



July 25, 2024

Ms. Lisa Felice  
Michigan Public Service Commission  
7109 W. Saginaw Hwy.  
Lansing, MI 48909

*Via E-File*

RE: MPSC Case No. U-21534

Dear Ms. Felice:

Attached please find the enclosed documents for filing:

- Direct Testimony and Exhibits of Graham G. Woolley on behalf of Citizens Utility Board of Michigan and Michigan Environmental Council (Exhibits CUB-30 through CUB-33); and
- Proof of Service.

Thank you for your assistance in this matter. If you have any questions, please feel free to contact me.

Sincerely,

Christopher M. Bzdok  
[chris@tropospherelegal.com](mailto:chris@tropospherelegal.com)

CC: Parties to Case No. U-21534

STATE OF MICHIGAN

BEFORE THE MICHIGAN PUBLIC SERVICE COMMISSION

In the matter of the application of **DTE  
ELECTRIC COMPANY** for authority to  
increase its rates, amend its rate schedules  
and rules governing the distribution and  
supply of electric energy, and for  
miscellaneous accounting authority.

U-21534

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**DIRECT TESTIMONY OF GRAHAM G. WOOLLEY**

**ON BEHALF OF**

**CITIZENS UTILITY BOARD OF MICHIGAN AND  
MICHIGAN ENVIRONMENTAL COUNCIL**

**July 25, 2024**

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1     **I.    INTRODUCTION & QUALIFICATIONS**

2     **Q.    Please state for the record your name, position, and business address.**

3     A.    My name is Graham G. Woolley. I am a consultant at 5 Lakes Energy, a limited liability  
4           corporation, located at Suite 218, 220 MAC Avenue, East Lansing, Michigan 48823.

5     **Q.    On whose behalf is this testimony being offered?**

6     A.    I am testifying on behalf of Citizens Utility Board of Michigan (CUB) and Michigan  
7           Environmental Council (MEC).

8     **Q.    Please summarize your experience in the field of utility regulation.**

9     A.    I have worked for 5 Lakes Energy since December 2022. In this role, I have done extensive  
10          modeling to assess the value of low-carbon energy infrastructure projects and analyze the  
11          impact of weather on transformer aging to assist distribution system planning efforts. I also  
12          completed the MSU Institute for Public Utilities course on the Fundamentals of Utility  
13          Regulation (August 7-11, 2023). My work experience is summarized in my resume,  
14          provided as Exhibit CUB-30.

15    **Q.    Please summarize your expertise on the topics you plan to address.**

16    A.    In 2019 I completed an undergraduate degree in physics at UC Berkeley, with very high  
17          marks, where my research work included modeling of dark matter theories and  
18          experimental nuclear physics, and where my coursework included the physics of power  
19          systems. The topics I address in this testimony are straightforward applications of  
20          undergraduate-level electricity, magnetism and thermodynamics, in which I am fluent.

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1 **Q. Have you testified before this Commission or as an expert in any other proceeding?**

2 A. No.

3 **Q. Are you sponsoring any exhibits?**

4 A. Yes, I am sponsoring the following exhibits:

5 Exhibit CUB-30: Resume of Graham G. Woolley

6 Exhibit CUB-31: Relationship between temperature and aging

7 Exhibit CUB-32: Derivation of power losses within a transformer

8 Exhibit CUB-33: Derivation of loss of life and expected lifetime

9 **II. SUMMARY**

10 **Q. What topics are you addressing in your testimony?**

11 A. On behalf of CUB and MEC, I am addressing the following topics:

- 12 • Transformer ratings and the physics of transformer aging; and
- 13 • Modeling transformer aging under real-world conditions

14 **Q. What are your principal conclusions?**

15 A. My principal conclusions are the following:

- 16 • Nominal transformer ratings don't capture the physics of transformer aging, and
- 17 they should not be the sole basis for transformer sizing decisions;
- 18 • The physics of transformer aging lends itself to a more thorough and rigorous
- 19 analysis that can be done with relatively simple modeling, which I demonstrate;
- 20 • Transformer aging occurs almost entirely in summer months (June through
- 21 August), while almost none happens in the winter (December through
- 22 February); and

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- 1           • Increasing load during winter months is unlikely to compromise the health of  
2           existing transformers, which are typically sized to accommodate summer peaks.

3   **III. TRANSFORMER RATINGS AND THE PHYSICS OF TRANSFORMER AGING**

4   **Q.    What is the basis for transformer ratings?**

5   **A.**    Like any other electronic device, heat dissipates in a transformer when an electric current  
6           runs through it, causing its temperature to rise. Components in the transformer degrade  
7           faster at elevated temperatures, most importantly its insulation system. This thermal aging  
8           is a key determinant of the transformer’s operational performance and longevity.  
9           Performance and safety become increasingly compromised as the insulation ages,  
10          eventually requiring repair or replacement. The transformer’s nominal expected lifetime is  
11          predicated on the operational lifespan of its insulation, assuming operation at its nominal  
12          power rating. This rating is established under specific industry standard test conditions that  
13          typically include a constant load and an ideal ambient temperature—conditions that don’t  
14          accurately reflect the fluctuating demands and environmental variables encountered in  
15          actual service. As such, while the nominal power rating serves as a benchmark for the  
16          transformer’s capacity to handle power, it is an imperfect proxy for real-world operating  
17          scenarios.

18 **Q.    When power flow exceeds a transformer’s rating, what is the effect on the**  
19 **transformer and its insulation aging rate?**

20 **A.**    Importantly, the transformer will accommodate power flows higher than the nominal  
21          rating; however, it does so at the cost of increased heat generation, which in turn accelerates  
22          the thermal aging of the transformer’s insulation system. Like most chemical reactions, the

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1 rate of aging is exponentially related to the temperature at which the reaction occurs. (Ex  
2 MEC-GGW-2) A useful rule of thumb is that the reaction rate doubles for every 10° C  
3 increase in reaction temperature. Consequently, as the operating temperature rises above  
4 the design limits, the aging process can accelerate significantly. However, the temperature  
5 (and hence the aging rate) is not determined by power flow alone. Other factors, such as  
6 the duration of overloading and the ambient temperature also play critical roles. In other  
7 words, while overload is a significant stressor, it is one of several variables that collectively  
8 influence the transformer's lifespan.

9 **Q. What determines a transformer's temperature?**

10 **A.** Transformer temperature changes based on how much heat is generated within it and how  
11 much is dissipated to the environment. This change can be described using a differential  
12 equation from thermodynamics, which tells us how temperature evolves over time. The  
13 key factors in this equation are the transformer's current temperature and the balance of  
14 heat within it over a given period; knowing both allows us to calculate the temperature at  
15 a later time. The balance of heat within the transformer can be resolved further into two  
16 components, namely the heat produced in the transformer during operation and the heat  
17 dissipated away to the surroundings. The change in temperature during a given period can  
18 be summarized by the following equation:  $\Delta T = (Q_{in} - Q_{out}) / C$ . Here is the change in  
19 temperature,  $Q_{in}$  is the heat produced,  $Q_{out}$  is the heat dissipated to the surroundings, and  $C$   
20 is the heat capacity of the transformer.<sup>1</sup>

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<sup>1</sup> The bolded equation is one way of *defining* the heat capacity; it measures how much heat it takes to change an object's temperature. See [https://en.wikipedia.org/wiki/Heat\\_capacity](https://en.wikipedia.org/wiki/Heat_capacity) for more information.

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1 **Q. How does the operation of a transformer result in the production of heat within it?**

2 **A.** In the equation describing temperature change,  $Q_{in}$  is the heat produced in the transformer  
3 over a given time frame, and it primarily consists of what we refer to as power losses,  
4 which are an inherent part of transformer operation. These power losses have two  
5 components: copper losses and core losses. Copper losses are named for the transformer's  
6 copper windings, in which, like with ordinary power lines, energy is lost due to the inherent  
7 electrical resistance of the material. Core losses are associated with the transformer's iron  
8 core and come from the magnetic interactions between the electric current and the core.<sup>2</sup>  
9 In both cases, the lost energy appears as heat within the transformer, increasing its internal  
10 temperature. This can be summarized by the following equation:  $Q_{in} = E_{core} + E_{copper}$ .  
11 Although both core ( $E_{core}$ ) and copper ( $E_{copper}$ ) losses are conceptually straightforward, their  
12 mathematical expressions involve parameters that are not usually detailed on the  
13 transformer's specification sheet, such as magnetic flux density and electrical resistivity.  
14 Instead, manufacturers typically provide "losses at no load" and "losses at full load", which  
15 is enough for us to determine  $Q_{in}$  as a function of the load on the transformer. (Ex CUB-  
16 32).

17 **Q. What are the variables that determine heat dissipation away from the transformer?**

18 **A.** Heat dissipation away from a transformer, represented by  $Q_{out}$  in the temperature change  
19 equation, occurs in a very intuitive way: hot objects will transfer their heat to their cooler  
20 surroundings. The speed of this heat transfer hinges on three factors: the current  
21 temperature of the object in question, the temperature of the surroundings (also called the

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<sup>2</sup> Core losses include hysteresis and eddy current losses. See <https://evrpower.com/types-of-losses-and-efficiency-in-a-transformer/> for more information.

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1 ambient temperature), and a parameter called the heat transfer coefficient, which describes  
2 how quickly heat can flow into or out of an object. This parameter is influenced by many  
3 variables, such as the geometry of the object, the specific heat transfer mechanism,<sup>3</sup> and  
4 the material properties of the object and the surroundings. In a transformer, the cooling  
5 system also plays a critical role. In summary:  $Q_{out} = k(T_c - T_a)$ , where  $T_c$  is the object's  
6 current temperature,  $T_a$  is the current ambient temperature, and  $k$  is the overall heat transfer  
7 coefficient that takes into account all of the aforementioned variables. The equation for  
8  $Q_{out}$  is a special case of Newton's Law of Cooling and underscores a key principle: the  
9 greater the difference between the transformer's temperature and the ambient temperature,  
10 the more quickly the transformer dissipates heat. This relationship highlights the  
11 importance of ambient temperature in determining a transformer's internal temperature,  
12 with lower ambient temperatures enhancing the transfer of heat away from the transformer.

13 **Q. What is the relationship between a transformer's temperature and its aging rate?**

14 **A.** I've already discussed all the factors that determine a transformer's temperature and the  
15 temperature's exponential relationship to the aging rate of the insulation system. This  
16 relationship is characterized by a number called the aging acceleration factor, or  $F_{AA}$ , which  
17 is given by the following expression, which is cited in Exhibit MEC-GGW-2:  $F_{AA} =$   
18  $\exp(A/T_{ref} - A/T)$ , where  $A$  is a parameter determined by the thermal properties of the  
19 transformer and  $T$  is the temperature within the transformer expressed in degrees Kelvin,  
20 also known as the absolute temperature. Here  $T_{ref}$  is a reference temperature given by the  
21 manufacturer and it usually has a value of 110 °C, or 383 Kelvin. An  $F_{AA}$  value greater

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<sup>3</sup>See [https://energyeducation.ca/encyclopedia/Heat\\_transfer\\_mechanisms](https://energyeducation.ca/encyclopedia/Heat_transfer_mechanisms).

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1 than 1 indicates that the transformer will age faster than normal and shorten the expected  
2 life, while a value less than 1 lengthens it.

3 **Q. What is the relationship between a transformer's aging rate and its expected lifetime?**

4 **A.** The aging rate in each unit of time can be readily translated into a measure of lost life of  
5 the transformer, which is usually expressed as a percentage or as a fraction between 0 and  
6 1 and is denoted by LoL. To calculate the actual expected lifetime, we would need to add  
7 together LoL values until they cumulatively add up to 1. In practice, to predict the expected  
8 life, we produce hourly LoL values for a single representative year to get a yearly LoL  
9 value, whose inverse is the expected lifetime expressed in years. (Ex MEC-GGW-4)

10 **Q. What are the conditions that constitute a steady state in a transformer?**

11 **A.** Steady-state refers to a situation where the transformer temperature doesn't change, or  $\Delta T$   
12 = 0. Referring to the temperature change equation above, this is only possible when the  
13 heat production within the transformer is exactly balanced by the dissipation of heat to the  
14 surroundings, i.e. when  $Q_{out} = Q_{in}$ .  $Q_{out}$  is determined by the ambient temperature, while  
15  $Q_{in}$  is determined by the magnitude of the power flow within a given period. In  
16 manufacturer testing, both ambient temperature and power flow are often held constant to  
17 establish a steady-state temperature and evaluate performance. In steady-state conditions,  
18 transformer aging and expected life are primarily influenced by the magnitude of the power  
19 flow and the ambient temperature.

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1 **Q. Under steady-state ambient temperature and power flow, what is the relationship**  
2 **between power flow and expected transformer life?**

3 **A.** In steady-state conditions, higher power flow leads to higher internal temperature, mainly  
4 through increased copper losses, which accelerates aging and reduces expected lifetime.

5 **Q. Under steady-state ambient temperature and power flow, what is the relationship**  
6 **between ambient temperature and expected transformer life?**

7 **A.** In steady-state conditions, lower ambient temperature leads to lower transformer  
8 temperature and hence a slower aging rate, extending its expected lifetime.

9 **Q. Under steady-state ambient temperature and power flow, and for fixed expected**  
10 **transformer life, what is the relationship between ambient temperature and power**  
11 **flow?**

12 **A.** For a fixed expected transformer life, there is an inverse relationship between ambient  
13 temperature and power flow. This means that a transformer can accommodate higher loads  
14 during the winter than in the summer, thanks to lower ambient temperatures.

15 **Q. When power flow varies with time in steady-state ambient temperature, what**  
16 **happens to transformer temperature and aging?**

17 **A.** Under constant ambient temperature conditions, power flow and transformer aging vary in  
18 the same direction: higher power flow in one hour leads to higher temperature, and hence  
19 accelerated aging. Thus, all else being equal, hours with high load account for more  
20 transformer aging than hours with low load.

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1 **Q. When ambient temperature varies with time and power flow is steady-state, what**  
2 **happens to transformer temperature and aging?**

3 **A.** Under constant power flow conditions, ambient temperature and transformer aging also  
4 vary in the same direction: higher ambient temperature in one hour leads to higher  
5 transformer temperature, and hence accelerated aging. Thus, all else being equal, warm  
6 hours account for more transformer aging than cold hours.

7 **Q. Is it reasonable to think of a transformer as having a power flow rating that depends**  
8 **on ambient temperature?**

9 **A.** The IEEE has a rule of thumb for estimating an “effective power flow rating” of a  
10 transformer based on ambient temperature.<sup>4</sup> In short, a lower ambient temperature yields a  
11 higher effective power flow rating. This heuristic is more accurate than using a single, fixed  
12 rating, but it has some drawbacks: it fails to capture the exponential relationship between  
13 a transformer’s temperature and its aging rate and doesn’t account for the time-dependent  
14 physics of transformer aging. To better capture these complexities, I created a weather-  
15 dependent transformer aging model that considers a time-varying 8760-hour annual profile  
16 of both ambient temperature and power flow. This model provides a comprehensive  
17 estimate of transformer loss of life throughout the year and allows us to quantify aging  
18 patterns on a time-of-day, seasonal, or annual basis.

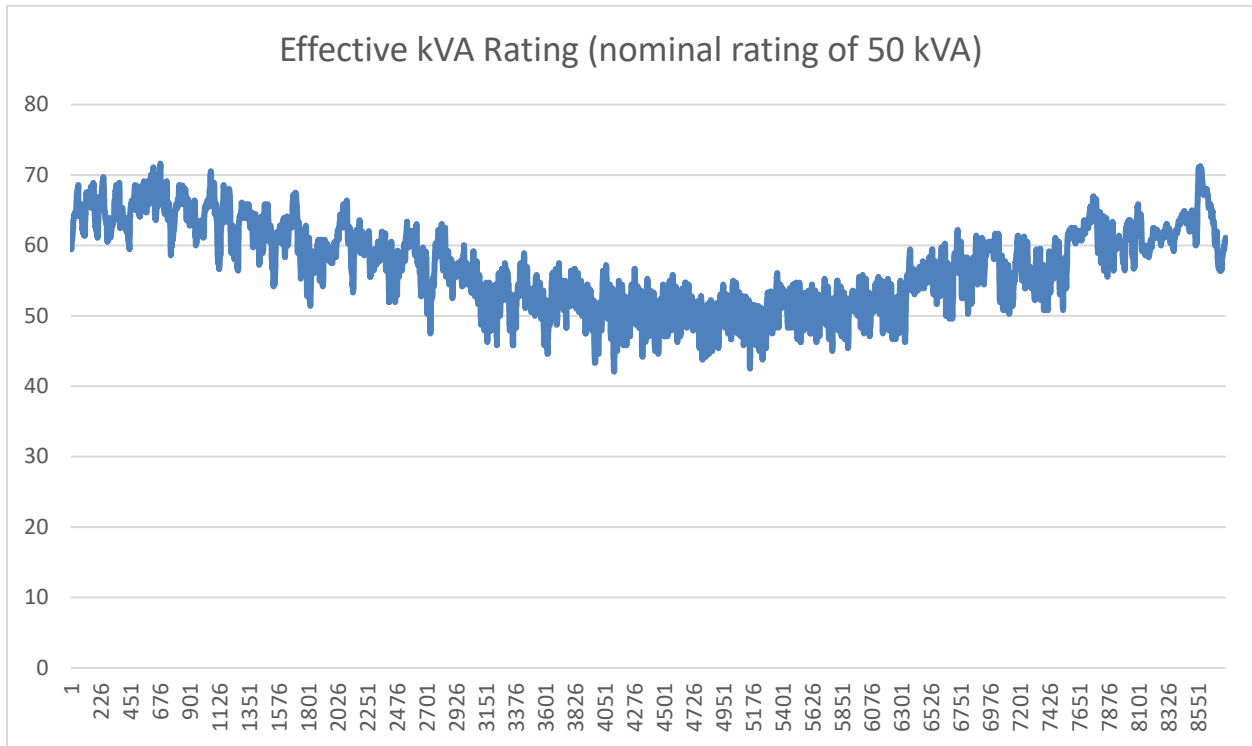
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<sup>4</sup> See Table 3 in Section 6.4 of the IEEE guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators, which can be found at <https://ieeexplore.ieee.org/document/6166928>.

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1 **Q. Does your model include the IEEE heuristic for effective rating as a function of**  
2 **ambient temperature?**

3 **A.** Yes. While this is not the principal output of the model, it does provide a rough picture,  
4 given by this IEEE recommendation, of the transformer's effective rating. The chart below  
5 illustrates this heuristic for a transformer serving residential customers:



6  
7 Qualitatively, we see that in winter months (December-February), the transformer can  
8 accommodate higher loads than in the summer months (June-August). There are daily  
9 fluctuations throughout the year as well, but the seasonality is important for the discussion  
10 in the following section, in which I quantify some of these trends.

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1 **Q. Is it reasonable to allocate costs for distribution system maintenance and upgrades**  
2 **based on peak loads?**

3 **A.** No. Doing so fails to accurately account for what causes transformer aging. For example,  
4 residential peak loads may be quite high, but brief, due to demand for air conditioning,  
5 whereas commercial and industrial loads may be persistently high, leading to higher overall  
6 aging. In winter months, if a large portion of residential buildings have electrified their  
7 space heating requirements, peak loads may be quite high, but aging would be slowed by  
8 cold ambient temperatures. Rates paid by each customer class should reflect what they  
9 contribute to real transformer aging rather than peak demands. Our model provides a much  
10 more accurate picture of these costs.

11 **IV. MODELING TRANSFORMER AGING UNDER REAL-WORLD CONDITIONS**

12 **Q. What data does your model need to calculate transformer aging?**

13 **A.** It is, in practice, impossible to exactly solve the differential equations from  
14 thermodynamics that govern transformer aging due to the lack of high-resolution data. The  
15 model uses a standard numerical approach which applies the equations over discrete  
16 intervals. This method requires an 8760-hour profile for both the ambient temperature and  
17 the power flow through the transformer, representing an entire year's worth of hourly data.<sup>5</sup>  
18 Several manufacturer specifications are also necessary to fully capture the dynamics of  
19 transformer temperature: the model requires the mass of some of the transformer's  
20 components, its nominal expected lifetime, its nominal kVA rating, its cooling system type,  
21 and the core and copper losses observed during manufacturer testing. These specifications

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<sup>5</sup> Hourly intervals are the industry standard practice; more granular data is not usually available.

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1 give an adequate proxy for the physical characteristics relevant for this kind of thermal  
2 analysis on a transformer; they allow the model to calculate the loss of life (LoL) in each  
3 hour, providing a comprehensive view of the aging rate throughout the year.

4 **Q. Please describe how your model calculates the aging rate and loss of life.**

5 **A.** Detailed calculations can be seen in the logic of the model itself, which documents the  
6 relevant formulas extensively. A blank version of the model is found in the workpaper  
7 titled “Transformer Weather-Dependent Aging Model for DTE 2024 Rate Case.xlsx”. To  
8 summarize: given the inputs listed above, the model calculates the transformer’s heat  
9 capacity (C), and then for each hour it calculates the heat generated in the transformer ( $Q_{in}$ ),  
10 the heat dissipated to the surroundings ( $Q_{out}$ ), and the resulting change in transformer  
11 temperature ( $\Delta T$ ). This temperature change is used to update the transformer temperature  
12 from the previous hour to the current hour. To be conservative, the model adds 5 °C to the  
13 result, a buffer recommended by the IEEE,<sup>6</sup> to represent the so-called hottest spot  
14 temperature of the transformer, which in turn is used to calculate the aging acceleration  
15 factor and the loss of life in each hour. The hourly values are summed to an annual total,  
16 which represents an annual loss of life.

17 **Q. Does the temperature in one hour depend on the conditions of the previous hour?**

18 **A.** Yes: the heat dissipated to the surroundings in one hour is proportional to the difference  
19 between the transformer’s temperature and the ambient temperature in the previous hour.  
20 This is an effect called “hysteresis”, where a system’s behavior depends on its history.

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<sup>6</sup> See section 6.2 of <https://ieeexplore.ieee.org/document/6166928>.

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1    **Q.    Does it matter what the model assumes for the temperature in the first hour?**

2    **A.**    The initial transformer temperature is not a significant factor in the outcome of the model  
3            calculations, which take place over an entire year. The hysteretic nature of heat dissipation  
4            is such that the transformer effectively erases any memory of its previous temperature after  
5            enough time has elapsed. In our model, given a load profile, starting temperatures of 1000  
6            °C and 10 °C converge to nearly the same conditions after 24 hours. Since it makes a  
7            negligible difference where the model starts, we set the initial temperature to 20 °C.

8    **Q.    How does your model calculate the heat transfer coefficient of the transformer?**

9    **A.**    The heat transfer coefficient is the one variable that the model leaves free to calibrate itself  
10           to any transformer. Before we run the model with real-world conditions, we first run the  
11           model with an input of constant ambient temperature and constant load, with the  
12           magnitudes of each equal to the manufacturer’s reference ambient temperature and the  
13           nominal kVA rating, respectively. These are the conditions that determine the  
14           transformer’s expected lifetime. Thus, our initial run of the model should give us an  
15           expected lifetime that matches the number in the manufacturer specifications. If this is not  
16           the case, we tune the heat transfer coefficient to give us that result. Once the heat transfer  
17           coefficient is calibrated to match the manufacturer’s specifications for expected life, we  
18           can then apply the model to real-world conditions.

19   **Q.    What scenarios are you considering for the subsequent analysis, and what are they**  
20           **meant to represent?**

21   **A.**    I constructed load profiles for three scenarios in the Company’s transformer network: (1)  
22           a line transformer serving only residential customers, (2) a line transformer serving only

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1 secondary commercial customers, and (3) a representative substation transformer. To  
2 perform an analysis with this model, I needed to specify a few characteristics of the  
3 transformer in question, which I attempted to obtain through discovery. The Company  
4 provided requirements sheets for transformers in their network, but these are different from  
5 the specifications the model requires. We assumed a 50 kVA transformer for scenarios (1)  
6 and (2) and a 5 MVA transformer for scenario (3). Lacking the necessary specifications  
7 from the Company, we used manufacturer’s specs through Larson Electronics as a proxy,  
8 which provide all the information we need to run the model. Details can be found in the  
9 following workpapers:

- 10 • Transformer Weather-Dependent Aging Model - Residential Line  
11 Transformer.xlsx (Scenario 1);
- 12 • Transformer Weather-Dependent Aging Model - Secondary Commercial Line  
13 Transformer.xlsx (Scenario 2);
- 14 • Transformer Weather-Dependent Aging Model – Substation Transformer.xlsx  
15 (Scenario 3).

16 **Q. How did you construct the load profiles for these scenarios?**

17 **A.** The construction of the load profile for each scenario is documented in the workpaper titled  
18 “dte\_transformer\_config.ipynb”. In brief, I took the Company’s rate-specific hourly loads  
19 from “U-21534 MNSCDE-10.15 - Part III Attachment 5 (28) COMPLETE\_Updated  
20 2022.xlsx”, a copy of which I included as a workpaper, for 2022 and aggregated selected  
21 rates to separately represent all residential customers, all secondary commercial customers,  
22 and the system as a whole. I then scaled each profile to a magnitude meant to represent a

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1 single residential customer, a single secondary commercial customer, and a single  
2 substation transformer.

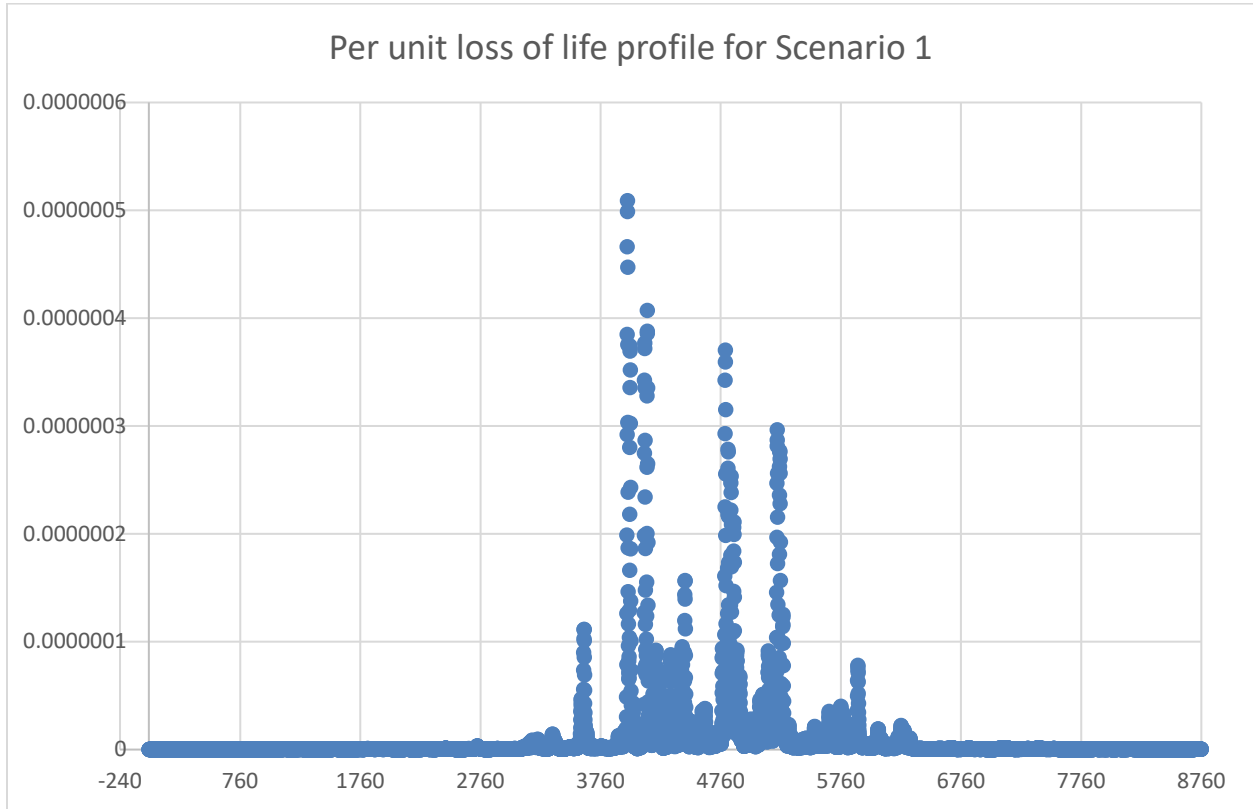
3 **Q. Does the loss of life computed in your model match what the Company has observed**  
4 **in its service transformers?**

5 **A.** It is unlikely that our model matches the Company’s historical observations, for several  
6 reasons. First, a line transformer usually serves a mix of residential and commercial  
7 customers, while our load profiles represent one or the other. Second, the ideal input for  
8 the model is the transformer’s hourly power flow. This data is unavailable, so we had to  
9 construct representative load profiles and scale them to the transformer level by choosing  
10 a “number of customers per transformer”. This number is critically important because it  
11 affects the magnitude of the transformer load, but it is in practice very difficult to choose  
12 it correctly. Our approach was to apply a standard practice in which the transformer size is  
13 chosen so that its nominal capacity can accommodate the anticipated annual peak load.  
14 Third, we used specifications for models of transformers that may not reflect the real  
15 characteristics of the Company’s transformers. Thus, our analysis likely does not represent  
16 the reality of most of the Company’s service transformers, but our intention here is not to  
17 do a comprehensive aging analysis for the Company’s network. The analysis that follows  
18 is necessarily qualitative and imprecise since we lack data on specific transformer loads  
19 and real transformer characteristics. Our scenarios are intended to demonstrate the  
20 qualitative differences between different customer classes with respect to transformer  
21 aging and to illustrate how aging depends on more than peak loads.

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1 **Q. For Scenario 1 (a transformer serving only customers with the Company's average**  
2 **residential load profile), what is the annual transformer aging profile?**

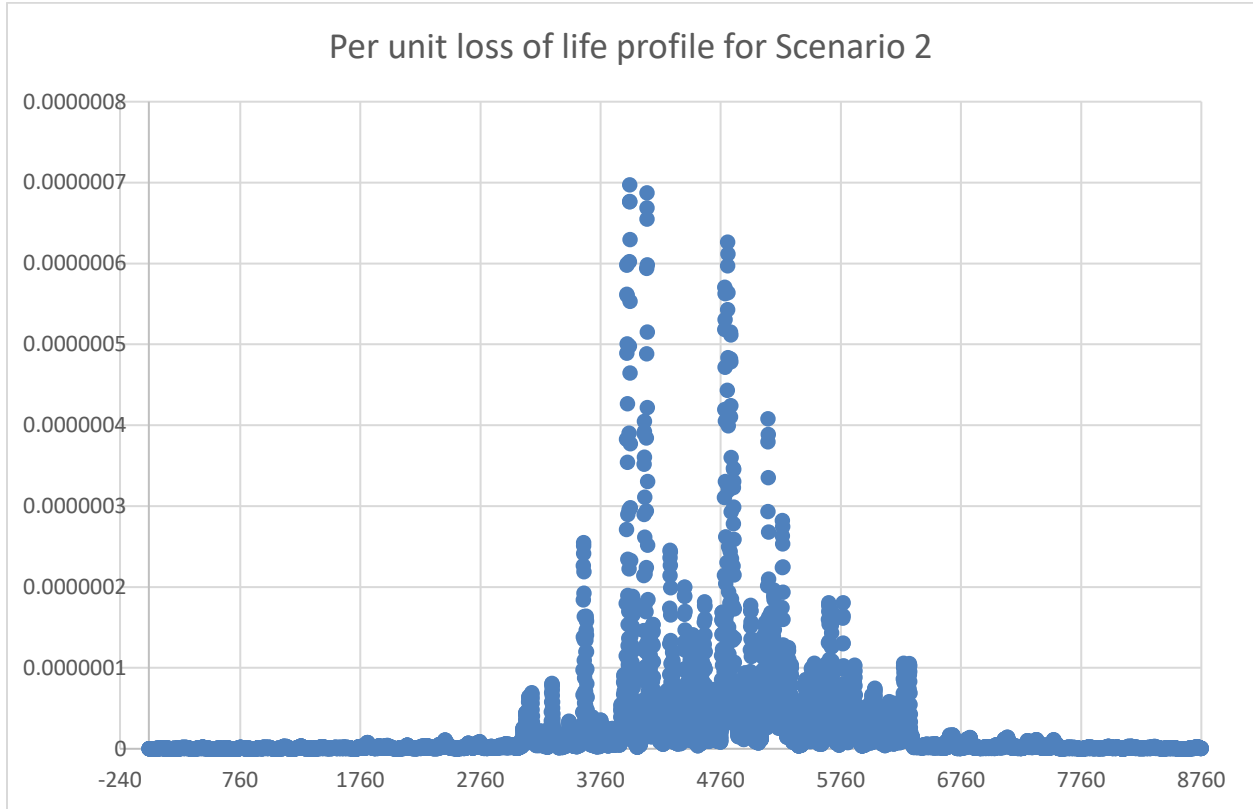
3 **A.** The aging profile below is directly from the Scenario 1 workpaper.



5 **Q. For Scenario 2 (a transformer serving only customers with the Company's average**  
6 **secondary commercial load profile), what is the annual transformer aging profile?**

7 **A.** The aging profile below is directly from the Scenario 2 workpaper.

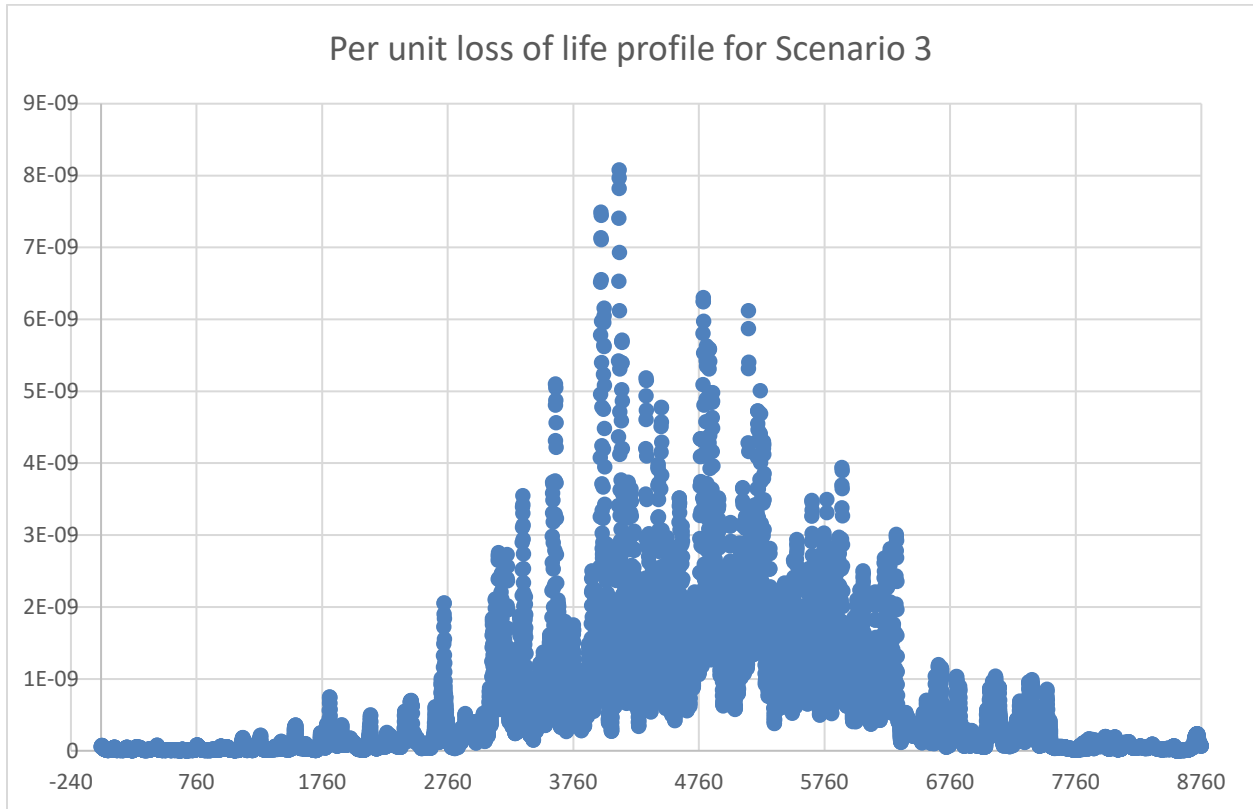
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2 **Q. For Scenario 3 (a representative substation transformer serving a portion of the**  
3 **system load), what is the annual transformer aging profile?**

4 **A. The aging profile below is directly from the Scenario 3 workpaper.**

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2 **Q. What qualitative conclusions should be drawn from the above profiles?**

3 **A.** I want to highlight that in each of these scenarios, almost all the aging occurs during the  
4 summer, especially during the very warm hours of June through August. While this is  
5 attributable in part to increased electricity demand from air conditioning, the ambient  
6 temperature also plays a role, as I'll demonstrate.

7 **Q. What are the key statistics to draw from each scenario?**

8 **A.** The key statistics I want to highlight are summarized in the following table. Please note  
9 that I'm defining winter as December-February and summer as June-August.

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<b>Statistic</b>	<b>Scenario 1</b>	<b>Scenario 2</b>	<b>Scenario 3</b>
Expected life / peak load (years per kW of peak hourly load)	304.7	123.3	123.4
Average load / peak load	0.3512	0.5292	0.5272
Fraction of annual aging occurring during summer months (June-August)	0.8859	0.8080	0.6551
Fraction of annual aging occurring during winter hours (December-February)	0.0035	0.0082	0.0128
Average load / average temperature during summer months (kW per degree Kelvin)	0.0749	0.0990	2.689
Average load / average temperature during winter months (kW per degree Kelvin)	0.0669	0.0979	2.557

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**Q. What conclusions can be made given the above statistics?**

**A.** Several important points can be drawn from the table above:

- 1) The ratio of expected life to peak load demonstrates that peak loads are a poor proxy for transformer aging. While Scenario 2 has the same peak load as Scenario 1, the aging is significantly accelerated because loads are persistently high in Scenario 2, as evidenced by the higher ratio of average load to peak load.
- 2) In all scenarios, almost all aging occurs during the summer months, while almost none occurs in the winter. This observation highlights the critical point that transformer aging is significantly influenced by ambient temperatures.
- 3) In all scenarios, despite the average load to average temperature ratios being nearly the same for summer and winter months, the fraction of aging occurring in winter remains extremely low compared to summer. This indicates that higher ambient temperatures in the summer exacerbate aging effects even when the average load relative to temperature is similar. For instance, in Scenario 3, the average load to average temperature ratio during summer months is comparable to the same ratio

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1           in the winter. However, the aging fraction during winter is negligible, highlighting  
2           a cold winter's protective effect on transformer longevity.

3           In conclusion, the predominant transformer aging during the summer can be attributed to  
4           the combined effect of higher loads and elevated ambient temperatures. Conversely, during  
5           the winter, the lower ambient temperatures significantly reduce aging, even if the loads are  
6           comparably high relative to temperatures. This supports the argument that winter months  
7           can accommodate higher loads without compromising transformer longevity.

8   **V.   CONCLUSIONS**

9   **Q.   Please summarize the conclusions of the above discussion.**

10 **A.**   My analysis has shown the following:

- 11           (1)   Nominal transformer ratings are an imperfect proxy for transformer aging;
- 12           (2)   It is possible to do a more thorough and rigorous accounting of transformer  
13           aging by applying the first physical principles of transformer operation, if one has  
14           access to the relevant data;
- 15           (3)   Transformer aging occurs primarily during the summer months; and
- 16           (4)   The practice of sizing transformers for summer loads means that they can  
17           accommodate substantially higher winter loads without sacrificing transformer  
18           longevity.

19 **Q.   Do you have any recommendations for the Commission?**

20 **A.**   No. My testimony is intended as technical support for other witnesses on this topic.

21 **Q.   Does that complete your testimony?**

22 **A.**   Yes.



## Graham Woolley

Consultant

[gwoolley@5lakesenergy.com](mailto:gwoolley@5lakesenergy.com)

### Expertise

Physical and economic modeling, programming, data analytics, data science, statistics, physics, utility performance data reporting, climate technology expert, quantitative analysis of energy use in buildings, and analysis of transformer aging cost implications.

### Selected Projects

- **Low Carbon Infrastructure Project Analysis.** Designed and built a cost/benefit analysis toolkit to assess the impacts of building electrification and energy efficiency projects for the state of Michigan.
- **Citizens Utility Board of Michigan *Utility Performance Report*.** Built a data pipeline and Tableau workbook for the latest edition of the MICUB's annual *Utility Performance Report*, which scores the performance of Michigan's electric utilities on reliability, affordability, and environmental responsibility with in-state and nationwide comparisons.
- **Physical modeling of transformer aging in real world conditions.** Created a physics-based weather-dependent transformer aging model for use in analysis of distribution system costs.
- **Climate legislation modeling.** Modeled the physical and economic effects of proposed climate legislation in Michigan that became law in 2023.

### Past Employment

- **STEM Teacher | ARISE High School | California | 2020-2022**
- **Founding Fellow | Climatebase | California | 2022**
- **Data Analytics Intern | New Sun Road PBC | California | 2020**

### Awards, Affiliations, and Service

Olsen Memorial Award, University of California, Berkeley, Department of Physics | 2018

The loss of life as a function of temperature can be quantified by an Aging Acceleration Factor, denoted as  $F_{AA}$ , which is given by the following equation:

$$F_{AA}(T) = \exp\left(\frac{15,000}{383} - \frac{15000}{T + 273}\right)$$

Here  $T$  is the hottest-spot temperature of the transformer, expressed in degrees Celsius. We've assumed a rated hottest-spot temperature of 110 °C. This expression illustrates the exponential relationship between temperature and aging, and it's an example of an Arrhenius relationship, in which linear changes to temperature result in exponential changes in the rates of many chemical reactions. The aging of a transformer's insulation system is an example of such a reaction.

This expression was adapted from equation 17.83 in section 17.11 on Thermal Design of the textbook *Transformer Design Principles*, Third Edition, by Robert M. Del Vecchio, Bertrand Poulin, Pierre T. Feghali, Dilipkumar M. Shah, and Rajendra Ahuja

Let  $Q_{in}$  denote the total power losses in the transformer; this is the heat generated within it.

Let  $E_{core}$  denote the core losses.

Let  $E_{copper}$  denote the copper losses.

The losses in a transformer can be summarized as follows:

$$Q_{in} = E_{core} + E_{copper} \quad (1)$$

Core and copper losses are not usually specified in manufacturer testing. Rather, a measure of “loss at no load” and “loss at full load” is often included. These are measured empirically. Loss at no load is what remains constant regardless of the load. This corresponds directly to the core losses. Loss at full load is the total loss that occurs when the transformer is running at its rated capacity. Since the core loss remains constant, the loss at full load includes both copper losses and core losses.

Let  $L_0$  denote the loss at no load.

Let  $L_1$  denote the loss at full load.

Let  $R_{nom}$  denote the rated kVA capacity of the transformer.

Knowing these three values from the manufacturer allows us to write down an expression for the loss occurring at any load. The argument is as follows:

The core loss is simply given by:

$$E_{core} = L_0 \quad (2)$$

The copper loss, also known as the resistive loss, is given by Ohm's law, a very well-known result in elementary circuit analysis. We then have:

$$P = VI \text{ (definition of electric power)} \quad (3)$$

$$V = IR \text{ (Ohm's law)} \quad (4)$$

Combining equations (3) and (4):

$$P = I^2R \quad (5)$$

Equation (5) expresses the relationship between the current flowing through a resistor and the power dissipated from it. Here the resistor is the copper windings of the transformer. We don't need to know the resistance of these windings to determine the copper losses, however. Consider the following proportionality relationships:

$$E_{copper} = I^2R \propto I^2 \propto P^2 \quad (6)$$

Here the symbol  $\propto$  means "proportional to". The first step is a restatement of equation (5), and the last step is a restatement of equation (3), since electric power is proportional to the current. Since the copper loss is proportional to the square of the power flow (load), it suffices to know the value of the copper loss at any single value of the load. The following equation expresses the copper loss when the transformer runs at its nominal load:

$$E_{copper}(R_{nom}) = L_1 - E_{core} = L_1 - L_0 \quad (7)$$

In the first step, we used equation (1), and in the last step we applied equation (2). But equation (6) allows us to write down the following, using  $k$  as an unknown constant:

$$E_{copper}(P) = kP^2 \quad (8)$$

This is the definition of proportionality. Combining equations (7) and (8), we get:

$$E_{copper}(R_{nom}) = kR_{nom}^2 = L_1 - L_0 \quad (9)$$

Solving this equation for our unknown constant  $k$ , we get:

$$k = \frac{L_1 - L_0}{R_{nom}^2} \quad (10)$$

Combining (8) and (10), we obtain:

$$E_{copper}(P) = \frac{L_1 - L_0}{R_{nom}^2} P^2 \quad (11)$$

Finally, combining (1), (2), and (11), we get an expression for the loss at any load, assuming  $L_0$ ,  $L_1$ , and  $R_{nom}$  are known:

$$Q_{in}(P) = L_0 + (L_1 - L_0) * \left(\frac{P}{R_{nom}}\right)^2$$

This expression for  $Q_{in}$  is what we use in the model.

The following discussion is adapted from section 17.11 on Thermal Design, particularly after equation 17.85, of the textbook *Transformer Design Principles*, Third Edition, by Robert M. Del Vecchio, Bertrand Poulin, Pierre T. Feghali, Dilipkumar M. Shah, and Rajendra Ahuja.

Given an aging acceleration factor,  $F_{AA}$  for each hour of the year, we can express the fraction of the transformer's life lost in that hour. The desired expression is as follows:

$$LoL(F_{AA}) = \frac{(F_{AA} * \Delta t) / 8760}{L_{nom}}$$

Here  $LoL$  is the loss of life of the transformer in each hour,  $L_{nom}$  is the nominal expected life (in years) of the transformer, which is given in the model as an assumption, and  $\Delta t$  is the time interval over which the aging acceleration factor applies. Since the model uses hourly intervals,  $\Delta t = 1\text{hr}$ , and so we might re-express the equation as:

$$LoL(F_{AA}) = F_{AA} \frac{\Delta t / 8760}{L_{nom}}$$

We've separated the aging acceleration factor from the rest of the expression to illustrate the following: the numerator,  $\Delta t / 8760$ , is one hour expressed as a fraction of a year, and the denominator is the expected lifetime in years. In other words, the fraction of the transformer's nominal lifetime that passes in one hour is multiplied by  $F_{AA}$  to yield the *effective* fraction of its life lost in that hour.

Since  $F_{AA}$  changes from hour to hour, it makes more sense to consider an annual loss of life, which is simply the sum of the hourly  $LoL$  values throughout the year. Once we have an annual  $LoL$ , we simply take its inverse to yield the computed expected lifetime. For example, if  $F_{AA} = 1$  for every hour of the year, then the annual loss of life is  $1 / L_{nom}$ , as expected.. If  $L_{nom} = 30$  years,

this corresponds to roughly a 3.3% loss of life per year. If  $F_{AA} < 1$ , there will be a smaller annual loss of life, also as expected.

The hourly *LoL*, the annual *LoL*, and the computed expected lifetime are all stated prominently in the Calculations tab of the model.

STATE OF MICHIGAN

BEFORE THE MICHIGAN PUBLIC SERVICE COMMISSION

In the matter of the Application of **DTE ELECTRIC COMPANY** for authority to increase its rates, amend its rate schedules and rules governing the distribution and supply of electric energy, and for miscellaneous accounting authority.

Case No. U-21534

**Proof of Service**

On the date below, an electronic copy of **Direct Testimony and Exhibits of Graham G. Woolley on behalf of Citizens Utility Board of Michigan and Michigan Environmental Council (Exhibits CUB-30 through CUB-33)** was served on the following:

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{signature on following page}

The statements above are true to the best of my knowledge, information and belief.

**Troposphere Legal, PLC**  
Counsel for MEC, NRDC, SC & CUB

Date: July 25, 2024

By: \_\_\_\_\_

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