To: Dr. Hedengren

From: Tyrel Hess, Cameron Price, Derek Prestwich

Re: Control and Optimization of Zero-Carbon Power Grid

For our project, we have elected to optimize the control of a Pressurized Water Nuclear Reactor (PWR) within an integrated, carbon-free power grid. This has been done to demonstrate the feasibility of using nuclear energy as the main power source in a system of varying renewable sources and customer energy demand. The proof-of-concept simulation uses the point reactor kinetic equations with six delayed neutron precursor groups to create a digital twin that is manipulated through control rod position.

The main contributions of this project are:

- A model that provides accurate responses and simulations of a PWR
- Moving horizon estimation for varying parameters, such as the overall heat transfer coefficient
- A model predictive controller that optimizes nuclear power response based on varying levels of solar, wind, and hydroelectric power.
- Solid evidence of reaching a carbon-free power grid with central support from nuclear energy

Our model predictive controller has successfully optimized the response of the nuclear reactor to constantly meet the power demand with its equivalent supply. We recommend further work to be done on the economics and models of such a plan and further research on potential of government policy changes to make this more feasible.

Sincerely,

Tyrel Hess

Derek Prestwich

Cameron Price

Control and Optimization of a Zero-Carbon Power Grid

Tyrel Hess, Derek Prestwich, Cameron Price

Ch En 593R – Dynamic Optimization

Dr. John Hedengren

Brigham Young University

Contents

Abstract

For our project, we have elected to optimize the control of a Pressurized Water Nuclear Reactor (PWR) within an integrated, carbon-free power grid. This has been done to demonstrate the feasibility of using nuclear energy as the main power source in a system of varying renewable sources and customer energy demand. The model uses the point reactor kinetic equations with six delayed neutron precursor groups to create a digital twin that is manipulated through control rod position.

To meet our objective, a proof-of-concept for a zero-carbon power grid that uses nuclear energy as its primary load following mechanism has been presented. The hypothesized system also includes variable solar and wind sources and a reservoir that may provide energy storage or production according to grid needs. Between these four energy sources an effort has been made to optimize the power grid to prevent under or overproduction of energy, as shown in Figure AB1.

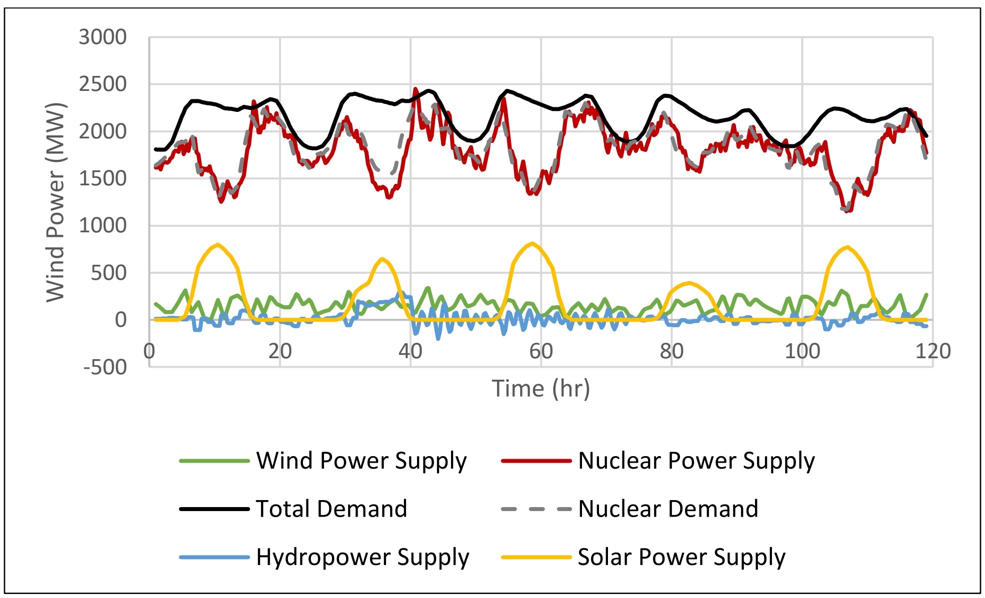

Figure AB1: Simulated energy integration results

Based on these results, we conclude that nuclear power is capable of load following to meet energy demands. We recommend that further work be done to develop a more accurate, heterogeneous model of the PWR, increase time resolution, and perform an economic analysis of the power grid.

Introduction

In a time where climate change has become a significant concern, many governments are searching for ways to minimize carbon emissions while maintaining ample energy supplies. Until now, the primary answer has been the development of renewable energy sources; this, however, has not found success due to the inconsistent nature of renewables and the current lack of sufficient energy storage systems. Our objective in this paper is to propose nuclear energy as a superior solution and demonstrate this industry's ability to satisfy variable power demand while optimizing usage of available renewable energy sources. Although nuclear reactors are generally not made to load follow because of economic limitations, our results demonstrate how, in a more educated political environment, they may be controlled to provide variable power output.

To meet our objective, a proof-of-concept for a zero-carbon power grid that uses nuclear energy as its primary load following mechanism is presented. The hypothesized system also includes variable solar and wind sources, and a reservoir that may provide energy storage or production according to grid needs. Between these four energy sources an effort has been made to optimize the power grid to prevent under or overproduction of energy. The scope of this study is to demonstrate the technical feasibility of such an undertaking, and no economic analysis is included in this report.

Literature Review

Na et. al (2003) presented a simplified reactor model that we drew on to develop our model. The model is useful because of its simplicity, as we are not exceptionally well-versed in nuclear systems. Espinosa-Paredes et. al (2006) presented a more complex BWR model that was drawn upon to strengthen the accuracy of our digital twin. The latter publication provided a wealth of useful parameters that we included in our model. Using this model, we will be able to add additional functionality to the model and controller as needed and as time permits.

Integrated Power Grid Control

An integrated power grid is considered, wherein four sources of power need to be simultaneously incorporated: solar power, wind power, nuclear power, and hydropower. The solar power production follows a cyclic pattern of production that coincides with available daylight, while the wind power results from randomized wind vectors. These two sources are both uncontrollable and provide no means of storage. Thus, as these two renewable sources generate electricity the nuclear reactor and hydropower station will react to accommodate for increases or decreases in solar and wind power production. In this hypothetical power grid, it is assumed that if solar and wind sources were at 100% utilization (which serves as a theoretical upper limit for their power contributions), solar power would provide 35% of the total demand and wind power would meet 15% of the total demand.

The nuclear reactor will serve as a load-following power source in this power grid while the hydropower will provide storage capabilities that will pair with the nuclear reactor to optimize energy production and minimize overproduction. The electricity demand and accompanying grid management were modelled across a five-day window, and the demand profile used for the study is shown in Figure 1. The shape of these data was drawn from energy demand data provided by the State of California, but the actual values were scaled such that the available simulated sources could meet this demand.

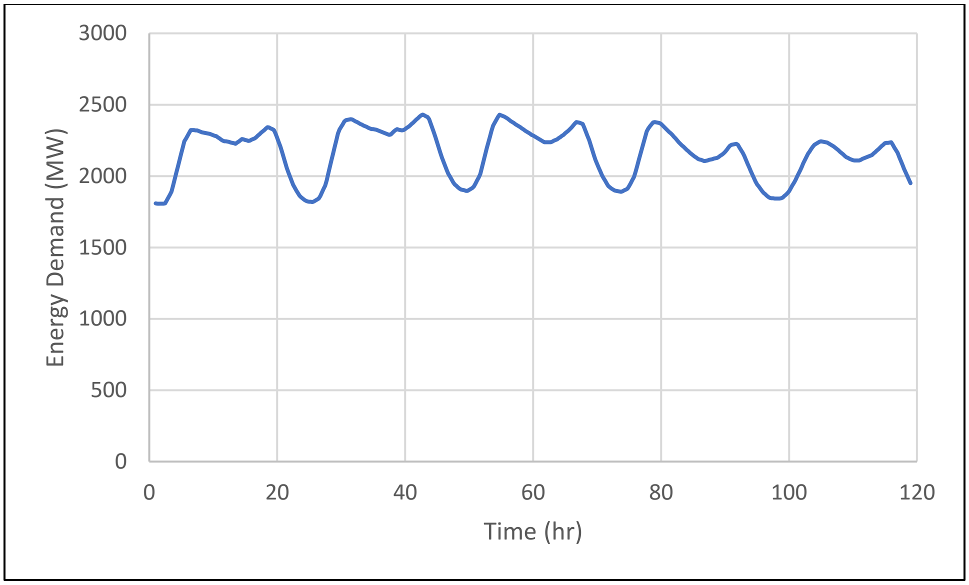

Figure 1: Total energy demand over a five-day period.

Nuclear Reactor

Model

Our nuclear reactor model is based on the design of a Pressurized Water Reactor (PWR). This is the most commonly used design in the U.S. and would be more easily implemented because of its maturity and existing licenses. Our PWR is composed of a primary loop that circulates the moderator (light water) through the reactor and exchanges heat with the coolant stream in the secondary loop that generates power from the turbine. For simplicity, however, we have left the secondary loop as a black box and are only modeling its effects on the primary loop.

The power of the reactor is being controlled through the reactivity and is adjusted with control rods constructed from barium (due to its large microscopic absorbance cross section). The actuator of the system is the position of this control rod, which is quantified by "steps" that range from 50 to 200. These step numbers correspond to control rod positions within the system. A diagram of the system is shown in Figure 2.

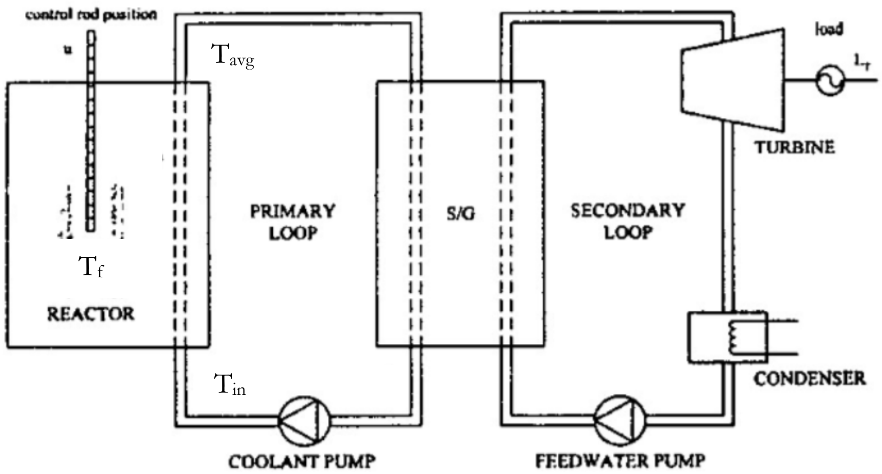

Figure 2: A diagram of the nuclear reactor presented by Na et. al (2003)

Equations 1-5 present the point reactor kinetic equations with six delayed neutron precursor groups that were used to model the primary loop as shown in Figure 2. These equations are based on a homogenous reactor design, but offer a sufficiently accurate approximation of our heterogeneous PWR. These equations were modelled in Python 3.6 and solved using the odeint routine provided in the scipy package. This model in odeint served as a digital twin with which the estimator and controller could subsequently interact. The constant parameters used in Equations 1-5 are described in Table 1, while the variables are described in Table 2.

$$\frac{dP}{dt} = \frac{\rho - \beta}{l} P + \sum_{i=1}^{6} \lambda_i \beta_i \tag{1}$$

$$\frac{dT_f}{dt} = -\frac{UA}{M_f c_{p,f}} \left(T_f - T_{avg}\right) + \frac{J}{M_f c_{p,f}} P \tag{2}$$

$$\frac{dT_{avg}}{dt} = \frac{UA}{M_c c_{p,c}} \left(T_f - T_{avg}\right) - \frac{\dot{m}}{M_c} \left(T_{avg} - T_{in}\right) \tag{3}$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{l}P - \gamma_i C_i \quad (i = 1, \ldots, 6) \tag{4}$$

$$\rho = \rho_0 + \alpha_f T_f + \alpha_c T_{avg} + b \cdot u \tag{5}$$

Table 1: Description of constant parameters used in equations X-X*

Parameter Symbol	Parameter Definition
β_i	i^{th} group delayed neutron precursor coefficient
λ_i	Decay constant for i^{th} group neutron precursor (s^{-1})
α_f, α_c	Fuel and moderator temperature coefficients of reactivity
b	Differential control rod worth
l	Neutron generation time (s)
U	Overall heat transfer coefficient ($W/(m^2K)$)
A	Heat transfer surface area (m^2)
M_f, M_c	Fuel and moderator masses (kg)
$c_{p,f}$, $c_{p,c}$	Fuel and moderator heat capacity (J/(molK))
J	Conversion Factor (MW / %Power)
ρ_0	Initial reactivity

*The values of the parameters included in this table are included in the code in the Appendix

Table 2: Description of variables used in equations X-X*

Controlled, Manipulated, and Disturbance Variables	**Variable Definition**
u (MV)	Control rod step (in)
T_{avg} (CV)	Coolant outlet temperature (K)
C_i (DV)	Delayed neutron precursors
T_f (DV)	Fuel temperature (K)
ρ (DV)	Reactivity

*The initial values of these variables are included in the code in the Appendix

Equations 1-5 were also used to create a moving horizon estimator (MHE) and a model predictive controller (MPC). The dynamic optimization package GEKKO was used in the development of estimation and control for this project. The code for the odeint model and the GEKKO estimator and controller are included in the code in the appendix. Specific features of the estimator and controller are discussed below.

Estimation

The most uncertain parameter and the parameter that is most likely to change over time within this modeled nuclear reactor is U, the overall heat transfer coefficient between the fuel and the moderator. This parameter would likely be unknown at the beginning of operation although a first approximation could be determined with a heat transfer correlation. We simulated this initial uncertainty by providing the model with an incorrect initial U. Also, over time as fouling occurs and heat transfer decreases, the model will need to adjust for these variations. Therefore, we created a model horizon estimation scheme that will follow this trend and update the model as needed. There will likely be a significant amount of noise in the actual heat transfer that is occurring throughout the course of a day, but the estimation should only follow long term trends.

To demonstrate our design's capacity to accomplish this task, we simulated a decreasing trend in heat transfer over time that had random noise built into it. Although this trend likely occurs much slower than is here simulated, this is mainly a proof of concept to show that as this controller ran over the course of a year it could compensate for changes in operating conditions especially for those that occur due to fouling. The Estimation Results section of this paper explores the estimator's capacity to achieve its objective.

Control and Energy Storage

The control for the nuclear reactor energy output was done using a model predictive controller that utilized the model outlined above and adjusted control rod position to change the energy output at any given time. While many nuclear reactors in the United States were not designed to load follow using frequent control rod movement, this type of control would be appropriate for smaller Light Water Reactors such as those used in France. New control rod positions were chosen at 15 minute intervals throughout the course of each day and each time the MPC solved it made its predictions based on a time horizon that looked five hours into the future. This is quite computationally efficient as each iteration took less than a minute to run and therefore is negligible compared to the time difference between each adjustment.

The novel part of this MPC is that it was integrated with a water reservoir energy storage system. Even though control rods were adjusted every 15 minutes, there still tended to be some mismatch between demand and output supply of the nuclear reactor. This meant that at some times, economic opportunity would be lost because not enough power was produced to fulfill all potential demands, and at other times there would be waste because too much power was produced. To compensate for this mismatch, we incorporated an energy storage system that pumped water to store excess energy as gravitational potential energy. That energy could also be used to fulfill demand in times when the nuclear power being produced was less than the energy demanded.

Along with this integration, it was desired that the reservoir could be drained and filled on command. This would be especially useful if the reservoir levels dropped significantly or if a lot of rain was forecast for the next day. Therefore, a proportional, integral, derivative (PID) controller was integrated into the objective function of the model predictive controller to achieve this purpose. This PID controller was designed in such a way that an operator could turn it on and select a desired level within the reservoir at will, but it would not be functioning at other times. The PID controller outputs a variable that is fed to the objective function of the MPC for each time step that it is on. The objective function is written as:

$$\min_{u}\left(E_{demand} - P_{nuclear} - P_{hydro}\right)^2 \tag{6}$$

where E_{demand} is the total energy demanded from the integrated hydronuclear system, $P_{nuclear}$ is the power output of the nuclear reactor and P_{hydro} is the hydropower being produced at any time. P_{hydro} is calculated and fed to this objective function by the PID controller used to control the level of the reservoir. Because the change in the level of the reservoir is directly related to the difference between E_{demand} and $P_{nuclear}$ this ensures part of the total demand is fulfilled by the reservoir when P_{hydro} is positive. Similarly, it will make the nuclear plant produce excess energy that will be used to fill the reservoir when P_{hydro} is negative. Since the magnitude of P_{hydro} is related to the error between the reservoir level and the desired level, when the reservoir is at the desired level it is zero and the controller will once again attempt to fulfill the entire energy demand with nuclear power. This controller can also be turned off if the reservoir level does not need to be adjusted or maintained.

Renewable Energy

The solar energy provided to the power grid is a function of daylight and cloud cover on any given day. Assuming no cloud cover, the quantity of solar power was assumed to be greatest at 12:00 PM and at zero through the night, with a supply gradient occurring through the day between the nighttime minimum and the daytime maximum. A plot of the solar supply over the simulated five-day period is shown below in Figure 3. It should be noted that the first, third, and fifth days represent cloudless days, while the second day represents a partially cloudy day and the fourth day represents an overcast day.

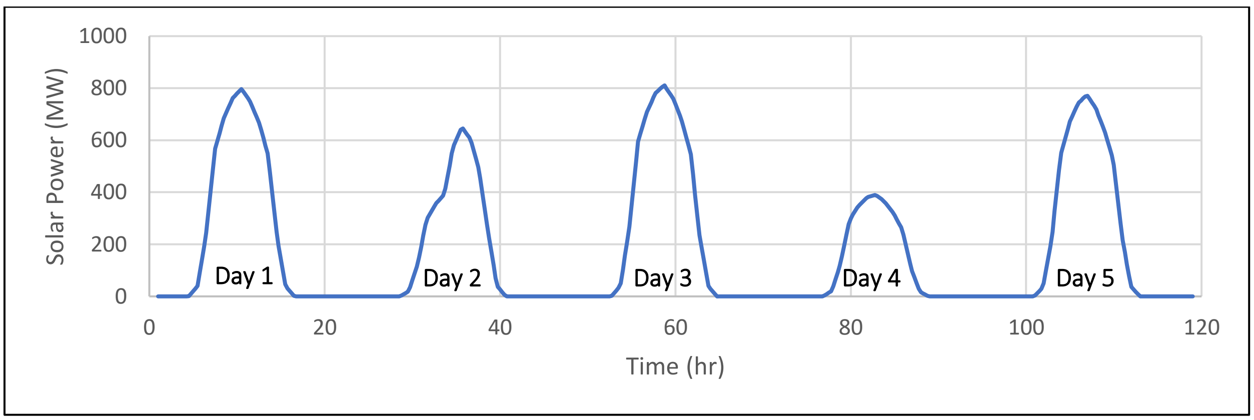

Figure 3: Plot of solar power supply over five-day period, with the days numbered.

The wind power is assumed to come from a wind farm that is integrated into the power grid. The power from this farm is assuming to come from randomly generated wind vectors that are independent of time of day or year. While this is an inaccurate representation, wind activity is variable enough that randomization allows this simulation to capture the overall features of wind power. The wind power data used for the five-day simulation is shown in Figure 4.

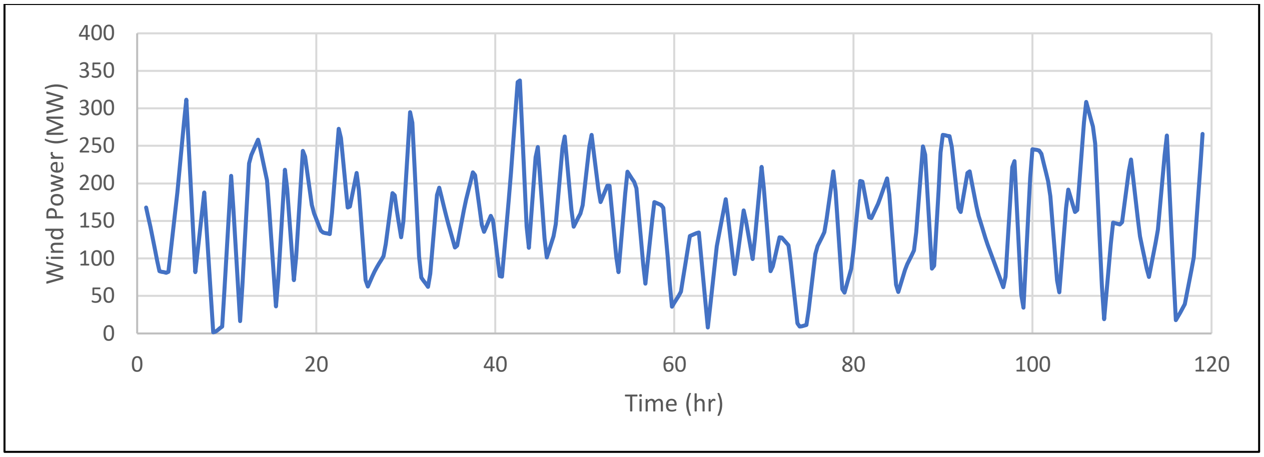

Figure 4: Plot of wind power supply over five-day period.

Results and Discussion

Estimation Results

Figure 5 demonstrates the functionality of the MHE that was developed for this model. The random noise that was generated in this simulation does not cause much parameter variation which is desired as the estimator should compensate for general trends while ignoring random fluctuations. As the overall mass transfer coefficient steadily decreases due to simulated fouling, the MHE is successful at matching those changes. This would ensure that over the course of a few years, parameters would not have to be manually updated or changed within the program. Also, if there was ever a significant disturbance within the process, extreme variation to the overall heat transfer coefficient could signify a problem with the process and give and early warning to operators of impending malfunction.

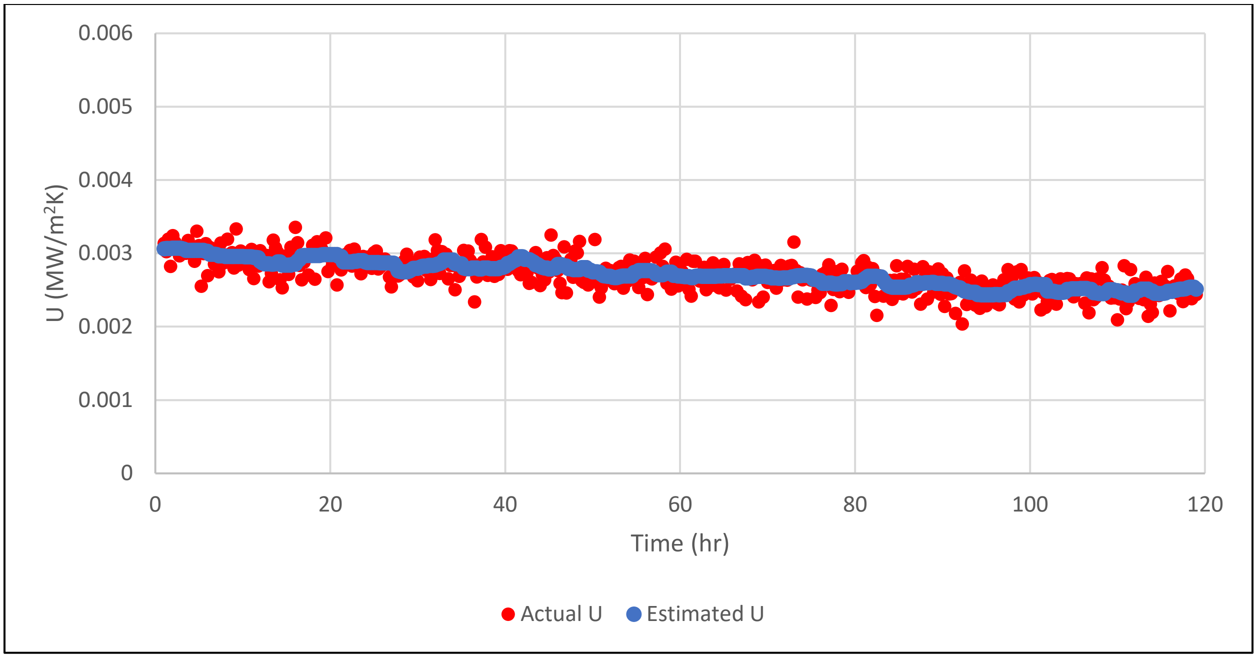

Figure 5: Model Horizon Estimation Results

Control and Optimization Results

The results of the integration of nuclear, wind, solar, and hydro power are shown in Figure 6. Across the simulated five-day period, the nuclear reactor supplies appropriate load-following capabilities, allowing the system to meet the total energy demand across that period. The swings in total demand are typical of daily energy use for a given population. The solar and wind energy sources shown in Figure 6 (as well as Figures 3 and 4) were disturbance variables to the system.

The nuclear demand line was generated by subtracting the wind and solar sources from the total demand. However, the controller didn't perfectly match the nuclear reactor output to the nuclear demand line. This was resolved using the final energy source in the system, the reservoir. This reservoir was an integral part of the system as it provided not only energy generation, but a place for energy storage. When the hydropower production line is negative in Figure 6, it indicates that water is being pumped into the reservoir for later use. Mismatch between the nuclear demand and nuclear reactor supply was addressed with the reservoir. When the reactor overproduced, the surplus energy was used to pump water into the reservoir and when the reactor under produced, water was drawn from the reservoir to generate any additional energy required. The reservoir level across the five-day simulation period is shown in Figure 7.

Generally, the reservoir level is allowed to fluctuate uncontrolled, with only hard limitations at the empty and full levels. However, there are periods where it may be desirable to control the level in the reactor, and such control has been built into this simulation. For the purposes of the simulation, it was assumed that rain fell during the fourth day, between hours 72 and 90. This caused a decrease in the solar power produced that day, while causing a natural (non-pumped) increase in the reservoir level. It is desirable to preemptively empty the reservoir to some degree to prevent overflow during precipitation events. The level controller was turned on at 32 hours to decrease the reservoir level to 50% before the onset of the rainstorm. Control was deactivated at 72 hours a (the onset of the rain) and from that point the reservoir naturally filled for a time then levelled off as the rain stopped.

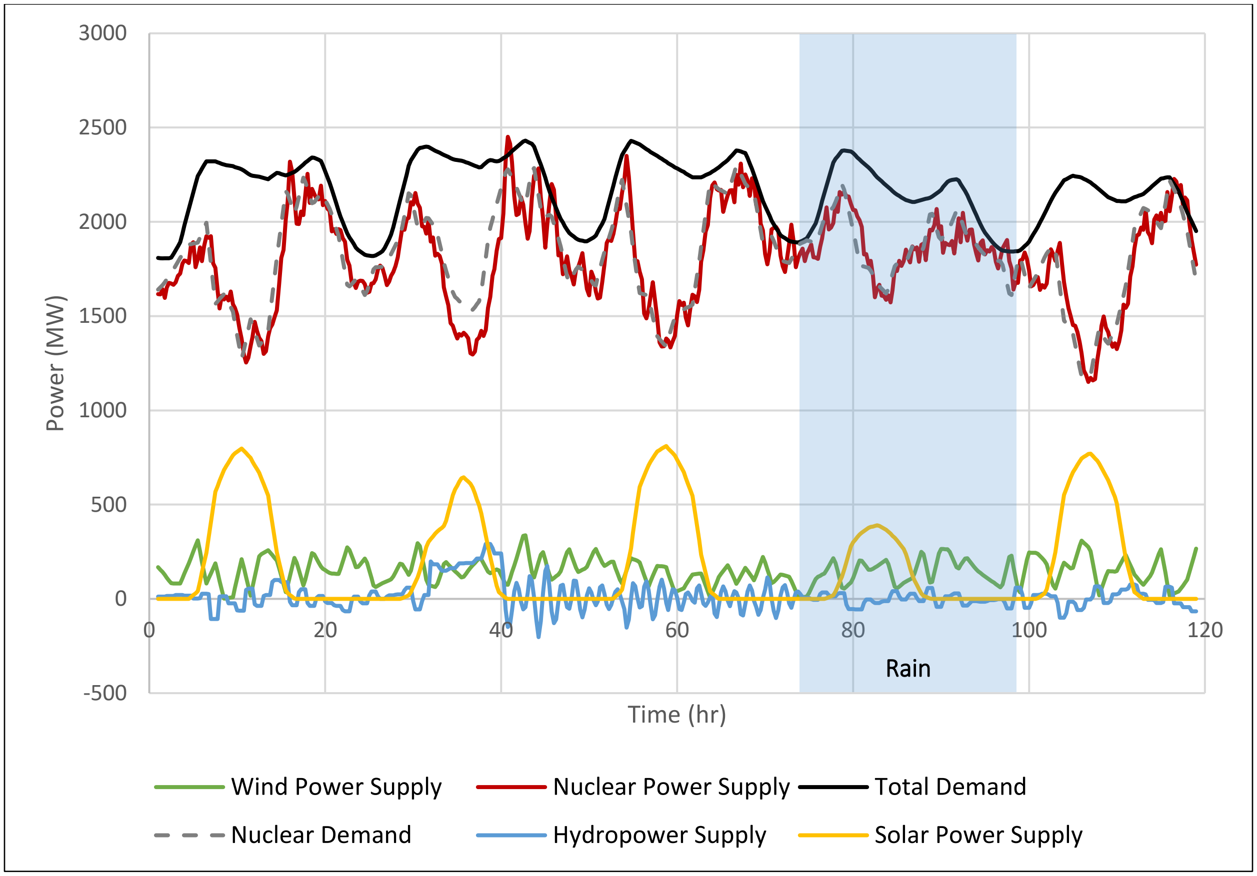

Figure 6: Power demand and supply for a simulated five-day period

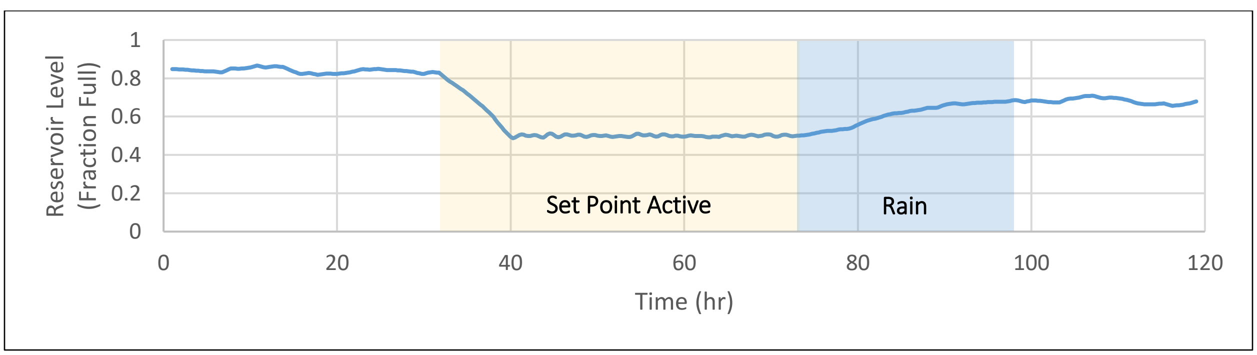

Figure 7: Reservoir level during a simulated five-day period, with highlighted regions of interest

Figure 8 is a plot of supply and demand data overlaid with a plot of the reservoir level at a time in the simulation when our reservoir PID controller was turned on. It is a magnified portion of Figure 6 above. This is intended to show a closer look how a reservoir level set point could be satisfied while simultaneously fulfilling the total energy demand using the method outlined in the Control section above. The PID controller was turned on at 32 hours, at which point the reservoir began to drain and the energy supplied from the hydro facility increased. At the same time, the nuclear reactor began to produce less than the energy demanded because a larger portion of that demand was being fulfilled by the draining reservoir.

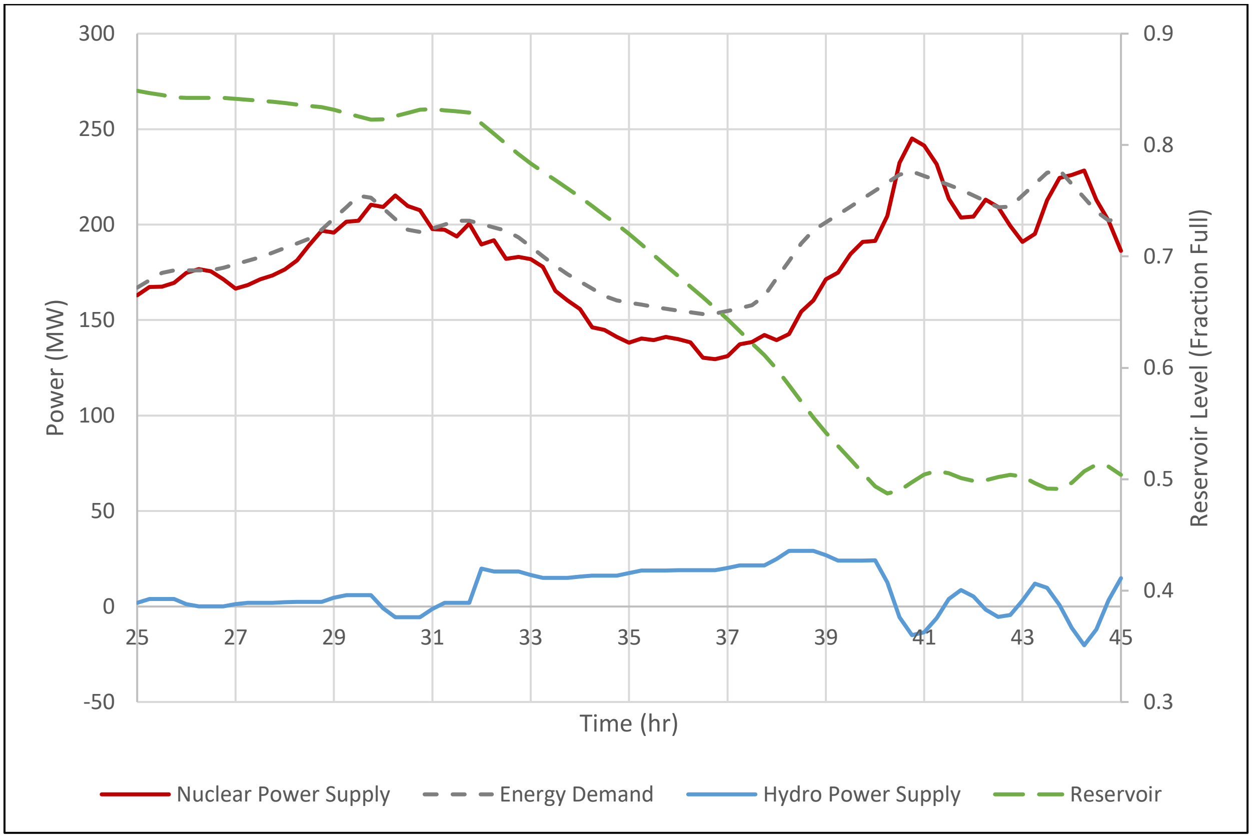

Figure 8: Integrated reservoir and nuclear control

Figure 9 below shows how the control rod was used to manage the system. The control rod position over time is shown, as well as the fuel temperature and coolant temperature. For safety reasons the fuel was maintained at under 900 °C and the cooling water was maintained below its critical temperature of 375 °C. The control rod step was maintained between 50 and 200, and manipulated in order to efficiently manage the energy output of the reactor according to the power grid demand.

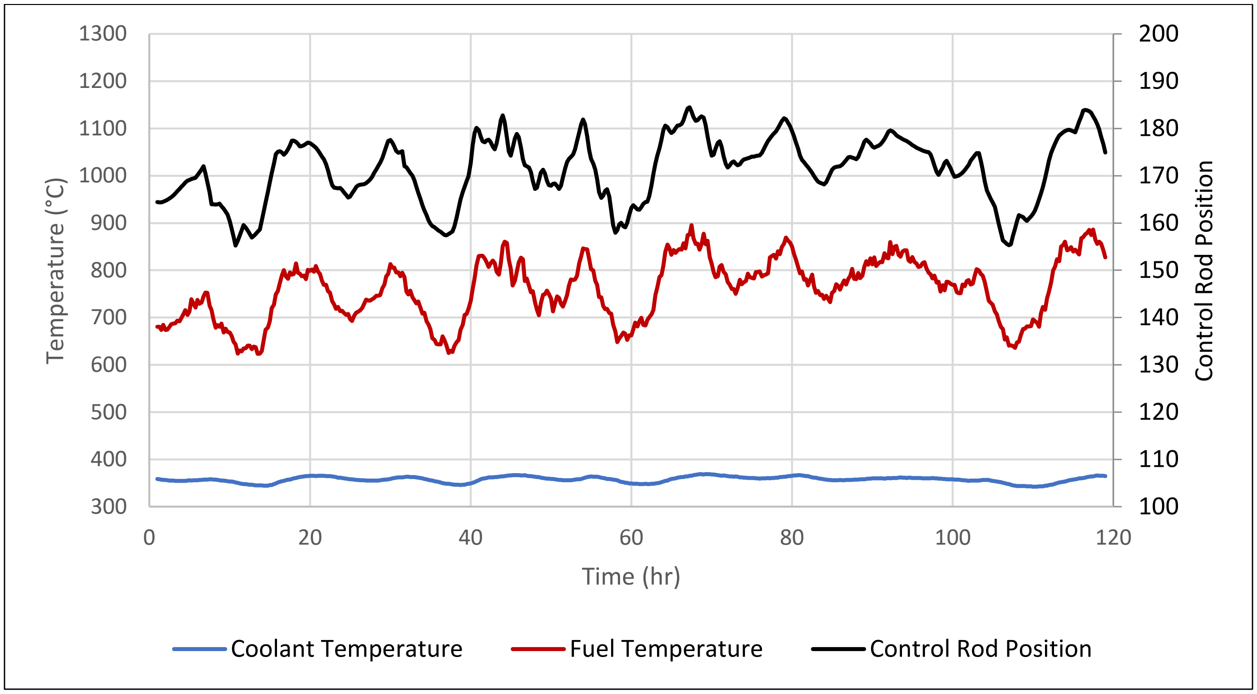

Figure 9: Fuel and coolant temperatures of the nuclear reactor plotted with the control rod steps

Conclusion

As the world strives to rely less on fossil fuels, we need to be able to develop integrated systems of emissionless energy sources that can work together to fulfill the energy demands of an increasingly electricity dependent society. One such ideal system would be a nuclear power plant that is supplemented by various renewable energy sources. The control described in this paper fulfills variable energy demand while optimizing the use of available energy sources. In so doing, it presents a potential prototype for energy schemes that will lead to an emmisionless future. As this is a first look at such an integrated system, there are several avenues of future work that should be pursued to analyze this system in depth.

First of all, this paper did not take into account any economic parameters. More work can be done to ensure that the system is not only able to meet energy demand needs, but also maximizes profitability. Also, there is potential that there is some economic infeasibility associated with some of our assumptions. As government regulations on nuclear reactors are strict and complex, such an analysis was outside of the scope of this paper. We hope that papers such as this which demonstrate nuclear energy's potential to reduce emissions will convince those in government to reduce regulations that stifle the ability of nuclear plants to contribute meaningfully to clean energy production.

The model described above used the point kinetic equations which are a good assumption for a homogeneous reactor, but these equations generate some error when considering a heterogeneous reactor. Since the reactor for which this controller was developed was a PWR, it would likely be more accurate to describe it with a more complex model. It is possible that the point kinetics model would be sufficient for the controller to use in its predictions, but this should be investigated by pairing the controller with a better nuclear reactor simulation.

Finally, this simulation integrated the numerical models over time steps of 15 minutes, this means there might be some inherent error due to poor resolution. This was done to view results faster, but increased resolution would provide more conclusive findings. Therefore, we recommend further investigation of this system with better resolution and perhaps with real-time integration.

Citations

Espinosa-Paredes, Gilberto, Alejandro Nunez-Carrera, and Alejandro Vazquez-Rodriguez. "Simplified Distributed Parameters BWR Dynamic Model for Transient and Stability Analysis." *Annals of Nuclear Energy*, vol. 33, 2006, pp. 1245-1259.

Ichikawa, T., and T. Inoue. "Light Water Reactor Plant Modeling for Power Systems Dynamics Simulation." *IEEE Transactions on Power Systems*, vol. 3, no. 2, 1988, pp. 463-471.

Na, Man G., Sun H. Shin, and Whee C. Kim. "A Model Predictive Controller for Nuclear Reactor Power." *Journal of the Korean Nuclear Society*, vol. 35, no. 5, 2003, pp. 399-411.

Appendix

Raw Data

The raw simulation data is included below in Tables A1 and A2. Negative time refers to time used at the beginning of the simulation to equilibrate the system.

Table A1: Raw nuclear reactor simulation data

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE (MW/m^2K)	U actual (MW/m^2K)
-48.75	418.0	295.8	100.0	-0.007257	0.004846	0.003465
-48.5	389.5	297.4	100.0	-0.006767	0.004846	0.003301
-48.25	363.4	298.3	100.0	-0.006291	0.004846	0.003230
-48	345.1	298.7	100.0	-0.005945	0.004846	0.003252
-47.75	332.9	298.8	100.0	-0.005707	0.004846	0.003249
-47.5	324.7	298.7	100.0	-0.005538	0.004846	0.003284
-47.25	318.9	298.5	100.0	-0.005413	0.004846	0.003352
-47	315.2	298.3	100.0	-0.005324	0.004846	0.003255
-46.75	312.6	298.0	100.0	-0.005259	0.004846	0.003110
-46.5	310.3	297.7	100.0	-0.005198	0.004846	0.003231
-46.25	308.5	297.4	100.0	-0.005146	0.004846	0.003226
-46	307.4	297.0	100.0	-0.005107	0.004846	0.002987
-45.75	306.3	296.7	100.0	-0.005071	0.004846	0.002987
-45.5	304.7	296.5	100.0	-0.005025	0.004846	0.003489
-45.25	303.6	296.2	100.0	-0.004991	0.004846	0.003346
-45	302.7	296.0	100.0	-0.004960	0.004846	0.003365
-44.75	302.2	295.7	100.0	-0.004938	0.004846	0.003033
-44.5	301.6	295.5	100.0	-0.004914	0.004846	0.003142
-44.25	300.8	295.3	100.0	-0.004887	0.004846	0.003490
-44	300.3	295.1	100.0	-0.004868	0.004846	0.003144
-43.75	299.8	294.9	100.0	-0.004849	0.004846	0.003236
-43.5	299.3	294.7	100.0	-0.004829	0.004846	0.003466
-43.25	298.9	294.5	100.0	-0.004814	0.004846	0.003176
-43	298.4	294.4	100.0	-0.004796	0.004846	0.003512
-42.75	298.1	294.2	140.0	-0.004782	0.004846	0.003339
-42.5	305.5	294.2	140.0	0.005073	0.004846	0.003276

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE (MW/m²·K)	U actual (MW/m²·K)
-42.25	318.6	294.3	140.0	0.004808	0.004846	0.002989
-42	331.5	294.6	140.0	0.004531	0.004846	0.003472
-41.75	345.8	295.2	140.0	0.004217	0.004846	0.003251
-41.5	360.5	295.8	140.0	0.003890	0.004846	0.002980
-41.25	372.1	296.7	140.0	0.003617	0.004846	0.003027
-41	377.3	297.7	140.0	0.003460	0.004846	0.003489
-40.75	388.4	298.6	140.0	0.003195	0.004846	0.002974
-40.5	391.4	299.7	140.0	0.003079	0.004846	0.003436
-40.25	395.7	300.8	140.0	0.002940	0.004846	0.003409
-40	400.3	301.8	140.0	0.002799	0.004846	0.003385
-39.75	406.6	302.7	140.0	0.002628	0.004846	0.003194
-39.5	411.3	303.5	140.0	0.002489	0.004846	0.003165
-39.25	414.7	304.4	140.0	0.002379	0.004846	0.003175
-39	413.2	305.4	140.0	0.002361	0.004846	0.003498
-38.75	420.1	306.0	140.0	0.002191	0.004846	0.003017
-38.5	419.0	306.8	140.0	0.002170	0.004846	0.003390
-38.25	426.1	307.3	140.0	0.002004	0.004846	0.002907
-38	425.3	308.0	140.0	0.001985	0.004846	0.003232
-37.75	425.0	308.7	140.0	0.001959	0.004846	0.003280
-37.5	424.6	309.3	140.0	0.001935	0.004846	0.003344
-37.25	429.3	309.7	140.0	0.001822	0.004846	0.003051
-37	433.1	310.1	140.0	0.001728	0.004846	0.002969
-36.75	431.7	310.6	140.0	0.001729	0.004846	0.003197
-36.5	430.0	311.0	140.0	0.001740	0.004846	0.003309
-36.25	430.1	311.5	140.0	0.001717	0.004846	0.003286
-36	432.7	311.8	140.0	0.001650	0.004846	0.003143
-35.75	435.1	312.0	140.0	0.001589	0.004846	0.003088
-35.5	438.5	312.2	140.0	0.001510	0.004846	0.002949
-35.25	437.1	312.6	140.0	0.001522	0.004846	0.003160
-35	438.1	312.8	140.0	0.001490	0.004846	0.003071
-34.75	438.2	313.1	140.0	0.001476	0.004846	0.003111
-34.5	437.1	313.3	140.0	0.001483	0.004846	0.003201
-34.25	437.0	313.6	140.0	0.001474	0.004846	0.003202
-34	435.3	313.8	140.0	0.001493	0.004846	0.003339
-33.75	438.0	314.0	140.0	0.001433	0.004846	0.003132
-33.5	439.4	314.1	140.0	0.001398	0.004846	0.003143
-33.25	443.5	314.2	140.0	0.001313	0.004846	0.002927
-33	442.4	314.4	140.0	0.001325	0.004846	0.003129
-32.75	439.8	314.6	140.0	0.001365	0.004846	0.003280

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE (MW/m²·K)	U actual (MW/m²·K)
-32.5	443.7	314.6	140.0	0.001287	0.004846	0.002970
-32.25	441.0	314.9	140.0	0.001329	0.004846	0.003271
-32	448.4	314.7	140.0	0.001186	0.004846	0.002732
-31.75	444.0	315.0	140.0	0.001262	0.004846	0.003229
-31.5	444.3	315.1	140.0	0.001252	0.004846	0.003097
-31.25	443.6	315.2	140.0	0.001258	0.004846	0.003161
-31	444.1	315.3	140.0	0.001243	0.004846	0.003124
-30.75	442.8	315.5	140.0	0.001263	0.004846	0.003244
-30.5	441.9	315.6	140.0	0.001273	0.004846	0.003282
-30.25	446.0	315.6	140.0	0.001191	0.004846	0.003006
-30	440.5	315.9	140.0	0.001287	0.004846	0.003504
-29.75	442.9	315.9	140.0	0.001237	0.004846	0.003205
-29.5	447.6	315.9	140.0	0.001146	0.004846	0.002990
-29.25	442.8	316.2	140.0	0.001228	0.004846	0.003441
-29	445.1	316.2	140.0	0.001180	0.004846	0.003170
-28.75	446.3	316.3	140.0	0.001154	0.004846	0.003178
-28.5	446.8	316.3	140.0	0.001139	0.004846	0.003183
-28.25	447.8	316.4	140.0	0.001118	0.004846	0.003151
-28	448.3	316.4	140.0	0.001104	0.004846	0.003152
-27.75	454.1	316.3	140.0	0.000995	0.004846	0.002817
-27.5	445.4	316.7	140.0	0.001151	0.004846	0.003519
-27.25	447.1	316.7	140.0	0.001116	0.004846	0.003181
-27	453.3	316.5	140.0	0.001000	0.004846	0.002859
-26.75	451.8	316.6	140.0	0.001025	0.004846	0.003123
-26.5	449.4	316.8	140.0	0.001066	0.004846	0.003233
-26.25	451.4	316.8	140.0	0.001026	0.004846	0.003050
-26	449.9	316.9	140.0	0.001052	0.004846	0.003208
-25.75	453.5	316.8	140.0	0.000982	0.004846	0.002949
-25.5	451.8	316.9	140.0	0.001011	0.004846	0.003157
-25.25	456.9	316.8	140.0	0.000915	0.004846	0.002807
-25	454.8	316.8	140.0	0.000954	0.004846	0.003074
-24.75	456.2	316.8	140.0	0.000927	0.004846	0.002929
-24.5	453.2	316.9	140.0	0.000981	0.004846	0.003151
-24.25	454.5	316.9	140.0	0.000955	0.004846	0.002993
-24	449.5	317.1	140.0	0.001045	0.004846	0.003343
-23.75	445.8	317.3	140.0	0.001110	0.004846	0.003465
-23.5	452.0	317.2	140.0	0.000992	0.004846	0.002983
-23.25	450.1	317.3	140.0	0.001024	0.001479	0.003290
-23	454.1	317.2	140.0	0.000947	0.001578	0.002996

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE ($MW/m^2 \cdot K$)	U actual ($MW/m^2 \cdot K$)
-22.75	455.0	317.2	140.0	0.000929	0.001693	0.003056
-22.5	457.5	317.2	140.0	0.000882	0.001787	0.002933
-22.25	455.8	317.3	140.0	0.000911	0.001969	0.003099
-22	454.8	317.3	140.0	0.000928	0.002061	0.003115
-21.75	456.6	317.3	140.0	0.000894	0.002182	0.002985
-21.5	455.7	317.4	140.0	0.000910	0.002264	0.003094
-21.25	455.4	317.4	140.0	0.000914	0.002398	0.003089
-21	449.9	317.6	140.0	0.001013	0.002512	0.003426
-20.75	454.5	317.5	140.0	0.000926	0.002566	0.003006
-20.5	449.3	317.7	140.0	0.001019	0.002657	0.003467
-20.25	449.8	317.8	140.0	0.001005	0.002726	0.003306
-20	454.4	317.7	140.0	0.000919	0.002854	0.003053
-19.75	459.4	317.6	140.0	0.000824	0.002892	0.002877
-19.5	459.2	317.6	140.0	0.000827	0.002923	0.003022
-19.25	459.6	317.6	140.0	0.000820	0.002935	0.002988
-19	457.7	317.7	140.0	0.000854	0.002936	0.003105
-18.75	454.1	317.8	140.0	0.000918	0.002937	0.003271
-18.5	454.3	317.9	140.0	0.000913	0.002969	0.003174
-18.25	456.6	317.8	140.0	0.000870	0.003009	0.003050
-18	456.6	317.8	140.0	0.000867	0.003009	0.003112
-17.75	460.8	317.7	140.0	0.000790	0.003009	0.002872
-17.5	458.1	317.8	140.0	0.000840	0.003001	0.003138
-17.25	458.0	317.8	140.0	0.000840	0.002987	0.003067
-17	462.2	317.7	140.0	0.000764	0.002987	0.002830
-16.75	461.8	317.7	140.0	0.000771	0.002987	0.002957
-16.5	457.7	317.8	140.0	0.000847	0.002987	0.003182
-16.25	458.1	317.8	140.0	0.000839	0.002974	0.003054
-16	456.8	317.9	140.0	0.000862	0.002974	0.003147
-15.75	460.4	317.8	140.0	0.000795	0.002969	0.002906
-15.5	460.3	317.8	140.0	0.000796	0.002968	0.003007
-15.25	465.7	317.6	140.0	0.000698	0.002940	0.002700
-15	462.7	317.7	140.0	0.000753	0.002938	0.003000
-14.75	463.6	317.7	140.0	0.000737	0.002937	0.002866
-14.5	457.9	317.8	140.0	0.000842	0.002937	0.003216
-14.25	458.5	317.8	140.0	0.000830	0.002940	0.003034
-14	460.8	317.8	140.0	0.000788	0.002938	0.002927
-13.75	460.3	317.8	140.0	0.000797	0.002920	0.003017
-13.5	459.8	317.8	170.0	0.000805	0.002920	0.003034
-13.25	720.3	320.3	152.3	0.002973	0.002930	0.003132

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE ($MW/m^2 \cdot K$)	U actual ($MW/m^2 \cdot K$)
-13	660.9	323.5	153.3	-0.000433	0.002931	0.002866
-12.75	613.4	325.8	153.1	0.000650	0.002933	0.003031
-12.5	595.8	327.0	153.0	0.000890	0.003277	0.002821
-12.25	589.7	327.8	152.5	0.000960	0.003277	0.002714
-12	578.4	328.6	152.5	0.001010	0.003268	0.002902
-11.75	574.2	329.2	152.7	0.001073	0.003268	0.002866
-11.5	569.7	329.8	153.1	0.001194	0.003238	0.002984
-11.25	560.4	330.6	154.0	0.001430	0.003238	0.003331
-11	570.0	331.0	155.6	0.001441	0.003206	0.003012
-10.75	587.0	331.3	157.2	0.001482	0.003206	0.002806
-10.5	597.7	331.9	158.7	0.001631	0.003149	0.002944
-10.25	598.4	333.2	160.1	0.001944	0.003145	0.003382
-10	620.8	334.0	160.7	0.001794	0.003115	0.002959
-9.75	631.8	335.0	161.3	0.001677	0.003068	0.002995
-9.5	644.9	335.8	162.0	0.001539	0.003068	0.002831
-9.25	652.0	336.7	163.0	0.001521	0.003060	0.002861
-9	654.6	337.9	164.7	0.001649	0.003015	0.003012
-8.75	680.0	338.4	166.5	0.001542	0.003015	0.002605
-8.5	672.4	340.4	168.3	0.002045	0.003015	0.003370
-8.25	695.6	341.8	170.0	0.001962	0.003015	0.003062
-8	707.7	343.8	171.6	0.002057	0.003037	0.003279
-7.75	730.6	345.4	173.1	0.001908	0.003037	0.003079
-7.5	747.9	347.2	174.6	0.001847	0.003038	0.003062
-7.25	762.4	349.1	175.8	0.001840	0.003102	0.003074
-7	772.7	351.0	175.7	0.001829	0.003104	0.003121
-6.75	785.5	352.5	175.6	0.001488	0.003104	0.002874
-6.5	768.0	354.6	175.3	0.001693	0.003104	0.003319
-6.25	779.4	355.6	175.0	0.001354	0.003110	0.002904
-6	778.9	356.6	174.5	0.001229	0.003110	0.002908
-5.75	767.5	357.8	174.0	0.001285	0.003103	0.003078
-5.5	753.8	358.9	173.5	0.001373	0.003103	0.003254
-5.25	765.8	359.0	173.1	0.000996	0.003103	0.002791
-5	764.5	359.2	173.6	0.000928	0.003093	0.002826
-4.75	758.1	359.7	174.1	0.001144	0.003075	0.002992
-4.5	768.4	359.7	174.8	0.001073	0.003059	0.002776
-4.25	758.3	360.6	175.3	0.001398	0.003021	0.003187
-4	768.6	360.9	174.8	0.001294	0.003020	0.002969
-3.75	769.0	361.4	174.2	0.001156	0.003020	0.002980
-3.5	772.8	361.4	173.4	0.000928	0.003003	0.002803

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE ($MW/m^2 \cdot K$)	U actual ($MW/m^2 \cdot K$)
-3.25	757.9	361.8	172.6	0.001004	0.003001	0.003053
-3	732.4	362.7	171.9	0.001262	0.003001	0.003470
-2.75	745.7	362.2	171.1	0.000834	0.003003	0.002854
-2.5	744.2	361.9	170.2	0.000679	0.003003	0.002868
-2.25	714.1	362.5	169.5	0.001034	0.003003	0.003485
-2	721.4	361.9	169.4	0.000734	0.003025	0.002954
-1.75	718.1	361.6	169.3	0.000805	0.003025	0.003079
-1.5	715.8	361.3	169.3	0.000848	0.003055	0.003099
-1.25	708.4	361.3	169.3	0.000997	0.003055	0.003284
-1	725.3	360.4	169.2	0.000688	0.003055	0.002778
-0.75	718.9	360.3	169.1	0.000800	0.003055	0.003057
-0.5	720.7	359.9	169.1	0.000770	0.003054	0.002945
-0.25	718.5	359.7	168.9	0.000816	0.003034	0.003008
0	711.9	359.6	167.9	0.000907	0.003034	0.003145
0.25	705.1	359.5	166.8	0.000799	0.003034	0.003153
0.5	693.4	359.5	165.6	0.000757	0.003039	0.003262
0.75	690.2	359.0	164.4	0.000538	0.003039	0.003077
1	680.7	358.5	164.4	0.000455	0.003061	0.003137
1.25	680.4	357.8	164.4	0.000495	0.003067	0.003021
1.5	673.7	357.4	164.4	0.000638	0.003067	0.003195
1.75	684.6	356.5	164.5	0.000472	0.003067	0.002820
2	673.6	356.3	164.7	0.000723	0.003069	0.003239
2.25	674.3	356.0	164.9	0.000778	0.003069	0.003151
2.5	679.9	355.5	165.2	0.000747	0.003069	0.003044
2.75	686.0	355.1	165.5	0.000711	0.003069	0.002966
3	687.6	354.9	165.9	0.000764	0.003065	0.003020
3.25	688.3	354.8	166.3	0.000852	0.003059	0.003074
3.5	693.7	354.6	166.7	0.000856	0.003039	0.003002
3.75	692.1	354.8	167.2	0.000991	0.003039	0.003174
4	699.2	354.8	167.7	0.000974	0.003039	0.003058
4.25	707.2	354.8	168.1	0.000924	0.003039	0.002981
4.5	715.7	354.8	168.5	0.000866	0.003039	0.002892
4.75	705.5	355.5	169.0	0.001140	0.003039	0.003300
5	713.2	355.8	169.1	0.001078	0.003039	0.003105
5.25	738.7	355.2	169.3	0.000639	0.003039	0.002551
5.5	728.7	355.7	169.4	0.000854	0.003039	0.002996
5.75	720.9	356.2	169.6	0.001017	0.003026	0.003132
6	737.0	355.9	170.1	0.000743	0.003025	0.002695
6.25	729.3	356.5	170.7	0.001009	0.002987	0.003079

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE ($MW/m^2\cdot K$)	U actual ($MW/m^2\cdot K$)
6.5	731.8	356.9	171.4	0.001078	0.002987	0.003051
6.75	745.1	357.0	172.0	0.000981	0.002987	0.002854
7	752.9	357.2	170.4	0.000974	0.002983	0.002857
7.25	752.2	357.3	168.6	0.000597	0.002966	0.002747
7.5	725.1	357.9	166.5	0.000647	0.002966	0.003140
7.75	716.0	357.6	164.0	0.000306	0.002966	0.002865
8	696.0	357.3	164.0	0.000104	0.002959	0.002981
8.25	678.6	357.1	163.9	0.000451	0.002959	0.003193
8.5	683.7	356.3	164.0	0.000383	0.002959	0.002872
8.75	680.4	355.9	164.1	0.000488	0.002959	0.003011
9	687.2	355.1	163.6	0.000423	0.002959	0.002803
9.25	668.1	355.3	163.0	0.000661	0.002959	0.003332
9.5	676.4	354.5	162.4	0.000396	0.002959	0.002842
9.75	669.7	354.1	161.8	0.000403	0.002959	0.003030
10	668.2	353.5	160.3	0.000310	0.002959	0.002913
10.25	660.8	352.9	158.7	0.000118	0.002954	0.002919
10.5	648.7	352.3	157.0	-0.000009	0.002952	0.002977
10.75	643.1	351.3	155.2	-0.000274	0.002952	0.002779
11	623.8	350.6	156.3	-0.000308	0.002952	0.003055
11.25	630.3	349.3	157.3	-0.000118	0.002943	0.002655
11.5	628.3	348.6	158.4	0.000225	0.002943	0.002900
11.75	634.4	347.8	159.6	0.000420	0.002940	0.002827
12	635.4	347.5	159.0	0.000700	0.002893	0.003034
12.25	640.4	347.1	158.4	0.000483	0.002869	0.002860
12.5	640.4	346.6	157.7	0.000354	0.002857	0.002847
12.75	633.3	346.4	156.9	0.000339	0.002857	0.002969
13	638.9	345.6	157.3	0.000069	0.002857	0.002613
13.25	637.6	345.1	157.7	0.000207	0.002851	0.002726
13.5	623.3	345.3	158.1	0.000586	0.002851	0.003180
13.75	623.9	345.1	158.6	0.000691	0.002858	0.003074
14	628.9	344.9	160.5	0.000712	0.002885	0.003010
14.25	651.8	344.4	162.4	0.000755	0.002885	0.002640
14.5	674.3	344.1	164.4	0.000804	0.002838	0.002529
14.75	678.6	344.7	166.5	0.001180	0.002838	0.002919
15	692.0	345.5	168.5	0.001414	0.002838	0.002967
15.25	719.8	346.0	170.5	0.001332	0.002838	0.002712
15.5	727.4	347.5	172.5	0.001607	0.002838	0.003086
15.75	749.3	348.8	174.6	0.001602	0.002853	0.002969
16	755.7	351.0	175.1	0.001866	0.002853	0.003352

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE ($MW/m^2\cdot K$)	U actual ($MW/m^2\cdot K$)
16.25	771.7	352.8	175.2	0.001583	0.002897	0.003144
16.5	789.4	354.0	174.9	0.001196	0.002918	0.002835
16.75	800.1	354.8	174.4	0.000877	0.002964	0.002641
17	787.4	356.0	174.9	0.000955	0.002972	0.002880
17.25	782.1	357.1	175.6	0.001111	0.002972	0.002941
17.5	795.4	357.6	176.4	0.001000	0.002972	0.002705
17.75	790.9	358.8	177.4	0.001245	0.002972	0.003000
18	792.0	360.1	177.4	0.001401	0.002972	0.003111
18.25	814.3	360.4	177.1	0.000946	0.002972	0.002647
18.5	794.6	361.8	176.7	0.001197	0.002972	0.003157
18.75	793.1	362.6	176.2	0.001080	0.002972	0.003016
19	787.4	363.4	176.3	0.001023	0.002978	0.003062
19.25	788.6	363.9	176.5	0.000989	0.002985	0.002996
19.5	781.1	364.7	176.7	0.001151	0.002985	0.003210
19.75	800.8	364.6	177.0	0.000827	0.002985	0.002751
20	798.6	365.0	176.9	0.000924	0.002985	0.002946
20.25	801.7	365.2	176.6	0.000825	0.002985	0.002841
20.5	797.2	365.5	176.3	0.000830	0.002985	0.002910
20.75	809.1	365.0	175.9	0.000533	0.002982	0.002571
21	797.2	365.1	175.3	0.000668	0.002958	0.002830
21.25	792.0	365.0	174.7	0.000629	0.002955	0.002776
21.5	777.8	365.2	174.0	0.000750	0.002883	0.002973
21.75	769.3	365.2	173.5	0.000746	0.002883	0.002982
22	769.3	364.9	172.4	0.000633	0.002883	0.002856
22.25	755.6	364.9	171.1	0.000643	0.002884	0.003042
22.5	753.2	364.3	169.6	0.000386	0.002884	0.002826
22.75	734.4	364.1	168.0	0.000399	0.002891	0.003059
23	727.8	363.3	167.5	0.000168	0.002891	0.002859
23.25	718.8	362.6	167.4	0.000250	0.002902	0.002927
23.5	722.5	361.6	167.3	0.000210	0.002902	0.002723
23.75	713.7	361.0	167.4	0.000403	0.002902	0.002957
24	714.4	360.3	167.0	0.000436	0.002885	0.002863
24.25	709.6	359.8	166.5	0.000460	0.002874	0.002949
24.5	705.8	359.2	165.9	0.000432	0.002874	0.002940
24.75	707.3	358.5	165.4	0.000306	0.002874	0.002797
25	696.6	358.1	165.6	0.000394	0.002874	0.003011
25.25	692.9	357.7	166.2	0.000552	0.002874	0.003032
25.5	704.1	357.0	166.9	0.000522	0.002874	0.002786
25.75	710.4	356.5	167.6	0.000588	0.002869	0.002816

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE (MW/m²·K)	U actual (MW/m²·K)
26	712.4	356.3	168.0	0.000737	0.002869	0.002920
26.25	715.4	356.2	168.1	0.000765	0.002869	0.002925
26.5	720.3	356.0	168.2	0.000702	0.002871	0.002854
26.75	729.6	355.7	168.2	0.000555	0.002871	0.002677
27	738.4	355.2	168.4	0.000416	0.002868	0.002543
27.25	736.1	355.0	168.8	0.000530	0.002867	0.002681
27.5	735.8	355.0	169.2	0.000633	0.002823	0.002706
27.75	738.5	354.9	169.8	0.000681	0.002759	0.002691
28	741.5	354.9	170.6	0.000758	0.002754	0.002715
28.25	746.4	355.0	171.3	0.000852	0.002749	0.002732
28.5	745.9	355.5	172.1	0.001028	0.002749	0.002901
28.75	747.7	356.2	172.7	0.001143	0.002749	0.002987
29	762.2	356.4	173.8	0.001012	0.002756	0.002781
29.25	768.9	357.1	175.0	0.001103	0.002773	0.002880
29.5	787.6	357.4	176.2	0.001017	0.002794	0.002679
29.75	792.4	358.2	177.4	0.001176	0.002794	0.002865
30	812.8	358.6	177.6	0.001042	0.002794	0.002625
30.25	805.5	359.8	177.0	0.001185	0.002810	0.002949
30.5	805.7	360.6	176.2	0.001004	0.002820	0.002840
30.75	795.6	361.5	175.2	0.000961	0.002828	0.002956
31	795.3	361.8	174.8	0.000705	0.002828	0.002765
31.25	787.6	362.2	175.0	0.000742	0.002835	0.002857
31.5	795.0	362.0	175.2	0.000640	0.002835	0.002645
31.75	785.2	362.5	172.0	0.000863	0.002835	0.002922
32	755.0	363.2	171.8	0.000638	0.002840	0.003185
32.25	749.1	363.2	171.2	0.000700	0.002852	0.003039
32.5	756.9	362.6	170.6	0.000417	0.002860	0.002728
32.75	743.1	362.6	170.0	0.000544	0.002881	0.003023
33	736.8	362.3	169.0	0.000536	0.002911	0.002984
33.25	729.6	362.0	167.7	0.000456	0.002911	0.002988
33.5	734.0	361.1	166.4	0.000086	0.002911	0.002653
33.75	720.6	360.5	165.0	0.000051	0.002911	0.002834
34	708.3	359.8	163.8	-0.000005	0.002911	0.002837
34.25	710.5	358.4	162.6	-0.000294	0.002861	0.002502
34.5	692.1	357.7	161.6	-0.000173	0.002859	0.002828
34.75	685.0	356.6	160.6	-0.000228	0.002857	0.002686
35	674.9	355.6	159.8	-0.000237	0.002857	0.002742
35.25	656.1	355.0	159.4	-0.000020	0.002800	0.003038
35.5	652.6	354.0	159.1	-0.000015	0.002791	0.002861

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE (MW/m²·K)	U actual (MW/m²·K)
35.75	643.9	353.2	158.8	0.000119	0.002791	0.003032
36	643.5	352.3	158.4	0.000096	0.002791	0.002904
36.25	643.3	351.4	158.1	0.000067	0.002803	0.002863
36.5	659.9	349.9	157.8	-0.000268	0.002803	0.002338
36.75	652.4	349.1	157.4	-0.000165	0.002803	0.002679
37	641.6	348.6	157.4	-0.000005	0.002786	0.002836
37.25	625.1	348.4	157.7	0.000318	0.002786	0.003188
37.5	630.0	347.7	158.0	0.000325	0.002801	0.002882
37.75	627.1	347.4	158.2	0.000470	0.002801	0.003085
38	640.0	346.6	159.3	0.000315	0.002801	0.002699
38.25	647.9	346.1	161.2	0.000445	0.002793	0.002741
38.5	652.4	346.1	163.0	0.000829	0.002793	0.002951
38.75	673.7	345.9	165.0	0.000885	0.002793	0.002687
39	684.3	346.3	166.5	0.001131	0.002793	0.002909
39.25	705.5	346.6	167.7	0.001089	0.002793	0.002712
39.5	707.8	347.6	168.8	0.001279	0.002810	0.003036
39.75	718.6	348.6	169.9	0.001301	0.002810	0.002987
40	735.4	349.3	172.7	0.001189	0.002820	0.002832
40.25	760.1	350.2	176.4	0.001359	0.002860	0.002784
40.5	782.8	351.9	179.1	0.001746	0.002864	0.003037
40.75	810.7	353.9	180.1	0.001748	0.002883	0.003031
41	830.0	355.9	179.7	0.001535	0.002899	0.002950
41.25	830.9	357.8	178.3	0.001305	0.002914	0.002958
41.5	830.4	359.0	177.3	0.000909	0.002953	0.002762
41.75	824.4	359.8	177.1	0.000729	0.002953	0.002707
42	816.4	360.6	177.5	0.000805	0.002953	0.002764
42.25	807.2	361.6	177.6	0.001037	0.002918	0.002934
42.5	814.8	362.1	177.2	0.000894	0.002918	0.002734
42.75	820.8	362.2	176.1	0.000656	0.002916	0.002591
43	814.9	362.3	175.6	0.000509	0.002897	0.002605
43.25	796.9	362.8	176.9	0.000715	0.002878	0.002846
43.5	790.7	363.5	179.3	0.001126	0.002844	0.003012
43.75	815.1	363.8	181.7	0.001222	0.002844	0.002801
44	850.8	363.9	182.8	0.001113	0.002824	0.002560
44.25	860.5	364.7	181.3	0.001140	0.002810	0.002709
44.5	858.0	365.2	178.1	0.000799	0.002800	0.002640
44.75	822.8	366.2	175.1	0.000655	0.002799	0.002941
45	803.9	366.2	174.3	0.000287	0.002789	0.002742
45.25	767.9	366.9	175.9	0.000759	0.002789	0.003252

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE ($MW/m^2 \cdot K$)	U actual ($MW/m^2 \cdot K$)
45.5	778.2	366.7	177.9	0.000963	0.002801	0.002970
45.75	797.2	366.7	178.8	0.001088	0.002801	0.002917
46	816.4	366.6	178.2	0.000941	0.002847	0.002768
46.25	826.7	366.3	175.9	0.000587	0.002847	0.002592
46.5	823.2	365.8	173.5	0.000118	0.002846	0.002463
46.75	777.5	366.4	172.2	0.000407	0.002828	0.003088
47	782.9	365.2	172.0	0.000031	0.002828	0.002459
47.25	766.9	364.8	171.7	0.000316	0.002791	0.002786
47.5	753.8	364.5	170.8	0.000523	0.002791	0.002918
47.75	755.4	363.7	168.9	0.000294	0.002780	0.002674
48	731.8	363.4	167.2	0.000316	0.002780	0.003031
48.25	716.3	362.9	167.5	0.000231	0.002780	0.003007
48.5	705.2	362.5	169.0	0.000528	0.002780	0.003162
48.75	730.2	361.2	170.6	0.000488	0.002803	0.002626
49	748.5	360.4	171.2	0.000567	0.002803	0.002605
49.25	749.3	360.2	170.5	0.000706	0.002803	0.002818
49.5	757.0	359.5	169.0	0.000389	0.002772	0.002571
49.75	750.3	359.0	168.0	0.000178	0.002772	0.002613
50	740.3	358.6	167.9	0.000157	0.002747	0.002648
50.25	712.9	358.9	168.3	0.000664	0.002747	0.003190
50.5	729.5	358.0	168.3	0.000469	0.002746	0.002602
50.75	744.5	357.0	167.8	0.000235	0.002745	0.002404
51	741.7	356.5	167.2	0.000191	0.002716	0.002529
51.25	729.1	356.3	167.9	0.000294	0.002695	0.002707
51.5	723.1	356.1	169.6	0.000591	0.002689	0.002798
51.75	735.2	355.8	171.5	0.000803	0.002689	0.002683
52	747.7	355.8	172.9	0.001025	0.002688	0.002764
52.25	768.0	355.8	173.6	0.000967	0.002676	0.002612
52.5	780.7	356.0	174.0	0.000877	0.002668	0.002586
52.75	779.3	356.6	174.5	0.000967	0.002668	0.002760
53	780.8	357.2	175.6	0.001049	0.002678	0.002805
53.25	787.8	357.9	177.3	0.001142	0.002686	0.002822
53.5	814.8	358.1	179.2	0.001013	0.002690	0.002525
53.75	829.1	358.8	180.9	0.001161	0.002690	0.002648
54	846.2	359.7	181.9	0.001200	0.002690	0.002623
54.25	844.9	361.2	180.9	0.001410	0.002690	0.002908
54.5	844.2	362.4	178.3	0.001115	0.002690	0.002816
54.75	824.3	363.5	175.5	0.000803	0.002739	0.002892
55	802.4	364.1	173.6	0.000510	0.002743	0.002869

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE ($MW/m^2 \cdot K$)	U actual ($MW/m^2 \cdot K$)
55.25	799.3	363.6	172.5	0.000123	0.002764	0.002534
55.5	778.2	363.6	171.3	0.000286	0.002766	0.002793
55.75	769.2	363.1	169.2	0.000182	0.002766	0.002669
56	743.7	362.9	166.5	0.000182	0.002766	0.002932
56.25	742.7	361.6	165.3	-0.000416	0.002766	0.002439
56.5	724.6	360.7	165.8	-0.000311	0.002766	0.002669
56.75	718.0	359.7	166.8	-0.000002	0.002762	0.002652
57	718.1	358.8	167.1	0.000292	0.002750	0.002678
57.25	709.4	358.5	165.6	0.000563	0.002719	0.002949
57.5	708.6	357.7	162.6	0.000228	0.002711	0.002741
57.75	685.3	357.3	159.6	-0.000029	0.002711	0.003007
58	670.5	356.4	157.9	-0.000439	0.002711	0.002823
58.25	648.1	355.6	158.5	-0.000365	0.002722	0.003058
58.5	655.5	354.0	159.7	-0.000291	0.002744	0.002592
58.75	661.0	352.8	160.1	-0.000041	0.002744	0.002625
59	668.7	351.6	159.3	-0.000048	0.002744	0.002514
59.25	665.5	350.7	159.1	-0.000129	0.002702	0.002604
59.5	652.5	350.2	160.0	0.000096	0.002701	0.002877
59.75	662.2	349.2	161.7	0.000199	0.002692	0.002558
60	662.5	348.9	163.2	0.000617	0.002692	0.002856
60.25	674.9	348.6	163.7	0.000771	0.002685	0.002750
60.5	689.3	348.2	163.4	0.000627	0.002684	0.002592
60.75	681.3	348.5	162.8	0.000683	0.002684	0.002920
61	692.0	348.0	162.8	0.000361	0.002684	0.002510
61.25	699.3	347.6	163.3	0.000236	0.002670	0.002416
61.5	684.8	348.0	164.0	0.000635	0.002670	0.002891
61.75	683.2	348.2	164.5	0.000825	0.002689	0.002893
62	694.4	348.1	164.5	0.000713	0.002689	0.002668
62.25	701.1	348.0	165.7	0.000592	0.002689	0.002620
62.5	706.9	348.2	168.0	0.000780	0.002689	0.002677
62.75	716.1	348.7	170.5	0.001137	0.002689	0.002808
63	747.4	348.8	172.6	0.001120	0.002689	0.002503
63.25	764.0	349.6	174.3	0.001269	0.002689	0.002672
63.5	785.9	350.4	175.8	0.001221	0.002689	0.002562
63.75	789.3	352.0	177.6	0.001468	0.002689	0.002871
64	809.7	353.2	179.6	0.001435	0.002689	0.002735
64.25	838.6	354.3	180.6	0.001314	0.002692	0.002553
64.5	854.2	355.5	180.3	0.001177	0.002692	0.002530
64.75	847.1	357.1	179.5	0.001171	0.002692	0.002712

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE (MW/m²·K)	U actual (MW/m²·K)
65	833.0	358.7	179.1	0.001172	0.002695	0.002848
65.25	843.2	359.2	179.4	0.000832	0.002695	0.002500
65.5	836.7	360.2	180.1	0.000990	0.002695	0.002696
65.75	841.3	361.0	180.6	0.001041	0.002695	0.002648
66	844.7	361.8	180.6	0.001064	0.002695	0.002675
66.25	843.9	362.6	180.9	0.001044	0.002695	0.002718
66.5	856.9	362.9	181.8	0.000842	0.002695	0.002486
66.75	846.4	364.1	183.0	0.001203	0.002695	0.002856
67	874.5	364.1	184.3	0.000948	0.002695	0.002418
67.25	875.5	365.2	184.5	0.001194	0.002695	0.002704
67.5	895.5	365.3	183.6	0.000835	0.002665	0.002370
67.75	867.6	366.7	182.4	0.001094	0.002665	0.002876
68	856.0	367.6	181.6	0.000992	0.002665	0.002814
68.25	856.6	367.8	181.7	0.000779	0.002674	0.002640
68.5	843.4	368.6	182.3	0.001031	0.002674	0.002903
68.75	854.6	368.7	182.6	0.000929	0.002686	0.002675
69	877.2	368.1	182.3	0.000582	0.002686	0.002340
69.25	855.3	368.9	180.8	0.000908	0.002687	0.002830
69.5	862.2	368.4	178.4	0.000418	0.002687	0.002404
69.75	827.5	368.8	175.9	0.000490	0.002687	0.002838
70	814.1	368.3	174.2	0.000183	0.002680	0.002602
70.25	796.0	367.7	174.4	0.000138	0.002680	0.002663
70.5	785.7	367.2	175.8	0.000425	0.002664	0.002731
70.75	787.7	366.7	177.0	0.000741	0.002664	0.002763
71	807.4	365.9	177.3	0.000687	0.002664	0.002523
71.25	810.8	365.6	176.2	0.000712	0.002659	0.002640
71.5	797.2	365.7	174.2	0.000698	0.002659	0.002834
71.75	791.8	365.3	172.5	0.000343	0.002663	0.002638
72	775.5	364.9	171.8	0.000266	0.002663	0.002745
72.25	769.7	364.2	172.1	0.000230	0.002665	0.002636
72.5	760.1	363.8	172.8	0.000531	0.002665	0.002825
72.75	760.3	363.5	173.0	0.000713	0.002679	0.002836
73	749.9	363.7	172.6	0.000968	0.002682	0.003153
73.25	761.8	363.2	172.2	0.000639	0.002692	0.002767
73.5	779.8	362.1	172.4	0.000239	0.002696	0.002403
73.75	770.7	361.9	173.0	0.000489	0.002696	0.002735
74	774.6	361.5	173.4	0.000576	0.002701	0.002638
74.25	777.4	361.3	173.6	0.000635	0.002701	0.002658
74.5	792.6	360.5	173.7	0.000414	0.002701	0.002379

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE (MW/m²·K)	U actual (MW/m²·K)
74.75	785.2	360.5	173.9	0.000594	0.002694	0.002649
75	784.1	360.4	174.0	0.000655	0.002693	0.002636
75.25	782.6	360.4	174.0	0.000722	0.002646	0.002685
75.5	796.0	359.9	174.2	0.000486	0.002646	0.002400
75.75	796.1	359.7	174.2	0.000527	0.002635	0.002498
76	797.7	359.5	174.3	0.000523	0.002632	0.002466
76.25	786.5	359.8	174.8	0.000744	0.002590	0.002713
76.5	789.5	359.8	175.7	0.000816	0.002590	0.002643
76.75	791.1	360.2	176.5	0.000980	0.002590	0.002754
77	793.8	360.7	177.3	0.001106	0.002596	0.002845
77.25	827.1	360.2	177.9	0.000678	0.002596	0.002292
77.5	829.9	360.4	178.4	0.000753	0.002588	0.002506
77.75	832.4	360.7	178.9	0.000810	0.002583	0.002523
78	824.8	361.5	179.4	0.001045	0.002583	0.002754
78.25	840.2	361.6	180.1	0.000854	0.002587	0.002476
78.5	833.8	362.5	180.8	0.001103	0.002587	0.002781
78.75	848.7	362.9	181.5	0.000970	0.002614	0.002554
79	856.6	363.4	182.2	0.000971	0.002614	0.002580
79.25	869.0	363.7	181.9	0.000872	0.002611	0.002468
79.5	863.5	364.3	181.3	0.000890	0.002599	0.002612
79.75	858.3	364.8	180.5	0.000798	0.002603	0.002597
80	850.1	365.3	179.5	0.000741	0.002603	0.002625
80.25	834.8	365.8	178.3	0.000774	0.002610	0.002755
80.5	823.2	366.1	177.1	0.000707	0.002611	0.002761
80.75	807.2	366.4	175.7	0.000693	0.002616	0.002868
81	793.2	366.5	174.3	0.000628	0.002645	0.002900
81.25	797.7	365.8	173.4	0.000217	0.002667	0.002534
81.5	780.2	365.6	172.8	0.000354	0.002688	0.002809
81.75	781.2	364.7	172.3	0.000228	0.002688	0.002572
82	768.0	364.4	171.8	0.000375	0.002689	0.002793
82.25	778.0	363.3	171.2	0.000127	0.002689	0.002414
82.5	790.8	361.8	170.6	-0.000201	0.002689	0.002154
82.75	764.9	361.6	169.9	0.000162	0.002679	0.002695
83	752.0	361.1	169.3	0.000279	0.002679	0.002684
83.25	756.1	360.0	168.8	0.000093	0.002624	0.002418
83.5	747.3	359.4	168.5	0.000173	0.002589	0.002582
83.75	748.2	358.5	168.3	0.000134	0.002562	0.002448
84	739.2	358.0	168.2	0.000289	0.002547	0.002628
84.25	746.1	357.0	168.6	0.000156	0.002540	0.002374

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE (MW/m²·K)	U actual (MW/m²·K)
84.5	739.1	356.7	169.5	0.000436	0.002538	0.002633
84.75	732.7	356.7	170.4	0.000777	0.002538	0.002833
85	752.5	356.0	171.3	0.000632	0.002538	0.002455
85.25	756.5	356.0	171.7	0.000780	0.002538	0.002648
85.5	770.2	355.7	171.9	0.000634	0.002538	0.002446
85.75	766.9	355.9	172.0	0.000726	0.002538	0.002646
86	759.0	356.4	172.0	0.000884	0.002543	0.002820
86.25	770.2	356.2	172.3	0.000681	0.002564	0.002536
86.5	778.6	356.1	172.8	0.000603	0.002567	0.002475
86.75	769.6	356.6	173.3	0.000874	0.002573	0.002785
87	782.3	356.5	173.9	0.000751	0.002598	0.002517
87.25	788.2	356.7	174.0	0.000762	0.002598	0.002551
87.5	802.7	356.4	173.8	0.000514	0.002591	0.002307
87.75	781.7	357.2	173.7	0.000856	0.002591	0.002820
88	781.1	357.5	173.5	0.000817	0.002599	0.002677
88.25	794.5	357.2	174.0	0.000522	0.002599	0.002377
88.5	783.1	357.8	175.0	0.000832	0.002599	0.002746
88.75	789.0	358.1	176.1	0.000952	0.002605	0.002672
89	807.4	358.1	177.2	0.000856	0.002605	0.002474
89.25	819.4	358.3	177.6	0.000894	0.002591	0.002496
89.5	811.8	359.3	177.3	0.001096	0.002591	0.002789
89.75	825.6	359.3	176.8	0.000740	0.002591	0.002441
90	812.8	360.1	176.2	0.000840	0.002591	0.002723
90.25	827.1	359.6	175.9	0.000412	0.002583	0.002275
90.5	809.4	360.2	176.1	0.000676	0.002583	0.002665
90.75	814.8	360.1	176.4	0.000625	0.002583	0.002448
91	817.6	360.0	176.6	0.000628	0.002574	0.002450
91.25	817.2	360.1	177.1	0.000699	0.002555	0.002501
91.5	835.9	359.5	177.8	0.000470	0.002542	0.002182
91.75	826.5	360.0	178.5	0.000807	0.002535	0.002545
92	825.3	360.4	179.3	0.000995	0.002531	0.002604
92.25	860.1	359.7	179.6	0.000533	0.002506	0.002038
92.5	834.3	360.9	179.4	0.001060	0.002487	0.002763
92.75	849.7	360.7	179.1	0.000706	0.002487	0.002303
93	851.4	360.7	178.6	0.000595	0.002475	0.002330
93.25	832.4	361.4	178.2	0.000818	0.002470	0.002634
93.5	828.7	361.7	178.0	0.000789	0.002470	0.002550
93.75	839.7	361.3	177.8	0.000537	0.002470	0.002294
94	842.2	361.0	177.5	0.000443	0.002440	0.002283

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE (MW/m²·K)	U actual (MW/m²·K)
94.25	842.4	360.7	177.3	0.000391	0.002440	0.002253
94.5	821.2	361.2	177.1	0.000745	0.002435	0.002621
94.75	817.8	361.3	176.8	0.000743	0.002435	0.002527
95	827.8	360.8	176.5	0.000497	0.002435	0.002287
95.25	816.9	360.9	176.2	0.000627	0.002435	0.002524
95.5	814.7	360.8	176.0	0.000606	0.002435	0.002462
95.75	807.2	360.9	175.7	0.000693	0.002435	0.002571
96	808.1	360.7	175.5	0.000625	0.002436	0.002481
96.25	815.5	360.2	175.3	0.000446	0.002436	0.002316
96.5	817.4	359.8	175.2	0.000382	0.002434	0.002300
96.75	804.1	359.9	175.1	0.000610	0.002437	0.002547
97	794.6	360.1	175.0	0.000764	0.002437	0.002640
97.25	791.7	360.2	174.5	0.000790	0.002438	0.002639
97.5	782.8	360.5	173.5	0.000839	0.002478	0.002777
97.75	788.7	360.1	172.2	0.000481	0.002480	0.002483
98	773.9	360.1	170.8	0.000450	0.002506	0.002687
98.25	775.7	359.3	170.2	0.000111	0.002524	0.002379
98.5	754.8	359.3	170.9	0.000372	0.002524	0.002746
98.75	768.3	358.4	171.8	0.000333	0.002524	0.002340
99	757.6	358.5	172.8	0.000755	0.002537	0.002779
99.25	776.0	357.9	173.2	0.000669	0.002537	0.002428
99.5	775.4	358.0	172.4	0.000781	0.002552	0.002645
99.75	771.3	358.1	171.5	0.000674	0.002557	0.002665
100	769.4	357.9	170.5	0.000494	0.002573	0.002573
100.25	769.0	357.4	169.8	0.000264	0.002573	0.002446
100.5	753.8	357.4	169.9	0.000385	0.002576	0.002671
100.75	751.7	357.1	170.0	0.000475	0.002576	0.002593
101	751.4	356.8	170.3	0.000537	0.002575	0.002601
101.25	769.6	355.9	170.7	0.000283	0.002575	0.002229
101.5	766.6	355.6	171.2	0.000444	0.002575	0.002463
101.75	777.2	355.0	171.7	0.000389	0.002574	0.002263
102	779.5	354.8	172.3	0.000491	0.002487	0.002347
102.25	770.1	355.1	173.1	0.000808	0.002487	0.002628
102.5	771.9	355.4	173.8	0.000970	0.002487	0.002642
102.75	788.5	355.3	174.3	0.000798	0.002481	0.002402
103	802.3	355.1	174.8	0.000666	0.002472	0.002307
103.25	799.5	355.5	174.8	0.000830	0.002467	0.002514
103.5	792.2	356.1	173.2	0.000932	0.002467	0.002653
103.75	789.1	356.3	171.2	0.000585	0.002467	0.002508

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE ($MW/m^2 \cdot K$)	U actual ($MW/m^2 \cdot K$)
104	776.0	356.4	168.9	0.000357	0.002474	0.002542
104.25	754.0	356.5	166.8	0.000220	0.002507	0.002657
104.5	735.3	356.3	166.0	0.000084	0.002508	0.002652
104.75	731.2	355.5	165.1	-0.000014	0.002517	0.002456
105	726.9	354.7	164.4	-0.000095	0.002517	0.002410
105.25	713.1	354.2	163.4	0.000014	0.002517	0.002585
105.5	706.7	353.4	161.7	-0.000056	0.002517	0.002493
105.75	692.6	352.7	159.9	-0.000179	0.002522	0.002587
106	680.0	351.9	158.0	-0.000334	0.002523	0.002560
106.25	675.9	350.6	156.3	-0.000668	0.002523	0.002320
106.5	653.6	349.9	156.0	-0.000588	0.002523	0.002666
106.75	658.4	348.3	155.6	-0.000698	0.002509	0.002188
107	640.9	347.5	155.3	-0.000406	0.002509	0.002650
107.25	641.3	346.3	155.5	-0.000424	0.002467	0.002367
107.5	640.2	345.3	157.2	-0.000305	0.002466	0.002399
107.75	635.9	344.7	158.8	0.000238	0.002455	0.002652
108	647.5	343.9	160.4	0.000442	0.002449	0.002470
108.25	648.6	343.9	161.7	0.000828	0.002449	0.002806
108.5	662.8	343.7	161.5	0.000872	0.002449	0.002637
108.75	675.6	343.4	161.2	0.000580	0.002478	0.002465
109	676.5	343.4	160.8	0.000502	0.002503	0.002551
109.25	681.2	343.1	160.4	0.000311	0.002503	0.002391
109.5	681.0	342.9	160.9	0.000231	0.002503	0.002393
109.75	681.8	342.8	161.4	0.000341	0.002491	0.002396
110	696.4	342.1	161.9	0.000199	0.002491	0.002092
110.25	692.6	342.2	162.6	0.000415	0.002474	0.002378
110.5	688.9	342.4	163.8	0.000649	0.002461	0.002498
110.75	680.7	343.1	165.0	0.001074	0.002461	0.002830
111	708.7	342.8	166.3	0.000835	0.002461	0.002246
111.25	722.7	343.0	167.6	0.000858	0.002431	0.002337
111.5	716.7	344.1	169.5	0.001258	0.002431	0.002781
111.75	741.0	344.5	171.3	0.001214	0.002431	0.002442
112	755.2	345.5	173.2	0.001346	0.002485	0.002587
112.25	775.5	346.5	174.8	0.001364	0.002485	0.002526
112.5	799.6	347.3	175.9	0.001241	0.002495	0.002385
112.75	807.5	348.6	176.8	0.001275	0.002512	0.002518
113	823.6	349.5	177.7	0.001150	0.002512	0.002371
113.25	818.9	351.2	178.5	0.001379	0.002512	0.002673
113.5	850.4	351.5	178.9	0.000937	0.002512	0.002143

Table A1 Time (hr)	Fuel Temperature (°C)	Water Temperature (°C)	Control Rod Step Position	Reactivity	U MHE ($MW/m^2 \cdot K$)	U actual ($MW/m^2 \cdot K$)
113.75	852.8	352.5	179.2	0.000931	0.002488	0.002309
114	860.4	353.1	179.5	0.000821	0.002486	0.002196
114.25	842.0	354.6	179.7	0.001191	0.002455	0.002596
114.5	844.1	355.5	179.7	0.001153	0.002455	0.002485
114.75	848.7	356.3	179.6	0.001030	0.002452	0.002423
115	839.2	357.4	179.4	0.001135	0.002452	0.002618
115.25	843.9	358.0	179.2	0.000962	0.002455	0.002452
115.5	838.7	358.8	180.3	0.000980	0.002459	0.002552
115.75	833.5	359.9	181.4	0.001299	0.002483	0.002752
116	867.9	359.7	182.6	0.000903	0.002483	0.002216
116.25	869.7	360.6	183.8	0.001114	0.002483	0.002503
116.5	875.7	361.5	183.9	0.001253	0.002494	0.002555
116.75	878.9	362.4	183.8	0.001164	0.002500	0.002559
117	885.2	363.0	183.6	0.000994	0.002507	0.002453
117.25	874.5	364.1	183.3	0.001104	0.002512	0.002653
117.5	886.0	364.2	182.6	0.000785	0.002512	0.002342
117.75	864.5	365.2	181.8	0.000983	0.002515	0.002705
118	855.7	365.7	180.8	0.000930	0.002531	0.002657
118.25	860.8	365.6	179.8	0.000610	0.002540	0.002403
118.5	856.5	365.3	178.3	0.000444	0.002540	0.002381
118.75	842.0	365.1	176.7	0.000361	0.002540	0.002445
119	827.4	364.8	175.0	0.000269	0.002512	0.002439

Table A2: Raw power supply and demand simulation data

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
-48.75	524.0	1581.5	0.0	263.0	33.0	1844.5	0.748
-48.5	207.0	1613.9	0.0	221.3	-106.6	1835.2	0.754
-48.25	136.9	1646.3	0.0	179.6	-44.4	1825.9	0.756
-48	106.6	1678.7	0.0	137.9	-27.0	1816.6	0.757
-47.75	89.1	1711.0	0.0	96.2	-23.0	1807.2	0.758
-47.5	77.0	1698.0	0.0	104.8	-21.9	1802.8	0.759
-47.25	67.6	1684.1	0.0	114.3	-21.0	1798.4	0.761
-47	60.0	1670.3	0.0	123.8	-20.2	1794.1	0.762
-46.75	53.6	1656.4	0.0	133.3	-19.4	1789.7	0.763

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
-46.5	48.4	1627.0	0.0	162.6	-18.7	1789.6	0.763
-46.25	43.9	1597.0	0.0	192.6	-18.0	1789.6	0.764
-46	40.1	1567.0	0.0	222.7	-17.4	1789.6	0.765
-45.75	36.9	1537.0	0.0	252.7	-16.8	1789.6	0.766
-45.5	34.1	1557.9	0.0	238.2	-16.4	1796.2	0.767
-45.25	31.7	1581.8	0.0	221.2	-16.0	1803.0	0.768
-45	29.6	1605.7	0.0	204.2	-15.6	1809.9	0.768
-44.75	27.8	1629.6	0.0	187.2	-15.3	1816.8	0.769
-44.5	26.1	1674.4	0.0	155.6	-15.1	1829.9	0.770
-44.25	24.6	1720.8	0.0	122.7	-14.9	1843.6	0.771
-44	23.3	1767.3	0.0	89.9	-14.7	1857.2	0.771
-43.75	22.1	1813.7	0.0	57.1	-14.5	1870.8	0.772
-43.5	21.0	1827.3	7.7	52.7	-14.4	1887.7	0.773
-43.25	20.0	1837.5	16.1	51.2	-14.3	1904.9	0.774
-43	19.1	1847.8	24.6	49.6	-14.2	1922.0	0.774
-42.75	18.3	1858.1	33.1	48.1	-14.2	1939.2	0.775
-42.5	167.2	1780.4	73.3	102.8	-14.1	1956.5	0.776
-42.25	258.8	1692.1	117.4	164.3	-14.1	1973.8	0.776
-42	341.3	1603.8	161.5	225.8	-14.1	1991.1	0.777
-41.75	406.2	1515.5	205.6	287.3	-14.0	2008.4	0.778
-41.5	449.3	1491.6	276.1	258.3	-14.0	2026.0	0.779
-41.25	480.9	1476.9	350.5	216.3	-14.0	2043.7	0.779
-41	517.6	1462.2	424.9	174.2	-14.0	2061.3	0.780
-40.75	534.2	1447.5	499.3	132.1	-14.1	2078.9	0.781
-40.5	559.3	1424.6	534.9	127.5	-14.1	2087.0	0.781
-40.25	580.4	1400.3	564.0	129.1	-14.1	2093.5	0.782
-40	595.8	1376.1	593.1	130.7	-14.1	2099.9	0.783
-39.75	601.7	1351.8	622.2	132.4	-14.1	2106.4	0.783
-39.5	605.7	1318.1	642.6	147.5	-14.2	2108.2	0.784
-39.25	610.3	1282.5	661.3	165.3	-14.2	2109.1	0.785
-39	625.8	1247.0	679.9	183.1	-14.2	2110.0	0.786
-38.75	622.0	1211.5	698.6	200.8	-14.2	2110.9	0.786
-38.5	631.5	1235.4	708.9	165.2	-14.3	2109.5	0.787
-38.25	623.4	1272.3	717.5	117.9	-14.3	2107.7	0.788
-38	628.7	1309.2	726.0	70.6	-14.3	2105.8	0.788
-37.75	635.9	1346.2	734.6	23.2	-14.4	2104.0	0.789
-37.5	643.6	1299.7	727.9	73.0	-14.4	2100.6	0.790
-37.25	639.3	1232.6	717.5	146.7	-14.4	2096.9	0.791
-37	633.3	1165.6	707.1	220.4	-14.4	2093.1	0.791

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
-36.75	637.9	1098.6	696.7	294.1	-14.5	2089.4	0.792
-36.5	646.3	1141.0	679.0	264.7	-14.5	2084.7	0.793
-36.25	651.8	1213.5	659.4	206.9	-14.5	2079.8	0.794
-36	650.7	1285.9	639.7	149.2	-14.6	2074.8	0.794
-35.75	648.3	1358.4	620.0	91.4	-14.6	2069.9	0.795
-35.5	642.4	1366.7	594.4	106.4	-14.6	2067.5	0.796
-35.25	646.2	1355.4	567.0	143.5	-14.6	2065.9	0.796
-35	646.9	1344.1	539.6	180.6	-14.7	2064.3	0.797
-34.75	649.0	1332.8	512.2	217.8	-14.7	2062.7	0.798
-34.5	654.1	1406.2	451.8	207.5	-14.7	2065.5	0.799
-34.25	658.2	1508.2	380.4	181.3	-14.7	2069.8	0.799
-34	666.1	1610.1	309.0	155.1	-14.8	2074.2	0.800
-33.75	664.8	1712.0	237.6	128.8	-14.8	2078.5	0.801
-33.5	664.3	1786.6	185.4	114.0	-14.8	2086.0	0.802
-33.25	657.0	1851.0	140.3	103.4	-14.8	2094.7	0.802
-33	659.5	1915.5	95.1	92.8	-14.8	2103.4	0.803
-32.75	667.8	1979.9	50.0	82.2	-14.9	2112.1	0.804
-32.5	663.0	2013.7	30.4	77.9	-14.9	2122.1	0.805
-32.25	670.0	2035.1	21.2	76.2	-14.9	2132.5	0.805
-32	656.8	2056.5	12.0	74.5	-14.9	2143.0	0.806
-31.75	664.9	2077.9	2.8	72.8	-14.9	2153.5	0.807
-31.5	667.6	2051.0	0.0	111.7	-15.0	2162.7	0.808
-31.25	671.6	2002.8	0.0	168.6	-15.0	2171.4	0.808
-31	673.4	1954.5	0.0	225.5	-15.0	2180.0	0.809
-30.75	679.1	1906.3	0.0	282.3	-15.0	2188.7	0.810
-30.5	685.0	1937.0	0.0	264.5	-15.0	2201.5	0.811
-30.25	679.3	2005.3	0.0	210.9	-15.1	2216.2	0.811
-30	693.2	2073.6	0.0	157.3	-15.1	2231.0	0.812
-29.75	693.4	2142.0	0.0	103.8	-15.1	2245.7	0.813
-29.5	685.2	2168.4	0.0	79.4	-15.1	2247.8	0.814
-29.25	696.3	2173.1	0.0	70.2	-15.1	2243.3	0.814
-29	695.4	2177.7	0.0	61.0	-15.1	2238.8	0.815
-28.75	694.7	2182.4	0.0	51.9	-15.1	2234.3	0.816
-28.5	695.0	2134.5	0.0	80.7	-15.2	2215.2	0.817
-28.25	694.5	2057.0	0.0	131.0	-15.2	2188.0	0.817
-28	694.6	1979.6	0.0	181.2	-15.2	2160.8	0.818
-27.75	682.7	1902.1	0.0	231.4	-15.2	2133.6	0.819
-27.5	700.5	1885.6	0.0	217.2	-15.2	2102.8	0.820
-27.25	701.8	1906.0	0.0	163.9	-15.2	2069.8	0.820

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
-27	689.8	1926.3	0.0	110.6	-15.2	2036.9	0.821
-26.75	691.5	1946.7	0.0	57.2	-15.2	2004.0	0.822
-26.5	698.0	1927.2	0.0	46.4	-15.3	1973.6	0.823
-26.25	695.9	1881.7	0.0	63.3	-15.3	1945.0	0.823
-26	700.2	1836.2	0.0	80.2	-15.3	1916.4	0.824
-25.75	694.0	1790.6	0.0	97.1	-15.3	1887.7	0.825
-25.5	697.4	1751.8	0.0	113.7	-15.3	1865.5	0.826
-25.25	687.4	1717.5	0.0	130.2	-15.3	1847.7	0.827
-25	690.3	1683.3	0.0	146.7	-15.3	1830.0	0.827
-24.75	687.9	1649.1	0.0	163.1	-15.3	1812.3	0.828
-24.5	694.5	1650.8	0.0	149.4	-15.3	1800.2	0.829
-24.25	693.6	1679.6	0.0	112.8	-15.4	1792.4	0.830
-24	705.9	1708.4	0.0	76.2	-15.4	1784.6	0.830
-23.75	719.3	1737.2	0.0	39.6	-15.4	1776.9	0.831
-23.5	710.1	1750.6	0.0	21.8	-15.4	1772.4	0.832
-23.25	714.8	1751.4	0.0	19.3	-15.4	1770.7	0.833
-23	708.1	1752.3	0.0	16.7	-15.4	1769.0	0.833
-22.75	705.6	1753.1	0.0	14.2	-4.2	1767.3	0.834
-22.5	700.0	1725.5	0.0	44.3	1.2	1769.8	0.834
-22.25	702.7	1673.0	0.0	103.1	3.7	1776.1	0.833
-22	705.8	1620.5	0.0	161.8	4.8	1782.3	0.833
-21.75	703.0	1567.9	0.0	220.6	4.9	1788.5	0.833
-21.5	705.1	1585.4	0.0	217.1	4.6	1802.5	0.833
-21.25	706.8	1668.7	0.0	155.2	3.9	1823.9	0.832
-21	720.8	1752.1	0.0	93.2	3.1	1845.3	0.832
-20.75	714.8	1835.4	0.0	31.3	2.1	1866.7	0.832
-20.5	727.3	1887.1	0.0	13.0	1.1	1900.1	0.832
-20.25	730.6	1906.9	0.0	38.9	0.2	1945.8	0.832
-20	722.8	1926.7	0.0	64.8	-0.7	1991.5	0.832
-19.75	710.7	1946.4	0.0	90.8	-1.5	2037.2	0.832
-19.5	708.7	1978.5	4.7	98.2	-2.4	2081.3	0.832
-19.25	706.9	2023.8	14.4	85.4	-3.1	2123.6	0.833
-19	710.4	2069.1	24.1	72.7	-3.6	2165.9	0.833
-18.75	719.5	2114.5	33.8	60.0	-3.9	2208.2	0.833
-18.5	721.9	2123.4	62.3	53.4	-4.1	2239.0	0.833
-18.25	718.4	2089.7	112.7	54.0	-4.2	2256.3	0.833
-18	718.4	2055.9	163.1	54.6	-4.3	2273.6	0.834
-17.75	709.6	2022.2	213.5	55.2	-4.6	2290.9	0.834
-17.5	713.8	1949.2	277.2	74.6	-4.7	2301.0	0.834

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
-17.25	714.8	1826.7	357.6	117.8	-4.8	2302.1	0.834
-17	706.0	1704.2	438.0	161.0	-4.8	2303.2	0.835
-16.75	704.8	1581.7	518.5	204.1	-4.7	2304.3	0.835
-16.5	713.4	1517.3	577.3	209.6	-4.7	2304.1	0.835
-16.25	714.6	1531.4	606.8	163.9	-4.7	2302.1	0.835
-16	718.6	1545.6	636.3	118.3	-4.6	2300.2	0.835
-15.75	712.1	1559.7	665.9	72.7	-4.6	2298.3	0.836
-15.5	711.3	1543.0	691.2	62.0	-4.5	2296.2	0.836
-15.25	699.3	1481.4	710.5	102.0	-4.5	2293.8	0.836
-15	702.7	1419.8	729.7	142.0	-4.4	2291.4	0.836
-14.75	700.7	1358.2	748.9	182.0	-4.3	2289.0	0.837
-14.5	712.7	1303.0	763.8	218.8	-4.2	2285.7	0.837
-14.25	714.3	1258.0	772.1	250.7	-4.2	2280.8	0.837
-14	710.6	1213.0	780.3	282.5	-4.2	2275.8	0.837
-13.75	711.4	1168.0	788.6	314.4	-4.2	2270.9	0.837
-13.5	713.1	1145.1	789.8	332.0	-4.1	2266.9	0.838
-13.25	2780.2	1159.9	779.0	325.4	-708.3	2264.3	0.873
-13	1050.3	1174.6	768.3	318.9	14.7	2261.7	0.872
-12.75	1125.2	1189.3	757.6	312.3	14.7	2259.2	0.872
-12.5	1137.4	1208.2	743.5	305.3	14.7	2257.1	0.871
-12.25	1135.2	1234.6	723.5	297.7	18.9	2255.8	0.870
-12	1129.5	1261.0	703.4	290.0	26.4	2254.5	0.869
-11.75	1138.3	1287.4	683.4	282.3	26.4	2253.2	0.867
-11.5	1164.7	1329.7	659.4	259.8	26.4	2248.9	0.866
-11.25	1228.2	1403.5	627.5	207.9	42.3	2238.8	0.864
-11	1262.0	1477.2	595.5	155.9	73.7	2228.7	0.860
-10.75	1305.1	1550.9	563.6	104.0	73.7	2218.6	0.856
-10.5	1378.1	1606.7	517.6	89.5	73.7	2213.9	0.853
-10.25	1522.6	1624.0	441.3	155.7	55.8	2221.0	0.850
-10	1548.9	1641.3	365.0	221.8	17.3	2228.1	0.849
-9.75	1544.7	1658.6	288.7	287.9	17.3	2235.3	0.848
-9.5	1529.7	1695.5	220.6	325.6	17.3	2241.7	0.847
-9.25	1543.1	1778.0	171.9	296.5	36.8	2246.4	0.845
-9	1611.8	1860.5	123.2	267.5	82.5	2251.2	0.841
-8.75	1630.5	1943.1	74.5	238.4	82.5	2256.0	0.837
-8.5	1857.9	2021.1	36.8	203.4	82.5	2261.2	0.833
-8.25	1939.3	2087.6	26.9	153.2	78.0	2267.8	0.829
-8	2066.5	2154.2	17.1	103.0	66.5	2274.3	0.826
-7.75	2092.8	2220.7	7.2	52.8	66.5	2280.8	0.823

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
-7.5	2130.2	2262.1	0.0	25.1	66.5	2287.2	0.819
-7.25	2190.4	2233.2	0.0	60.2	41.4	2293.3	0.817
-7	2243.7	2204.2	0.0	95.2	-28.9	2299.5	0.819
-6.75	2116.8	2175.3	0.0	130.3	-28.9	2305.6	0.820
-6.5	2202.7	2145.5	0.0	165.9	-28.9	2311.4	0.822
-6.25	2089.8	2113.0	0.0	203.2	-29.8	2316.2	0.823
-6	2025.6	2080.5	0.0	240.5	-32.5	2321.0	0.825
-5.75	2032.3	2048.0	0.0	277.8	-32.5	2325.8	0.826
-5.5	2068.4	2030.1	0.0	297.1	-32.5	2327.2	0.828
-5.25	1935.2	2061.9	0.0	255.5	-17.9	2317.4	0.829
-5	1883.7	2093.8	0.0	213.9	31.8	2307.6	0.827
-4.75	1951.0	2125.6	0.0	172.2	31.8	2297.8	0.826
-4.5	1940.0	2140.1	0.0	144.0	31.8	2284.1	0.824
-4.25	2070.0	2089.3	0.0	166.3	14.5	2255.6	0.823
-4	2069.0	2038.6	0.0	188.6	-50.8	2227.1	0.826
-3.75	2016.2	1987.8	0.0	210.8	-50.8	2198.6	0.828
-3.5	1924.4	1939.6	0.0	229.3	-50.8	2168.9	0.831
-3.25	1925.3	1902.2	0.0	231.6	-48.2	2133.8	0.833
-3	2013.8	1864.8	0.0	234.0	-37.4	2098.7	0.835
-2.75	1879.7	1827.4	0.0	236.3	-37.4	2063.7	0.837
-2.5	1799.4	1798.0	0.0	231.5	-37.4	2029.5	0.839
-2.25	1885.9	1807.2	0.0	192.2	-29.3	1999.5	0.840
-2	1797.3	1816.4	0.0	153.0	9.2	1969.5	0.840
-1.75	1804.4	1825.6	0.0	113.8	9.2	1939.5	0.839
-1.5	1813.0	1833.7	0.0	77.7	9.2	1911.3	0.839
-1.25	1861.8	1835.3	0.0	57.9	8.0	1893.3	0.839
-1	1771.9	1837.0	0.0	38.2	1.7	1875.2	0.839
-0.75	1785.3	1838.7	0.0	18.5	1.7	1857.2	0.838
-0.5	1773.6	1832.4	0.0	8.1	1.7	1840.5	0.838
-0.25	1781.9	1776.6	0.0	56.3	-6.2	1832.8	0.839
0	1809.1	1720.7	0.0	104.5	-55.9	1825.1	0.841
0.25	1769.2	1664.8	0.0	152.6	-55.9	1817.4	0.844
0.5	1743.0	1617.0	0.0	193.5	-55.9	1810.5	0.847
0.75	1665.0	1628.8	0.0	180.7	-47.8	1809.5	0.849
1	1616.3	1640.5	0.0	167.8	11.8	1808.4	0.849
1.25	1614.7	1652.3	0.0	155.0	11.8	1807.3	0.848
1.5	1642.3	1664.5	0.0	141.9	11.8	1806.4	0.848
1.75	1596.4	1679.9	0.0	126.9	12.1	1806.7	0.847
2	1650.7	1695.3	0.0	111.8	15.4	1807.1	0.846

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
2.25	1675.7	1710.7	0.0	96.7	15.4	1807.4	0.846
2.5	1673.6	1726.6	0.0	82.9	15.4	1809.4	0.845
2.75	1665.3	1747.2	0.0	82.2	15.9	1829.4	0.844
3	1680.2	1767.9	0.0	81.6	20.7	1849.4	0.843
3.25	1712.8	1788.5	0.0	80.9	20.7	1869.4	0.842
3.5	1725.8	1809.0	0.0	82.0	20.7	1891.0	0.841
3.75	1778.2	1826.7	0.0	108.4	20.5	1935.2	0.840
4	1794.6	1844.5	0.0	134.8	17.8	1979.3	0.839
4.25	1792.3	1862.3	0.0	161.2	17.8	2023.5	0.838
4.5	1781.8	1879.3	0.5	187.9	17.8	2067.6	0.837
4.75	1879.1	1882.0	10.2	219.4	17.0	2111.6	0.836
5	1891.0	1884.6	20.0	251.0	2.7	2155.6	0.836
5.25	1759.7	1887.3	29.8	282.5	2.7	2199.6	0.836
5.5	1802.1	1890.7	40.8	311.4	2.7	2242.9	0.836
5.75	1864.1	1917.2	91.7	253.7	3.4	2262.6	0.836
6	1792.2	1943.6	142.6	196.0	26.5	2282.2	0.834
6.25	1873.8	1970.1	193.5	138.3	26.5	2301.9	0.833
6.5	1923.4	1995.0	244.7	81.7	26.5	2321.4	0.832
6.75	1915.3	1887.5	325.6	108.2	24.9	2321.3	0.831
7	1923.2	1780.0	406.4	134.7	-107.5	2321.2	0.836
7.25	1779.9	1672.5	487.3	161.3	-107.5	2321.1	0.841
7.5	1755.9	1565.1	568.2	187.8	-107.5	2321.0	0.847
7.75	1636.0	1577.6	597.5	141.5	-107.5	2316.6	0.852
8	1541.2	1590.8	626.5	94.9	12.5	2312.1	0.851
8.25	1608.0	1604.0	655.5	48.2	13.2	2307.7	0.851
8.5	1588.5	1617.2	684.5	1.5	13.2	2303.2	0.850
8.75	1604.1	1594.5	704.1	2.5	13.2	2301.1	0.849
9	1583.1	1570.8	723.4	4.7	-22.8	2299.0	0.851
9.25	1630.0	1547.2	742.8	6.9	-23.6	2296.9	0.852
9.5	1562.5	1523.6	762.2	9.1	-23.6	2294.8	0.853
9.75	1544.6	1461.9	771.2	57.7	-23.6	2290.8	0.854
10	1508.0	1398.5	779.8	108.5	-61.7	2286.8	0.857
10.25	1437.4	1335.2	788.4	159.2	-63.3	2282.8	0.860
10.5	1380.0	1271.9	797.0	209.9	-63.3	2278.7	0.864
10.75	1296.8	1319.3	785.7	166.1	-63.3	2271.0	0.867
11	1254.1	1373.7	773.1	116.3	47.4	2263.1	0.864
11.25	1278.7	1428.2	760.5	66.5	54.5	2255.2	0.862
11.5	1339.6	1482.6	748.0	16.7	54.5	2247.3	0.859
11.75	1389.7	1453.3	728.4	63.0	54.5	2244.8	0.856

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
12	1469.3	1417.0	708.2	117.6	-29.3	2242.8	0.858
12.25	1422.4	1380.6	688.1	172.1	-36.4	2240.7	0.859
12.5	1384.4	1344.2	667.9	226.6	-36.4	2238.7	0.861
12.75	1368.2	1359.0	638.8	237.9	-36.4	2235.7	0.863
13	1300.0	1379.2	608.8	244.6	14.8	2232.6	0.862
13.25	1313.9	1399.3	578.8	251.4	20.2	2229.5	0.861
13.5	1393.4	1419.5	548.8	258.1	20.2	2226.4	0.860
13.75	1435.5	1510.0	477.5	246.3	20.2	2233.8	0.859
14	1455.8	1609.5	400.8	232.2	90.5	2242.5	0.855
14.25	1495.0	1709.1	324.2	218.1	99.5	2251.3	0.850
14.5	1530.1	1808.6	247.5	203.9	99.5	2260.0	0.845
14.75	1665.0	1898.3	194.6	164.8	99.5	2257.7	0.840
15	1807.8	1986.5	145.3	121.9	89.7	2253.7	0.835
15.25	1851.7	2074.7	96.0	79.0	88.2	2249.7	0.831
15.5	2014.3	2162.9	46.7	36.1	88.2	2245.7	0.827
15.75	2106.6	2147.1	31.0	71.3	88.2	2249.3	0.822
16	2318.6	2112.9	21.2	120.2	-15.8	2254.3	0.823
16.25	2266.9	2078.7	11.4	169.2	-34.2	2259.3	0.825
16.5	2126.4	2044.6	1.6	218.1	-34.2	2264.3	0.826
16.75	1990.4	2081.1	0.0	192.6	-34.2	2273.7	0.828
17	1987.7	2131.9	0.0	152.0	36.5	2284.0	0.826
17.25	2054.2	2182.7	0.0	111.5	50.8	2294.2	0.824
17.5	2036.6	2233.5	0.0	71.0	50.8	2304.5	0.821
17.75	2142.4	2212.2	0.0	101.8	50.8	2314.0	0.819
18	2255.5	2174.4	0.0	148.9	-21.3	2323.3	0.820
18.25	2099.5	2136.6	0.0	196.0	-37.8	2332.6	0.822
18.5	2175.0	2098.9	0.0	243.1	-37.8	2342.0	0.823
18.75	2147.9	2104.0	0.0	235.6	-37.8	2339.6	0.825
19	2124.9	2120.1	0.0	214.1	5.1	2334.2	0.825
19.25	2119.8	2136.1	0.0	192.6	16.1	2328.7	0.824
19.5	2191.9	2152.2	0.0	171.1	16.1	2323.3	0.823
19.75	2088.4	2138.2	0.0	160.3	16.1	2298.5	0.823
20	2109.8	2115.6	0.0	152.5	-14.0	2268.2	0.823
20.25	2070.6	2093.0	0.0	144.8	-22.6	2237.8	0.824
20.5	2060.2	2070.5	0.0	137.0	-22.6	2207.5	0.826
20.75	1949.1	2037.0	0.0	134.6	-22.6	2171.6	0.827
21	1961.2	2000.0	0.0	133.9	-33.5	2133.9	0.828
21.25	1935.5	1963.1	0.0	133.1	-36.9	2096.3	0.830
21.5	1960.6	1926.2	0.0	132.4	-36.9	2058.6	0.832

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
21.75	1955.8	1867.0	0.0	160.1	-36.9	2027.1	0.834
22	1913.9	1800.2	0.0	197.6	-59.1	1997.8	0.837
22.25	1895.8	1733.3	0.0	235.1	-66.9	1968.4	0.840
22.5	1798.9	1666.5	0.0	272.6	-66.9	1939.1	0.844
22.75	1768.0	1657.3	0.0	260.5	-66.9	1917.8	0.847
23	1678.4	1670.0	0.0	229.6	-9.2	1899.5	0.847
23.25	1674.0	1682.7	0.0	198.6	12.7	1881.3	0.847
23.5	1649.1	1695.4	0.0	167.6	12.7	1863.0	0.846
23.75	1682.5	1682.5	0.0	169.1	12.7	1851.6	0.846
24	1688.8	1659.1	0.0	184.0	-12.8	1843.1	0.846
24.25	1685.6	1635.6	0.0	199.0	-23.5	1834.6	0.847
24.5	1668.8	1612.2	0.0	213.9	-23.5	1826.1	0.848
24.75	1624.1	1631.4	0.0	191.0	-23.5	1822.4	0.850
25	1629.0	1669.9	0.0	151.1	19.2	1821.0	0.849
25.25	1672.6	1708.4	0.0	111.1	38.5	1819.5	0.847
25.5	1674.5	1746.9	0.0	71.2	38.5	1818.1	0.845
25.75	1695.3	1759.8	0.0	62.5	38.5	1822.3	0.843
26	1746.8	1760.1	0.0	69.3	12.9	1829.4	0.842
26.25	1767.0	1760.5	0.0	76.0	0.3	1836.5	0.842
26.5	1755.8	1760.8	0.0	82.7	0.3	1843.5	0.842
26.75	1713.5	1773.2	0.0	88.3	0.3	1861.5	0.842
27	1664.5	1792.1	0.0	93.1	12.4	1885.2	0.842
27.25	1683.0	1810.9	0.0	98.0	18.8	1908.9	0.841
27.5	1713.4	1829.7	0.0	102.9	18.8	1932.6	0.840
27.75	1734.0	1852.3	0.0	119.0	18.8	1971.3	0.839
28	1766.3	1877.0	0.0	141.7	22.6	2018.7	0.838
28.25	1812.2	1901.7	0.0	164.3	24.7	2066.0	0.836
28.5	1892.2	1926.4	0.0	186.9	24.7	2113.3	0.835
28.75	1968.0	1972.5	3.1	184.1	24.7	2159.7	0.834
29	1958.5	2031.9	8.2	165.4	46.1	2205.4	0.832
29.25	2016.0	2091.3	13.2	146.7	59.4	2251.2	0.829
29.5	2020.1	2150.7	18.2	128.0	59.4	2296.9	0.826
29.75	2103.6	2140.9	35.9	149.6	59.4	2326.4	0.823
30	2092.1	2084.9	62.1	198.0	-9.7	2345.0	0.823
30.25	2152.5	2028.8	88.3	246.5	-56.1	2363.6	0.826
30.5	2097.2	1972.8	114.5	294.9	-56.1	2382.2	0.829
30.75	2075.1	1960.8	149.8	280.8	-56.1	2391.4	0.832
31	1976.8	1980.8	191.8	221.4	-11.9	2393.9	0.832
31.25	1973.0	2000.7	233.7	162.0	19.9	2396.4	0.831

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
31.5	1938.2	2020.6	275.7	102.6	19.9	2398.9	0.830
31.75	2004.6	2019.7	302.3	74.4	19.9	2396.4	0.829
32	1895.6	2002.8	317.0	70.3	199.2	2390.1	0.819
32.25	1917.9	1985.8	331.8	66.3	183.0	2383.8	0.810
32.5	1820.3	1968.8	346.5	62.2	183.0	2377.6	0.801
32.75	1830.5	1933.8	358.4	79.4	183.0	2371.6	0.792
33	1818.3	1883.7	367.7	114.4	165.0	2365.8	0.784
33.25	1778.2	1833.6	377.1	149.4	149.9	2360.1	0.776
33.5	1652.6	1783.5	386.5	184.3	149.9	2354.4	0.769
33.75	1602.8	1739.9	414.6	194.4	149.9	2348.9	0.761
34	1556.9	1702.1	459.4	182.3	156.4	2343.8	0.753
34.25	1461.7	1664.3	504.2	170.1	162.2	2338.6	0.745
34.5	1448.3	1626.5	549.1	157.9	162.2	2333.5	0.737
34.75	1411.6	1602.3	581.1	146.5	162.2	2330.0	0.729
35	1381.8	1591.3	600.9	135.9	175.8	2328.1	0.720
35.25	1404.1	1580.3	620.7	125.2	189.0	2326.2	0.711
35.5	1395.5	1569.3	640.5	114.5	189.0	2324.3	0.701
35.75	1412.1	1559.2	645.0	116.9	189.0	2321.0	0.692
36	1400.4	1550.0	633.6	132.8	189.9	2316.3	0.682
36.25	1383.5	1540.7	622.2	148.6	190.8	2311.6	0.673
36.5	1303.1	1531.5	610.9	164.5	190.8	2306.9	0.663
36.75	1295.5	1533.5	590.2	178.5	190.8	2302.3	0.654
37	1311.1	1548.0	559.2	190.5	202.0	2297.7	0.644
37.25	1373.4	1562.5	528.1	202.6	214.5	2293.2	0.633
37.5	1385.8	1577.1	497.0	214.6	214.5	2288.6	0.622
37.75	1421.7	1626.6	453.4	211.1	214.5	2291.0	0.611
38	1394.7	1717.9	394.8	188.9	249.5	2301.7	0.599
38.25	1427.2	1809.3	336.2	166.8	291.4	2312.3	0.584
38.5	1544.5	1900.7	277.5	144.7	291.4	2323.0	0.570
38.75	1602.2	1970.2	222.4	135.3	291.4	2327.9	0.555
39	1713.2	2011.4	171.6	142.5	269.5	2325.5	0.542
39.25	1749.4	2052.6	120.8	149.6	241.2	2323.1	0.530
39.5	1846.4	2093.9	70.1	156.7	241.2	2320.6	0.518
39.75	1909.2	2135.5	36.4	150.5	241.2	2322.4	0.506
40	1914.4	2177.7	26.3	125.9	241.6	2329.8	0.493
40.25	2044.5	2219.8	16.1	101.3	125.9	2337.3	0.487
40.5	2322.7	2262.0	6.0	76.7	-55.4	2344.8	0.490
40.75	2451.0	2278.0	0.0	75.5	-149.8	2353.5	0.497
41	2413.9	2254.8	0.0	109.4	-134.5	2364.2	0.504

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
41.25	2316.5	2231.6	0.0	143.3	-61.3	2374.9	0.507
41.5	2136.1	2208.4	0.0	177.1	39.6	2385.5	0.505
41.75	2036.4	2182.4	0.0	213.5	85.5	2396.0	0.501
42	2042.1	2152.0	0.0	254.1	53.1	2406.1	0.498
42.25	2130.5	2121.6	0.0	294.6	-15.5	2416.2	0.499
42.5	2092.2	2091.2	0.0	335.1	-55.3	2426.3	0.502
42.75	1992.9	2093.5	0.0	337.1	-43.7	2430.7	0.504
43	1909.6	2152.9	0.0	272.3	30.6	2425.2	0.503
43.25	1950.9	2212.2	0.0	207.4	120.4	2419.6	0.497
43.5	2127.3	2271.6	0.0	142.5	97.4	2414.1	0.492
43.75	2244.9	2285.2	0.0	114.1	7.1	2399.3	0.491
44	2260.5	2212.9	0.0	154.4	-111.6	2367.3	0.497
44.25	2284.0	2140.6	0.0	194.7	-202.9	2335.3	0.507
44.5	2128.5	2068.3	0.0	234.9	-119.2	2303.2	0.513
44.75	2019.6	2021.5	0.0	248.6	33.0	2270.0	0.511
45	1862.0	2026.6	0.0	207.9	147.9	2234.5	0.504
45.25	1981.3	2031.6	0.0	167.2	175.0	2198.9	0.495
45.5	2102.6	2036.7	0.0	126.6	64.1	2163.3	0.492
45.75	2201.0	2028.2	0.0	101.5	-67.2	2129.7	0.495
46	2169.2	1989.7	0.0	110.8	-128.8	2100.5	0.502
46.25	2022.4	1951.2	0.0	120.1	-108.5	2071.3	0.507
46.5	1821.5	1912.7	0.0	129.4	-11.9	2042.1	0.508
46.75	1842.9	1869.9	0.0	145.8	69.5	2015.7	0.504
47	1722.5	1816.6	0.0	179.6	74.1	1996.2	0.501
47.25	1766.2	1763.4	0.0	213.3	11.6	1976.7	0.500
47.5	1816.8	1710.2	0.0	247.0	-44.0	1957.2	0.502
47.75	1741.7	1678.1	0.0	262.5	-52.7	1940.6	0.505
48	1712.7	1701.4	0.0	229.9	1.4	1931.3	0.505
48.25	1668.5	1724.6	0.0	197.4	96.3	1922.1	0.500
48.5	1745.7	1747.9	0.0	164.9	95.3	1912.8	0.495
48.75	1760.3	1763.0	0.0	142.2	23.0	1905.3	0.494
49	1791.0	1754.5	0.0	148.1	-56.6	1902.6	0.497
49.25	1833.3	1746.0	0.0	154.0	-97.5	1900.0	0.502
49.5	1732.9	1737.5	0.0	159.9	-55.0	1897.4	0.505
49.75	1643.5	1726.4	0.0	170.6	18.1	1897.0	0.504
50	1610.2	1707.0	0.0	196.9	56.7	1903.8	0.501
50.25	1735.0	1687.5	0.0	223.1	34.9	1910.7	0.499
50.5	1703.9	1668.1	0.0	249.4	-7.7	1917.5	0.499
50.75	1630.8	1663.0	0.0	264.5	-33.8	1927.5	0.501

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
51	1592.6	1707.9	0.0	240.6	-13.8	1948.4	0.502
51.25	1597.4	1752.7	0.0	216.6	61.6	1969.4	0.499
51.5	1680.8	1797.6	0.0	192.7	72.0	1990.3	0.495
51.75	1776.2	1841.0	0.0	175.1	25.8	2016.1	0.494
52	1889.1	1878.5	0.0	182.3	-29.7	2060.7	0.495
52.25	1911.6	1915.9	0.0	189.5	-55.0	2105.4	0.498
52.5	1897.8	1953.4	0.0	196.6	-32.7	2150.0	0.500
52.75	1937.3	1995.4	1.9	196.6	8.5	2194.0	0.499
53	1992.0	2057.7	12.1	165.1	37.7	2235.0	0.497
53.25	2066.0	2120.0	22.4	133.6	51.5	2276.0	0.495
53.5	2067.4	2182.3	32.6	102.1	23.2	2317.0	0.494
53.75	2156.4	2222.7	50.1	81.7	-15.4	2354.5	0.494
54	2218.8	2154.3	103.4	116.7	-54.7	2374.3	0.497
54.25	2348.9	2085.9	156.6	151.6	-152.0	2394.1	0.505
54.5	2241.9	2017.5	209.9	186.5	-110.9	2414.0	0.510
54.75	2087.3	1946.8	267.7	215.6	3.0	2430.1	0.510
55	1945.9	1863.1	351.3	211.0	84.0	2425.3	0.506
55.25	1791.9	1779.3	434.8	206.4	68.6	2420.5	0.503
55.5	1791.9	1695.6	518.3	201.8	5.7	2415.7	0.502
55.75	1735.5	1622.4	594.7	193.4	-45.8	2410.5	0.505
56	1694.3	1618.7	623.8	159.9	-39.5	2402.4	0.507
56.25	1512.6	1615.0	652.8	126.4	64.3	2394.2	0.503
56.5	1487.1	1611.2	681.9	92.9	93.9	2386.1	0.499
56.75	1536.7	1601.8	709.8	66.4	45.7	2378.1	0.496
57	1605.8	1548.5	728.1	94.3	-30.4	2370.9	0.498
57.25	1679.3	1495.1	746.5	122.2	-108.7	2363.7	0.503
57.5	1583.2	1441.7	764.8	150.0	-85.9	2356.5	0.508
57.75	1484.1	1392.1	782.1	175.1	-4.4	2349.3	0.508
58	1361.0	1378.2	789.7	173.8	63.8	2341.6	0.505
58.25	1338.8	1364.3	797.2	172.4	102.8	2333.9	0.499
58.5	1340.8	1350.4	804.7	171.1	54.9	2326.2	0.497
58.75	1380.8	1340.6	810.7	167.3	-22.2	2318.5	0.498
59	1370.4	1379.2	798.2	133.8	-59.3	2311.2	0.501
59.25	1334.0	1417.9	785.6	100.4	5.8	2303.9	0.500
59.5	1365.5	1456.5	773.1	66.9	50.3	2296.6	0.498
59.75	1394.6	1493.5	760.0	35.8	45.9	2289.3	0.496
60	1505.0	1504.3	738.2	40.6	6.5	2283.1	0.495
60.25	1578.7	1515.0	716.4	45.4	-54.2	2276.8	0.498
60.5	1558.8	1525.7	694.6	50.2	-59.1	2270.5	0.501

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
60.75	1570.8	1536.2	672.4	55.6	-18.4	2264.2	0.502
61	1492.8	1541.9	641.1	74.3	25.6	2257.2	0.501
61.25	1450.8	1547.5	609.8	93.0	34.6	2250.2	0.499
61.5	1539.6	1553.1	578.5	111.6	15.4	2243.2	0.498
61.75	1613.8	1560.5	546.1	129.9	-10.6	2236.4	0.499
62	1604.8	1637.2	468.1	131.1	-20.4	2236.4	0.500
62.25	1574.8	1713.8	390.2	132.4	56.8	2236.4	0.497
62.5	1638.2	1790.5	312.3	133.7	72.2	2236.4	0.493
62.75	1788.5	1867.2	234.5	134.7	29.5	2236.4	0.492
63	1849.9	1952.9	185.9	103.0	-24.5	2241.9	0.493
63.25	1947.3	2038.7	137.3	71.3	-37.6	2247.3	0.495
63.5	1982.7	2124.5	88.7	39.5	-19.2	2252.7	0.496
63.75	2126.1	2210.2	40.1	7.8	9.0	2258.1	0.495
64	2193.2	2201.7	29.8	34.4	23.4	2265.9	0.494
64.25	2208.6	2192.0	20.0	61.7	-77.6	2273.7	0.498
64.5	2173.2	2182.4	10.1	89.0	-96.3	2281.4	0.503
64.75	2166.8	2172.7	0.3	116.3	-38.1	2289.2	0.505
65	2170.0	2166.7	0.0	132.2	34.1	2298.9	0.503
65.25	2052.1	2160.8	0.0	147.8	66.4	2308.5	0.500
65.5	2100.6	2154.9	0.0	163.3	40.9	2318.2	0.498
65.75	2141.1	2149.0	0.0	178.9	-8.9	2327.9	0.498
66	2167.2	2185.1	0.0	155.5	-39.6	2340.5	0.500
66.25	2169.0	2223.3	0.0	130.0	9.1	2353.3	0.500
66.5	2103.6	2261.5	0.0	104.6	40.9	2366.1	0.498
66.75	2250.0	2299.7	0.0	79.2	34.1	2378.9	0.496
67	2197.7	2278.4	0.0	98.0	3.4	2376.4	0.496
67.25	2309.3	2252.8	0.0	120.0	-81.8	2372.8	0.500
67.5	2182.9	2227.2	0.0	142.0	-88.5	2369.2	0.504
67.75	2251.7	2201.6	0.0	164.0	-27.2	2365.6	0.506
68	2220.3	2188.5	0.0	150.2	39.2	2338.7	0.504
68.25	2137.3	2176.5	0.0	133.2	72.0	2309.7	0.500
68.5	2230.8	2164.6	0.0	116.1	43.8	2280.7	0.498
68.75	2219.9	2152.6	0.0	99.1	-10.2	2251.7	0.498
69	2089.8	2090.8	0.0	126.1	-43.1	2216.9	0.501
69.25	2174.1	2023.4	0.0	158.0	-85.2	2181.5	0.505
69.5	1990.9	1956.1	0.0	189.9	-58.5	2146.0	0.508
69.75	1955.2	1888.7	0.0	221.9	5.4	2110.5	0.508
70	1829.5	1890.5	0.0	193.4	49.3	2083.8	0.505
70.25	1774.9	1901.7	0.0	156.6	114.4	2058.3	0.499

Table A2 Time (hr)	**Nuclear Supply (MW)**	**Nuclear Demand (MW)**	**Solar Supply (MW)**	**Wind Supply (MW)**	**Hydro Supply (MW)**	**Total Demand (MW)**	**Reservoir Fill Fraction**
70.5	1842.2	1912.9	0.0	119.9	86.9	2032.8	0.495
70.75	1959.4	1924.1	0.0	83.1	1.1	2007.2	0.495
71	1968.1	1897.8	0.0	89.3	-64.1	1987.1	0.498
71.25	1973.7	1865.5	0.0	102.3	-102.4	1967.8	0.503
71.5	1954.2	1833.2	0.0	115.4	-60.4	1948.6	0.506
71.75	1822.8	1800.9	0.0	128.4	16.5	1929.3	0.505
72	1765.2	1792.6	0.0	127.6	61.7	1920.2	0.502
72.25	1734.5	1788.7	0.0	124.3	73.4	1913.0	0.499
72.5	1811.3	1784.8	0.0	121.0	31.5	1905.8	0.497
72.75	1882.7	1780.9	0.0	117.7	-23.5	1898.5	0.498
73	1985.0	1801.0	0.0	94.7	-47.1	1895.7	0.501
73.25	1894.2	1826.1	0.0	67.7	-5.5	1893.8	0.501
73.5	1760.1	1851.3	0.0	40.6	34.9	1891.9	0.502
73.75	1804.8	1876.4	0.0	13.6	39.0	1890.0	0.502
74	1836.0	1885.5	0.0	9.0	25.2	1894.5	0.503
74.25	1857.5	1890.7	0.0	9.7	9.0	1900.4	0.506
74.5	1791.2	1895.9	0.0	10.5	5.2	1906.3	0.508
74.75	1828.8	1901.1	0.0	11.2	5.2	1912.3	0.510
75	1852.2	1898.8	0.0	31.1	5.2	1929.9	0.512
75.25	1879.4	1894.6	0.0	56.1	-2.3	1950.7	0.515
75.5	1811.3	1890.4	0.0	81.1	-4.2	1971.5	0.518
75.75	1810.0	1886.1	0.0	106.1	-4.2	1992.3	0.520
76	1802.9	1912.1	0.0	116.5	-4.2	2028.6	0.523
76.25	1867.1	1946.9	0.0	122.6	25.9	2069.6	0.524
76.5	1912.8	1981.8	0.0	128.8	34.8	2110.5	0.525
76.75	1994.2	2016.6	0.0	134.9	34.8	2151.5	0.526
77	2077.4	2035.8	3.8	152.4	34.8	2192.0	0.526
77.25	1959.8	2049.9	8.9	173.7	19.2	2232.5	0.528
77.5	1969.2	2064.1	13.9	194.9	14.1	2272.9	0.530
77.75	1993.5	2078.2	19.0	216.1	14.1	2313.3	0.532
78	2091.8	2105.1	39.5	189.7	14.1	2334.3	0.533
78.25	2053.4	2136.5	65.6	146.2	26.9	2348.3	0.535
78.5	2157.2	2168.0	91.6	102.7	31.5	2362.3	0.535
78.75	2144.1	2199.5	117.6	59.2	31.5	2376.2	0.536
79	2159.7	2169.6	154.6	54.5	31.5	2378.7	0.537
79.25	2136.6	2115.7	195.8	65.1	-29.8	2376.7	0.541
79.5	2134.5	2061.9	237.0	75.7	-53.9	2374.6	0.547
79.75	2095.5	2008.0	278.2	86.4	-53.9	2372.6	0.552
80	2063.3	1952.8	300.3	111.1	-53.9	2364.1	0.557

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
80.25	2061.2	1897.0	314.1	141.9	-55.2	2352.9	0.562
80.5	2029.0	1841.1	327.9	172.6	-55.8	2341.7	0.567
80.75	2009.2	1785.3	341.7	203.4	-55.8	2330.4	0.573
81	1973.9	1765.5	351.9	202.4	-55.8	2319.8	0.578
81.25	1826.7	1762.6	360.3	186.5	-19.8	2309.3	0.582
81.5	1828.7	1759.6	368.7	170.7	-3.0	2298.9	0.584
81.75	1777.0	1756.6	377.1	154.8	-3.0	2288.4	0.587
82	1793.6	1740.8	381.6	153.8	-3.0	2276.2	0.589
82.25	1713.7	1718.5	384.3	160.2	-15.8	2263.0	0.593
82.5	1599.4	1696.2	387.0	166.7	-22.3	2249.9	0.596
82.75	1646.3	1674.0	389.7	173.1	-22.3	2236.7	0.600
83	1666.3	1658.1	386.4	180.9	-22.3	2225.4	0.604
83.25	1609.2	1645.7	379.8	189.5	-15.9	2215.0	0.607
83.5	1606.9	1633.4	373.2	198.1	-12.4	2204.6	0.610
83.75	1586.1	1621.0	366.6	206.7	-12.4	2194.3	0.613
84	1610.9	1642.1	357.2	184.8	-12.4	2184.0	0.616
84.25	1573.2	1682.9	346.2	144.9	21.1	2173.9	0.618
84.5	1636.4	1723.7	335.1	105.0	40.8	2163.7	0.618
84.75	1750.0	1764.5	324.1	65.0	40.8	2153.6	0.619
85	1739.5	1778.9	310.6	55.5	40.8	2144.9	0.619
85.25	1794.1	1776.4	295.6	65.2	14.4	2137.1	0.621
85.5	1765.6	1773.9	280.6	74.9	-2.5	2129.4	0.623
85.75	1791.3	1771.4	265.6	84.6	-2.5	2121.6	0.626
86	1852.4	1786.6	237.5	92.2	-2.5	2116.3	0.629
86.25	1807.8	1814.0	200.4	98.3	15.2	2112.8	0.630
86.5	1784.0	1841.4	163.3	104.4	27.4	2109.2	0.632
86.75	1869.7	1868.8	126.2	110.5	27.4	2105.6	0.633
87	1855.0	1873.7	97.3	135.0	27.4	2106.0	0.634
87.25	1864.4	1861.8	74.4	173.2	4.8	2109.4	0.636
87.5	1788.8	1849.9	51.5	211.3	-11.9	2112.8	0.639
87.75	1877.7	1838.0	28.7	249.5	-11.9	2116.1	0.642
88	1885.0	1865.1	16.0	238.2	-11.9	2119.2	0.645
88.25	1796.7	1923.1	11.3	187.6	27.0	2122.0	0.647
88.5	1884.6	1981.1	6.7	136.9	58.0	2124.8	0.646
88.75	1957.4	2039.1	2.1	86.3	58.0	2127.6	0.646
89	1954.6	2043.4	0.0	90.1	58.0	2133.5	0.645
89.25	1983.5	2001.7	0.0	140.4	4.3	2142.1	0.648
89.5	2067.9	1959.9	0.0	190.8	-41.7	2150.7	0.652
89.75	1959.6	1918.2	0.0	241.1	-41.7	2159.3	0.657

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
90	1975.7	1905.7	0.0	264.9	-41.7	2170.6	0.661
90.25	1835.8	1920.2	0.0	264.2	-12.5	2184.3	0.665
90.5	1887.7	1934.6	0.0	263.5	14.5	2198.1	0.666
90.75	1879.8	1949.1	0.0	262.8	14.5	2211.9	0.668
91	1877.0	1971.0	0.0	248.8	14.5	2219.8	0.670
91.25	1898.2	2000.3	0.0	221.7	21.9	2222.0	0.669
91.5	1831.6	2029.6	0.0	194.7	29.3	2224.2	0.667
91.75	1927.0	2058.9	0.0	167.6	29.3	2226.4	0.666
92	2019.0	2056.6	0.0	162.0	29.3	2218.6	0.664
92.25	1891.5	2020.8	0.0	179.3	-2.3	2200.1	0.664
92.5	2047.4	1985.0	0.0	196.6	-35.8	2181.6	0.666
92.75	1953.4	1949.2	0.0	213.9	-35.8	2163.1	0.668
93	1900.8	1925.0	0.0	215.8	-35.8	2140.9	0.670
93.25	1958.4	1914.0	0.0	200.4	-24.2	2114.4	0.671
93.5	1959.9	1903.1	0.0	184.9	-11.0	2088.0	0.672
93.75	1880.0	1892.1	0.0	169.5	-11.0	2061.5	0.672
94	1830.7	1879.4	0.0	156.5	-11.0	2035.9	0.673
94.25	1795.7	1864.7	0.0	146.8	-12.7	2011.4	0.673
94.5	1888.3	1849.9	0.0	137.0	-14.7	1986.9	0.674
94.75	1902.1	1835.2	0.0	127.2	-14.7	1962.4	0.675
95	1827.1	1823.7	0.0	118.2	-14.7	1941.9	0.676
95.25	1849.0	1816.6	0.0	110.1	-11.5	1926.7	0.676
95.5	1842.2	1809.4	0.0	102.1	-7.2	1911.5	0.676
95.75	1866.5	1802.3	0.0	94.1	-7.2	1896.3	0.677
96	1848.7	1797.3	0.0	86.0	-7.2	1883.3	0.677
96.25	1788.7	1795.6	0.0	77.9	-4.9	1873.4	0.677
96.5	1752.9	1793.8	0.0	69.7	-1.8	1863.6	0.678
96.75	1804.8	1792.1	0.0	61.6	-1.8	1853.7	0.678
97	1859.7	1771.2	0.0	75.9	-1.8	1847.1	0.678
97.25	1882.1	1721.1	0.0	124.5	-20.9	1845.6	0.679
97.5	1904.1	1670.9	0.0	173.1	-50.1	1844.0	0.681
97.75	1791.4	1620.8	0.0	221.7	-50.1	1842.5	0.684
98	1753.4	1612.3	0.0	229.6	-50.1	1841.8	0.686
98.25	1640.7	1672.4	0.0	170.3	-8.5	1842.7	0.687
98.5	1679.0	1732.5	0.0	111.0	60.1	1843.5	0.684
98.75	1676.4	1792.7	0.0	51.7	60.1	1844.4	0.681
99	1795.1	1814.4	0.0	34.5	60.1	1848.8	0.678
99.25	1800.1	1767.5	0.0	92.2	21.7	1859.7	0.677
99.5	1837.5	1720.6	0.0	149.9	-46.9	1870.5	0.679

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
99.75	1803.5	1673.8	0.0	207.6	-46.9	1881.4	0.681
100	1741.2	1649.6	0.0	245.5	-46.9	1895.1	0.684
100.25	1657.9	1669.3	0.0	245.0	-24.2	1914.2	0.685
100.5	1665.2	1688.9	0.0	244.5	19.7	1933.4	0.684
100.75	1688.8	1708.6	0.0	244.0	19.7	1952.6	0.683
101	1706.2	1730.5	2.9	239.6	19.7	1973.0	0.682
101.25	1638.2	1757.1	11.9	227.3	21.9	1996.3	0.681
101.5	1664.2	1783.7	20.8	215.0	26.6	2019.5	0.679
101.75	1650.3	1810.3	29.8	202.7	26.6	2042.8	0.678
102	1672.1	1832.7	50.5	182.8	26.6	2065.9	0.677
102.25	1769.1	1845.6	97.7	145.4	22.4	2088.7	0.676
102.5	1854.3	1858.5	144.9	108.0	12.9	2111.4	0.675
102.75	1828.6	1871.4	192.1	70.7	12.9	2134.2	0.674
103	1793.4	1852.0	248.5	54.8	12.9	2155.3	0.674
103.25	1844.2	1752.4	327.6	92.2	-19.4	2172.2	0.675
103.5	1888.1	1652.9	406.7	129.6	-99.5	2189.2	0.680
103.75	1773.6	1553.3	485.8	167.0	-99.5	2206.1	0.685
104	1679.0	1476.7	551.9	191.7	-99.5	2220.2	0.690
104.25	1607.4	1462.2	582.8	181.7	-76.6	2226.6	0.693
104.5	1542.8	1447.6	613.7	171.8	-14.5	2233.1	0.694
104.75	1497.4	1433.1	644.6	161.9	-14.5	2239.5	0.695
105	1452.0	1407.1	672.4	164.3	-14.5	2243.8	0.696
105.25	1449.3	1347.2	691.3	203.2	-25.9	2241.8	0.697
105.5	1414.5	1287.3	710.2	242.2	-59.9	2239.7	0.700
105.75	1360.4	1227.5	729.0	281.2	-59.9	2237.6	0.703
106	1301.3	1180.9	745.2	308.5	-59.9	2234.6	0.706
106.25	1210.8	1178.0	752.8	297.5	-46.6	2228.3	0.708
106.5	1188.2	1175.1	760.3	286.6	-2.9	2222.0	0.708
106.75	1150.8	1172.2	767.9	275.6	-2.9	2215.7	0.709
107	1172.9	1184.4	771.0	253.4	-2.9	2208.7	0.709
107.25	1158.1	1251.1	758.2	190.0	12.1	2199.3	0.708
107.5	1165.0	1317.7	745.5	126.6	66.7	2189.8	0.705
107.75	1267.3	1384.4	732.7	63.2	66.7	2180.3	0.701
108	1331.5	1433.6	718.1	19.0	66.7	2170.7	0.698
108.25	1446.5	1411.8	696.2	52.7	49.2	2160.8	0.696
108.5	1498.2	1390.0	674.3	86.5	-21.8	2150.8	0.697
108.75	1438.0	1368.2	652.4	120.2	-21.8	2140.8	0.698
109	1415.3	1354.7	629.2	147.7	-21.8	2131.7	0.699
109.25	1366.6	1379.4	600.0	146.9	-13.5	2126.3	0.700

Table A2 Time (hr)	Nuclear Supply (MW)	Nuclear Demand (MW)	Solar Supply (MW)	Wind Supply (MW)	Hydro Supply (MW)	Total Demand (MW)	Reservoir Fill Fraction
109.5	1336.4	1404.1	570.9	146.0	24.7	2121.0	0.698
109.75	1355.1	1428.8	541.7	145.1	24.7	2115.7	0.697
110	1324.4	1457.6	505.3	148.1	24.7	2111.0	0.696
110.25	1361.7	1507.7	431.7	170.8	28.8	2110.2	0.694
110.5	1423.4	1557.9	358.0	193.4	50.1	2109.3	0.692
110.75	1561.0	1608.0	284.4	216.1	50.1	2108.5	0.689
111	1544.4	1662.0	214.7	231.8	50.1	2108.6	0.687
111.25	1565.9	1739.3	168.9	205.8	54.0	2114.0	0.684
111.5	1709.5	1816.5	123.1	179.9	77.2	2119.5	0.680
111.75	1764.5	1893.7	77.3	153.9	77.2	2125.0	0.676
112	1858.5	1964.8	36.1	129.4	77.2	2130.3	0.673
112.25	1927.6	1992.7	26.8	115.1	71.0	2134.6	0.669
112.5	1932.1	2020.6	17.6	100.7	27.9	2138.9	0.668
112.75	1969.7	2048.5	8.3	86.4	27.9	2143.2	0.666
113	1957.5	2072.9	0.0	75.3	27.9	2148.1	0.665
113.25	2065.6	2067.5	0.0	90.7	24.3	2158.2	0.664
113.5	1945.2	2062.1	0.0	106.1	-5.4	2168.2	0.664
113.75	1925.8	2056.8	0.0	121.4	-5.4	2178.2	0.664
114	1887.0	2049.9	0.0	138.4	-5.4	2188.3	0.664
114.25	2012.4	2027.3	0.0	171.5	-6.9	2198.7	0.665
114.5	2034.7	2004.6	0.0	204.5	-22.6	2209.2	0.666
114.75	2005.6	1982.0	0.0	237.6	-22.6	2219.6	0.667
115	2048.6	1965.7	0.0	263.8	-22.6	2229.4	0.668
115.25	2001.3	2030.1	0.0	201.4	-16.4	2231.5	0.669
115.5	2005.1	2094.6	0.0	139.0	64.5	2233.6	0.666
115.75	2158.0	2159.1	0.0	76.6	64.5	2235.6	0.663
116	2056.2	2218.8	0.0	17.8	64.5	2236.6	0.659
116.25	2133.9	2195.2	0.0	23.0	59.7	2218.2	0.656
116.5	2227.3	2171.6	0.0	28.2	-23.6	2199.8	0.658
116.75	2213.8	2148.0	0.0	33.3	-23.6	2181.3	0.659
117	2156.2	2123.7	0.0	38.9	-23.6	2162.6	0.660
117.25	2195.0	2080.5	0.0	54.4	-24.3	2134.8	0.661
117.5	2082.3	2037.2	0.0	69.8	-43.2	2107.1	0.663
117.75	2128.4	1994.0	0.0	85.3	-43.2	2079.3	0.665
118	2113.2	1950.3	0.0	101.3	-43.2	2051.6	0.668
118.25	1991.4	1884.0	0.0	142.4	-43.6	2026.4	0.670
118.5	1902.6	1817.7	0.0	183.5	-66.3	2001.2	0.673
118.75	1836.3	1751.3	0.0	224.6	-66.3	1976.0	0.676
119	1773.5	1685.0	0.0	265.8	-66.3	1950.8	0.680

Code

The following code was implemented in Python 3.6 to perform the simulation presented:

```python
"""
Ch En 593R - Dynamic Optimization
Control and Optimization of a Zero-Carbon Power Grid

Written by:
    Tyrel Hess
    Derek Prestwich
    Cameron Price
"""
##########################################################################
# Import relevant packages
import numpy as np
from gekko import GEKKO
import matplotlib.pyplot as plt
from scipy.integrate import odeint
import pandas as pd
from scipy.interpolate import interp1d

##########################################################################
# Demand data file import
filename = 'powergrid_week.csv'

##########################################################################
# Read demand data into arrays
data = pd.read_csv(filename)
time0 = data['hour'].values
power0 = data['nuc_power'].values/170.0
tot_power0 = data['tot_power'].values/170.0
solar_power0 = data['solar_power'].values/170.0
wind_power0 = data['wind_power'].values/170.0
time0 = time0-1

##########################################################################
# Interpolate demand data to match python data resolution
res = 4 #resolution multiplier

fnuc = interp1d(time0,power0)
fsol = interp1d(time0,solar_power0)
fwin = interp1d(time0,wind_power0)
ftot = interp1d(time0,tot_power0)

time = np.linspace(0,time0[-1],len(time0)*res)

power = np.zeros(len(time))
tot_power = np.zeros(len(time))
solar_power = np.zeros(len(time))
wind_power = np.zeros(len(time))

for i in range(len(time)):
    power[i] = fnuc(time[i])
    tot_power[i] = ftot(time[i])
```

```
    solar_power[i] = fsol(time[i])
    wind_power[i] = fwin(time[i])

###########################################################################
# Define n to set array lengths throughout the code
n = len(time)

###########################################################################
# Create a digital twin to be calculated with odeint
class save(): # Create a class to save values from the ODEINT model
    U = 0

def reactor(x,t,u,mult):
    # Parameters
    Beta = 0.007108
    Betas = [0.000216, 0.001416, 0.001349, 0.00218, 0.00095, 0.000322]

    Lambdas = [0.0125, 0.0308, 0.1152, 0.3109, 1.24, 3.3287] # s^-1

    l = 5e-4 # s

    rho_0 = -0.009108
    b = 0.00025

    alpha_f = -2e-5 # C^-1
    alpha_c = -5e-5 # C^-1

    Tin = 292 # C, being held constant by secondary loop

    # Reactor variables
    # Tout is approximately equal to Tavg

    #Create differentiable variables for odeint model
    P = x[0]
    C1 = x[1]
    C2 = x[2]
    C3 = x[3]
    C4 = x[4]
    C5 = x[5]
    C6 = x[6]
    Tf = x[7]
    Tavg = x[8]

    # Parameters
    A = 6.314e3 # m^2
    Mf = 122789.605 # kg
    Cpf = 0.0002999667 # MW * s * kg^-1 * C^-1 at 700 C for UO2
    J = 38 # MW/%
    Mc = 1.917e5 # kg
    mdot = 65.9e6 / 3600 # kg/s, alternative of 800 kg/s
    Cpc = 0.00571 # MW * s * kg^-1 * C^-1 at @ 298 C for water
    Cv = 0.0301 # flow coefficient
    De = 0.01297 # m
    Kc = 0.00000055 # MW/m*K
    mu = 0.000068 # Pa*s
    density = 1000 # kg/m^3

    # get U value
    # get velocity
    v = (mdot / 1000) / (np.pi * De**2 / 43) / 100000
    Re = De * v * density / mu
```

```
        Pr = Cpc * mu / Kc
        U = Cv * Re**0.8 * Pr**0.4 * (Kc / De) * mult
        save.U = U

        # reactivity
        rho = rho_0 + alpha_f * Tf + alpha_c * Tavg + b * u

        # differential equations
        dPdt = (rho - Beta) * P / l + (Lambdas[0] * C1 + Lambdas[1] * C2 + Lambdas[2] * C3 + Lambdas[3] * C4 + Lambdas[4] * C5 + Lambdas[5] * C6)
        dC1dt = (Betas[0] / l) * P - Lambdas[0] * C1
        dC2dt = (Betas[1] / l) * P - Lambdas[1] * C2
        dC3dt = (Betas[2] / l) * P - Lambdas[2] * C3
        dC4dt = (Betas[3] / l) * P - Lambdas[3] * C4
        dC5dt = (Betas[4] / l) * P - Lambdas[4] * C5
        dC6dt = (Betas[5] / l) * P - Lambdas[5] * C6
        dTfdt = -U * A / (Mf * Cpf) * (Tf - Tavg) + J * P / (Mf * Cpf)
        dTavgdt = U * A / (Mc * Cpc) * (Tf - Tavg) - (mdot / Mc) * (Tavg - Tin)

        diff_eqns = [dPdt, dC1dt, dC2dt, dC3dt, dC4dt, dC5dt, dC6dt, dTfdt, dTavgdt]

        return diff_eqns

    ##########################################################################
    # Set up parameters for GEKKO models
    # Parameters
    Beta = 0.007108
    Betas = [0.000216, 0.001416, 0.001349, 0.00218, 0.00095, 0.000322]

    Lambda = 0.078 # s^-1
    Lambdas = [0.0125, 0.0308, 0.1152, 0.3109, 1.24, 3.3287] # s^-1

    l = 5e-4 # s

    LT = 50 # potential efficiency of 0.34

    rho_0 = -0.009108

    b = 0.00025

    alpha_f = -2e-5 # C^-1
    alpha_c = -5e-5 # C^-1

    Tin = 292 # C

    A = 6.314e3 # m^2
    Mf = 122789.605 # kg
    Cpf = 0.0002999667 # MW * s * kg^-1 * C^-1 at 700 C for UO2
    J = 38 # MW/%
    Mc = 1.917e5 # kg
    mdot = 65.9e6 / 3600 # kg/s, alternative of 800 kg/s
    Cpc = 0.00571 # MW * s * kg^-1 * C^-1 at @ 298 C for water
    Cv = 0.0301 # flow coefficient
    De = 0.01297 # m
    Kc = 0.00000055 # MW/m*K
    mu = 0.000068 # Pa*s
    density = 1000 # kg/m^3

    v = (mdot / 1000) / (np.pi * De**2 / 43) / 100000
    Re = De * v * density / mu
    Pr = Cpc * mu / Kc
```

```
    U = Cv * Re**0.8 * Pr**0.4 * (Kc / De) * 0.03

    Ctot = 1e3

    u = np.linspace(0,n,n+1)

    u[0:25] = 100
    u[25:] = 140

    ###########################################################################
    # Create the MHE GEKKO Model
    mhe = GEKKO(remote=False)

    mhe.time = np.linspace(0,10,11)

    # Define GEKKO Parameters
    mhe.Beta = mhe.Param(Beta)
    mhe.Betas = [mhe.Param(Betas[i]) for i in range(len(Betas))]
    mhe.Lambdas = [mhe.Param(Lambdas[i]) for i in range(len(Lambdas))]
    mhe.rho_0 = mhe.Param(rho_0)
    mhe.b = mhe.Param(b)
    mhe.l = mhe.Param(l)
    mhe.alpha_f = mhe.Param(alpha_f)
    mhe.alpha_c = mhe.Param(alpha_c)
    mhe.A = mhe.Param(6.314e3) # m^2
    mhe.Mf = mhe.Param(122789.605) # kg
    mhe.Cpf = mhe.Param(0.0002999667) # MW * s * kg^-1 * C^-1 at 700 C for UO2
    mhe.J = mhe.Param(38) # MW/%
    mhe.Mc = mhe.Param(1.917e5) # kg
    mhe.mdot = mhe.Param(65.9e6 / 3600) # kg/s, alternative of 800 kg/s
    mhe.Cpc = mhe.Param(0.00571) # MW * s * kg^-1 * C^-1 at @ 298 C for water
    mhe.Cv = mhe.Param(0.0301) # flow coefficient
    mhe.De = mhe.Param(0.01297) # m
    mhe.Kc = mhe.Param(0.00000055) # MW/m*K
    mhe.mu = mhe.Param(0.000068) # Pa*s
    mhe.density = mhe.Param(1000) # kg/m^3

    # Define GEKKO Fixed Value, U will be estimated
    mhe.U = mhe.FV(value = U,lb = 0)
    mhe.U.STATUS = 0
    mhe.Tin = mhe.FV(value = Tin)

    # Define GEKKO Variables
    mhe.P = mhe.SV(value = 0)
    mhe.Cs = [mhe.Var(Ctot*Lambdas[i]) for i in range(len(Lambdas))]
    mhe.rho = mhe.Var(rho_0)
    mhe.Tavg = mhe.CV(300)
    mhe.Tavg.STATUS = 0
    mhe.Tavg.FSTATUS = 1
    mhe.Tf = mhe.SV(320)

    # Define manipulated variable that will accept measurements from the MPC
    mhe.u = mhe.MV(100)
    mhe.u.FSTATUS = 1

    # Define GEKKO equations
    for i in range(len(Lambdas)):
        mhe.Equation(mhe.Cs[i].dt() == mhe.Betas[i]/mhe.l * mhe.P - mhe.Lambdas[i] * mhe.Cs[i])
    mhe.Equation(mhe.P.dt() == (mhe.rho - mhe.Beta) * mhe.P / mhe.l +
```

```
                    (mhe.Lambdas[0] * mhe.Cs[0] + mhe.Lambdas[1] * mhe.Cs[1] + mhe.Lambdas[2] * mhe.Cs[2] +
                     mhe.Lambdas[3] * mhe.Cs[3] + mhe.Lambdas[4] * mhe.Cs[4] + mhe.Lambdas[5] * mhe.Cs[5]))
       mhe.Equation(mhe.Tf.dt() == -mhe.U * mhe.A / (mhe.Mf * mhe.Cpf) * (mhe.Tf - mhe.Tavg) + mhe.J * mhe.P / (mhe.Mf * mhe.Cpf))
       mhe.Equation(mhe.Tavg.dt()  == mhe.U * mhe.A / (mhe.Mc * mhe.Cpc) * (mhe.Tf - mhe.Tavg) - (mhe.mdot / mhe.Mc) * (mhe.Tavg - mhe.Tin))
       mhe.Equation(mhe.rho == mhe.rho_0 + mhe.alpha_f * mhe.Tf + mhe.alpha_c * mhe.Tavg + mhe.b * mhe.u)

       # Set GEKKO options
       mhe.options.IMODE = 5
       mhe.options.NODES = 2
       mhe.options.SOLVER = 3

       ###########################################################################
       # Create MPC GEKKO Model
       mpc = GEKKO(remote=False)

       mpc.time = np.linspace(0,20,21)

       # Create last array for use in MPC objective function
       last = np.zeros(len(mpc.time))
       last[5:] = 1
       mpc.last = mpc.Param(last)

       # Create a set point parameter for use in the objective function
       # that will be updated from within the model loop
       sp = np.ones(len(mpc.time))*165
       mpc.SP = mpc.Param(sp)

       # Create MPC parameters
       mpc.Beta = mpc.Param(Beta)
       mpc.Betas = [mpc.Param(Betas[i]) for i in range(len(Betas))]
       mpc.Lambdas = [mpc.Param(Lambdas[i]) for i in range(len(Lambdas))]
       mpc.rho_0 = mpc.Param(rho_0)
       mpc.b = mpc.Param(b)
       mpc.l = mpc.Param(l)
       mpc.alpha_f = mpc.Param(alpha_f)
       mpc.alpha_c = mpc.Param(alpha_c)
       mpc.A = mpc.Param(6.314e3) # m^2
       mpc.Mf = mpc.Param(122789.605) # kg
       mpc.Cpf = mpc.Param(0.0002999667) # MW * s * kg^-1 * C^-1 at 700 C for UO2
       mpc.J = mpc.Param(38) # MW/%
       mpc.Mc = mpc.Param(1.917e5) # kg
       mpc.mdot = mpc.Param(65.9e6 / 3600) # kg/s, alternative of 800 kg/s
       mpc.Cpc = mpc.Param(0.00571) # MW * s * kg^-1 * C^-1 at @ 298 C for water
       mpc.Cv = mpc.Param(0.0301) # flow coefficient
       mpc.De = mpc.Param(0.01297) # m
       mpc.Kc = mpc.Param(0.00000055) # MW/m*K
       mpc.mu = mpc.Param(0.000068) # Pa*s
       mpc.density = mpc.Param(1000) # kg/m^3
       mpc.resupper = mpc.Param(0.9)
       mpc.reslower = mpc.Param(0.4)
       mpc.HP = mpc.Param(0.0)

       # Create MPC fixed values
       mpc.U = mpc.FV(value = U,lb = 0) # Heat transfer coefficient
       mpc.U.FSTATUS = 1
```

```
        mpc.Tin = mpc.FV(value = Tin) # Inlet temperature (C)

        # Create MPC controlled variable (reactor power)
        mpc.P = mpc.CV(value = 0)

        # Create MPC manipulated variable (control rod position)
        mpc.u = mpc.MV(170)
        mpc.u.UPPER = 200
        mpc.u.LOWER = 50
        mpc.u.STATUS = 0
        mpc.u.DMAX = 50

        # Create other MPC variables
        mpc.Cs = [mpc.Var(Ctot*Lambdas[i]) for i in range(len(Lambdas))]
        mpc.rho = mpc.Var(rho_0) # Reactivity
        mpc.Tavg = mpc.SV(300) # Coolant temp (C)
        mpc.Tf = mpc.SV(320) # Fuel temp (C)

        # Create GEKKO MPC equations
        for i in range(len(Lambdas)):
            mpc.Equation(mpc.Cs[i].dt() == mpc.Betas[i]/mpc.l * mpc.P - mpc.Lambdas[i] * mpc.Cs[i])
        mpc.Equation(mpc.P.dt() == (mpc.rho - mpc.Beta) * mpc.P / mpc.l +
                    (mpc.Lambdas[0] * mpc.Cs[0] + mpc.Lambdas[1] * mpc.Cs[1] + mpc.Lambdas[2] * mpc.Cs[2] +
                     mpc.Lambdas[3] * mpc.Cs[3] + mpc.Lambdas[4] * mpc.Cs[4] + mpc.Lambdas[5] * mpc.Cs[5]))
        mpc.Equation(mpc.Tf.dt() == -mpc.U * mpc.A / (mpc.Mf * mpc.Cpf) * (mpc.Tf - mpc.Tavg) + mpc.J * mpc.P / (mpc.Mf * mpc.Cpf))
        mpc.Equation(mpc.Tavg.dt()  == mpc.U * mpc.A / (mpc.Mc * mpc.Cpc) * (mpc.Tf - mpc.Tavg) - (mpc.mdot / mpc.Mc) * (mpc.Tavg - mpc.Tin))
        mpc.Equation(mpc.rho == mpc.rho_0 + mpc.alpha_f * mpc.Tf + mpc.alpha_c * mpc.Tavg + mpc.b * mpc.u)
        mpc.Equation(mpc.Tf<950.0)
        mpc.Equation(mpc.Tavg<400.0)

        # Set MPC options
        mpc.options.IMODE = 6
        mpc.options.NODES = 2
        mpc.options.SOLVER = 3
        mpc.options.CV_TYPE = 1
        mpc.options.MAX_ITER = 1000

        ##########################################################################
        # Create and run the simulation loop
        #Create storage arrays
        Tfplot = np.zeros(n+1)
        Tavgplot = np.zeros(n+1)
        Pplot = np.zeros(n+1)
        rhoplot = np.zeros(n+1)
        Uplot = np.zeros(n+1)
        time = np.linspace(0,n,n+1)

        P_data = np.ones(n+1)
        Tf_data = np.ones(n+1)
        Tavg_data = np.ones(n+1)
        rho_data = np.zeros(n+1)
        U_data = np.zeros(n+1)
        dRv_data = np.zeros(n+1)
        Rv_data = np.zeros(n+1)
```

```
    HP_data = np.zeros(n+1)
    sp_store = np.zeros(n+1)

    # Set initial values
    P_ss = 0.0
    Tf_ss = 300 # C
    Tavg_ss = 294.1 # C
    Tin_ss = 292 # C
    Rv_data[0] = 0.75 #initial reservoir level

    # initial C values
    C1_ss = Ctot * Lambdas[0]
    C2_ss = Ctot * Lambdas[1]
    C3_ss = Ctot * Lambdas[2]
    C4_ss = Ctot * Lambdas[3]
    C5_ss = Ctot * Lambdas[4]
    C6_ss = Ctot * Lambdas[5]

    x0 = [P_ss, C1_ss, C2_ss, C3_ss, C4_ss, C5_ss, C6_ss, Tf_ss, Tavg_ss]

    # Create a random multiplier for the heat transfer coefficient, U
    mult1 = (0.001*np.random.randn(len(time)))
    mult2 = np.linspace(0.02,0.015,len(time))

    # A parameter relating outlet reservoir flow to power production
    # that is set to almost zero initially but will be increased after
    # control is turned on
    fudge = 0.00001

    # Set up PID controller
    e = np.zeros(n+1)
    ie = np.zeros(n+1)
    P_pid = np.zeros(n+1)
    I_pid = np.zeros(n+1)
    Rvsp = np.zeros(n+1)
    HPadj = np.zeros(n+1)

    Kp = -0.05/75.0
    Kc = 1/Kp
    res_setpoint = 0.5  # Initial set point, can be changed within
                        # the loop, but is only active when control = 1

    control = 0 # Controller switch

    # Run model and control/estimation loop
    print('i\tTavg\tTf\tU')
    for i in range(len(power)):
        # time span for this calculation step
        ts = [time[i],time[i+1]]

        #run the simulation
        mult = mult1[i] + mult2[i]
        y = odeint(reactor,x0,ts,args=(u[i],mult))

        # store results in respective arrays
        P_data[i+1] = y[-1][0]
        Tf_data[i+1] = y[-1][7]
        Tavg_data[i+1] = y[-1][8]
        U_data[i+1] = save.U
        rho_data[i+1] = rho_0 + alpha_f * Tf_data[i+1] + alpha_c * Tavg_data[i+1] +
b * u[i]
```

```

        # Prepare next initial condition
        x0 = [P_data[i+1],y[-1][1],y[-1][2],y[-1][3],y[-1][4],y[-1][5],y[-1][6],Tf_data[i+1],Tavg_data[i+1]]

        # Pass data to MHE model
        mhe.Tavg.MEAS = Tavg_data[i+1]
        mhe.u.MEAS = u[i]

        # Solve the MHE and MPC models in GEKKO
        mhe.solve(disp = False)
        mpc.solve(disp = False)

        # Perform reservoir level calculations
        dRv_data[i] = (mpc.P.VALUE[0] - mpc.SP.VALUE[0])*fudge
        Rv_data[i+1] = Rv_data[i] + (dRv_data[i])

        # Run PID controller if active
        HPadj[i+1] = 0.0
        if control == 1:
            e[i+1] = res_setpoint - Rv_data[i+1]
            P_pid[i+1] = Kc*e[i+1]

            HPadj[i+1] = P_pid[i+1]

            if HPadj[i+1] > 20:
                HPadj[i+1] = 20
            if HPadj[i+1] < -20:
                HPadj[i+1] = -20

        # Store reservoir level and hydropower data
        HP = -(dRv_data[i])*2000
        HP_data[i+1] = HP

        # Prepare hydropower implemenation in objective function, if turned on
        mpc.HP.VALUE = HPadj[i+1]

        # Turn on PID reservoir control at time 80 because it's going to rain soon
        if i == 80*res:
            control = 1
        # Turn off reservoir PID control
        if i == 122*res:
            control = 0.0

        # Add to reservoir to simulate rainfall
        if i > 122*res and i < 140*res:
            Rv_data[i+1] = Rv_data[i+1] + 0.01/res

        # Save U value for plotting and update value in MPC model
        Uplot[i+1] = mhe.U.NEWVAL
        mpc.U.MEAS = Uplot[i+1]

        # Turn on GEKKO MHE at time 25 hrs
        if i > 25*res:
            mhe.Tavg.STATUS = 1
            mhe.U.STATUS = 1

        # Turn on GEKKO MPC at time 35 hrs
        if i > 35*res:
            mpc.P.FSTATUS = 0
            mpc.P.STATUS = 0
```

```
                mpc.u.STATUS = 1

                # Update MV with new value for use in ODEINT and MHE in next cycle
                u[i+1] = mpc.u.NEWVAL

                # Feed the set point into the GEKKO MPC model
                sp_store[i] = mpc.SP.VALUE[-1]
                sp = np.ones(len(mpc.time))*power[i] # power[i] is the current demand=
                mpc.SP.VALUE = sp

                # Update the power to reservoir output relationship now that
                # the MHE and MPC are running
                fudge = 0.0005

                # MPC objective function. It ignores the first 5 values of the
                # power array because there is characteristic spiking that occurs
                # in nuclear systems that makes solving difficult if those values
                # are included.
                mpc.Obj((mpc.P*mpc.last-(mpc.SP - mpc.HP))**2)

            # Print some relevant information every 5 time steps
            if i%5 == 0:
                print(i,'\t',round(Tavg_data[i],1),'\t',round(Tf_data[i],1),'\t',round(U_data[i],5),'\t',round(mpc.P.VALUE[0],2))

            # Plot the data, update the plots every 10 time steps
            if i%10 == 0:
                plt.figure(1)
                plt.clf()

                plt.subplot(4,1,1)
                plt.plot(time[1:i]/res,Tf_data[1:i],'b--',label='Tf ODE')
                plt.plot(time[1:i]/res,Tavg_data[1:i],'g--',label='Tavg ODE')
                plt.ylabel('Temp (C)')
                plt.legend()

                plt.subplot(4,1,2)
                plt.plot(time[1:i]/res,u[1:i],'r--',label='Control Rod Step')
                plt.ylabel('Steps')
                plt.legend()

                plt.subplot(4,1,3)
                plt.plot(time[1:i]/res,rho_data[1:i],'r--',label='Reactivity ODE')
                plt.ylabel('Reactivity')
                plt.legend()

                plt.subplot(4,1,4)
                plt.plot(time[1:i]/res,Uplot[1:i],'-',label='MHE')
                plt.plot(time[1:i]/res,U_data[1:i],'.',label='Actual')
                plt.legend()
                plt.ylabel('U (MW/m^2/K')
                plt.xlabel('Time (hr)')
                plt.pause(0.000001)

                plt.figure(2)
                plt.clf()
                plt.subplot(2,1,1)
                plt.plot(time[1:i]/res,P_data[1:i],'r--',label='Nuclear Supply')
                plt.plot((time[1:i])/res,power[1:i],'c--',label='Nuclear Demand')
                plt.plot((time[1:i])/res,solar_power[1:i],'y--',label='Solar Supply')
                plt.plot((time[1:i])/res,wind_power[1:i],'g--',label='Wind Supply')
```

```
                plt.plot((time[1:i])/res,HP_data[1:i],'b--',label='Hydro Supply')
                plt.plot((time[1:i])/res,tot_power[1:i],'k--',label='Total Demand')
                plt.ylabel('Power')
                plt.legend()

                plt.subplot(2,1,2)
                plt.plot(time[1:i]/res,Rv_data[1:i],'b--',label='Reservoir Level')
                plt.legend()
                plt.ylabel('% Full')
                plt.xlabel('Time (hr)')
                plt.ylim(0,1)
                plt.pause(0.000001)

        ##########################################################################
        # Store the data in an excel file
        dictionary = {'time': time[1:]/res,
                      'fuel temp': Tf_data[1:],
                      'water temp': Tavg_data[1:],
                      'control rods': u[1:],
                      'rho': rho_data[1:],
                      'U MHE': Uplot[1:],
                      'U actual': U_data[1:],
                      'nuclear supply': P_data[1:],
                      'nuclear demand': power,
                      'solar supply': solar_power,
                      'wind supply': wind_power,
                      'hydro supply': HP_data[1:],
                      'total demand': tot_power,
                      'reservoir fill': Rv_data[1:]}

        df = pd.DataFrame.from_dict(dictionary)

        df.to_excel('DOFinalData.xlsx')
```