. GridPIQ leverages emission data from the Avoided Emissions and Generation Tool (AVERT) [22]. The AVERT considers the unit-level output of every fossil fuel plant in the country over 25 MW, and splits the country into 10 large regions that account for some of the boundary issues (such as power transfer between areas), while still capturing regional differences in emissions rate and fuel mixtures. These 10 regions are marked in Fig. 2. Users are asked to select one of the AVERT

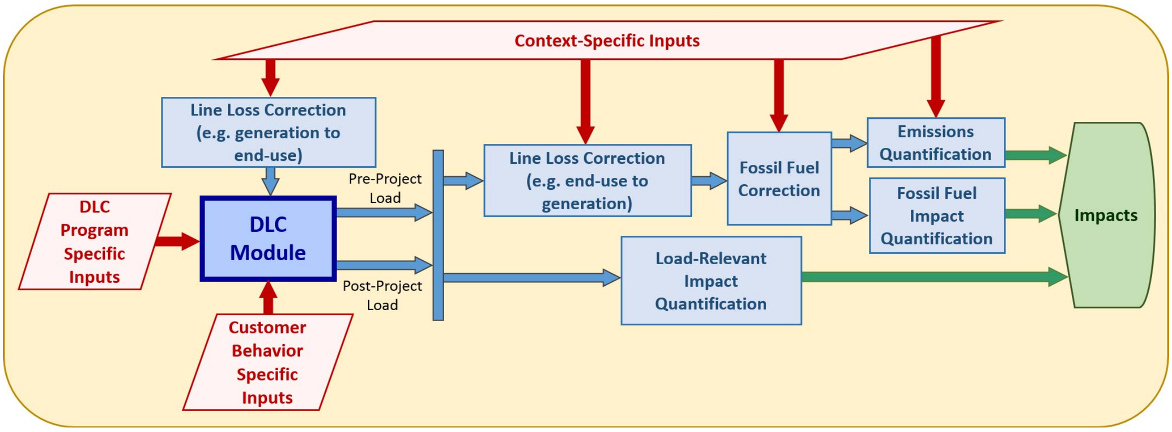


Fig. 1: This flow diagram illustrates how GridPIQ calculates the impacts of DLC projects.

regions that is most representative in terms of the above-mentioned contextual factors.

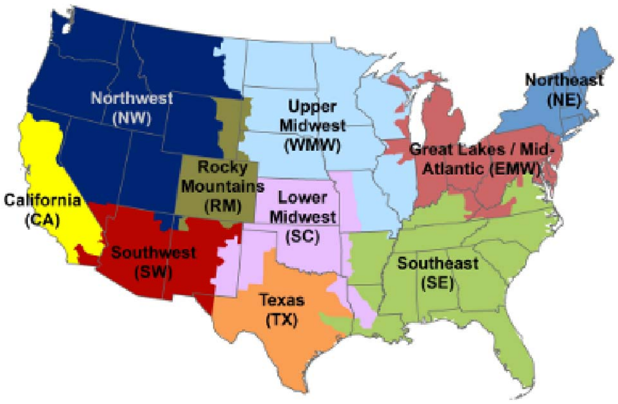


Fig. 2: Map showing ten AVERT regions [22]

- Pre-project load profile: The pre-project load profile establishes the shape of the hourly local load demand before the implementation of the DLC program under analysis. The pre-project load profiles provided through the GridPIQ website are hourly fossil fuel generation for each AVERT region [22].
- Pre-project maximum system load: The pre-project maximum system load represents the peak load demand before the introduction of the project, and therefore, the selected pre-project load profile is scaled to this value.
- Project grid location: The project's location within the grid dictates the modified line losses after the implementation of the project. A DLC project is typically located at the end-use and affects both transmission and distribution losses.

2) **DLC program-specific factors**: These factors refer to the specifications of the DLC program.
   - DLC participation: The percentage of the total load in the project that have been signed up by volunteering customers to participate in the DLC program.
   - DLC response: DLC response is defined as the percentage of the participating loads that are typically curtailed during DLC events. For accurately simulating DLC response, it is important to factor in the probability of the participating loads operating just before the event starts, and the percentage of DLC switches failing during each event. Loads not operating when an event starts or whose load control switches fail during the event cannot be curtailed.
   - DLC frequency: This input specifies the number of DLC events in each calendar year. Typically, the number of DLC events allowed in a calendar year is limited.
   - DLC duration: The DLC duration represents the duration of each DLC event. Typically, the total number hours of load curtailment that a utility is allowed to execute in a calendar day is limited.

3) **Customer behavior specific factors**: This includes information about the consumption behavior of the participating customers, and primarily determines the characteristics of the load shift due to DLC events. The utilities typically determine the customer-specific details by implementing pilot programs or surveys.
   - Load shift due to preconditioning and rebound: Customer behavior and the type of appliance being controlled influence the extent of load shift and whether it will be shifted before and/or after an event to compensate for the load curtailment. This factor is expressed as the percentage of the energy curtailed during each DLC event that gets shifted to before the event (preconditioning) and after the event (rebound).
   - Preconditioning and rebound ramp rates: The user may provide the preconditioning ramp rate (rate of increased energy consumption before the DLC event by those loads that will respond during the event) and the rebound ramp rate (rate of increased energy consumption by the affected loads after the DLC event). The rates are represented by the hourly rate of increase in consumption of additional energy, and is expressed as the percentage of the loads responsive to the DLC events. If the user provides the ramp rates, the duration of preconditioning and

rebound can be computed.
- Preconditioning and rebound durations: These inputs refer to the anticipated/typical duration of preconditioning and rebound. The preconditioning and rebound energy are equally distributed over the specified preconditioning and rebound durations. The user provides either the ramp rates or the durations for preconditioning and rebound.

B. *DLC Impacts Estimated by GridPIQ*

The three types of factors discussed in Section II-A are accepted and processed to compute the impacts of implementing the DLC project. The impacts listed below are provided as outputs by GridPIQ.

- Post-project load data: The modified local load demand data after the implementation of the DLC program are provided.
- Post-project maximum system load: DLC programs are typically aimed to shave the load peaks. Although the load curtailment during an event lowers the load consumption during the peak times, the preconditioning and/or rebound leads to increase in load before and/or after the event. As a result, the post-project maximum system load or peak demand may decrease or increase from the pre-project maximum system load. The percentage of change in this value before and after the DLC program implementation is computed.
- Maximum ramp rates (up and down): The instantaneous load curtailment during a DLC event and the aggressive load consumption before and/or after the event may lead to change in the maximum ramp rates (both ramp-up and ramp-down). The percentage of change in the ramp rates due to the implementation of the DLC program is reported.
- Total energy consumption: The percentage of change in the energy consumption after the implementation of the DLC program with respect to the pre-project energy consumption.
- Emissions: The changes in CO_2, SO_2 and NO_x emissions with respect to their corresponding pre-project emission estimates, expressed in the form of percentages, are provided.
- Fuel costs: The change in fossil fuel costs due to the shift of the load from the peaks to adjacent periods will be provided in the future. This feature is currently under construction.

III. Studies of the Impacts of DLC Programs Using GridPIQ

In this section, simulations are performed using GridPIQ, and the impacts of each of the factors on the peak load and maximum load ramp rates are demonstrated. The impact on the emissions are also touched upon. This section also highlights the importance of context when estimating the impacts of DLC programs.

A. *Details of Simulated DLC project*

A sample DLC project with the following inputs has been used, and only the input whose impact is being analyzed has been changed for each study.

- Contextual inputs: For the analysis provided in this section, AVERT generation data for the year 2015 have been used for the pre-project load profiles.
- Pre-project maximum system load: 50,000 MW
- DLC participation: 10%
- DLC response: 85%
- DLC frequency: 25 per calendar year
- DLC duration: 6 hours
- Load shift: (preconditioning 20%, rebound 80%)
- Load shift ramp rates: (preconditioning 33%, rebound 33%)

DLC frequency and duration have been specified based on a practical DLC program [23]. DLC response has been set to 85% based on the reported switch success rate [24].

B. *Study of Impacts*

The first analysis presents estimates of the impacts on local peak demand and generation ramp rates when each of the individual inputs are changed while holding other inputs constant. The importance of each of the factors considered in shaping the outcomes have been discussed. GridPIQ can be used to estimate the impacts of all the inputs mentioned in II-A when all of them act together, and hence it can be conveniently used a screening tool when designing DLC programs.

- **Study 1 - Varying contextual factors**: Hypothetical DLC programs with the same values of the DLC-specific inputs and the customer-behavior specific inputs, but different context-specific inputs have been run through GridPIQ to determine the impacts of context. Load profiles of the ten AVERT regions scaled to the same peak value have been used as pre-project load data. Fig. 3 and 4 show the change in peak demand and the ramp rates due to the implementation of the same DLC project at different locations. Fig. 5a, 5b, 5c and 5d show how the load profiles of NW, SC, SW, and NE regions, respectively, can result in vastly different impacts even when the same DLC program is implemented and the same customer behavior is assumed. When there is preconditioning and/or rebound phenomenon, if the peak being shaved is flatter, it may lead to formation of a new peak.
  The same DLC program can have widely different consequences on the peak demand and the maximum ramp rates. Although load curtailment due to the DLC events are anticipated to result in peak demand reduction, in a handful of cases preconditioning and/rebound may result in an increase in the peak demand. Fig. 3 shows that the DLC program being analyzed here may lead to decrease or increase in peak demand after program implementation. Here, the NW and SW regions experience increases in peak demand due to the same DLC program, which results in peak demand reduction in all the other regions. This illustrates the importance of tailoring a program

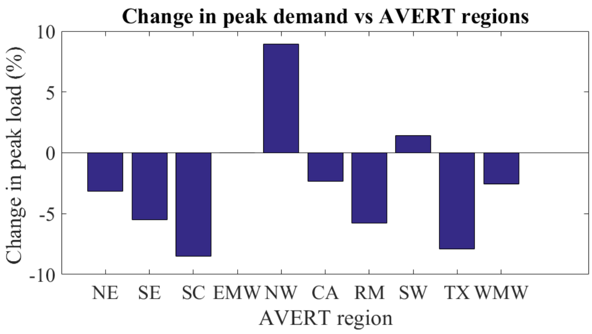


Fig. 3: Change in peak demand due to implementation of the DLC program.

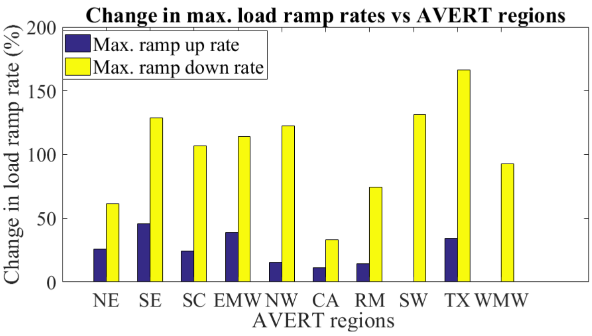


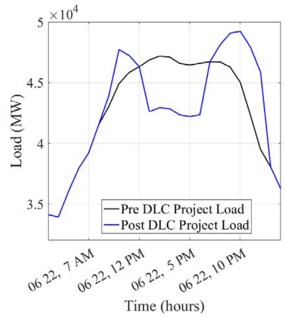
Fig. 4: Change in ramp rates (up and down) due to implementation of the DLC program.

to the specific context, and how GridPIQ could aid in screening different programs.

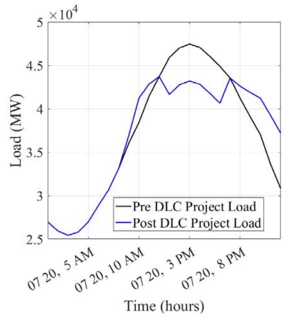
For the subsequent analyses, the SC, NW, and NE regions have been used, because they showed the highest decrease, highest increase, and median change in peak demand.

- **Study 2 - Increasing DLC participation and/or response**: DLC programs with different response values, keeping all other inputs constant have been run through GridPIQ to determine the influence of DLC response. Increase in DLC participation and/or response means greater load curtailment during DLC events. Fig. 6a shows that SC region experiences a reduction in peak demand with an increase in DLC response. In case of NE region as well, there is a decreasing trend even though not as significant as compared to SC region. However, in a handful of cases (e.g., NW region here), the increased load curtailment translates into increased load shift, and may lead to increased peak demand. It is seen that the trend established by the context is maintained in case of peak demand. An increase in DLC response typically leads to an increase in the maximum ramp-up rate as seen in Fig. 6b.
- **Study 3 - Varying load shift (preconditioning and/or rebound)**: In this study, all factors have been kept constant, and only the load shift due to preconditioning or rebound has been varied. Customer behavior plays a critical role in shaping the consequences of any DLC program. The increased load shift from the DLC event duration to the adjacent periods determines the effective peak demand after the project implementation. More load shift can lead to decreased reduction or increase in peak demand. Figure 7a shows that in NW region, an increase in load shift has resulted in an increase in peak demand. For the same load shift, the change in peak demand may be different in the case of preconditioning and rebound 7a, 7b.

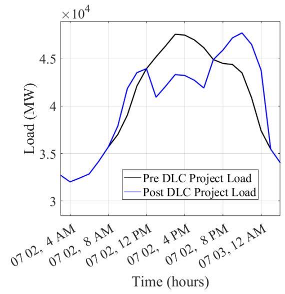
  Fig. 8a shows the impact of load shift on total energy consumption. As expected, a linear increase in load shift results in a linear increase in energy consumption after project implementation. Although the same pre-project maximum system load is used for all the simulations, the percentage of change in energy consumption is different based on the different pre-project load profiles, which lead to different energy consumptions.



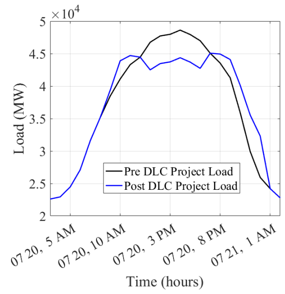
(a) Impact in the NW region.



(b) Impact in the SC region.

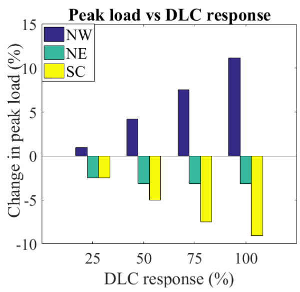


(c) Impact in the SW region.

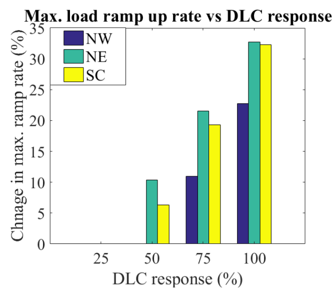


(d) Impact in the NE region.

Fig. 5: Pre-project and post-project load data for a sample DLC event day with same DLC project specifications and same customer behavior in four different AVERT regions.

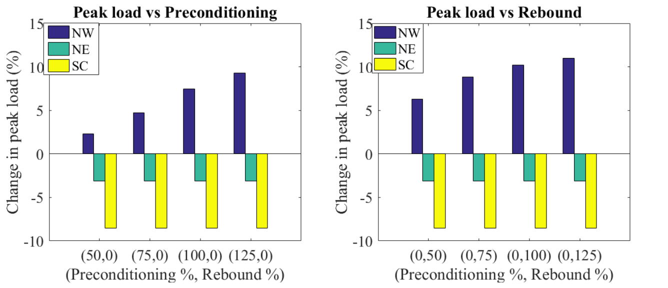


(a) Impact on peak load.



(b) Impact on ramp rate.

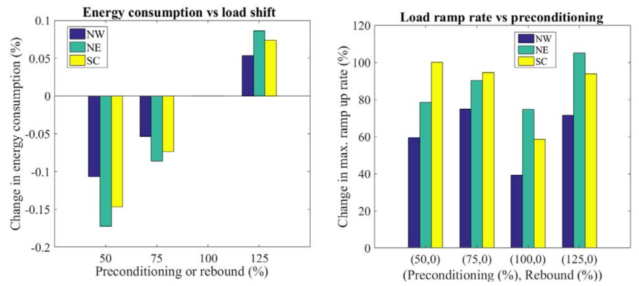
Fig. 6: Percentage change in load peak and maximum ramp-up rate due to different DLC responses.



(a) Impact on peak load. (b) Impact on peak load.

Fig. 7: Percentage change in load peak due to extent of preconditioning or rebound of DLC events.

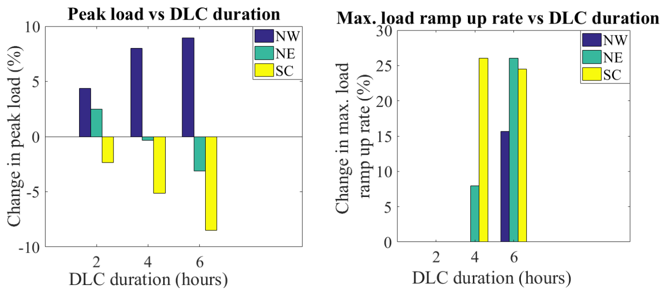
Fig. 8b shows that load ramp rate changed with the increase in preconditioning for the three regions. However, no definite trend was observed in this case. For the same increase in rebound, since no change in load ramp rate was observed, the plot has not been shown here.



(a) Impact on energy consumption. (b) Impact on maximum load ramp-up rate.

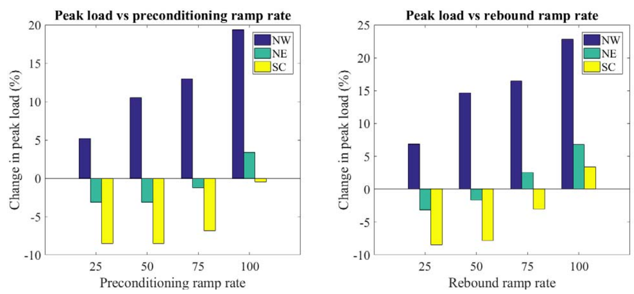
Fig. 8: Impact due to the extent of preconditioning or the rebound of DLC events.

- **Study 4 - Increasing DLC duration**: For this study, all factors were maintained constant except DLC duration. Greater DLC duration will typically lead to greater load curtailment. A peakier pre-project load profile will result in greater load curtailment for the same increase in DLC duration. However, for a given load shift, an increase in DLC duration can lead to either a decrease or an increase in the peak demand. Fig. 9a and 9b show the impact of changing DLC duration on the peak demand and the maximum ramp-up rate, respectively. Even for this study, the trends established by the contextual factors are observed to be maintained for this specific range of DLC duration values.
- **Study 5 - Preconditioning and/or rebound ramp rates**: The ramp rates of preconditioning and rebound have significant influence on the effective post-project peak demand and ramp rates. In this study, either the preconditioning or rebound rate was changed while all the other factors were maintained constant. Fig. 10a, 10b, 11 show that greater ramp rates of preconditioning and rebound result in decreased reduction or increase in peak load and maximum load ramp (up and down) rates after the implementation of the DLC project.



(a) Impact on peak load. (b) Impact on ramp rate.

Fig. 9: Percentage change in load peak and maximum positive ramp rate due to DLC duration. For DLC duration of 2 hours, there was no impact on maximum load ramp rate.



(a) Impact on peak load. (b) Impact on peak load.

Fig. 10: Percentage change in the load peak due to the preconditioning and rebound ramp rates.

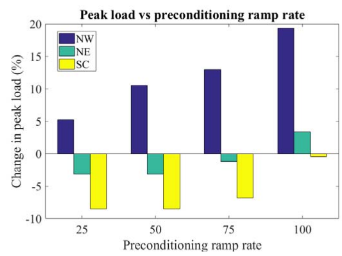


Fig. 11: Change in maximum ramp-up rate due to the preconditioning ramp rate.

It is important to determine the behavior of the customer to estimate the impacts of the DLC project with greater accuracy. For a system in which the customers are anticipated to compensate for the energy curtailment at a high ramp rate, the system might not experience effective reduction in peak load. The generator ramp-rate requirements are also expected to increase due to the increase in the maximum load ramp-up rate. But it should be noted that customer behavior alone does not decide any of the impacts, and the combination of all the discussed factors should be considered.

In this paper, we have illustrated and discussed the changes in peak load and maximum load ramp rates due to DLC project implementation. However, it should be mentioned that due to the shift in load (even in the case of a 100% load shift) from the DLC period to the adjacent period, the consumption of different fuels may change. This will lead to a change in the fuel costs incurred, and also result in a change in emissions. Fig. 12, 13 and 14 show a plot of estimated hourly CO_2, SO_2 and NO_x emissions, respectively, between 28 July and 3 August, 2015, for the NW region before and after DLC program implementation.

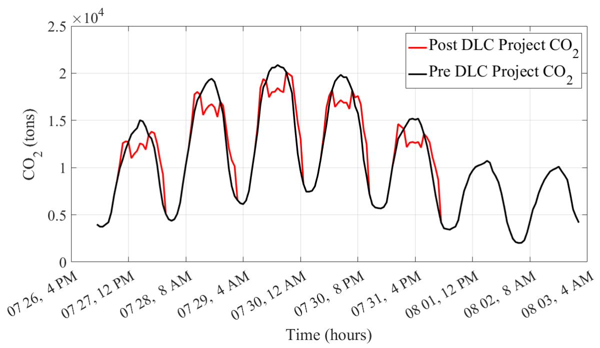


Fig. 12: Change in CO_2 emissions in July 2015 due to implementation of a DLC project.

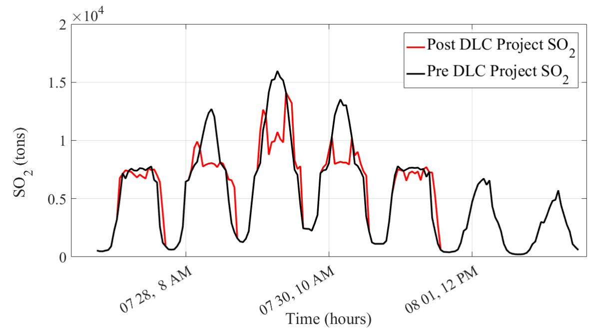


Fig. 13: Change in SO_2 emissions in July 2015 due to implementation of a DLC project.

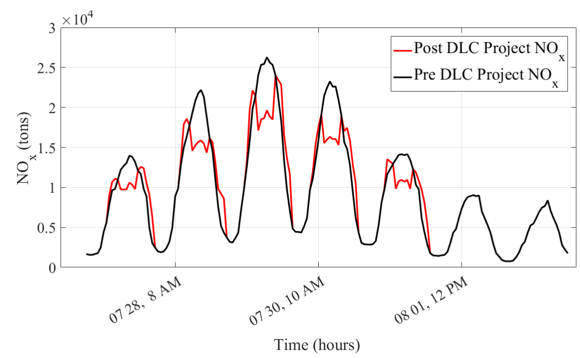


Fig. 14: Change in NO_x emissions in July 2015 due to implementation of a DLC project.

IV. Conclusion

In this paper we show that context, DLC program-specifications, and customer behavior collectively shape the impacts of a DLC project. Although load profiles can be similar—peaking around the afternoon time—the subtle differences in their slopes and so on can lead to different impacts even when the program specifications and customer base remain the same. The regional location dictates the dispatch stack and should be considered when estimating the change in the fuel cost and the emissions. Customer behavior determines the percentage and period of load shift, and the ramp rate of preconditioning and/or rebound, all of which are critical for estimating the post-project peak load, energy consumption, and generation ramp-rate requirements. The DLC program-specific details not only determine the load curtailment, but also influence the load shift. DLC frequency and duration are both controllable, and DLC participation can be motivated by using pricing schemes. Therefore, these specifications should be designed so that the project objectives are achieved. Prior analysis of the impacts of implementing a potential DLC project should be performed with due consideration to all of the discussed factors. GridPIQ allows researchers, utilities, regulators etc. to conveniently estimate the individual or combined system wide impacts of DLC programs, based on the specifics about their underlying context, program details, and customer behaviors.

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References

[1] PNNL. Grid impact quantification tool. Available: https://gridpiq.pnnl.gov/app and https://gridpiq.pnnl.gov/doc.

[2] K. E. Studarus, T. D. Hardy, B. L. Thayer, R. G. Pratt, and E. M. Lightner, "Quantifying the Emissions Impacts of Smart Grid Projects with a Publically Available Web-Calculator," in *IEEE PES General Meeting*, Boston, MA, July 2016.

[3] E. Barrett, B. Thayer, K. Studarus, and S. Pal, "The Varied Impacts of Energy Storage and Photovoltaics on Fossil Fuel Emissions," in *IEEE PES General Meeting*, Chicago, IL, July 2017.

[4] ——, "Investigating Time Varying Drivers of Grid Project Emissions Impacts," in *2017 IEEE Conf. on Technologies for Sustainability*, Phoenix, AZ, Nov. 2017.

[5] ——, "The Emissions Impacts of Varied Energy Storage Operational Objectives Across Regions," in *2017 IEEE Conf. on Technologies for Sustainability*, Phoenix, AZ, Nov. 2017.

[6] M. Alexander, K. Agnew, and M. Goldberg, "New Approaches to Residential Direct Load Control in California," in *ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA, Aug. 2008.

[7] "Direct Load Control Event," EPRI, 2010. [Online]. Available: http://smartgrid.epri.com/UseCases/Direct%20Load%20Control%20V3.2.pdf

[8] "Peak-to-average electricity demand ratio rising in New England and many other U.S. regions," EIA, 2014. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=15051

[9] "Report on Efforts to Reduce Electric Peak Demand," Michigan Public Service Commission, 2010. [Online]. Available: https://www.michigan.gov/documents/mpsc/reduce_peak_demand_12_10_341373_7.pdf

[10] Rocky Mountain Institute, "Demand Response: An Introduction," Boulder, CO, Tech. Rep., April 2006.

[11] "Emergency Demand Response (Load Management) Performance Report ," PJM, July 2012. [Online]. Available: http://www.pjm.com/~/media/markets-ops/dsr/emergency-dr-load-management-performance-report-2012-2013.ashx

[12] (2016) Residential Demand Response Programs. Clearly Energy. [Online]. Available: https://www.clearlyenergy.com/residential-demand-response-programs

[13] "Take a Load Off - Direct Load Control Program," JCPB, 2014. [Online]. Available: https://www.jcpb.com/pdf/dlcAgreementToParticipate.pdf

[14] J. D. Cook, "Residential air conditioners direct load control energy partners program," in *Proceedings of the First Annual Symposium on Improving Building Energy Efficiency in Hot and Humid Climates*, College Station, TX, 1994.

[15] Michaels Energy, "Demand Response and Snapback Impact Study," La Crosse, WI, Tech. Rep. COMM/OES-04042011-40697, Aug. 2013.

[16] S. Mecum, "A wish list for residential direct load control customers. ACEEE summer study on energy efficiency in buildings," American Council for an Energy Efficient Economy (ACEEE), Pacific Grove, CA, 2002. [Online]. Available: http://www.eceee.org/library/conference_proceedings/ACEEE_buildings/2002/Panel_2/p2_15/paper

[17] A. Belov, N. Meratnia, B. J. van der Zwaag, and P. Havinga, "An efficient water flow control approach for water heaters in direct load control," 2014.

[18] "Smart Grid 2.0: Empowering Consumers with New Demand Response Technologies," Landis+Gyr, 2014. [Online]. Available: http://www.landisgyr.com/webfoo/wp-content/uploads/2014/06/LAN-14022_Ezine_Issue9_lowresFINAL.pdf

[19] B. J. Johnson, M. R. Starke, O. A. Abdelaziz, R. K. Jackson, and L. M. Tolbert, "A dynamic simulation tool for estimating demand response potential from residential loads," in *2015 IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Feb 2015, pp. 1–5.

[20] M. A. A. Faruque and F. Ahourai, "Gridmat: Matlab toolbox for gridlab-d to analyze grid impact and validate residential microgrid level energy management algorithms," in *ISGT 2014*, Feb 2014, pp. 1–5.

[21] "Electric Power Detailed State Data," U.S. Energy Information Administration, 2016. [Online]. Available: https://www.eia.gov/electricity/data/state/

[22] "AVoided Emissions and geneRation Tool (AVERT)," US Environmental Protection Agency, 2016. [Online]. Available: https://www.epa.gov/statelocalclimate/avoided-emissions-and-generation-tool-avert

[23] "Agricultural and Pumping Interruptible Program (AP-I)," Southern California Edison, 2013. [Online]. Available: https://www.sce.com/wps/wcm/connect/bed771c5-9e2f-4246-a539-919248499b1d/AgriculturalPumpingFactSheet.pdf?MOD=AJPERES

[24] Stephen S. George and Josh Schellenburg and Peter Malaspina and Dries Berghman, "Load Impact Estimates for Southern California Edison's Demand Response Programs: Agricultural and Pumping Interruptible Program Real Time Pricing," San Francisco, CA, Tech. Rep. SCE0313.03, June 2012.