Control of Cogeneration in Small Modular Reactors to Enable Load Following

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Abstract

This study explores cogeneration control in Small Modular Reactors (SMRs) to enable load following within microgrids. This project investigates whether SMRs, traditionally used as baseload generators, can adapt to fluctuating demands using steam extraction and bypass valves. A dynamic model simulates a 50 MWe NuScale SMR, evaluating Proportional-Integral (PI) and Model Predictive Control (MPC) methods. Results suggest that MPC significantly outperforms PI control, adeptly balancing load demands while minimizing steam waste. This offers a promising avenue for integrating SMRs into renewable-heavy microgrids, potentially reducing reliance on auxiliary Distributed Energy Resources (DERs).

1. Introduction

Small Modular Reactors (SMRs) and microreactors are a class of nuclear reactors that have been gaining notable traction in the last decade. Distinct from traditional, large nuclear reactors, SMRs typically have capacities under 300 MWe, while microreactors are even more compact, relatively speaking with a range under 15MWe. SMRs are betting that smaller upfront costs and eventual buy- in from a larger range of communities will compensate for their smaller generative capacities.

As the grid becomes more saturated with renewable resources, flexibility of the resources participating in the grid becomes increasingly important. This is especially true within microgrid contexts where the inherent unpredictability of wind and solar, paired with the smaller total capacity, require additional resources such as batteries, grid management and even fossil fuel power plants to cope with the slack left in the grid.

Traditional Nuclear Power Plants (NPPs) operate as baseload resources and do not often deviate their power output in accordance to the grid's load demand for a variety of reasons. For one, it is quite inefficient to fluctuate a nuclear reactor's power output and doing so is also expensive in terms of maintenance costs. Directly adjusting reactor power levels is quite slow and would not be applicable to the fine tuned adjustments load following requires. And most importantly, NPPs are highly capital intensive, but enjoy low operating costs compared to gas-fired plants. Consequently the economic incentive to load follow is not the same as with other power generating assets.

Even with increased renewable capacity like solar and wind there remains a demand for a generative resource that is carbon-neutral, reliable and flexible, especially in microgrid contexts where variability is heightened.

One solution is to utilize SMRs paired with cogenerative capabilities. In this scenario, cogeneration would shave off a portion of the reactor's thermal output, in the form of steam, away from the plant's turbine system. Such a process would be flexible, able to change the proportion of extracted thermal energy in a highly dynamic way. The result would be a SMR whose turbine is able to match the desired demand of the grid by directing the unused energy to another economically valuable industrial process. The additional "product" generated can range from desalination to hydrogen production to simply district heating services, which further broadens the contexts in which such a system could function. In this formulation, the lost efficiency required to load follow, is made up in part by the generation of another economically valuable product.

2. Problem Statement

This project seeks to build a model of a cogenerative process attached to a fully powered SMR that can be manipulated by the use of a steam bypass valve and steam extraction valve to achieve load following as well as provide thermal energy to an exterior industrial process. With such a model two control methods have been developed, a traditional proportional-integral (PI) controller and a Model Predictive Controller (MPC). Both will be evaluated under different operating scenarios.

Fundamentally this project seeks to answer these main questions:

- Keeping the reactor at full power, is it possible to load follow satisfactorily, solely with the use of a steam extraction and steam bypass valves located in the turbine system of an SMR?
- Can a MPC framework improve the load following capabilities of a nuclear cogeneration plant given operating constraints as opposed to simple PID control?
- Is the load following precise enough to potentially significantly reduce the need for auxiliary distributed energy resources (DERs) such as battery storage within a microgrid?

3. Literature Review

Michaelson and Jiang in [4] survey the current state of research on how SMRs can play integral roles in microgrids and remote off-grid applications. In these scenarios, load following is imperative and they argue flexible SMR control could offset or even eliminate "large amount(s) of storage" and other traditional dispatchable resources such as diesel generators. Especially within the context of completely isolated remote grids, such as in Canada or Alaska, very small SMRs (microreactors) could eliminate the need for fossil fuel powered auxiliary resources, another motivation for this project

Furthermore they identify the cogeneration process as an "alternative to adjusting the SMR power level" in order "to keep the reactor at full power and redirect a portion of its thermal output to another downstream process". The authors note, "taking this approach can lead to faster return on investment than nuclear-electricity-only applications". Michaelson and Jiang identify three main motivations to enable an SMR with cogenerative capabilities: reduce reliance on dispatchable diesel generators, minimize the size of energy storage required and increase the economic viability of the project. These motivations will be referenced throughout this project.

As Michaelson and Jiang also note, much effort has gone into the modeling efforts of the entire SMR system, particularly the Nuscale design. Owing to the breadth of available resources and data, this project will also be based on the specifications of a Nuscale SMR.

Ma et al's [3] problem is similar to this project's wherein, "the demand for load following arises" in the contexts of microgrids, but the use of control rods is "inherently inefficient... therefore, reducing the power output does not significantly reduce the operating expenses". Subsequently the authors focus on the control of the cogeneration of a nuclear power plant to enable load following. The authors simplify the overall model into the core model, once-through steam generator (OTSG), the turbine and the flexible load. A key takeaway from is the power generated by the plant is simply a function of the steam mass flow rate of the turbine which will be a key assumption in the model used in this project. It is also important to note Ma et al.'s show the actual power output of the reactor core is unaffected by the use of differing valves to alter the relative steam mass flow rates through differing portion of the turbine system. This conclusion justifies disregarding the reactor and steam generation systems in this project's model.

In terms of the modeling and PID control of a nuclear cogeneration facility the papers, [7],[6] and [5] were highly influential. To begin, [7] is helpful in its conception of the turbine system as simply a modification of the standardized GGOV1 turbine-governor model that incorporates a steam bypass valve before the turbine. Although this project will seek a control that differs from the governor model used, the standard specifications of a turbine in GGOV1 model will be used as well as the modifications imposed by a steam bypass valve before the entire turbine system.

[6] expands on their earlier work by including a "steam extraction valve" between the High Pressure and Low Pressure turbines, used to supply a District Heating network. Poudel et al. are able to demonstrate their model can use the control inputs of the steam bypass and extraction valves to load follow in a microgrid setting that includes PV, wind and battery storage resources. Importantly the control of the two valves were independent of one another. The steam bypass valve was set to reference the reactor's coolant temperature, while the steam extraction valve was manipulated by the turbine governor.

[5] introduces a turbine valve operation rate limit of $\pm 60\%$ of Rated Electrical Output (REO) per min which is utilized as a constraint in this projects MPC. They find their design can support up to 50% of generation originating from renewables. However, and this is obvious, the higher the percentage of renewable penetration, the higher the percentage of steam heat wasted by the SMR. This project expects to also see a similar trend where higher load following capabilities results in more steam energy waste. Then the question becomes, how can steam waste and load following be balanced?

Finally, in [8], Wang et al. directly compares traditional PID to MPC to control the reactor power of a traditional Pressurized Water Reactor (PWR) under low-load scenarios. The authors show that PID methods fail to stabilize to differing power levels when the reactor is operating near the bottom of its rated capacity. Meanwhile, an MPC method was able to satisfactorily track the trajectory. It should be noted the power output was completely controlled by the manipulation of the reactor's control rods. As noted, this project starts with the assumption that operating control rods is a suboptimal solution to the question of load following. Furthermore this paper does not consider the change rate limits imposed on control rod manipulation due to maintenance and regulatory considerations.

Regardless the MPC method generated by this project should be evaluated at low levels of REO and should be compared to the performance of the alternative PID approach.

4. Dynamic Model

The model developed focuses on the turbine and steam extraction system powered by a 50 MWe Nuscale SMR. The equations used to build the state space system are as follows.

$$\dot{m}_{HP} = \dot{m}_{nsss} - \dot{m}_{bv} \tag{1}$$

$$\dot{m}_{RH} = \dot{m}_{HP} - \dot{m}_{ev} \tag{2}$$

$$\dot{m}_{LP} = \dot{m}_{RH} \tag{3}$$

$$P_{mech} = \eta_T(\Delta H_{HP}\dot{m}_{HP} + \Delta H_{LP}\dot{m}_{LP}) \tag{4}$$

where $\dot{m}_{nsss}$ and η_T, which represent the steam mass flow rate from the nuclear steam supply system (NSSS) and the turbine efficiency rate respectively, are considered constants. Furthermore, ΔH, the specific enthalpy difference between in the inlet and outlet of the HP and LP turbines can be ignored.

These equations, along with the transfer functions given in [2], give rise to the state space system:

$$\dot{x}(t) = Ax(t) + Bu(t),$$
$$y(t) = Cx(t),$$

where

$$A = \begin{bmatrix} -\frac{1}{T_{HP}} & 0 & 0 \\ \frac{1}{T_{RH}} & -\frac{1}{T_{RH}} & 0 \\ 0 & \frac{1}{T_{LP}} & -\frac{1}{T_{LP}} \end{bmatrix}, \quad B = \begin{bmatrix} -\frac{1}{T_{HP}} & 0 \\ 0 & -\frac{1}{T_{RH}} \\ 0 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} F_{HP} * \eta_T & 0 & F_{LP} * \eta_T \end{bmatrix}.$$

Furthermore the following parameters are used:

Table 1: System Design Parameters

Component	Parameter
SMR	REO $= 50\,\mathrm{MWe}$
NSSS	$\dot{m}_{\mathrm{nsss}} = 65.93\,\mathrm{kg/s}$
Turbine	$\eta = 0.758$
HP Fraction	$F_{\mathrm{HP}} = 0.3$
LP Fraction	$F_{\mathrm{LP}} = 0.7$
Bypass Valve	$\dot{m}_{\mathrm{bv}}^{\mathrm{max}} = 65.93\,\mathrm{kg/s}$
	$\dot{m}_{\mathrm{bv}}^{\mathrm{min}} = 0\,\mathrm{kg/s}$
Extraction Valve	$\dot{m}_{\mathrm{ev}}^{\mathrm{max}} = 65.93\,\mathrm{kg/s}$
	$\dot{m}_{\mathrm{ev}}^{\mathrm{min}} = 0\,\mathrm{kg/s}$
Ramping Constraints	$R\dot{E}O_{\mathrm{min}}^{\mathrm{max}} = \pm 60\,\%/\mathrm{min}$

This state space equation models the total power output of the turbine system where $\vec{x}$ contains the steam mass flow rates of the HP turbine, the reheater and the LP turbine.

Furthermore the control input, $\vec{u}$ specifies the steam mass flow rate designated to be released through the steam bypass valve and steam extraction valves respectively. 1 is a graphical representation of the model developed.

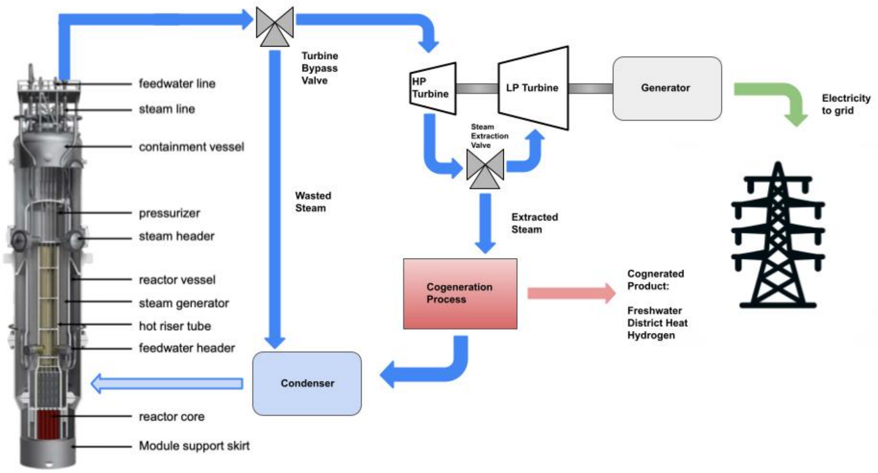
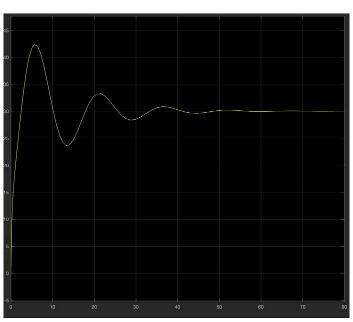


Figure 1: Model of Turbine and Steam Extraction System

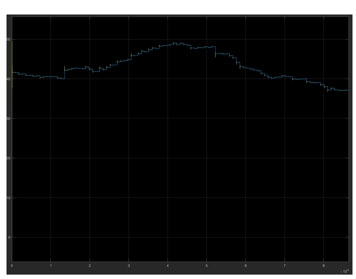
5. PID and MPC Control

5.1 Steam Extraction PI Control

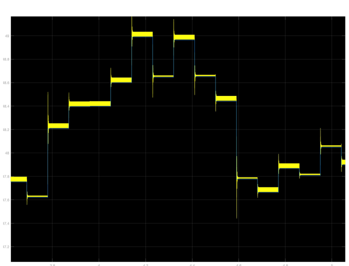
First a PI controller was used to control the steam extraction valve in a way similar to [6]. $K_p = -1.322$ and $K_i = -2.581$ were found to be the best tuned parameters for this model. Note, only the steam extraction valve was controlled and the steam bypass valve was assumed to be fully open. As this project assumes the coolant temperature is stable along with the total reactor power, and because competing PID controllers on the bypass and extraction valves would be ineffectual, just the extraction valve is controlled.



(a) Setting Output to 30MWe



(b) Typical Demand with PI Control



(c) Typical Demand Zoomed

Figure 2: PID control of the Steam Extraction Valve.

2a Shows the reaction of the turbine system when the reference signal is set to 30 MWe. 2b details the systems response to following a typical load demand curve over a 24 hour time period. 6b is an enlarged look at 2b. The block like structure of the reference signal is due to demand changes being updated every 15 minutes, while the simulation is run at a one second time interval. As is apparent, the system struggles to stabilize satisfactorily at each new level of demand (the yellow is the oscillations caused by the PI control). It comes as no suprise that PI control of the steam extraction valve alone, is unable to provide fine enough control over the entire system.

5.2 Steam Bypass and Extraction MPC Control

MPC is a method that solves an optimization problem over a finite time horizon (H), seeking the optimal sequence of controls ($u_0, u_1 ... u_H$) that maximize the expected value of a reward function $R_t()$. This formulation is given by [1].

$$\begin{aligned} \text{maximize}_{u_t} \quad & E_{w_t}\left[\sum_{t=0}^{H} R_t(X_t, u_t)\right] \\ \text{subject to} \quad & X_{t+1} = f_t(X_t, u_t, W_t) \\ & (X_0 = x). \end{aligned}$$

The control action is then set to the *newest* u_0 and the optimization problem is repeated with updated information regarding the new state of the system and the effect of the previous control action.

MPC is highly useful, because the reward function can be configured to accompany certain requirements PID control alone can not meet. For one, in this situation the optimal control input at each step will include the input to the steam extraction and steam bypass valves. Furthermore it is possible to configure an MPC to penalize the use of the bypass valve as compared to the extraction valve. This weighting reflects the desire to use the steam extraction valve more and not purely waste steam through the bypass if not entirely necessary. Finally, the controller can also be tuned to respect the physical limitations of the valves themselves. Both control inputs will be limited to $[0, 65.93]$ and will also be limited to changing $[-.6593, .6593]$ per second. This second requirement reflects that the valves are unable to change their output by more than 60% per minute.

Using `mpc` in MATLAB, the following controller was built.

```
                          Ts: 1
     PredictionHorizon (P): 20
        ControlHorizon (C): 3
                     Model: [1x1 struct]
ManipulatedVariables (MV): [1x2 struct]
    OutputVariables (OV): [1x1 struct]
DisturbanceVariables (DV): [1x1 struct]
               Weights (W): [1x1 struct]
                 Optimizer: [1x1 struct]
```

`mpc` solves a QP at each interval, based on the constraints and weighting mentioned above, to generate the control outputs for both valves. The optimization problem is as follows:

$$J(z_k) = J_y(z_k) + J_u(z_k) + J_{\Delta u}(z_k) + J_{\varepsilon}(z_k). \tag{5}$$

where z_k is the QP decison.

5.2.1 Typical Load Demand

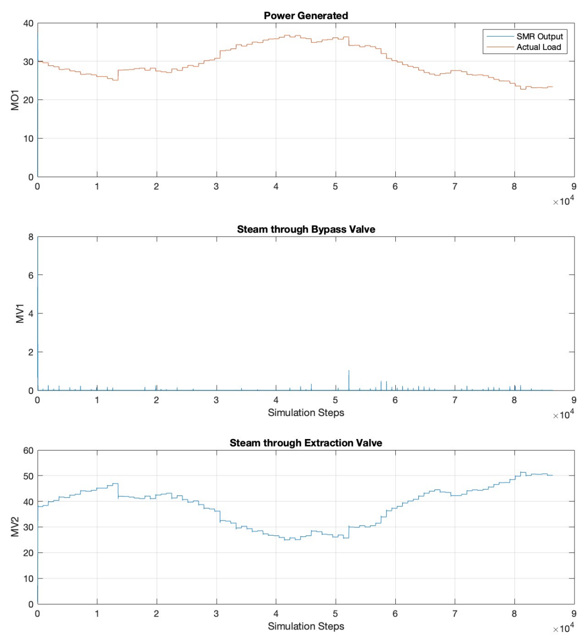
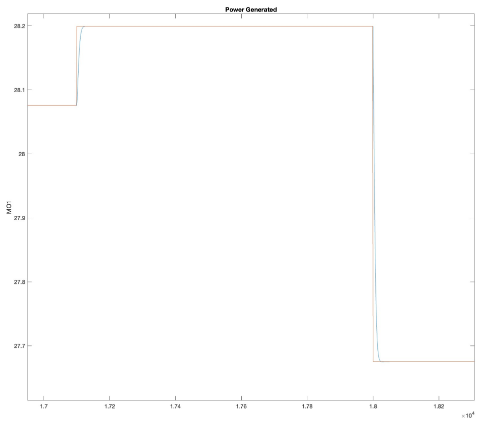
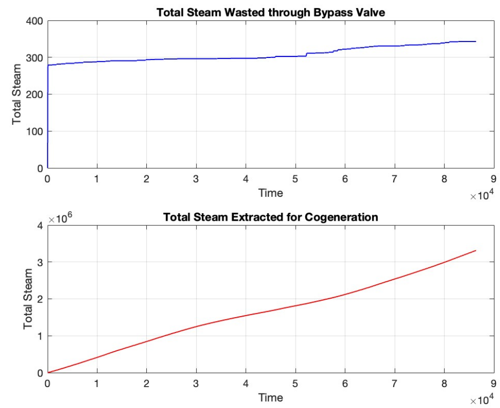


Figure 3: MPC used to track typical load demand

3 details the system output mapped over the original reference signal, the control inputs executed by the steam bypass valve and the steam extraction valve. As the demand never reaches 50MWe or above, the two valves are able, with MPC, to completely track the demand trajectory. Owing to the tuning of the controller, the steam extraction valve is used more heavily compared to the bypass valve. The bypass valve tends to provide short bursts of relief when the system needs to downgrade its output rapidly. 4a is a zoomed in look at the output (blue) and the demand (orange). The system tracks the demand easily. One can imagine the control would only be more accurate with finer grain reference data to reduce the extreme step like structure. 4b Details the total steam extracted through the two valves which is used as a proxy to estimate the total energy released. In this case, the steam extraction valve is able to extract over 10,000 times more steam than the bypass valve. This represents less than .01% of the total steam produced being ”wasted”. This is good confirmation the extreme penalty given to using the steam bypass valve is working.



(a) Control output and Demand Zoomed



(b) Total Steam Extracted

Figure 4: Total Steam Removed through each valve

5.2.2 Extreme Duck Curve Case

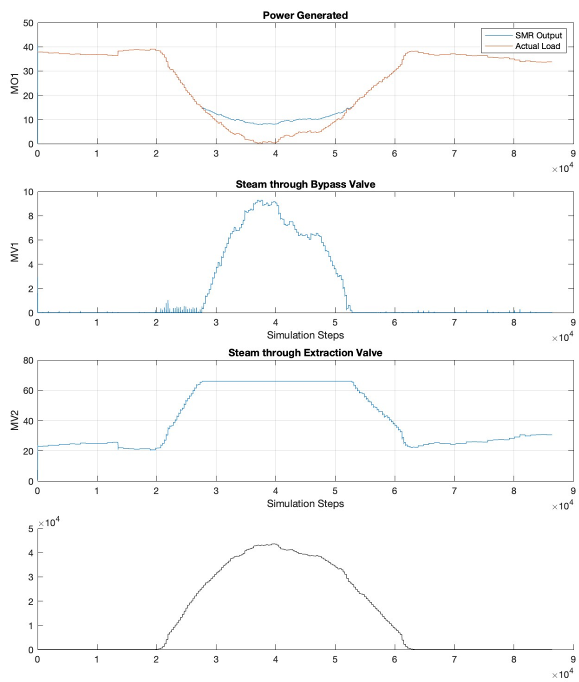
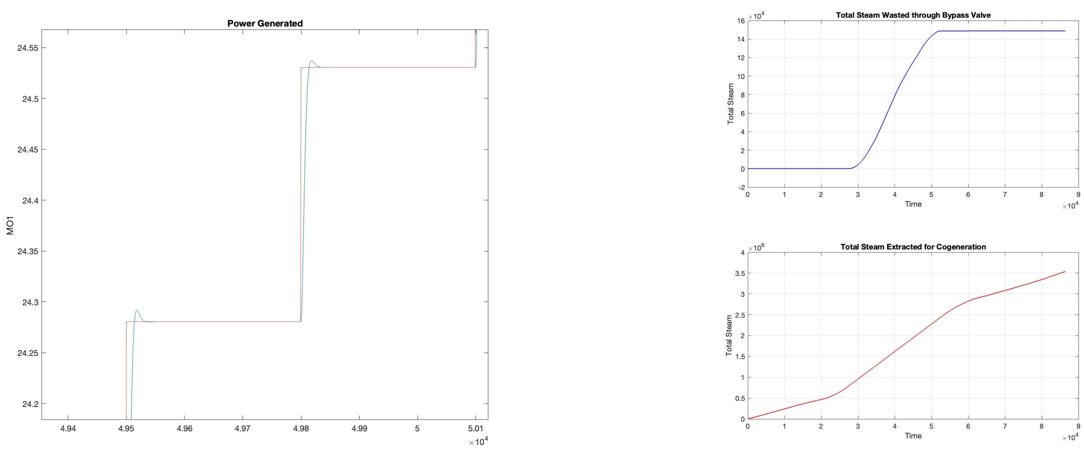


Figure 5: MPC used to track extreme duck curve demand

Here the typical load demand used before is paired with a large PV installation that is able to completely power the grid at its peak production at midday. The result is about the most extreme "duck curve" this microgrid could encounter.

The controller is able to to track the demand well but completely fails to reduce the turbines output to near zero at midday. Theoretically, if the steam bypass valve is operated at 100% capacity, the turbine output would be zero. However, as this control input is so severely penalized for being used, the MPC concludes a high error between output and the reference signal is more desirable than using the full strength of the bypass valve. During this time, the steam extraction valve is fully maxed out, removing all of the steam after the HP turbine.



(a) Control output and Demand Zoomed

(b) Total Steam Extracted

Figure 6: Total Steam Removed through each valve

Despite the fact that the controller fails to meet the bottom trough of the reference signal, the system is able to accurately track the large ramping of power needed at the end of the day. In this case, the controllers ability to match the extreme ramp rate of the duck curve far outweighs its failure to entirely cut power.

5.3 Discussion of Results

The use of a tuned MPC was highly effective compared to a singular PI control on the steam extraction valve. In how this project presents the problem, the turbine and extraction system is highly simplified (only three states are tracked) and the model is completely known, consequently a MPC may be an over engineered solution.

Yet I think MPC as a method shows obvious signs of promise in this problem domain, considering the potential subsystems that could be added to the model (actual reactor dynamics, steam generation dynamics). Furthermore the flexibility of the reward function MPC ultimatly seeks to maximize, lends itself nicely to further constraints on the system that would be certainly added by whatever "cogeneration" process would be configured to run off extracted steam. In this scenario, many questions come up, is there a certain level of steam needed by such a process? How would variations in steam temperature come into play? Is there a limit to the production of the second generation product?

Another distinct question prompted by this project, would be, what size of reactor, relative to the overall micro-grid size and renewable energy resources would be needed/optimal. The "extreme duck curve" scenario certainly suggests that even if you have renewables able to completely power the grid at a given point during their best days, the output of the SMR would still have to match the total demand of the grid when the sun turns off. [5] suggests a similar conclusion, where at most " 50% RES penetration level is optimum for the proposed hybrid energy system". In Poudel's system, the demand was at most 80MWe, while the system was powered by two 50MWe SMRs, one 30 MW wind plant, two 10 MWe solar installations and battery storage assets. From a purely practical standpoint, it would seem to reason that if a SMR is built with a capacity big enough for the entire microgrid, there would be much inefficiency by building additional renewable assets that would require additional cogeneration capacity. However, it seems that such a statement is a vast over simplification, and that such a problem could have meaningful solutions.

What would it mean that in a hybrid microgrid, an SMR could be smaller than the total demand? What are the economic implications? Would there be even more motivation to develop smaller SMR's verging on microreactors?

MPC was clearly able to balance demand and generation accurate enough. Of course much work would still need to be done on the the frequency response of the grid.

Finally, the MPC developed is completely reliant on an accurate estimation of the demand levels into the future. In this project, the demand curve was assumed to be perfectly known. And as a small prediction horizon (20s) compared to the total simulation length (24 hours) was found to be just as effective as larger horizons, it seems that total demand would be reasonably known at least 20 seconds into the future. However, I think future work that considers the stochastic nature of load demand prediction would be useful in the context of this MPC.

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