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Enabling Solar Power with Residential Water Heater Load Shifting

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ABSTRACT

As governments and international organizations aim to increase renewable energy production in response to climate change, there is a growing demand for energy storage. A temporal mismatch in the daily profiles of solar energy production and residential energy use causes an imbalance between generation and demand. Load shifting presents a key grid control strategy that minimizes this mismatch and the resulting rapid ramp rates in fossil fuel-based electricity generation. Water heaters are a principal contributor to residential electricity consumption from the grid, and they offer a good potential for thermal energy storage due to low ambient energy loss and water's high specific heat capacity. Load shifting of water heating loads maximizes self-consumption of solar power in residential buildings thereby improving homeowner utility costs and the ability of the electric grid to accept greater levels of intermittent solar generation.

Water heating load data was generated using the U.S. Department of Energy Residential Prototype Building Models for a cycling 50-gallon (189 L) electric water heater in a single-family house in Los Angeles with a roof-mounted solar photovoltaic system. The effects of load shifting on the fraction of the water-heating loads to the total house electric loads, the fraction of the water heating load met by solar power, and end-user electricity bills using time-of-use (TOU) electricity rates were analyzed. This study shows that shifting the load of water heaters to coincide with the solar profile lowers electricity costs significantly more than a solar photovoltaic system without load shifting which sends power to the grid using a net metering agreement. The results suggest that widespread use of smart water heaters that optimize load shifting by predicting hot water consumption and the solar profile could present an important value for the integration of renewable energy onto the grid.

1. INTRODUCTION

A discrepancy in the time profiles of solar energy production and residential energy use causes environmental, economic, and operational problems. While solar energy reaches its maximum output in the middle of the day, residential energy consumption peaks in the morning and in the evening (O'Shaughnessy, Cutlera, Ardania, & Margolisa, 2019). The California Independent System Operator (CAISO, 2019) consistently reported peak loads to occur between July and September at around 16:00. Daily electricity demand depends on the typical work schedule, while seasonal demand varies due to a difference in temperature.

This imbalance between renewable energy production and energy-use load profiles causes utilities to experience high variations in energy supply requirements. The report by Alcorn (2013) showed that self-generation from photovoltaic systems with a range of 1371-1604 MW of photovoltaic capacity will only reduce the peak demand for electricity by between 2.67% and 2.79%. Solar power production does not minimize the peak load due to the temporal mismatch. As the implementation of solar power has increased, utilities are faced with high ramp rates between the middle of the day (when solar power generation is highest) and peak hours (when electricity consumption from the grid is highest). These high ramp rates create a higher risk of over-generation in the middle of the day for utilities (Van Asselt, 2018).

To accommodate the increase in solar energy production, utilities and end users have therefore begun to invest in grid controls and energy storage, respectively (Van Asselt, 2018). Possible solutions include batteries and load management where self-consumption of the electricity generated from photovoltaic systems is encouraged. The relatively high cost and disposal issues for batteries limit the feasibility of this option. This study focuses on the effects of load shifting regarding residential water heaters which comprise almost one-fifth of residential energy use in the United States. Water heaters are beneficial for energy storage as water has a high specific heat capacity, and water heater tanks experience minimal energy loss (Gelažanskas & Gamage, 2016).

The hypothesis presented in this work is that load shifting of residential electric hot water heaters is a cost-effective means to reduce electricity consumption from the grid in favor of site-generated solar electricity. In this study, load shifting was applied to the water-heating load met by a 50-gallon residential electric resistance water heater.

The effects of load shifting on annual electricity bills, the fraction of the water-heating loads to the total house electric loads, and the fraction of the water heating load met by solar power were compared to the effects from the same solar array without load shifting. The control strategy carried out in this research may be applied to the development of an algorithm to develop smart water heaters that predict future solar production and water consumption profiles to maximize self-consumption of solar power. Such a control system could be integrated with existing systems designed for space heating and cooling applications.

2. MODELING

2.1 Water Heater Model and Load Data

The water heater model studied originates from the Residential Prototype Building Model of a single-family detached house in Los Angeles that is in accordance with the 2012 International Energy Conservation Code (IECC). This model is developed by the Pacific Northwest National Laboratory (PNNL) and used by the U.S. Department of Energy's (USDOE) Building Energy Codes Program.

The information for the water heater model is an input file for EnergyPlus, a building energy simulation program released by the USDOE. EnergyPlus was used to generate the water heating load and water consumption profile. The ambient heat loss, mass flow rate, water mains temperature, and the volume of water consumption were also determined using outputs from the energy simulation program.

The model is a single-node, mixed 50-gallon (189 L) electric domestic water heater with industry standard ratings for both the recovery efficiency and energy factor (USDOE, 2019). A single-node model was chosen due to its simple computational implementation and its low average percentage error in its output for the average output temperature (Kepplinger, Huber, Preißinger, & Petrasch, 2019). The water heater draws in cold water from the water main and heats it using an electric heating element with a heating capacity of

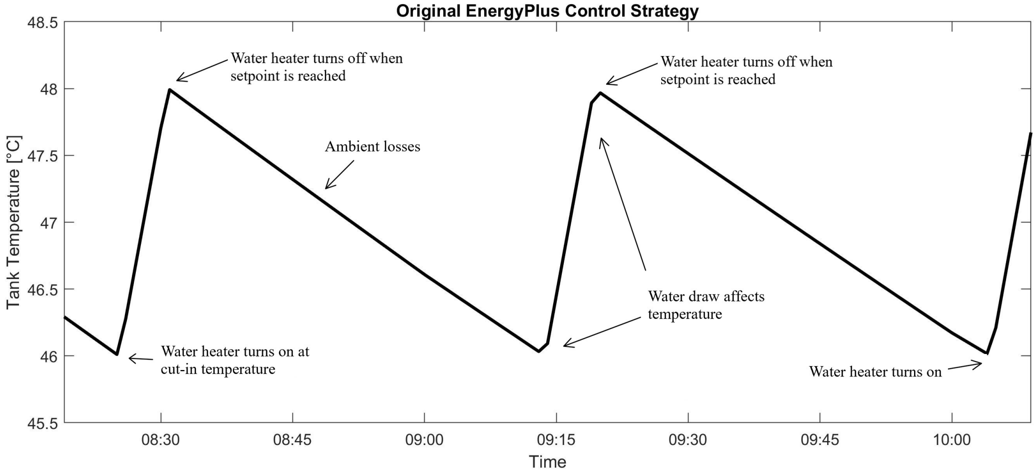

Figure 1: EnergyPlus Water Heater Original Control Algorithm

4500 W. The control type enables the heater to cycle on and off. The tank heats the water until it reaches the setpoint temperature of approximately 48 °C. When the setpoint temperature is reached, the water heater turns off and only turns on again when the temperature falls to 2 °C below the setpoint. The control model is shown in Figure 1 (USDOE, 2019). The data graphed is taken from the original water heater load on August 27. The schedule for the water heating load is based on the National Renewable Energy Laboratory (NREL) Seattle Benchmark model. Normally the modelled water heater turns on for about six minutes to reach the setpoint temperature, therefore the load data was gathered in one-minute time steps for the precision necessary to capture this behavior.

2.2 Weather, Solar Resource, and Solar Generation Data

Weather data was required as an input for the EnergyPlus and System Advisor Model (SAM) simulation programs. SAM was used for the solar power generation profile at one-minute time steps. The software uses the time, latitude, global horizontal irradiance, direct normal irradiance, and diffuse horizontal irradiance to estimate the solar resource and calculate solar power generation (Gilman, 2015). Ambient temperature was also used by both EnergyPlus and SAM. Ambient heat loss is calculated according to the thermal zone in which the water heater is located. Ambient heat loss from the water heater varies depending on the month, with a percent change of 9.02% and 10.0% in March and August, respectively. Ambient temperature is also used in SAM to calculate solar array performance (Gilman, 2015).

The weather data originates from the Typical Meteorological Year version 3 (TMY3). The monthly data is taken from a specific year deemed to have the most typical weather data for that month (Wilcox & Marion, 2008). The weather data was collected near the Los Angeles International Airport, shown in Figure 2.

However, the TMY3 weather resource only produces data in hourly time intervals as opposed to the one-minute time intervals required by SAM. To produce one-minute weather data, interpolation was necessary. However, simple linear interpolation for global horizontal radiation can cause large positive values at times close to sunrise and sunset (Duffie & Beckman, 2013). Therefore, the Transient System Simulation Tool (TRNSYS) was used to interpolate the diffuse horizontal irradiance according to the extraterrestrial radiation curve (Thermal Energy System Specialists LLC, 2016). Since global horizontal radiation takes diffuse horizontal radiation into account, it was not necessary to interpolate all three solar resource value inputs for SAM.

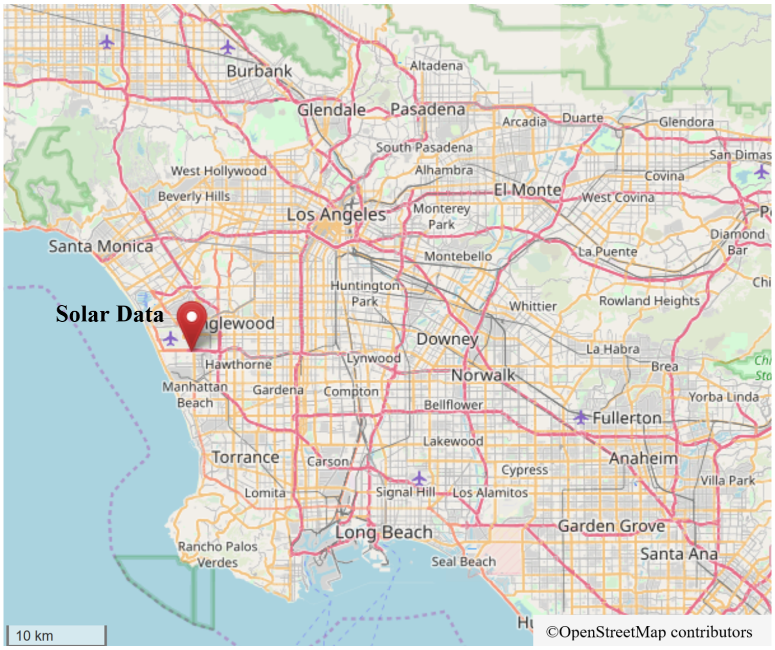

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Figure 2: Solar data location

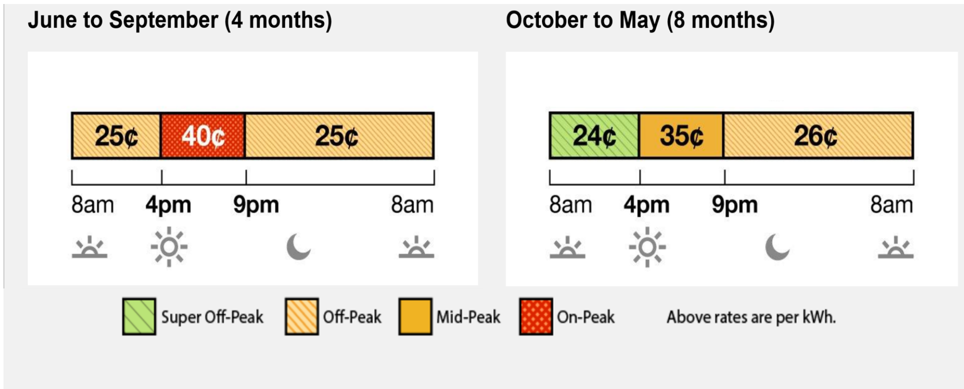

Figure 3: SCE TOU electricity rate

The X21-345 SunPower solar panel was chosen for the model with a nominal power of 345 W and an average panel efficiency of 21.5%. The water heating load generated by EnergyPlus was entered into the NREL's REopt Lite model used in O'Shaughnessy's recent study (2019). The solar array was appropriately sized to 1 kW (3 panels) and was assumed to be fixed to a roof at a tilt of 20 degrees.

2.3 Cost and Grid Mix Data

When determining which electricity rate structure is best to use for analyzing the savings of a solar photovoltaic system with and without load shifting, flat rates and time-of-use (TOU) rates with a net metering buy-back ratio of 1 were considered. A flat rate charges a constant amount for every kWh of electricity consumed, while a TOU rate structure charges different amounts for different periods during a day. The periods and charges vary based on electricity demand and peak hours. Load shifting is economically motivated by TOU rate structures because end users are encouraged to decrease electricity consumption during on-peak hours.

The TOU electricity rate was based on the 16:00-21:00 TOU rate of Southern California Edison (SCE) with a buy-back ratio of 1 to analyze the effect on electricity costs (SCE, 2019). This buy-back ratio indicates that a unit of electricity purchased from the grid has the same value as a unit of electricity produced by the solar array. The TOU rates are shown in Figure 3. Prices are raised during the peak time of electricity consumption, namely between 16:00 and 21:00 in the summer, in order to discourage over-consumption and to decrease peak demand. In the summer, the rate is 40¢ per kWh at this time while off-peak hours are 25¢ per kWh. The high summer peak rate is principally due to significant air-conditioning loads. During the winter, users are charged 35¢ during mid-peak hours, 24¢ between 8:00 and 16:00, and 26¢ at night.

3. CONTROL STRATEGY

A control strategy based on energy matching was developed for shifting the water heater load. Figure 4 shows the flow chart for the control strategy used. The control strategy assumes a variable heating element that can be powered with the electricity produced directly from the solar array. If the tank reaches minimum charge, a default condition is triggered and the water heater runs for 10 minutes at full capacity using electricity from the grid and available electricity generated through solar power. A variable is created to include the cumulative sum of solar energy, ambient heat loss (Q_{loss}), and heat transfer due to water draws (Q_{draw}) until the end of the day. This variable is added to the tank charge at the current time step, and if solar energy is available and the sum is less than maximum tank charge, then the water heater runs using available electricity produced from the solar array at that time step.

The control algorithm depends on tank charge, ambient heat loss, and the heat transfer on the use and source sides of the electric water heater. The well-mixed water tank heat transfer model used by EnergyPlus was implemented (USDOE, 2019).

A heat exchanger effectiveness of 1 was used. The default uniform skin loss coefficient per unit area to

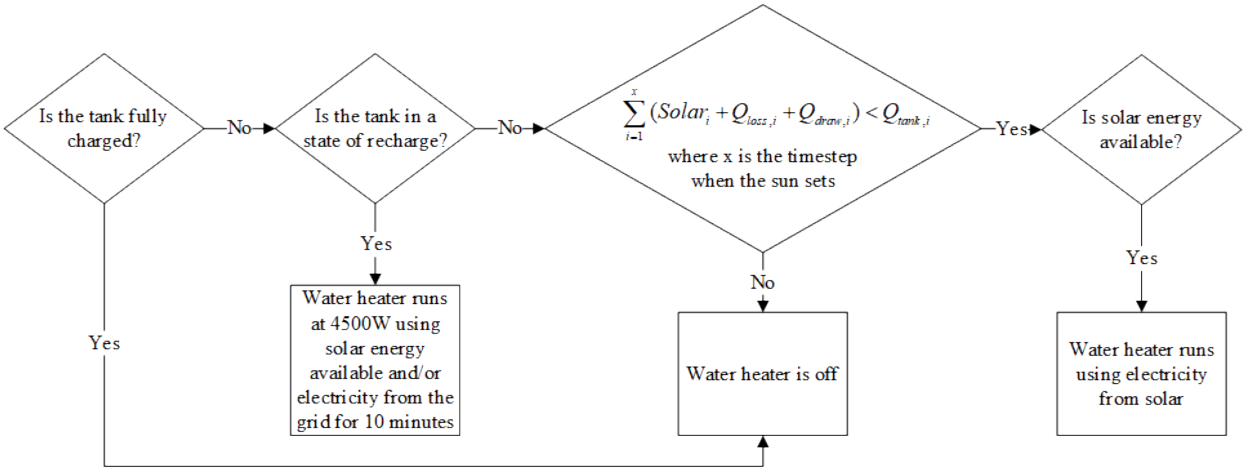

Figure 4: Flow chart for the load shifting control strategy

ambient temperature (UA), 1.33 W/K, was used. The conversion of electrical energy to thermal energy in the resistance heating element is assumed to have 100% efficiency.

The tank charge at a given time step is given by the following equation:

$$Q_{tank,i+1} = Q_{tank,i} + 60(q_{heater,i} + UA(T_{amb,i} - T_{tank,i}) + \dot{m}_{use,i}c_p(T_{tank,max} + T_{mains,i} - 2T_{tank,i})) \quad (1)$$

where q_{heater} is the heat transfer rate to the water in the tank from the heating element, T_{tank} is the water heater outlet temperature, T_{amb} is the ambient temperature, T_{mains} is the mains water temperature, $\dot{m}_{use}$ is the mass flow rate in kg/s, and c_p is the heat capacity of water. The maximum temperature is changed to 60°C to increase the capacity for energy storage.

The tank is at maximum charge when

$$Q_{tank,max} = V_{tank} \cdot c_p \cdot \rho \cdot T_{tank,max} \quad (2)$$

where V_{tank} is the total volume of water in the tank (50 gallons, 189 L). Similarly, the minimum tank charge occurs when $T_{tank,max}$ is replaced with $T_{tank,min} = 46°\text{C}$.

The cumulative heat transfer due to water draws is given by:

$$Q_{draw} = m_{cumulative} \cdot c_p \cdot (T_{mains,avg} - T_{max}) \quad (3)$$

where $m_{cumulative}$ is the cumulative mass of water drawn from the water heater during the given amount of time and $T_{mains,avg}$ is the average mains water temperature (20.2°C).

The ambient heat loss is the product of the tank's resistance to heat transfer (UA) and the ambient temperature. The water heater outlet temperature at each time step was calculated using a differential equation which takes into account UA, the heat transfer due to ambient heat loss and the heat transfer to/from the use and source sides of the water heater (USDOE, 2019).

4. RESULTS AND DISCUSSION

The original water heater load runs quickly and frequently to reach a setpoint of 48°C because the load only depends on water consumption and ambient heat loss and does not account for solar power generated. Alternatively, the shifted load directly uses electricity generated from the solar panels and electricity from the grid when solar power generation is not available. As seen in Figure 5, the tank temperature remains above the minimum allowable temperature of 46°C while maximizing the consumption of electricity generated by the solar array.

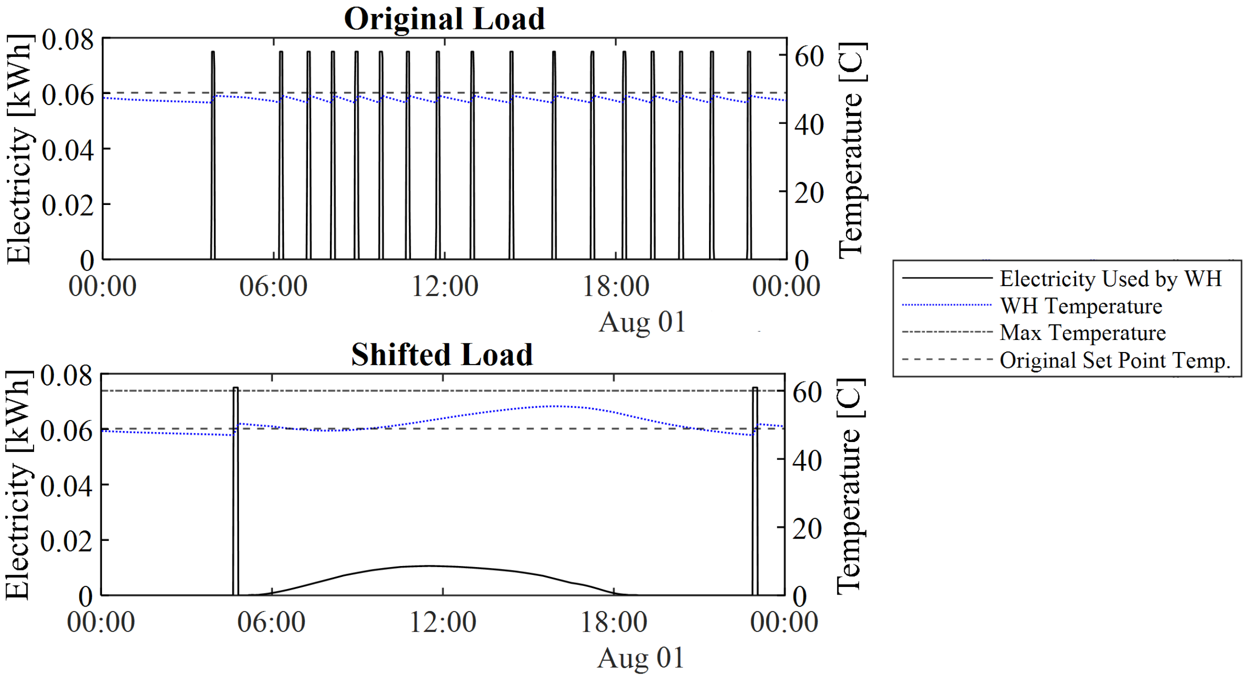

Figure 5: Original load and shifted load for August 1

It is important to note that the analysis uses ideal theoretical data. The hot water consumption appears to be relatively similar each day. However, the design of a control algorithm for a smart hot water heater would be able to predict users' hot water consumption schedule based on prior data. Solar power generation can be predicted, but these predictions are imperfect, particularly on a short-term basis.

Three metrics were used to quantify the results of the addition of a solar array with and without load shifting: the fraction of the water heating load met by solar power, annual end-user electricity bills, and the fraction of the water-heating load to the total house electricity.

Table 1 displays the results for these metrics under a system with no solar array, a 1 kW solar array, and a 1 kW array with load shifting. Only 5% of the water-heating load is met when a solar array is introduced without load shifting while 63% is met with load shifting. The annual electricity bill is reduced by $195 through the addition of load shifting. The water-heating load becomes only 16.6% of the house electricity when it is shifted while it was originally 22%.

The analysis of these results show that load shifting is more economically and environmentally effective than a solar photovoltaic system without load shifting. These results suggest that widespread use of smart water heaters that optimize load shifting has significant potential for the integration of renewable energy onto the grid. The development of smart hot water heaters would be able to predict users' hot water consumption schedule based on prior data. On an individual scale, load shifting for hot water heaters significantly decreases users' annual electricity bills.

In future work, the controls in this study should be tested experimentally. An optimization algorithm could be created according to economic savings through TOU rates and/or the amount of available solar energy. These controls can also be aggregated to hundreds of water heaters to determine the benefit to the grid through day-ahead market pricing which give a closer approximation of actual generation costs to utilities than TOU rates. This work could be expanded to encompass heat pump water heaters and a variety of different electricity rate structures. The inclusion of heat pump water heaters could also incorporate an accounting of the capital costs for equipment and the simple payback periods.

Table 1: Results With and Without a 1 kW Solar Array and Load Shifting

Metric	**No Solar Array**	**Solar Array**	**Solar Array and Load Shifting**
WH Load Met by Solar Array	0%	5%	63%
Annual End-User Electricity Bill	\$846	\$803	\$608
Fraction of WH Load to House Electric Load	22%	21%	16.6%

5. CONCLUSIONS

Energy simulation programs EnergyPlus and SAM were used to model a residential water heater load with one-minute time steps.

- 63% of the water-heating load was met by a 1 kW solar array with load shifting whereas only 5% of the load was met by a solar photovoltaic system without load shifting.
- The use of water heater load shifting with a solar photovoltaic system saved \$195 more on an annual water heater TOU electricity bill than a solar photovoltaic system without load shifting.
- The fraction of the water-heating load to the house electric load was 16.6% with load shifting and 21% without load shifting.
- Load shifting can be implemented as an economically and environmentally effective means of energy storage.

NOMENCLATURE

CAISO	California Independent System Operator
GHG	greenhouse gas
IECC	International Energy Conservation Code
PNNL	Pacific Northwest National Laboratory
USDOE	U.S. Department of Energy
NREL	National Renewable Energy Laboratory
SAM	System Advisor Model
TMY3	Typical Meteorological Year version 3
TOU	Time-of-use
TRNSYS	Transient System Simulation Tool

Variables

Q_{draw}	thermal energy leaving WH tank
Q_{loss}	sum of water heat loss energy for the month
Q_{tank}	total thermal energy in the WH tank at time step i
Q_{max}	maximum thermal WH tank energy
q_{heater}	heat transfer rate to the water in the tank from the heating element
$m_{cumulative}$	cumulative sum of the mass of water drawn
$\dot{m}_{use}$	mass flow rate from water heater
V_{tank}	total volume of water in the WH tank
c_p	specific heat of water
ρ	water density
T_{tank}	the outlet temperature of the water heater
T_{mains}	the mains water temperature
UA	uniform skin loss coefficient per unit area to ambient temperature

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