PNNL-36933

Evaluating the Thermal Impacts of Inadvertent Export on Service Transformers

October 2024

1 Eran Schweitzer
2 Todd Wall

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from
the Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062
www.osti.gov
ph: (865) 576-8401
fox: (865) 576-5728
email: reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
or (703) 605-6000
email: info@ntis.gov
Online ordering: http://www.ntis.gov

1 Introduction

In the context of the i2X project[1] PNNL was asked by Enphase to conduct a technical assistance investigation into the thermal impacts of inadvertent export on service transformer lifetime. Enphase manufactures microinverters and provides solar and storage solutions that allow for limited export operation.

Recently the BATRIES Toolkit [1] from IREC and EPRI investigated the challenges surrounding inadvertent export when a power control system (PCS) is used on a DER installation. Both the BATRIES toolkit and IEEE Std. 1547-2018 clause 4.6.2 [2] state that the response of a PCS should be no more than 30 seconds. This upper limit is intended to avoid interaction with other regulating devices on the system. At the same time, no lower limit has been established, and some grid operators were recommending a response time of 2 seconds, to align with the operation of non-export relays.

Enphase is under the impression that at least some of the desire for a quicker response, is due to concerns around transformer lifetime reduction, resulting from thermal impacts during inadvertent export events. In response, the goal of this study is to model the thermal impacts of inadvertent export on service transformers to evaluate the likelihood of substantial lifetime impacts.

The remainder of the report is structured as follows. The analysis methodology is presented in Section 2. The results are in Section 3, and Section 4 summarizes the findings.

2 Study Methodology

The thermal impacts are evaluated on the basis of IEEE Std C57.91-2011 [3] for a range of inadvertent export events. The impact of a single event is coupled with the decay back to normal temperature. The reasoning behind presenting the results in such a manner is that multiple events within the decay period, can be summed together to a single larger event, while events that are separated by more than the decay period, can be treated independently. This methodology is chosen to get around the difficulty of sampling from many different inadvertent export events to come up with probabilities. Assembling such a dataset is out of scope for this project. Instead, the methodology presented here is based on the concept of design assumptions. The benefit is that these could be adjusted on a feeder-by-feeder basis.

In addition to the core evaluation of transformer thermal impacts, 15-minute energy data provided by Enphase is processed and analyzed to develop a guide for estimating an appropriate nominal loading for the service transformer, which is needed in the thermal impacts calculations. Once again, the concept is that of design assumptions. In this case, the design assumptions are customer coincidence factors, and the choice of defining statistically what is “typical” flow.

[1] https://www.energy.gov/eere/i2x/interconnection-innovation-e-xchange

2.1 Thermal Impacts

2.1.1 Parameters

The study of the thermal effects of inadvertent export on service transformers focuses on the following 3 parameters:

- *Normal loading* L_n: the transformer loading (in per-unit) prior to an inadvertent export event.
- *Inadvertent loading* L_v: the transformer loading (in per-unit) during the inadvertent export event.
- *Inadvertent export duration* t_v: the duration (in seconds) of the inadvertent export event.

A test matrix of possible conditions consists of varying the above parameters over the following ranges:

- $L_n \in \{0.5, 0.75, 0.9, 1.0\}$ (4 variants)
- $L_v \in \{1.25, 1.5, \ldots, 2.5\}$ (6 variants)
- $t_v \in \{2, 5, 10, \ldots, 30\}$ (7 variants)

In total, these represent $4 \times 6 \times 7 = 168$ test cases.

2.1.2 Outcomes

For each case in the test matrix, the following outputs are derived:

- *Settling time*, t_s: duration (in seconds) following the inadvertent export event until the hot spot temperature settles back to within 1% of its initial value.
- *Loss of Life*: impact of the inadvertent export, measured using the equivalent aging factor, F_{EQA}.

The loss of life is based on the equivalent aging factor F_{EQA}, calculated from the start of the inadvertent export event until the end of the settling time:

$$F_{\mathrm{EQA}} = \frac{\sum_t F_{AA}[t] \times \Delta t[t]}{\sum_t \Delta t[t]} = \frac{\sum_t F_{AA}[t] \times \Delta t[t]}{t_v + t_s}.$$

This number represents a weighted average of the aging acceleration factors, $F_{AA}[t]$, calculated during the inadvertent export event. In general, if this number is < 1, there is no ageing impact beyond rated or nominal aging[2].

One way to understand the equivalent aging factor is as follows. Assume that the event recurs continuously for a whole day, separated in time such that settling has already occurred ($t_v + t_s$).

[2] Rated or nominal aging is the aging due to continuous operation at the nameplate rating.

Based on this assumption, we can treat the events independently and assume that the F_{EQA} is therefore constant for the day. The equivalent aging hours are then:

$$F_{EQA} \times 24\ \mathrm{hr}$$

For example, if $F_{EQA} = 1.05$ it corresponds to 25.2 hours. In other words, the transformer would have aged 1.2 hours more during the day than if it were operated at its rating. Actually, what the F_{EQA} is implying, is that the transformer ages $F_{EQA} \times (t_v + t_s)$ seconds in $t_v + t_s$ seconds; however, given the short duration, this may be a bit stranger to intuit.

The objective of looking at t_s is to isolate the frequency component of inadvertent export events. As long as the expected frequency of inadvertent export events is lower than $1/t_s$, they can be treated independently and separately.

2.1.3 Using the Results

The matrix of results is able to handle the following type of query, assuming:

a) the inadvertent export frequency is no higher than $1/t_s$;

b) a reasonable normal loading on the transformer, L_n;

c) an F_{EQA} up to some value, x, is acceptable for an inadvertent export even.

What limits must be set on the magnitude, L_v, and duration, t_v, of inadvertent export from the perspective of transformer thermal impacts?

2.1.4 Calculation Method

The analysis utilizes IEEE Std C57.91-2011 [3] Clauses 5 and 7, as well as developments towards a new revision that utilize differential equations to solve for the thermal effects[3] in an update to Clause 7. The thermal impacts of transformers, however, are usually measured over hours and days, not seconds, and the integration over the shorter time differential leads to instability and oscillation in the results. For that reason, all inadvertent export events shorter than one minute (which are all in this study) are converted to an equivalent load based on equation (5) in Clause 7.1.2 of [3]:

$$L_{eq}[\mathrm{p.u.}] = \sqrt{\frac{L_v^2 t_v + L_n^2(60[\mathrm{s}] - t_v)}{60[\mathrm{s}]}}.$$

For the rest of the analysis, the newer differential equations based results are used. However, the analytical method, that is not subject to oscillation is used to show the equivalence of modelling an equivalent load.

[3] https://opensource.ieee.org/inslife/ieee-c57.91-thermal-models

Figure 1 compares the results when $L_n = 1$ p.u, $L_v = 2$ p.u., and $t_v = 20\ s$ using the analytical method. The similarity in hotspot peak and aging acceleration factor F_{AA} supports the argument that the solution using averaged minute load is comparable to the actual second representation in terms of thermal impacts.

Figure 2 shows results under the same configuration for the differential equations method. The hot spot temperature and F_{AA} using the differential equations method peaks higher, but the trend is similar. This provides some confidence in the differential equations method and justifies its use in the rest of the analysis. At worst, it can be seen as a conservative estimate with respect to the analytical method.

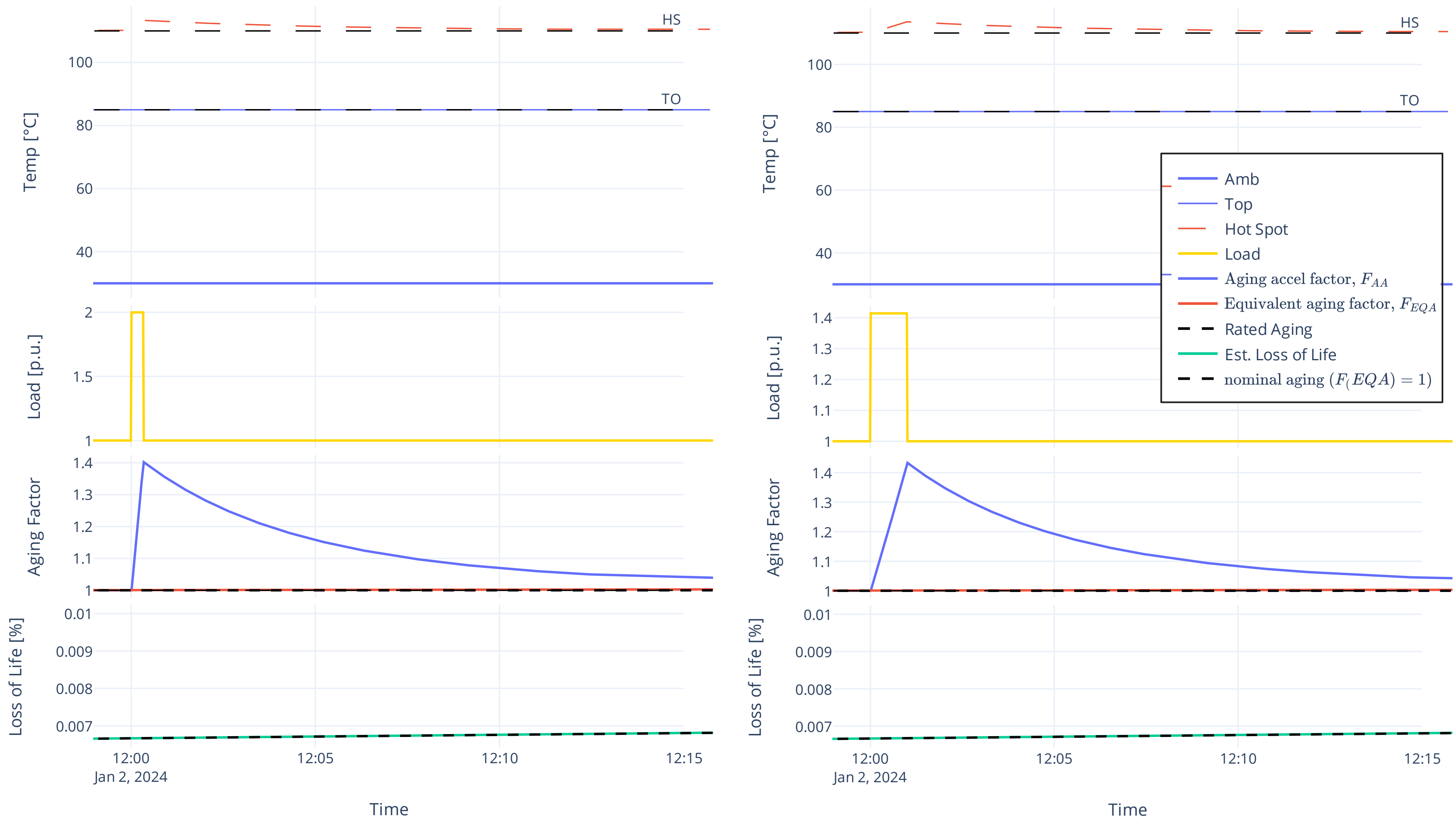


Figure 1 Comparison between results using the analytical method at the second level (left) and at loading averaged over a minute (right). The similarity between the two justifies the use of averaged minute load profiles.

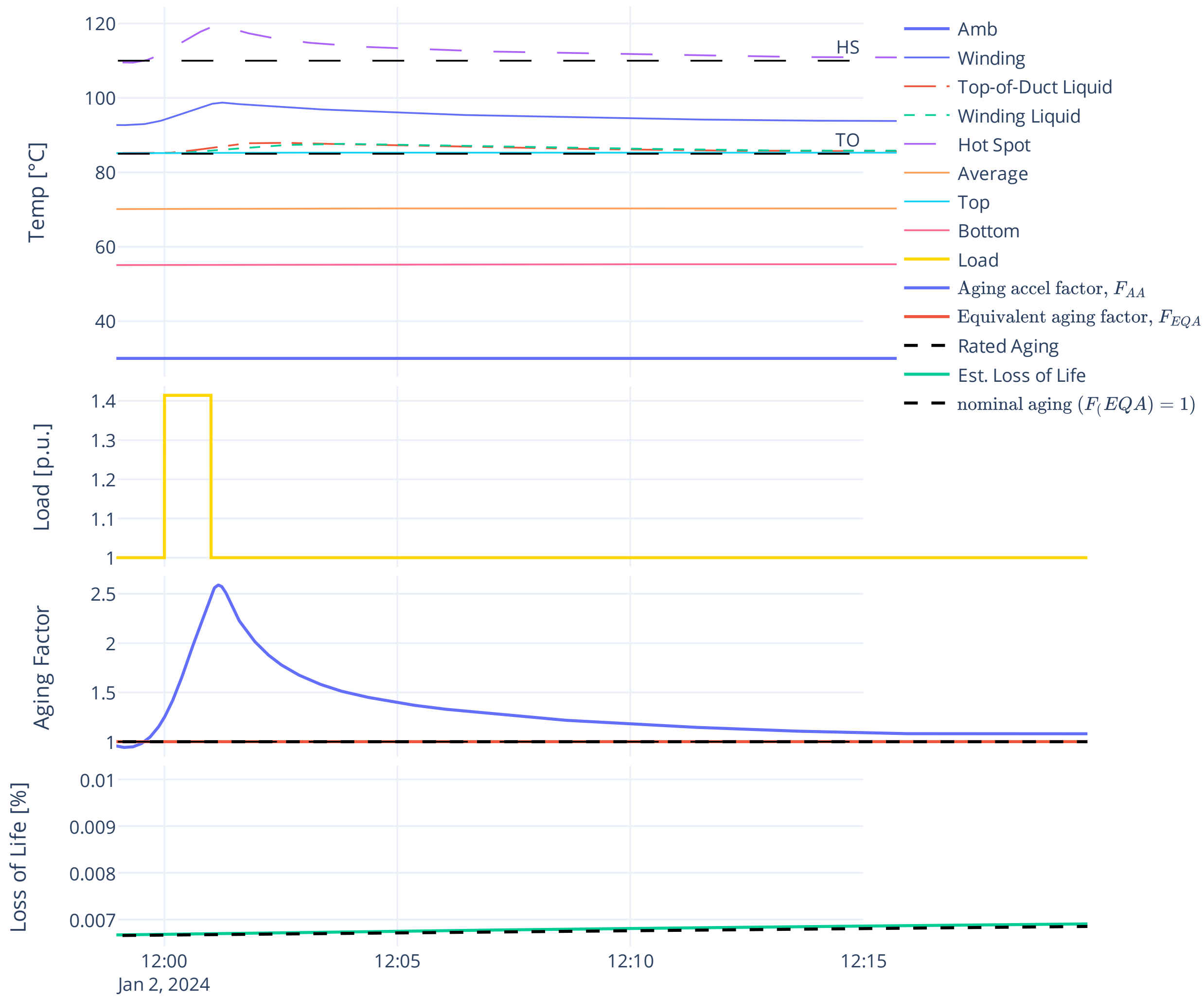


Figure 2 Results under same conditions in Figure 1 using the differential equations method.

2.2 Normal Loading Evaluation

Determining a transformer's normal loading is one of the main factors, in the method for determining the thermal impacts of inadvertent export. This final analysis is intended to compare the relative loading of a transformer serving "normal" loads to those with solar and storage.

Enphase provided over one year of 15-minute energy data for several locations. The data fields and their relationship to one another is illustrated in Figure 3.

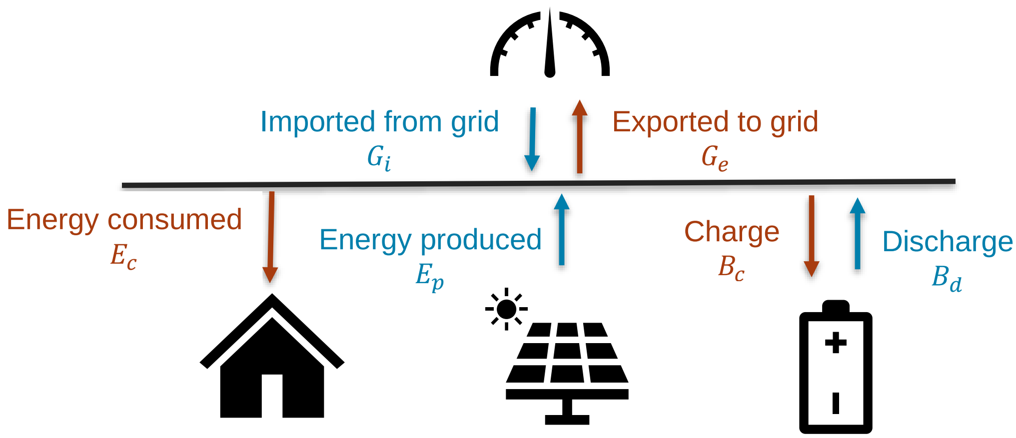


Figure 3 Relationship between reported values received from Enphase. All quantities are in Wh.

Based on the illustration the impact on the service connection *without* any solar or storage can be captured by the consumed energy, E_c. Similarly, the impact on the service connection *with* solar and storage is captured by the magnitude of the grid imports and exports, G_i and G_e. Since these are 15 minute energy values the average power value in Watts can be obtained by multiplying by 4 (dividing by 0.25 hours). Define,

$$\begin{aligned} p^0[t][\text{kW}] &= E_c[t] \times 4 \times 10^{-3} \\ p[t][\text{kW}] &= \max(G_i, G_e) \times 4 \times 10^{-3}, \end{aligned} \tag{1}$$

where p^0 and p represent the power impact to the service connection with and without solar and storage. The ordered statistics or simply the duration curve of the two curves can be compared to see which one is higher and at which part of the loading range. For example, it may be that one peaks higher, but is otherwise lower, etc.

Under the assumption of similar households connected to the same service transformer, these findings can be extrapolated to the service transformer. Specifically, the normalized order statistics can be used to estimate a normal loading. Under the assumption that the transformer rating, T_r, matches the maximum p^0 times a coincidence factor, c, the normal loading can be evaluated at a chosen percentile of p, for example, the 90$^{\text{th}}$ percentile. The transformer rating is assumed related to the maximum normal loading as:

$$T_r = c \times k \times \max p^0, \tag{2}$$

where k is the number of customers. Again, under the assumption that all the customers have similar systems, a "modified transformer rating" for the individual customer can be derived:

$$\frac{T_r}{k} = c \times \max p^0. \tag{3}$$

Note that this suggests that the transformer rating is smaller as the assumed coincidence factor decreases, since the utility is sizing the transformer based on that coincidence factor. The estimate of a reasonable transformer nominal loading, L_n, calculated based on a given percentile, i, of $p[t]$, and an assumed coincidence factor is:

$$L_n(c, i) = \frac{q_i(p)}{T_r/k} = \frac{q_i(p)}{c \times \max p^0}, \tag{4}$$

Where function $q_i(\cdot)$ returns the ith percentile of the argument data. For example, $q_{90}(p)$, would be the 90th percentile. Note that Equation (4) could be greater than one as described, however, assuming nominal loading above rating does not make sense. Therefore, the final definition is adjusted to:

$$L_n(c, i) = \min\left(\frac{q_i(p)}{c \times \max p^0}, 1.0\right). \tag{5}$$

Based on the resulting curve, an appropriate L_n can be selected if the system has, for example, a particular design coincidence factor and a choice of flow percentile to consider.

Note that this methodology only works under the assumption that the main function of the service is to provide load. This analysis does not hold for a connection that is predominantly a generation connection with perhaps just some auxiliary load.

2.2.1 Caveats

The relationship between p^0 and p is dependent on the optimization/operational mode of the solar and storage system. Available methods are:

- *Self Consumption*: Maximize local use of PV energy, minimize imports and exports.
- *Lowest Cost*: common for TOU rates, more imports at night and more exports during the day.

The method used in the provided data is not known, however, and is therefore a latent parameter in the analysis.

3 Results

3.1 Thermal Impacts

An evaluation of hotspot development and effect on transformer aging is conducted based on the test matrix developed in Section 2. The transformer parameters used in the simulations come from the IEEE Std C57.91 thermal models repository[4] and are reproduced in Table 1.

[4] https://opensource.ieee.org/inslife/ieee-c57.91-thermal-models/-/blob/main/Example_Data/transformer_thermal_nameplate.json?ref_type=heads

Table 1 Transformer Parameters Used in Simulations

Description	Value
Rated MVA of Transformer [MVA]	52
MVA at which losses were measured [MVA]	28
Temperature at which losses were measured [C]	75
Winding I^2R loss at rated load [W]	51690
Eddy loss of windings at rated load [W]	0
Power in stray losses [W]	21078
Power in core losses [W]	36986
Power in core losses when overexcited (load > 1) [W]	36986
Energy of hotspot [1]	1
Weight of core and coils [lb]	75600
Weight of tank and fittings [lb]	31400
Liquid volume [gal]	4910
Temperature of ambient at rated load [C]	30
Guarantee rated rise temperature [C]	65
Winding temperature rise at rated load [C]	63
Hotspot temperature rise at rated load [C]	80
Top Liquid temperature rise at rated load [C]	55
Bottom Liquid temperature rise at rated load [C]	25
Temperature correction for losses of winding [C]	234.5
Height of hotspot [1]	1
Winding time constant [min]	5
Cooling System	ONAN
Winding Material	Copper
Liquid Type	Mineral Oil
percent content of water in paper [%]	2
gas headspace pressure [mmHg]	760
Does transformer have thermally upgraded paper?	YES

Figure 4 shows the resulting equivalent aging factors, F_{EQA}, plotted against the time over which they are calculated, which is the time from when inadvertent export begins until the temperature settles, i.e. $t_v + t_s$. There are two key takeaways from the figure:

1. The only scenarios with an $F_{EQA} > 1$ have an initial loading of 100%. In other words, the aging due to inadvertent export thermal impacts when the initial loading, L_n, is below the transformer rating is no worse than normal operation at rated loading.
2. The most extreme F_{EQA} is around 2 and lasts somewhere around 25 minutes. This means that in 25 minutes the transformer would have aged something closer to 50 minutes under rated conditions. Under the assumption that inadvertent exports are not constant, this is a rather mild consequence, and under rather unlikely conditions of 100% loading pre-event and 250% loading during the event that lasts 25 seconds.

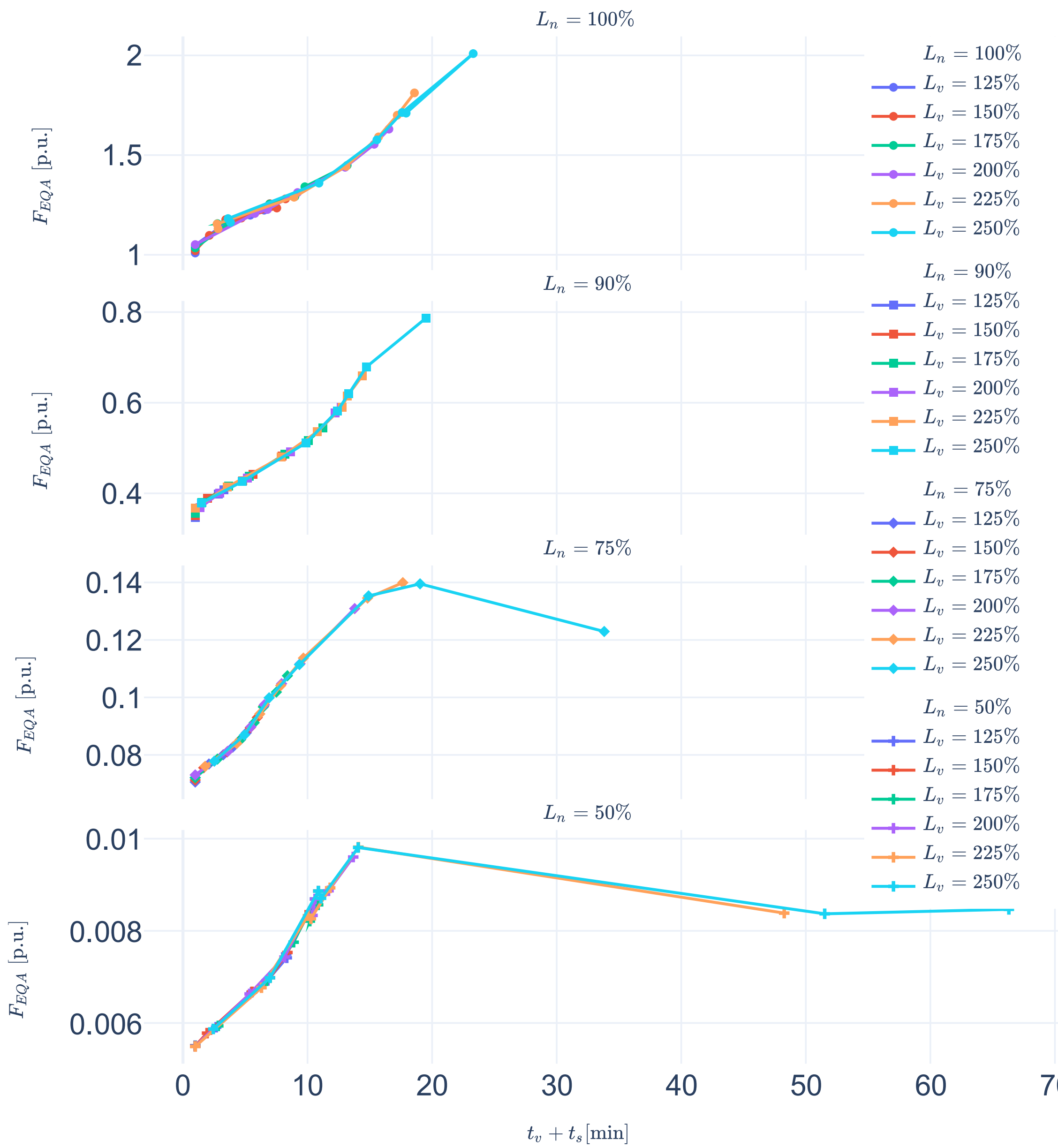


Figure 4 Results based on the differential equations method showing the equivalent aging factor,F_{EQA}.

An observation from Figure 4 is that the total time to settle is longest for low loading. This is largely a numerical artifact of the integration method under a very small perturbation. Given the low temperatures throughout, achieving the return to 1% of the original value appears to be close to the tolerance of the method. This is illustrated in Figure 5, showing that the long settling times exhibit a long flat stretch where the hot spot is very close to the 1% threshold. Importantly, the calculation method is designed to evaluate behavior *above* rating, therefore the slow decay for temperatures below rated values are largely not of significant concern.

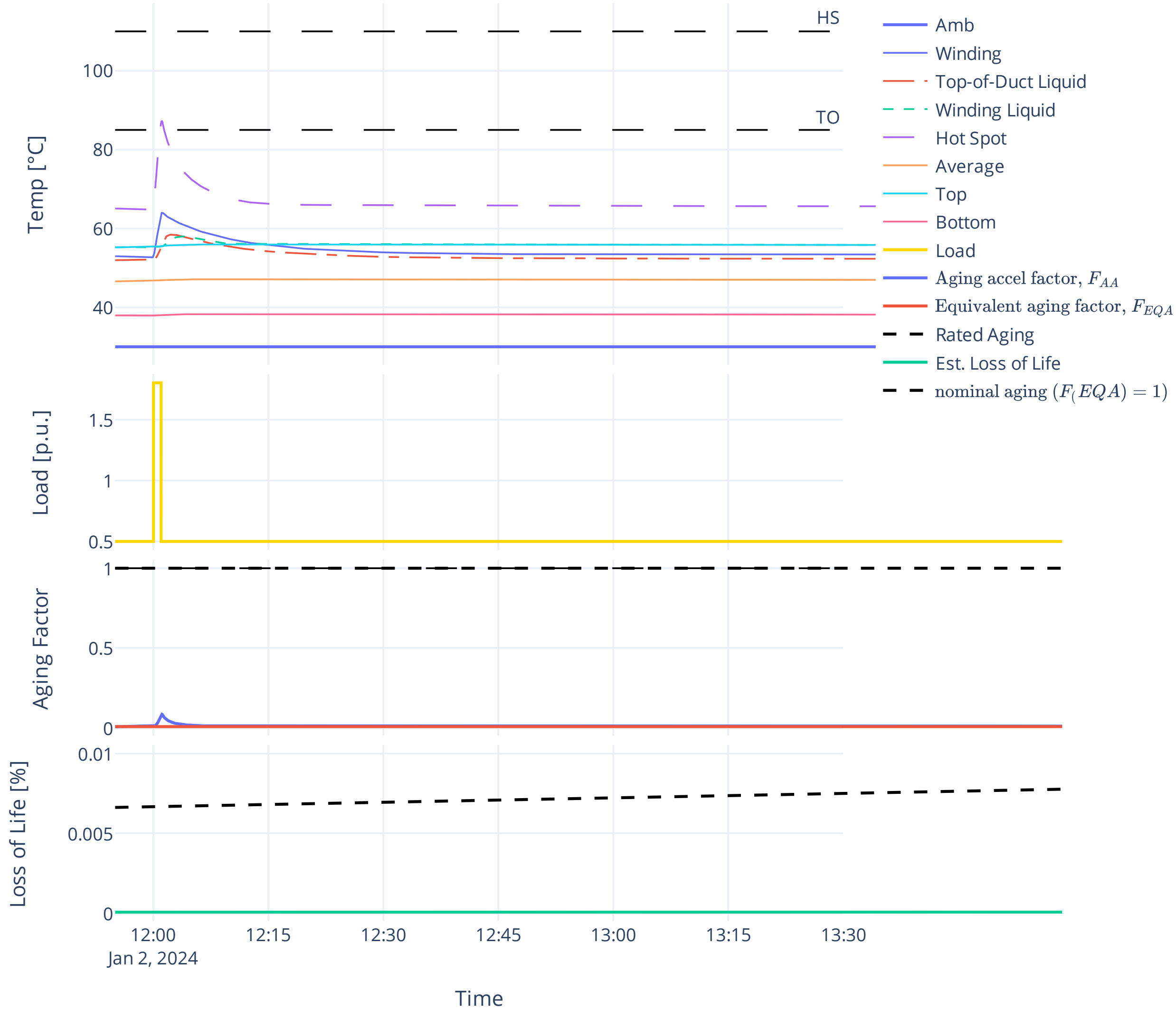


Figure 5 Thermal response of transformer with $L_n = 50\%, L_V = 250\%, t_v = 30\ s$. While hotspot settling within 1% of the initial value is reached around 13:15, the trace reveals that this is largely due to numerical precision. The trace appears very flat from roughly 12:30 on.

Given the stability and numerical issues with the differential equations method at these short time scales, the results based on the analytical method from [3] are also presented in Figure 6. The general trend is very similar, although the magnitude of F_{EQA} is lower by around 20-40%.

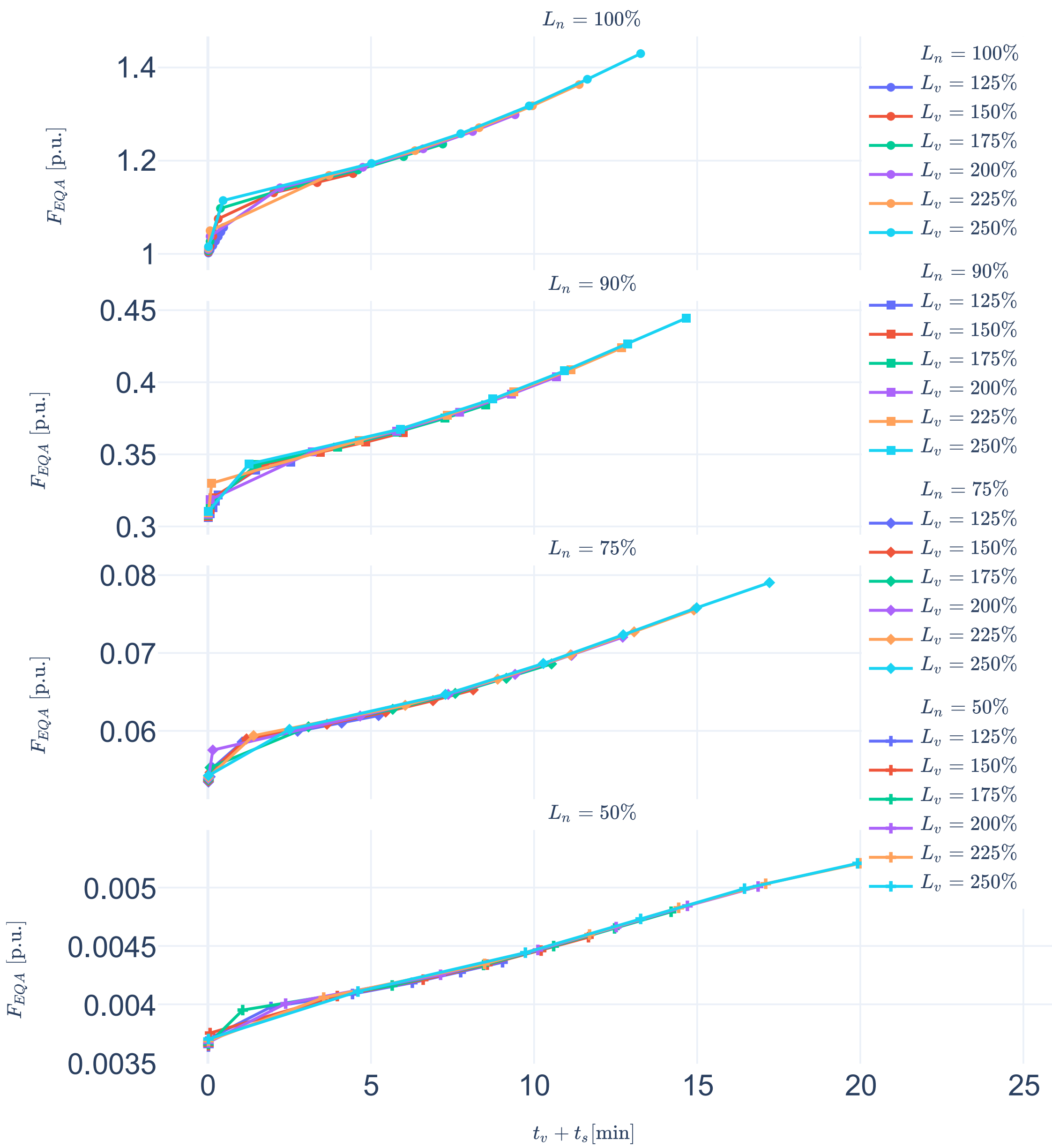


Figure 6 Results based on the analytical method from [3] showing the equivalent aging factor, F_{EQA}.

3.2 Normal Loading Evaluation

Enphase provided over a year's worth of data for six installations. The data was first processed and then loading statistics were developed as described in Section **Error! Reference source not found.**.

3.2.1 Data Cleaning

Some anomalies were observed in the data and were removed in a pre-processing step under the assumption that these are simply data error. The following describe these data cleaning steps.

Energy Balance

Figure 3 suggest the following energy balance:

$$\left(E_p - E_c\right) + (B_d - B_c) + (G_i - G_e) = 0. \quad (6)$$

Since the values are averaged over 15-minutes, there are some rounding errors that can accrue. However, it was observed that in a few cases, there are significant errors in the energy balance. Data points with an energy balance worse than $\pm 10\mathrm{Wh}$ according to (6) were discarded.

Negative Energy Consumed

In a few of the cases there are data points where the value of the consumed energy, E_c, is negative. Based on the definition in Figure 3, none of the values should be negative. A negative E_c, however, is particularly problematic for the analysis since it represents the impact on the service connection under normal condition according to (1). Therefore, data points with $E_c < 0$ were removed.

Extreme Value Removal

Working with the data showed that occasionally there were simply disproportionately large values in one of the fields. For example, normal energy produced generally peaks around 2500 Wh, but a couple trend above 100,000 Wh. For each of, E_c, E_p, G_i, G_e, the 99th percentile of the non-zero data is multiplied by 1.5 and used as an upper threshold. However, if this threshold leads to the elimination of 10 data points or more, the threshold is increased by successive multiples of 1.5, until no more than 10 points are eliminated.

Table 2 summarizes the number of data points removed from the data sets for each of the tests described above. The filtered chronological data traces are shown for reference and validation in Appendix A.

Table 2 Summary of Removed Data Points

Test\Site	A	B	C	D	E	F
Energy balance	174	0	0	0	3	3
$\boldsymbol{E_c < 0}$	468	282	0	1	139	98
Extreme $\boldsymbol{E_p}$	2	2	0	0	0	0
Extreme $\boldsymbol{E_c}$	0	1	0	2	1	6
Extreme $\boldsymbol{G_i}$	0	8	0	0	3	3
Extreme $\boldsymbol{G_e}$	0	0	0	0	0	0

3.2.2 Loading Statistics

The loading statistics for the six datasets (A-F) are presented in Figure 7, which shows the ordered statistics. The x-axis represents the quantiles of the data, so that the bin labeled 1 is showing the maximum value, while the bin labeled 0.8 is showing the 80^{th} percentile value.

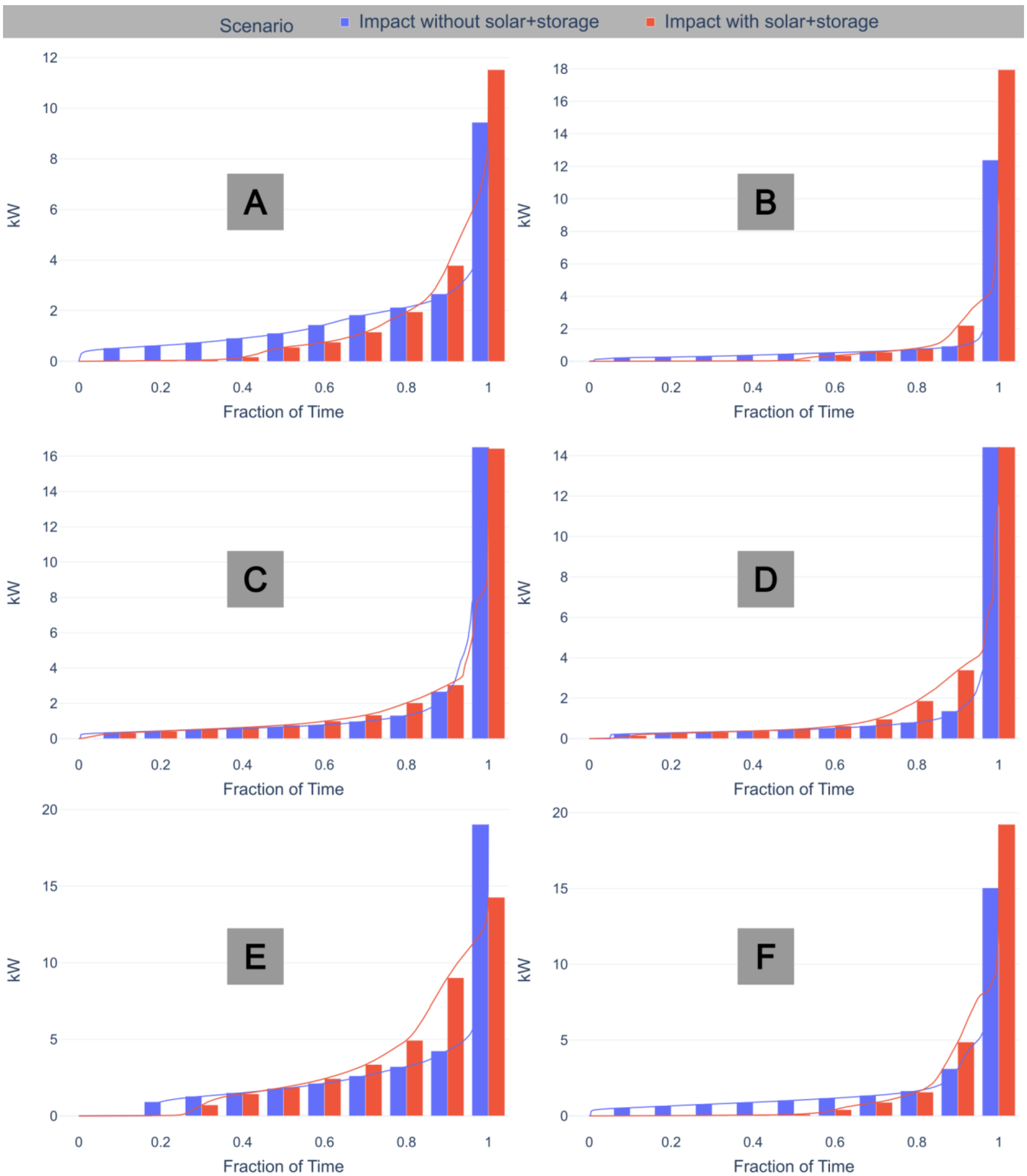


Figure 7 Ordered statistics for $p^0[t]$ and $p[t]$. Bars are shown for each of the 10th, 10^{th},20^{th},…,90^{th}, 100^{th} percentiles, while the lines show the full ordered data.

Figure 7 reveals several interesting pieces of information. First, the maximum power is generally somewhat higher with solar and storage compared to without. This is somewhat unexpected, as solar and storage is in general intended to reduce consumption/utilization of the service connection. A cursory inspection of the various curves in Appendix A suggests that these peaks may be due to occasional coincidence of charging and high consumption. This is, however, not the focus of this work and is therefore not investigated. A corollary second observation, is that solar and storage increases the percentage of time, where consumption is particularly low. In other words, solar and storage seems to push on both ends of the net exchange spectrum: more time with very low net consumption, balanced out by more weight on the upper percentiles and slightly higher peak values.

The estimated nominal loading, as a function of coincidence factor and chosen quantile according to Equation (5) is shown in Figure 8.

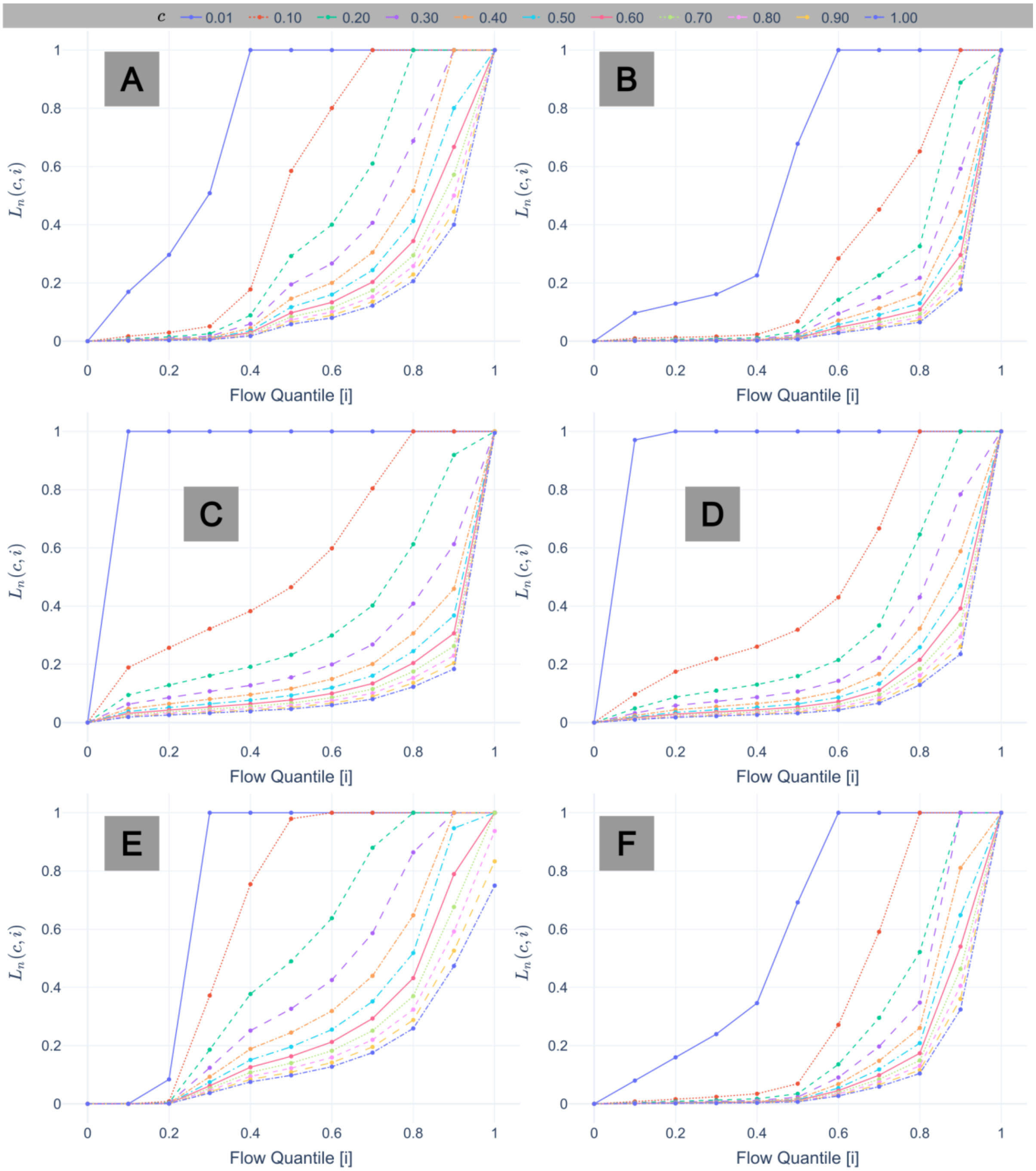


Figure 8 Estimated loading level based on assumed coincidence factor and chosen percentile flow, $L_n(c, i)$.

Figure 8 suggests that to estimate nominal loading L_n, as 100%, or even above 80%, requires assuming a fairly low coincidence factor (< 0.4, except for site E < 0.6), in combination with a high percentile choice of flow. This suggests that an appropriate choice of L_n from the thermal impacts results in Section 3.1 is less than 100%. Since inadvertent export only showed adverse thermal impacts at $L_n = 100\%$, this further supports a conclusion that thermal impacts are a negligeable concern with respect to inadvertent export.

4 Conclusions

A study of the thermal impacts of inadvertent exports on service transformers is investigated using the methods outlined in IEEE Std C57.91 for Mineral-Oil-Immersed Transformers [3], as well as current work on future revisions to the standard. The results demonstrate numerically that due to the very short duration of inadvertent export events and the comparatively long thermal time constants of transformers, the thermal impacts of inadvertent exports are largely negligeable. The findings are further strengthened by analysis of 15-minute energy data that are used to estimate the nominal loading assumption, L_n, on the service transformer. The analysis suggests that an appropriate L_n would be less than 100%. Since the only adverse thermal impacts from inadvertent export reported here occur under an assumption of $L_n = 100\%$, this data analysis provides further evidence that thermal impacts are of negligeable concern with respect to inadvertent export.

The BATRIES Toolkit from IREC [1] discusses various aspects of inadvertent export and suggests that response time should be no greater than 30 seconds to avoid interaction with voltage regulation equipment on the feeder. Additional concerns such as harmonics distortion in reverse operation could also play role. However, the analysis presented shows that, from a thermal perspective, there is no significant benefit of reaction times below 30 seconds.

5 References

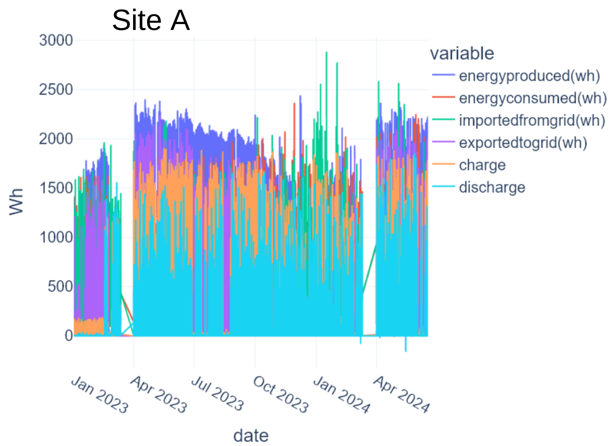
[1] "Toolkit & Guidance For the Interconnection of Energy Storage & Solar-Plus-Storage," 2022. [Online]. Available: https://energystorageinterconnection.org/resources/batries-toolkit/

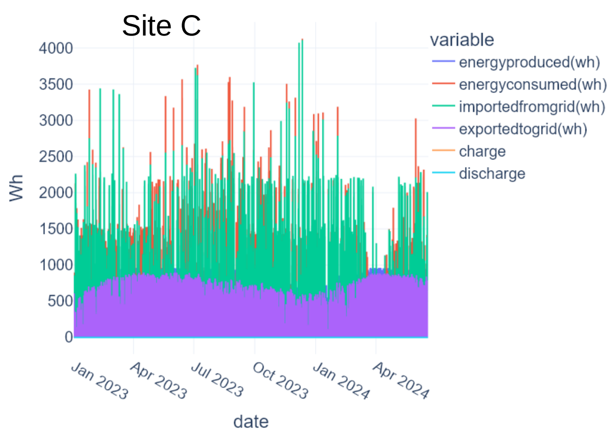
[2] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," *IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003),* https://doi.org/10.1109/IEEESTD.2018.8332112 pp. 1-138, 2018.

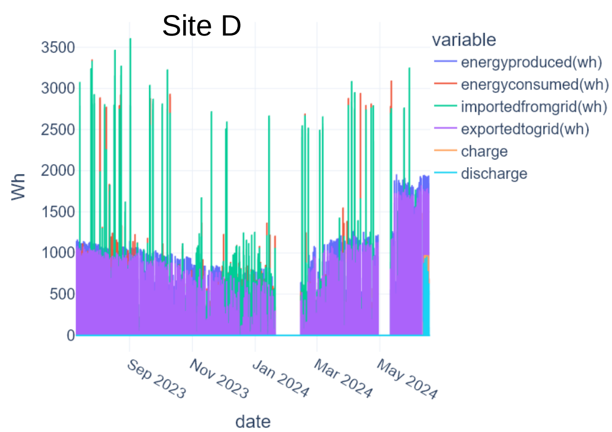
[3] "IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators," *IEEE Std C57.91-2011 (Revision of IEEE Std C57.91-1995),* https://doi.org/10.1109/IEEESTD.2012.6166928 pp. 1-123, 2012.

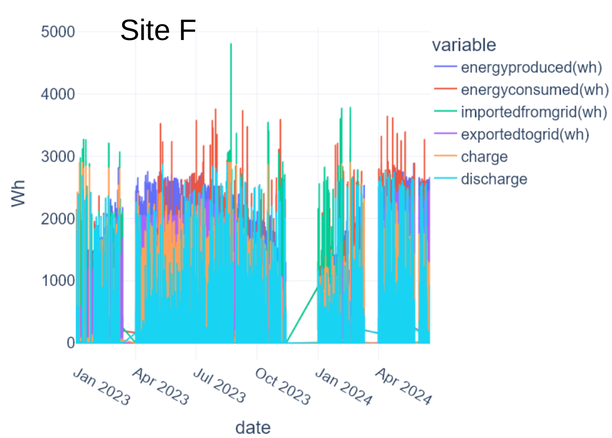
Appendix A Filtered Data Validation

The flowing figures show the filtered time series data for the 6 sites provided by Enphase. The apparent gaps are locations where data is missing, either because it was initially missing or because it was removed in the filtering process described in Section 3.2.1. The plots serve to show that the vast majority of the data is preserved and that there are no extreme peaks remaining in the data.









Pacific Northwest
National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov