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# Carbon Capture Storage Implemented On Flexible Power Plants And Their Grid Impacts

Michael Kenneth Misch

# CARBON CAPTURE STORAGE IMPLEMENTED ON FLEXIBLE POWER PLANTS AND THEIR GRID IMPACTS

by

Michael Kenneth Misch
Bachelor of Science – Electrical Engineering, University of Nevada Las Vegas, 2013
Master of Science in Engineering – Electrical Engineering, University of Nevada Las Vegas, 2017
Master of Science – Management and Leadership, Western Governors University, 2019

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This dissertation, submitted by Michael Misch in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Energy Engineering from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Dr. Hossein Salehfar
Chair/Advisor

Dr. Olusegun Stanley Tomomewo
Co-Chair/Co-Advisor

Dr. Saeed Assadi
Committee Member

Dr. Marylesa Howard
Committee Member

Dr. Brent Mchale
Committee Member

This dissertation is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Chris Nelson

Dean of the School of Graduate Studies

Date

PERMISSION

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|---|---|
| Title | Carbon Capture Storage Implemented on Flexible Power Plants and Their Grid Impacts |
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Michael Misch
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Dedication

*To Pratyusha Panchangam and keeping things honest.*

# Abstract

The energy grid is under a constant state of evolution from outside factors such as the rise of renewable energy in the form of solar and wind generation as well as competing with the changes in weather patterns from climate change leading to significant storms like the arctic event of 2022. Thermal power plants are greatly impacted by these changes. As a significant contributor of $CO_2$ emissions, thermal power plants play an important role in emerging green technology policies to help the efforts of climate change. There is a significant cost associated with this change, however, as thermal plants are some of the cheapest to implement and have provided baseline power supply for decades for both first world countries and especially those still under development.

An emerging technology that can bridge the gap between these two ideologies is carbon capture systems, which take the emissions normally emitted to the environment and allow them to be captured for storage later. Carbon Capture Storage (CCS) is not without its tradeoffs though. There is a significant change, of about 15%, in the power generation capability of the plant it is installed on, which can have drastic impacts on a grid already impacted by so many other changes. To combat these difficulties, flexible variations of thermal plants are being brought forth, but the capabilities of these options compared to the traditional is notional.

This study used a simulation-based approach to quantify these impacts. The simulations evaluated traditional thermal plants, their flexible counterparts, renewable energy hosting, and the capabilities of both in regard to carbon capture installations. Using results from the developed model, the benefits of pairing flexible plants with dynamic CCS units show that additional renewable energy and load can be hosted, as well as show the limitations that those parameters exhibited.

# Chapter 1

## 1.1 Introduction

This work will be separated into several sections that start out at a high level and gradually adjust to more granularity as time goes on. Chapter 1 will be an introduction to the broad idea of Carbon Capture Storage (CCS) but also the energy market evolution and the environmental concerns related to it. Chapter 2 will go further into detail about the technology and the surrounding influences that will help to dictate its use. Chapter 3 will begin to define the methodology to answer the important questions that remain. Chapter 4 will discuss the limitations of the study. The model introduced in this work is bound by the limitations and how they can be modified by others to help the work's impact spread. Chapter 5 will provide details about the results from the model developed here, while Chapter 6 will expand on those results to give insights into them. Chapter 7 will conclude the work's purpose, while Chapter 8 will give ideas for the next steps that others can take to improve on the work done here.

## 1.2 The Evolving Energy Market

The energy grid of the world runs on an amalgamation of different technologies and is evolving with the times to adapt to the changing landscape of energy policy and electrical demand. Along with this variety of technologies comes the growing pains of adapting to one another, as well as the difficulty of differing opinions and ideals towards the common goal of delivering power to those in need. Ultimately the necessity is that the grid's energy needs are met, but the way to meet that demand is quickly becoming convoluted and more difficult when you must also account for energy security, economic concerns, and environmental impacts.

CCS is a critical technology that is still in its relative infancy. Most of the world's power base remains to be that of coal due to the availability of the resource, the technological cost, and the ease of use. While other technologies are evolving and lowering prices, a significant portion of the world will remain tied to coal power for decades to come. It is important to remember that CCS can be used on both gas and coal power plants, but, given their proliferation in the world at large, coal quickly becomes the focus of these talks. This is best echoed in a report from the UN where they state that "Trapping and storing carbon dioxide ($CO_2$) emissions from fossil power generation and industry is needed urgently to achieve carbon neutrality" (United Nations, 2021). Coal remains one of the world's cheapest resources to capitalize on through its abundance and technological maturity. While advanced nations are working to wean themselves off the technology, it is not so easy for those that are still up and coming, as Kemp argues in his report that details the basic need many developing economies use coal for: "Coal, which is being phased out of the power system in many industrialized nations, is still a vital fuel for generation in many developing economies and may remain so for decades to come." (Kemp, 2021).

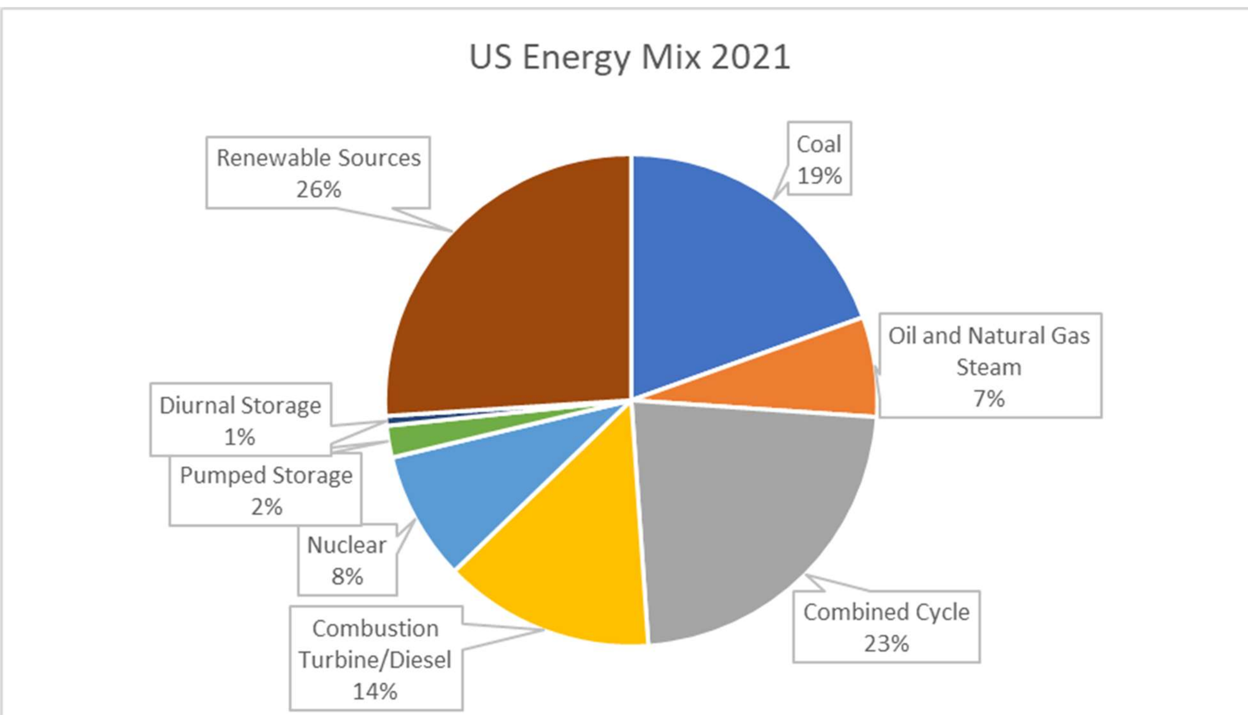


*Figure 1 USA energy mix 2021 from the Energy Information Administration (EIA) (EIA, 2022)*

None of this is to say it isn't a problem in our backyard of the USA, either. From Figure 1, the US uses coal to meet almost 20% of its energy needs. The dependence on that 20% cannot be adapted overnight, nor can it be shut down immediately, even if replaced with equivalent amounts of renewable energy. Again, while there is a focus on coal, other resources in the graph can also be adapted with CCS, such as the gas or combined cycle plants, leaving the door wide open for a large portion of the thermal fleet as possible candidates. This will not change in the near future either, and with the adoption of CCS it may not need to.

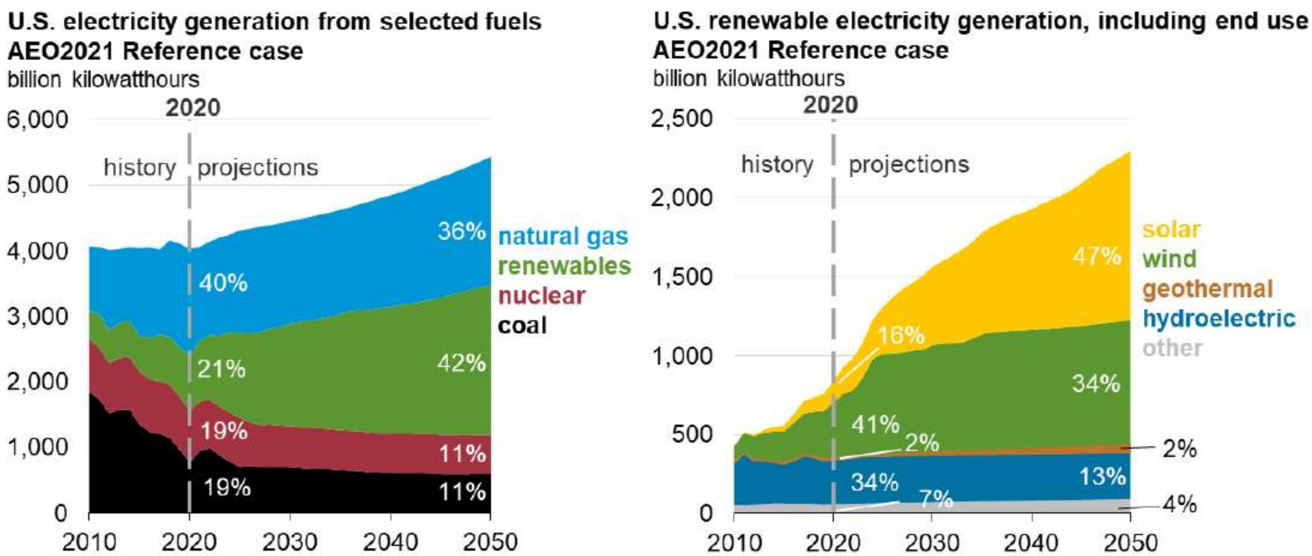


*Figure 2 An additional graph from the EIA showing their projections for expected energy resources in the coming years (Energy Information Administration, 2022)*

The US alone is expected to gradually wean itself off coal over time but never fully remove it. At the same time natural gas is expected to remain a large player. The variability of renewables is a major contributing factor in the future of our grid and certainly renewables are a key to the solution, but they cannot act alone. An article from MIT views thermal power plants as an opportunity to adapt *what* our grid is currently comprised of into *what is needed* by working on gradually evolving the fleet into a more flexible resource. They state that “these units will be required to provide flexibility in a power system where large-scale penetration of intermittent renewables is mandated in the absence of large-scale storage” (MIT energy initiative symposium, 2011). That is, if they can survive long enough to be adapted.

Chicago is looking to move towards a greener generation platform and has decided to shut down their coal power plants in 2022 (Chase, 2021) stemming from ongoing debates about air pollution in the community. There is a very real human component to this event, with over 100 workers suddenly finding themselves without work. Focusing more on generation, however, we can say that prior to this event these plants were expected to be phased out in 2035. There are hopes to convert the site to renewable energy generators, but in the meantime, that area of the US grid will suddenly find itself short of over 2GWs of thermal generation it had been historically using.

While this is a broad overview, there is an opportunity to flesh out the problem in its various aspects.

### 1.2.1 The Focus of Concern

Climate change is the long-term trends impacting the global weather patterns and temperatures. It can be caused by several natural processes and events, but, according to a report by the Intergovernmental Panel on Climate Change (IPCC), human activities are significantly driving climate change for the last couple of centuries (IPCC, 2021). The IPCC is not alone in its proclamation. A quick search finds many others have come to the same conclusion in that human activity has been the primary driver in relatively recent years (European Commission, 2023) (Herring, 2020) (Wuebbles, et al., 2017) and (Union of Concerned Scientists, 2009).

Furthermore, most of the studies all come to the same conclusion on what major contributing factors are leading these changes. The graphic in Figure 3 helps illustrate the point quickly.


*Figure 3 The infographic above helps to quickly summarize the major known contributors to climate change. GHGs are Green House Gases. (Delaware, 2023)*

While there are many contributing factors, and many of them are interrelated, most of the issue comes down to the emission and release of what are known as GHGs (greenhouse gases). Some of the activities above are producers of GHGs, such as the transportation sector and electricity sector. Others may inhibit the ability to reduce their existence in the first place. While a form of agricultural work produces GHGs, it also reduces GHGs at times through natural methods of breaking down GHGs in forested regions.

This may be a bit confusing, but it is helped by answering the question: what are GHG's?

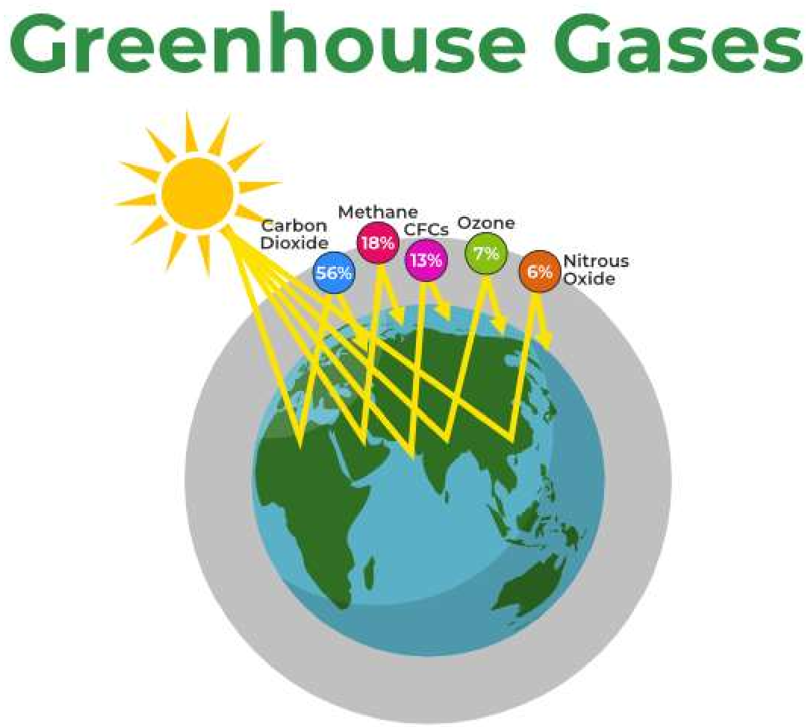


*Figure 4 Similar to the last figure, this once again shows the capturing of solar radiation by GHGs around the earth. (Sharma, 2023)*

GHG's are a conglomeration of many naturally occurring gases such as carbon dioxide, methane, nitrous oxide, ozone, and others. These gases create an insulating layer around the globe, helping retain the sun's heat as seen in Figure 4. This is where the name comes from. Picture a greenhouse that is in the sun, – the glass panels allow the heat in with their transparency but trap that heat causing the interior to quickly outpace the exterior's temperature. While this is natural and, in many ways, a good thing, the problem is that humans are beginning to throw this natural process out of balance.

The increase in agricultural operations has cleared forested regions, reducing the earth's natural process to eliminating GHG's, while at the same time increasing methane-producing byproducts. Since the industrial age, the burning of fossil fuels has continued releasing greater amounts of GHG's into the atmosphere. The construction industry similarly emits a great amount of them in the creation of steel, concrete, and aluminum (architecture2030, 2023).

Of these gases, $CO_2$ is the worst, despite trapping less heat than others simply due to its abundance. Recent work found that $CO_2$ makes up to 82% of all GHG emissions (Center for Science Education, 2023). This amount has outpaced anything in history, as some researchers have found that humans have increased the amount of $CO_2$ in the atmosphere by 50% since the industrial revolution began in the 18$^{th}$ century (NASA, 2023).

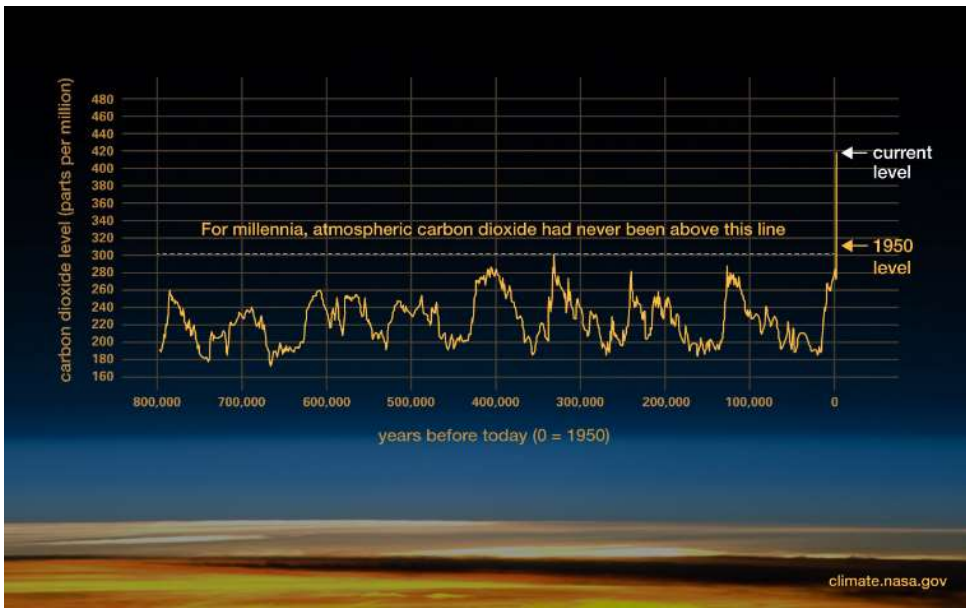


*Figure 5 The pace at which we have begun emitting $CO_2$ in the atmosphere far exceeds historically known values. (Luthi, 2010)*

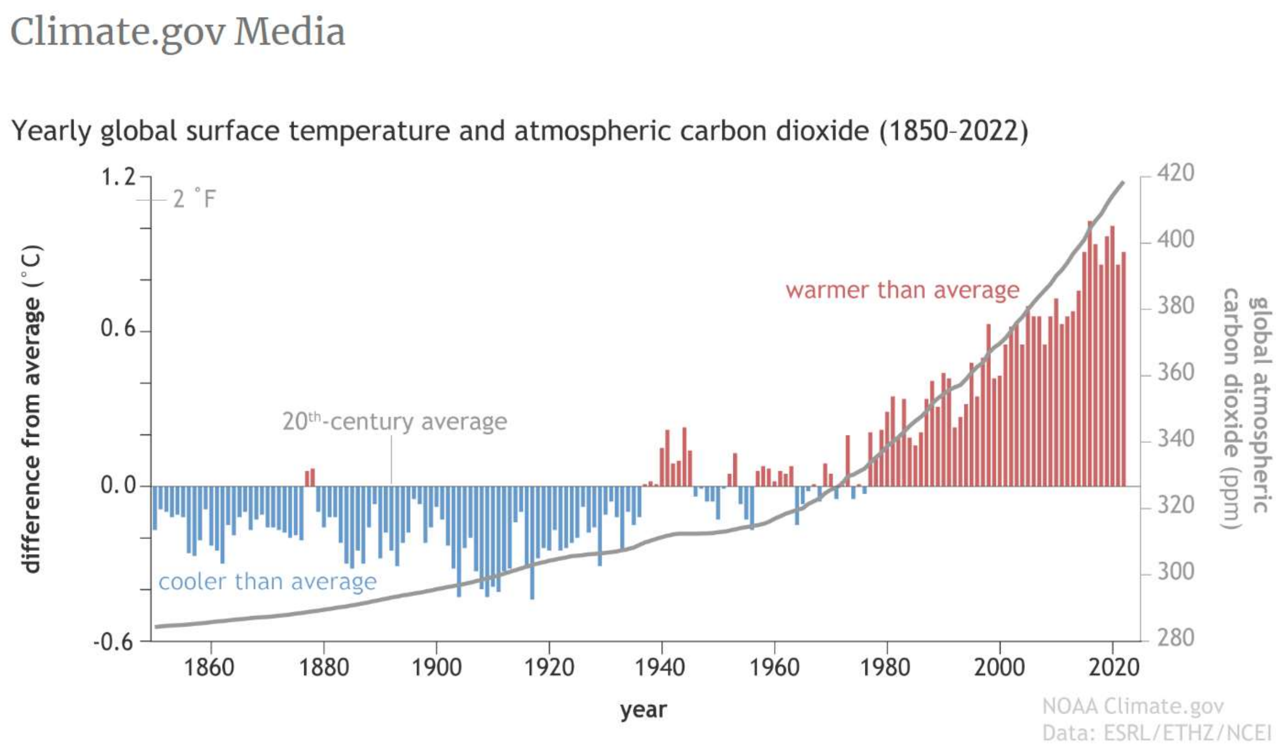


*Figure 6 This figure shows the rise in $CO_2$ along with the rise in average temperature over time. (Lindsey, If carbon dioxide hits a new high every year, why isn't every year hotter than the last?, 2023)*

So again, over the last few hundred of years, we have been gradually adding a very large amount of $CO_2$ into the atmosphere by industrial processes as shown in Figure 5 and Figure 6. The next question would likely be: what are those processes? Figure 7 and Figure 8 help to illustrate that it is coming from several sources such as electricity, transportation, industrial applications, and agriculture.

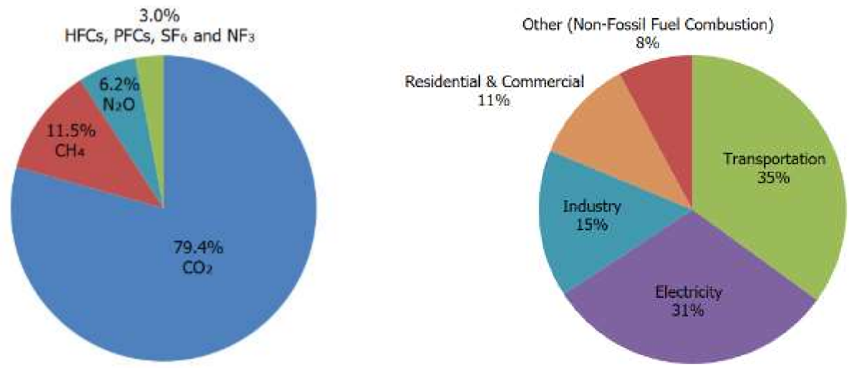


*Figure 7 Total estimated US emissions in 2021 and the associated generators by sector for $CO_2$. (EPA, 2023)*

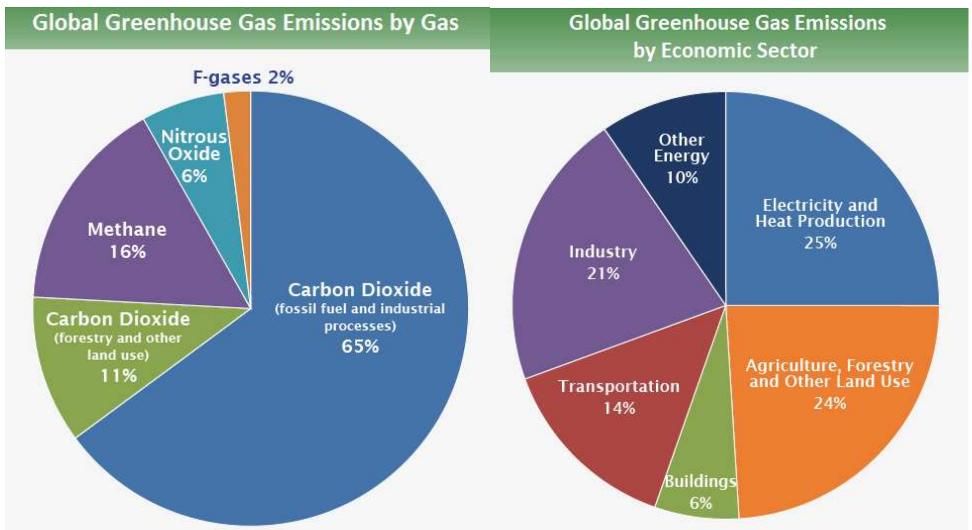


*Figure 8 Compared to the world, the trend is very similar with electricity generation being a major contributor. (EPA, 2023)*

Whether you look at the world, or more locally at the US, emissions, and the sectors responsible for those emissions are consistent with one another. All these sectors are things that touch our everyday lives and are difficult or impossible to eliminate. Over the last century, emissions have been steadily increasing, and “Although the rise in emissions last year was far smaller than the exceptional jump of over 6% in 2021, emissions still remain on an unsustainable growth trajectory” (IEA, 2023).

In the end, we have a problem with GHGs being emitted into the atmosphere at astounding rates. Since these emissions come from resources and sectors that are necessary for modern life, we expect (and show) that these trends will continue.

### 1.2.2 What Could Happen?

Much like the many causes of climate change, the outcomes are varied in both severity and number. Since the world is unlike almost any other realm of study, it is hard to pinpoint exact consequences, but we can predict general trends.

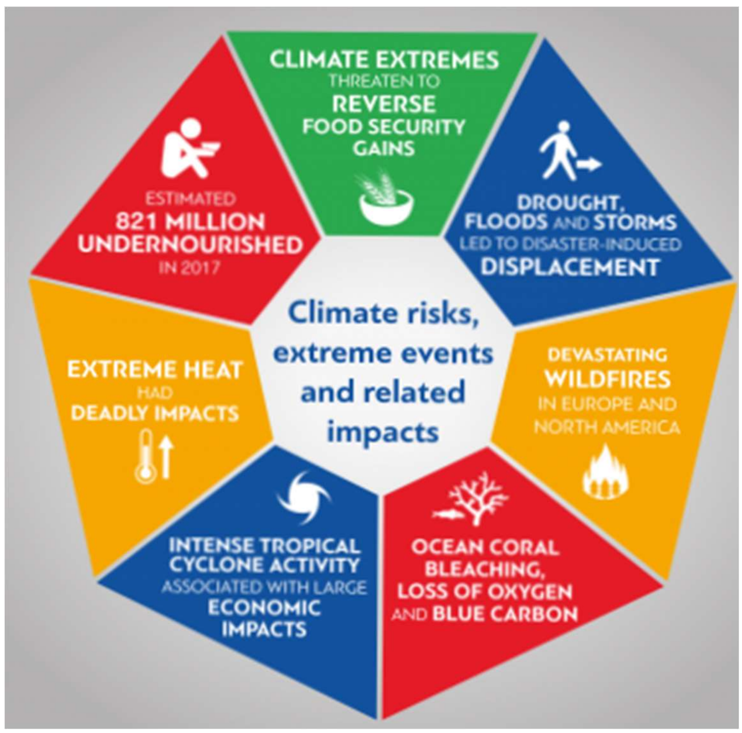


*Figure 9 The extent of climate change is not fully known but its impacts are expected to be far reaching. (World Meteorological Organization, 2018)*

Figure 9 shows several expected results of climate change. The increase in extreme heat sounds simplistic, but the consequences could be dire when one understands that with the rise in temperatures, there is also expected to be a shift in climate zones (European Commission, 2023). Climate zones are generally longitudinally oriented areas with a climate, such as a desert, forest, or jungle. As these zones rapidly change and adapt to the higher global extremes, flora and fauna will also be forced quickly to adapt or die off. It is expected that under current trends, nearly half the planet will shift into new climate zones by 2100 (Watson, 2023). The expected losses could range between 15%-37%, as life may not be able to quickly adapt, or the new zones cannot host the incoming displaced flora and fauna as they move (Thomas, et al., 2004).

Along with the expected new extreme heat periods, more extreme weather patterns are anticipated.

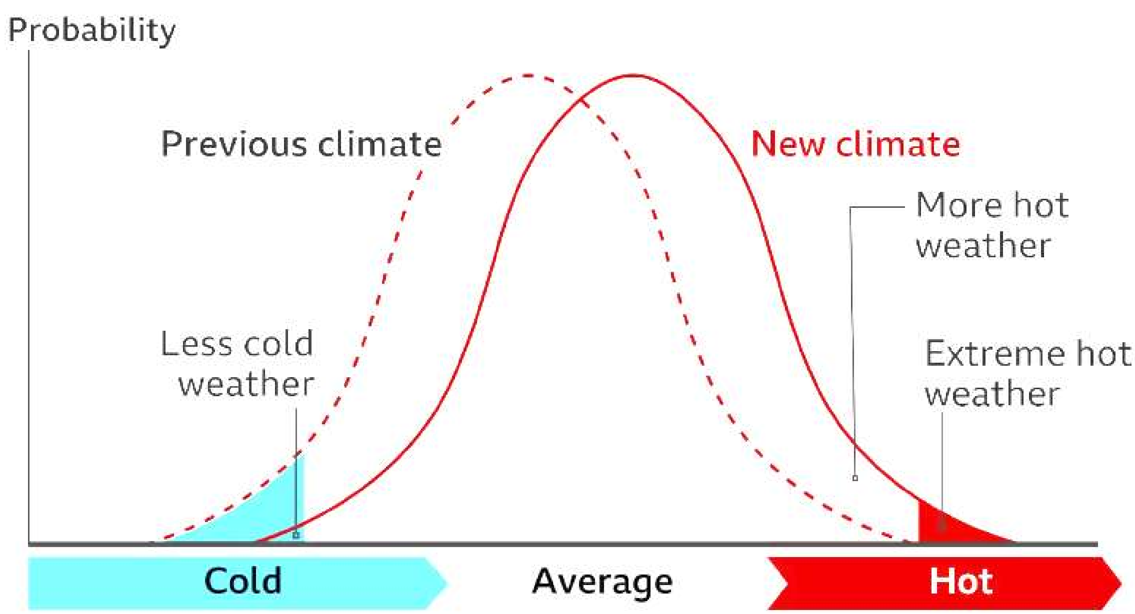


*Figure 10 It's difficult to directly quantify but subtle shifts in increased temperature is expected to lead to an overall significantly different pattern. (BBC, 2023)*

Figure 10 comes from a BBC article which discusses that these hotter periods then lead to the formation of heat domes, longer lasting droughts, more extreme rainfall events, and more wildfire events. Each of these can feed into the other easily. This can be found the world over, even in current times, as the droughts in California are expected to be the result of human-induced climate change. "In southwestern North America, about 19% of the severe 2021 drought, and 42% of the extended drought in the 21st century, can be attributed to human-caused climate change" (Clynes, 2023). These droughts are then feeding into the numerous numbers of wildfires the region is experiencing as the drought has taken the areas and left them as large fuel sources (California Air Resources Board, 2023).

As time goes on, the melting of glaciers and ice sheets, as well as the expansion of the sea itself, is leading to gradually increased global sea levels.

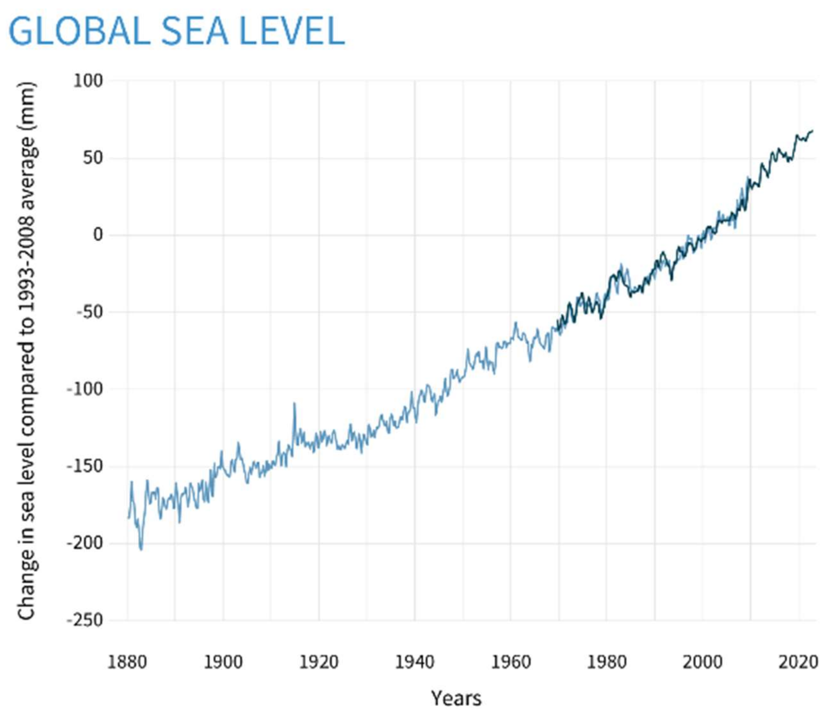


*Figure 11 Over time this rise in the level of the sea is expected to begin threatening the land and people close to the coasts. (Lindsey, Climate Change: Global Sea Level, 2022)*

Figure 11 comes from a report that explains the sea level has risen about 9 inches since 1880, and Figure 12 shows the various components contributing to the problem. This rising of the ocean can threaten the infrastructure along the coast such as roadways, power plants, and subways. If it were to get bad enough, the displacement of the populations along the coast would be significant with tens of millions becoming impacted (Kalin, 2008).

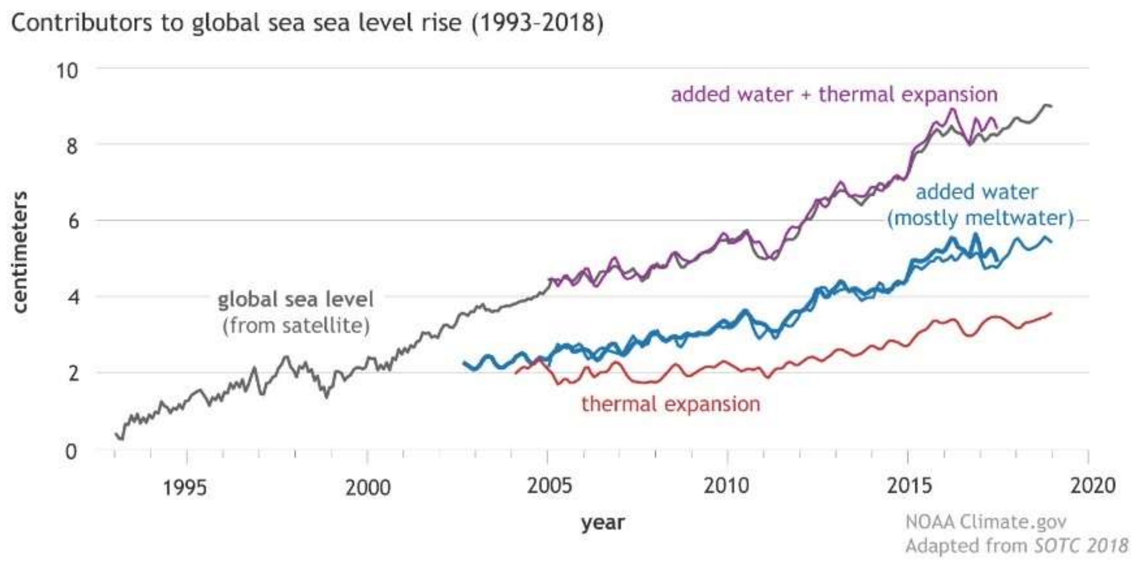


*Figure 12 Various factors are all contributing to the problem at hand. (Lindsey, Climate Change: Global Sea Level, 2022)*

Different parts of the world will of course be impacted in different ways but one study estimates that as much as 68% of the population will be adversely impacted in the long- term (Long & Gao, 2023). With all these issues at hand impacting so many different areas, are there any solutions to the problem?

### 1.2.3 Climate Change Solutions

As there are many factors to the problem of climate change, there are also numerous solutions for any of them. Figure 13 covers many of the major proposed solutions.

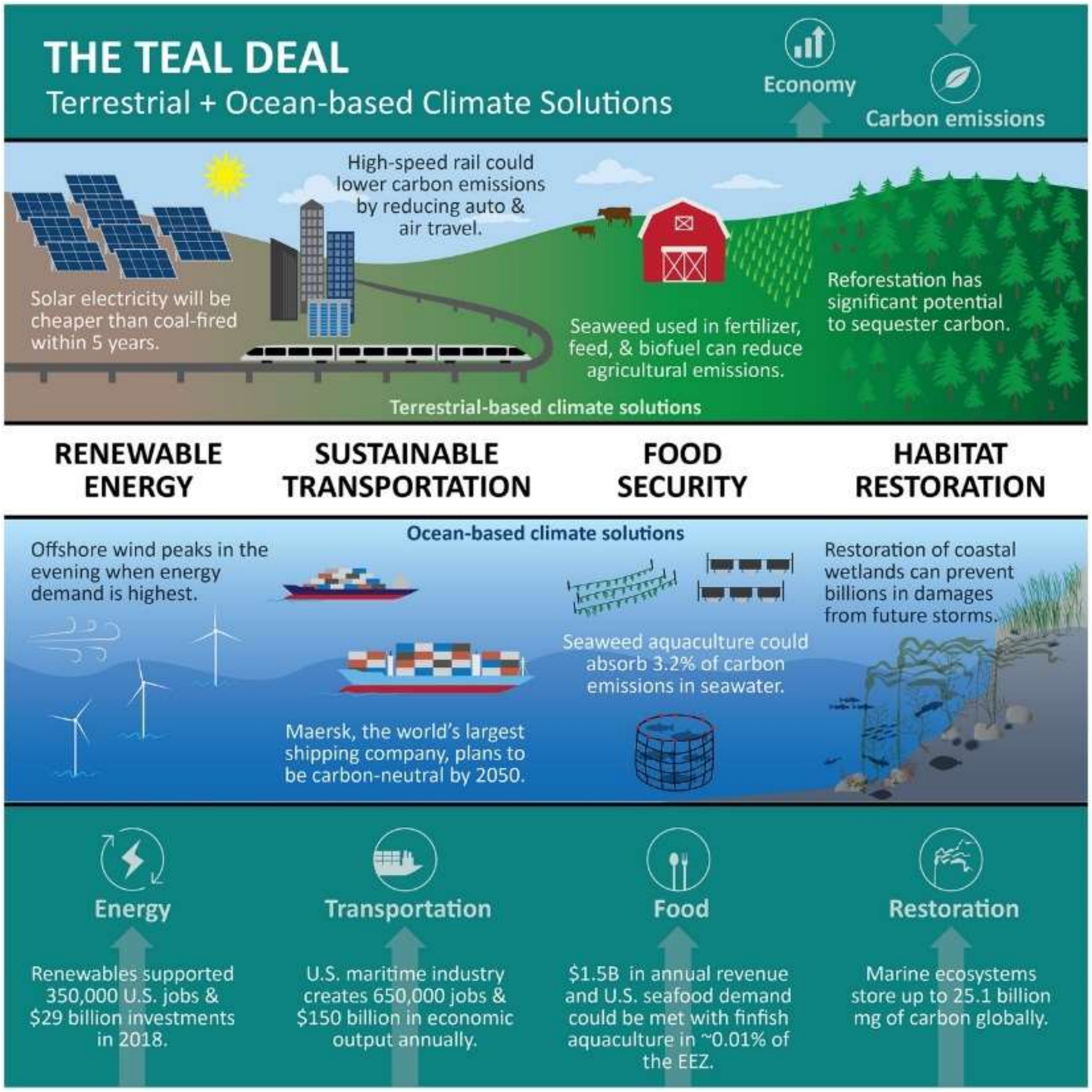


*Figure 13 There are many more solutions besides those presented above. (Dundas, et al., 2020)*

Reforestation efforts help to sequester additional carbon and bring back other supporting ecosystems that also work symbiotically. It is estimated that about 420 million hectares of forest land have been destroyed and repurposed for other uses since 1990, which led to 23% of the existing man-made GHGs (Fearon, 2021).

It is estimated that the farming done in the US generates up to 10% of the GHGs from the country each year (Stokstad, 2022). To combat this, last year, as part of an action against climate change, the government put forward funds to help farmers work towards more climate-friendly farming, namely no-till agricultural efforts and "cover crops" that protect the soil.

Furthermore, the meat industry is being observed as a major contributor, with "about 15% of global greenhouse emissions result from livestock farming — almost on par with those produced by the transport sector. (Wilde, 2022). Returning back to Figure 13, that is at least partly why seaweed is promoted as a choice of feedstock and fertilizer to both combat those emissions as well as symbiotically absorb more emissions from the surrounding ocean of the seaweed farm.

With so many solutions and ideas, the efforts to reduce climate change are ongoing, but where do the overall strategy and target come from? One of the best-known and widely recognized efforts comes from the Paris Agreement. The Paris Agreement is an international treaty on climate change, originally signed by 196 parties at the UN Climate Change Conference in Paris in 2015 on the 12$^{th}$ of December (United Nations, 2023). It was preceded by a few others, such as the Kyoto Protocol 2005 and the Montreal Protocol 1987, but in terms of impact, implementation, and current events, the Paris Agreement heavily overshadows its predecessors.

The overall goal of the treaty was to limit the increase in global average temperature below 2° C as measured from pre-industrial levels. This was later altered to 1.5°C to stave off the more severe impacts from climate change with the target date of halting it by the end of the century. To accomplish this, it is estimated that GHGs must peak before 2025 and decline 43% by 2030. An infographic collecting many of the key points is presented in Figure 14

Several years have passed since the agreement was originally signed, and many countries have continued to follow it after the initial thrust. While the agreement remains a debated topic, some find that it has been impactful already. "The Paris Agreement significantly lowered global projected temperature rise from 7° Fahrenheit to 5° Fahrenheit (3.9° Celsius to 2.8°Celsius). Less climate devastation will occur thanks to this agreement" (Schmidt & Guy, 2017).

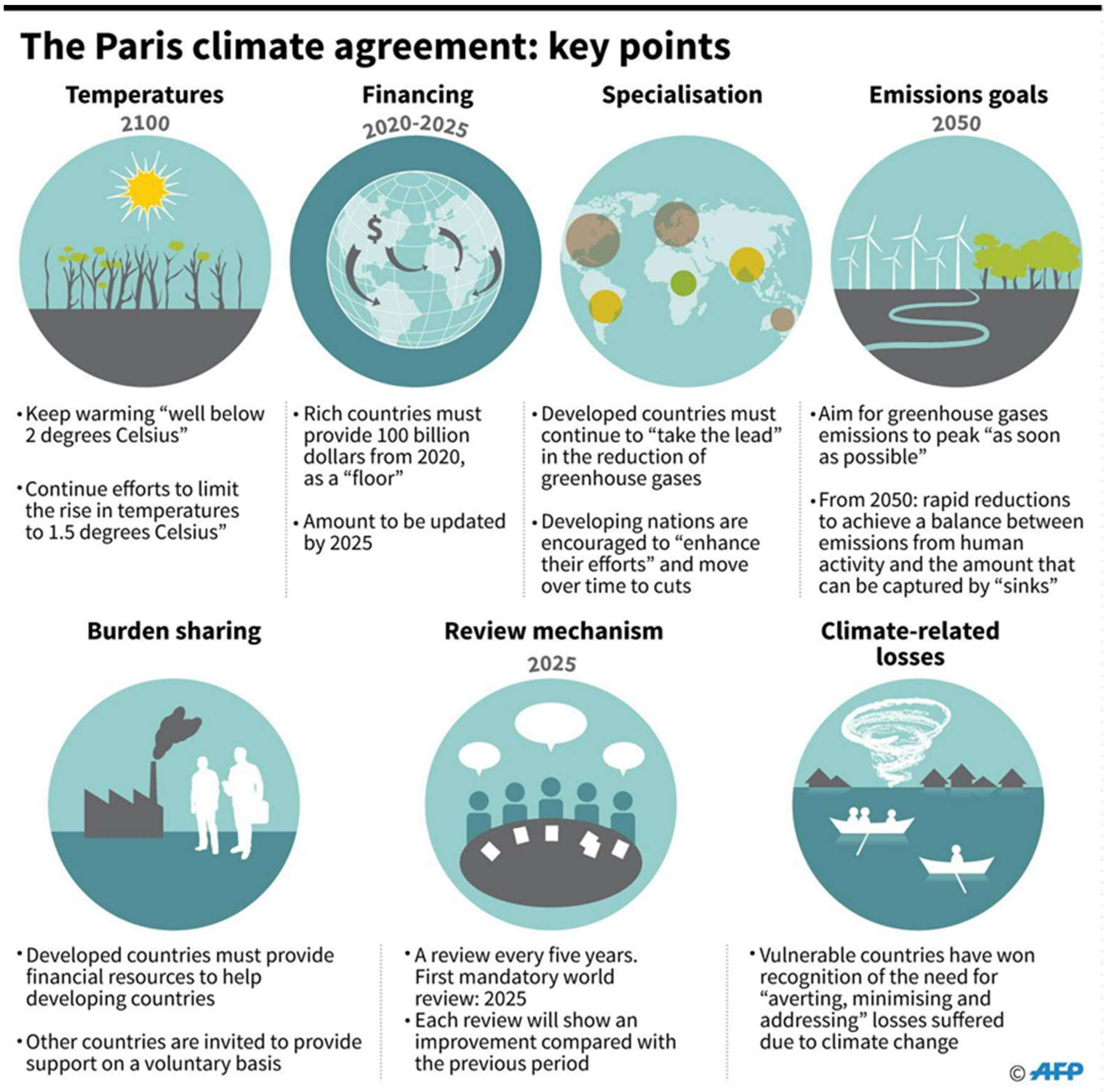


*Figure 14 Many of the key take-aways from the agreement are summarized here. Some of the most important take-aways are the setting of targets and revisiting dates to ensure that the work is being successfully completed. (France-Presse, 2017)*

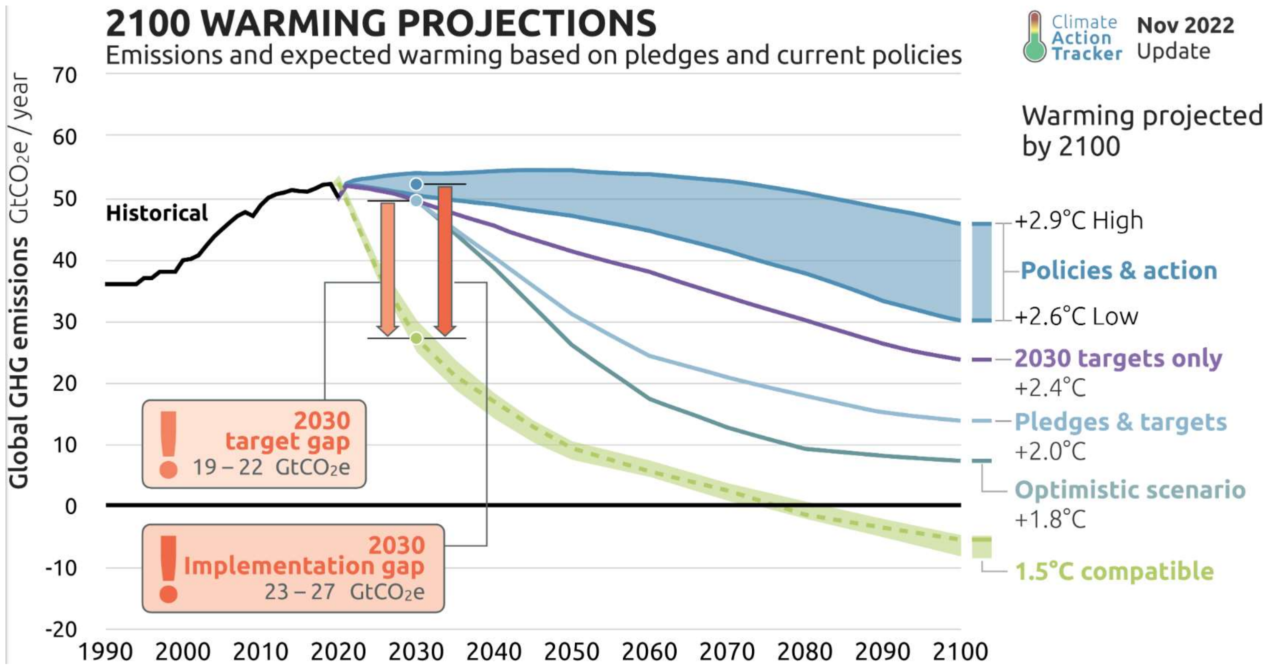


*Figure 15 An updated graph showing ongoing efforts of various climate actions, as well as the estimated gap that remains from targeted values. (Climate Action Tracker, 2022)*

Figure 15 describes how there is still a significant gap between what was found to be needed at the original signing event and how we are currently performing. Since there is a significant consensus about the causes of climate change and the influencing factors, where would the gap be coming from in addressing it? There is a significant disagreement on several points which slows down efforts to create meaningful change.

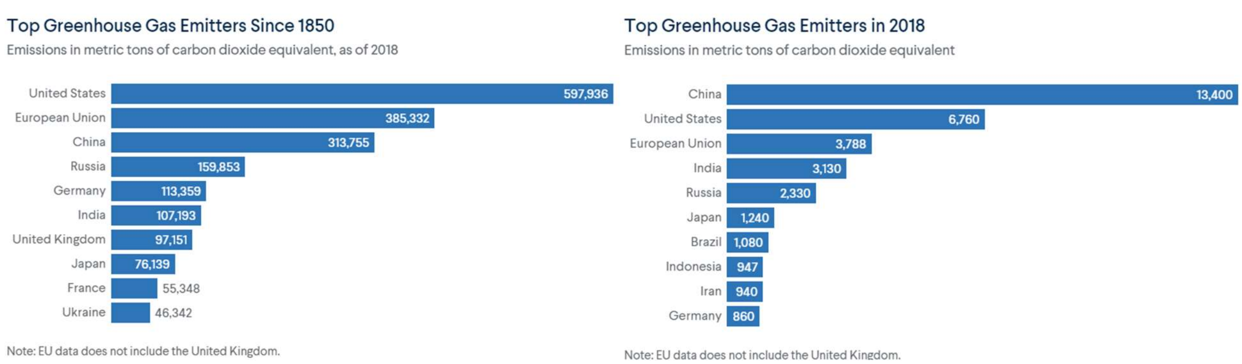


*Figure 16 One of the debatable points about the actions that need to take place is up to who is ultimately responsible and therefore who would need to create the most changes. (Maizland, 2022)*

The graphs in Figure 16 point to one of the major points of contention. On the left are the main contributors since 1850, when the United States outpaces many of the countries. On the right, however, since 2018, China has vastly outpaced even the United States. So, the question then becomes which of the above countries should be implementing the most changes, and it is further compounded by the fact that industrialization and the process of becoming a larger, more advanced country naturally incurs environmental costs, which explains why India is also starting to become a major contributor.

Some experts argue that even the original agreement was insufficient to impact the changes required. ""The Paris Agreement is not enough. Even at the time of negotiation, it was recognized as not being enough," says CFR's Hill. "It was only a first step, and the expectation was that as time went on, countries would return with greater ambition to cut their emissions."" (Maizland, 2022). Those that are critical of the agreement may not have been against the intent; instead, they hoped that the countries would begin to do additional shifts above and beyond the original requirements.

Maizland also applauded the United States in that under Biden additional commitments were made that exceeded Obama's commitments, when the agreement was first made (Maizland, 2022). Still looking back at the climate tracker graph in Figure 15 we can see that these moves have not been significant enough to impact the change needed. As we move into a more detailed discussion, it helps to begin splitting those actions up by what are considered the developed nations and the developing nations as the actions taken (or not taken) are more in line with their national policies.

### 1.2.4 Developed Nations

Calling back to the previous discussion on the Paris Agreements, we can see by Figure 17 there is a significant discrepancy between the developed and developing countries, and their approach towards climate change is radically different. Countries that have fully developed have the infrastructure and capability to take advantage of alternative means that developing countries cannot afford. In the process of developing, however, environmental concerns are not likely to be their major focus.

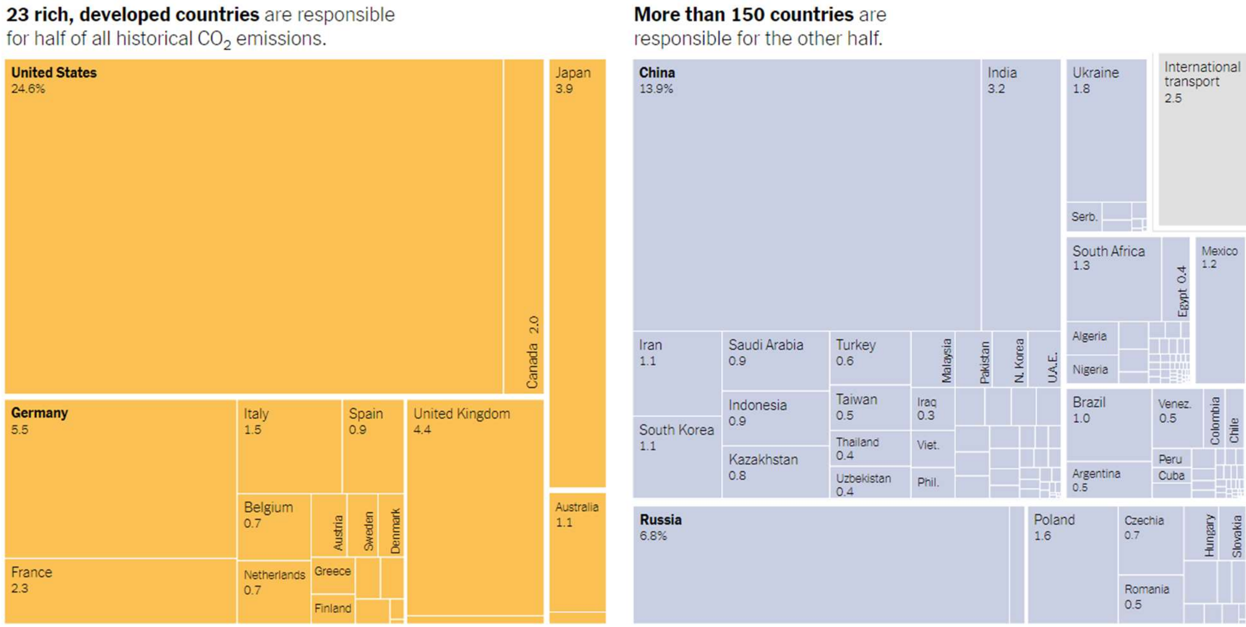


*Figure 17 Again calling back to the issues discussed about the Paris Agreement, there is a major discrepancy between the developed rich countries and the developing countries in their historical emissions. (Popovich & Plumer, 2021)*

Germany, for example, has been aggressive on their climate change stance, committing to a country-wide emission reduction of at least 65% by 2030 with hopes to continue capitalizing on those numbers with reduction of 88% by 2040 (OECD, 2022). They are looking to achieve this in a multi-faceted way, including energy production methods with renewable energy methods and the limiting of fossil fuels with a target 80% goal of renewable energy by 2030 (Nissler, 2022). Germany is also targeting the energy efficiency of its buildings, highlighting that many emissions are directly a result of inefficient designs and insulation. As such, they have set aside funds to refurbish their buildings to make them more efficient and reduce losses and therefore energy use.

Clearly Germany is making several steps towards offsetting their GHG emissions by enforcing the reduction of GHGs as part of their laws and restructuring their government to make sure these goals are held accountable. However, Germany is a prime example of a rich country that hoped to offset many of their emissions with renewable energy but recently had to fall back on cheaper, more widely available coal resources due to the Russian Ukrainian conflict.

Nationwide, Germany planned to phase out coal aggressively, citing its harmful GHG emissions, and replacing them with renewable resources. With Russia stopping natural gas exports in response to sanctions Western Europe placed due to the war with Ukraine, Germany suddenly suffered from an energy crisis (Meredith, 2022) (Schmitz, 2022). In response, they have halted the shutdown of 20 coal power plants as a measure to solve the crisis even though this went directly against their own environmental goals.

Moving to North America, Canada passed the Canadian Net-Zero Accountability Act on June 29th, 2021, to become net-zero on emissions by the year 2050. Since 2019, the country has set mandatory carbon prices to help drive down emissions, where possible, by forcing provinces to have a carbon budget they must meet or pay to exceed. Their transportation sector is the second largest emission source, and they are reducing those numbers through the adoption of electric vehicles by as much as 100% by the year 2040 with rebates and benefits. The direct environmental impact is best seen by an initiative wherein Canada plans to increase its carbon sink capabilities by planting as many as two billion trees over the next 10 years (Climate Action Tracker, 2022).

With all these varied changes, Canada sounds like it might be doing well, but not if you measure it against the numbers needed to meet the Paris Agreement targets.

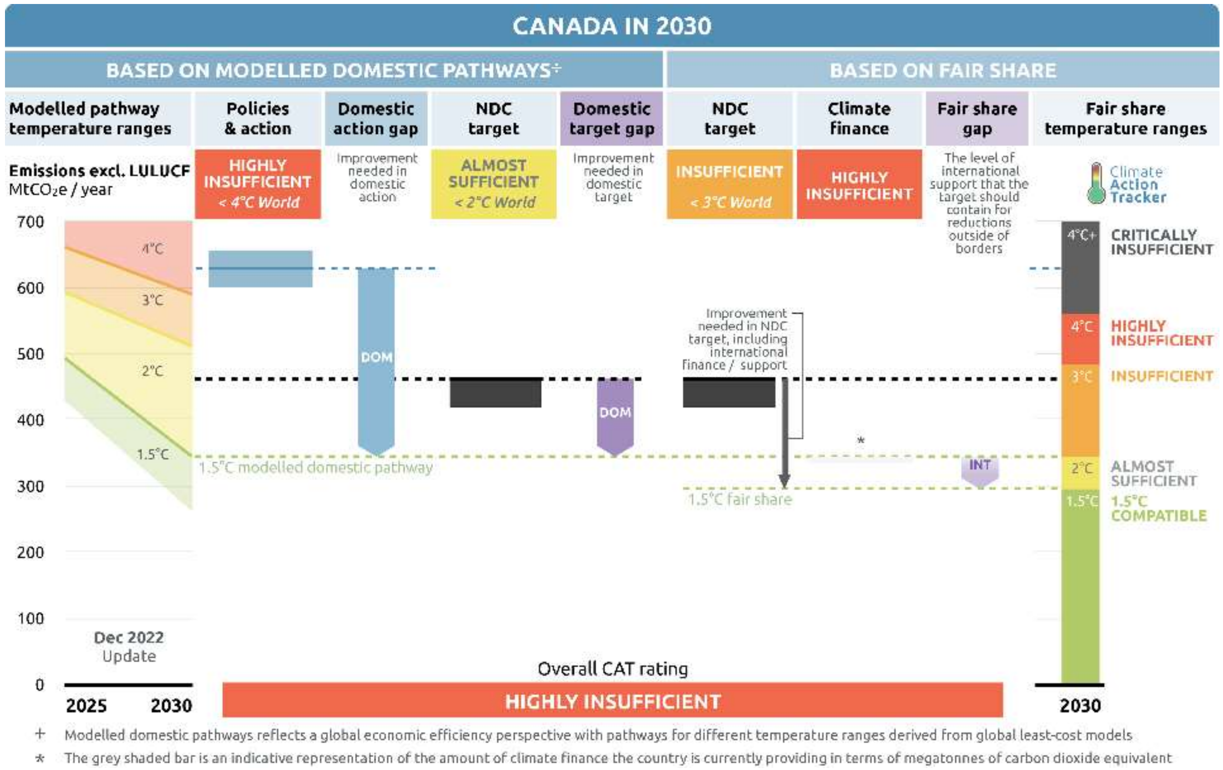


*Figure 18 A snapshot of Canada's efforts towards climate goals. The climate action tracker allows you to look up a country's overall climate strategy and how it measures up against the goals necessary to achieve the necessary targets. (Climate Action Tracker, 2022)*

None of this is to disparage the efforts that are being made. Instead, the focus should be made on what richer countries are doing to meet climate goals internally and externally, as well as draw a contrast to what and how these same efforts would likely not work in developing nations. Figure 18 shows that despite all the efforts Canada is making, they are still unable to meet its climate goals.

Due to the energy crisis that is occurring in Europe, there has been a renewed interest in Liquid Natural Gas (LNG) wherein Canada is considering helping Germany with its energy crisis by increasing fossil fuel production, despite both countries having policies that were supposed to reduce them (Rinke & Scherer, 2022).

These developed nations are the ones who could and should help to develop this technology not only for their own goals but also so others can capitalize on it increasing its ecological reach (Liu & Liang, 2011). CCS can help close these policy target gaps while allowing countries to meet these energy crisis issues utilizing existing infrastructure.

The next section will begin to look at developing nations. These nations are still relying on fossil fuels, and, although most have plans to reduce their reliance on fossil fuels, there are numerous reasons why they have not been able to. This is a critical point of CCS research in that developing nations will be unable to burden themselves with the high cost of research and development at the same time they are focusing on meeting modernization and power generation goals.

### 1.2.5 Developing Nations

This is where one can start exploring the other side of CCS as a technology that helps support climate policies while still allowing energy independence by letting a developing nation take advantage of a cheaper resource (like coal) and still be environmentally friendly. While it is debatable about the need for CCS in a mature grid with significant cross-support capabilities and advanced balancing technology, we must remember that the rest of the world may not be so lucky yet. A country that is still setting up its energy infrastructure cannot rely on intermittent renewables, and similarly, it will not be able to foot the cost of the technology without someone else doing the heavy lifting.

From 2022-2023, India is expected to commission ten additional coal power plants totaling over 7 GW of additional thermal power (Pande, Raj, & Chatterjee, 2022). China is looking to build upwards of 6 times more coal power plants than other countries (Simon, 2023). Many of the energy environments in Asia are expected to use coal power to drive their economic growth (IEA, 2022). Even parts of Europe (which could be considered a more stable and modern network) are being impacted by the war in Ukraine, which has led the desire to get away from energy dependence on Russia which is then leading to a possible rise of reliance on coal power. "Coal-fired production limits have been relaxed in France and the Netherlands. Phase-out delays and the temporary reopening of idle plants are being discussed and/or have been approved in Greece, Italy, the United Kingdom, Germany, and Austria" (IEA, 2022).

India recently announced the commissioning of a new coal plant that has been in the construction phase for nearly a decade. National Thermal Power Corporation (NTPC) commissioned India's first supercritical coal plant capable of just under 2-GW of coal power for the region. This plant was redesigned directly to address the water scarcity issues of the area where building a dam was deemed infeasible due to the surrounding villages and populations (Patel, 2023). Since CCS applications require an increased draw of water resources, it is easy to assume this is counter the idea of implementing it, but, in fact, this is not the case.

Patel goes on to discuss the need for the CCS unit to add to its already massive coal plant fleet which is currently at 179 coal plants 204GW capability supplying nearly 50% of its required power. Patel goes on to highlight multiple studies discussing the increased water draw these thermal plants have on the country and their impact. It counters that based upon India's unique geography; the overall plan is to leverage the country's vast coastal boundaries to help address this issue. Where does that leave CCS in comparison? Another study helps us look at that.

Generally, we can say that CCS increases a power plant's need for water. In fact, one study estimates retrofitting a unit onto an existing plant could raise the required water intensity of the plant by as much as 55% (Rosa, Sanchez, Realmonte, Baldocchi, & D'Odorico, 2023). That same study argues that while this is certainly a limiting factor, "The twin challenges of managing climate change and water scarcity cannot be considered independently." In other words, much like the location-specific solution of adapting a traditional coal plant design to a supercritical water-efficient design we don't need to focus on individual applications but instead on fleet wide solutions.

To summarize the last couple of paragraphs, India is still very much reliant on coal power, so even today they are commissioning new-age plants to meet their growing demand. Even in regions where the surrounding environment could potentially limit the application of coal power, they were willing to adapt to more expensive solutions to move forward. Admittedly, in the case of this specific new NTPC plant, it. It may not have been viable, but if it were looked at fleet-wide, solutions could be found. As studies have already been looking at the coal plant fleet water consumption, there are ways to design around the problem if it becomes a driving decision factor.

Coal power is critical because it is cheap, plentiful worldwide, and easy to implement. Natural gas isn't a "clean" energy resource, but it emits almost 50% less $CO_2$ than coal (MET group, 2020). While the US is trending away from coal and arguably moving towards a greener grid, that is not a world-over trend.

If a country is implementing the easiest, and one of the most secure, energy sources to meet its demands, it is unlikely they are looking to do experimental work or invest in technology counter to its current low-cost needs. Since cost is one of the main components limiting the implementation of CCS (Herzog & Vukmirovic, 2023), this could be a problem that never gets solved when the developed nations are trying to adjust directly to renewables and developing nations are trying to simply stabilize themselves.

## 1.3 What is CCS

Carbon Capture Storage is also known as Carbon Capture Use and Sequestration (CCUS), Carbon Capture Use (CCU), and other various names. This work focuses on the Carbon Capture portion of the technology. While use and sequestering are both important for the technology, this occurs post the grid operations. Figure 19 is useful to illustrate this concept.

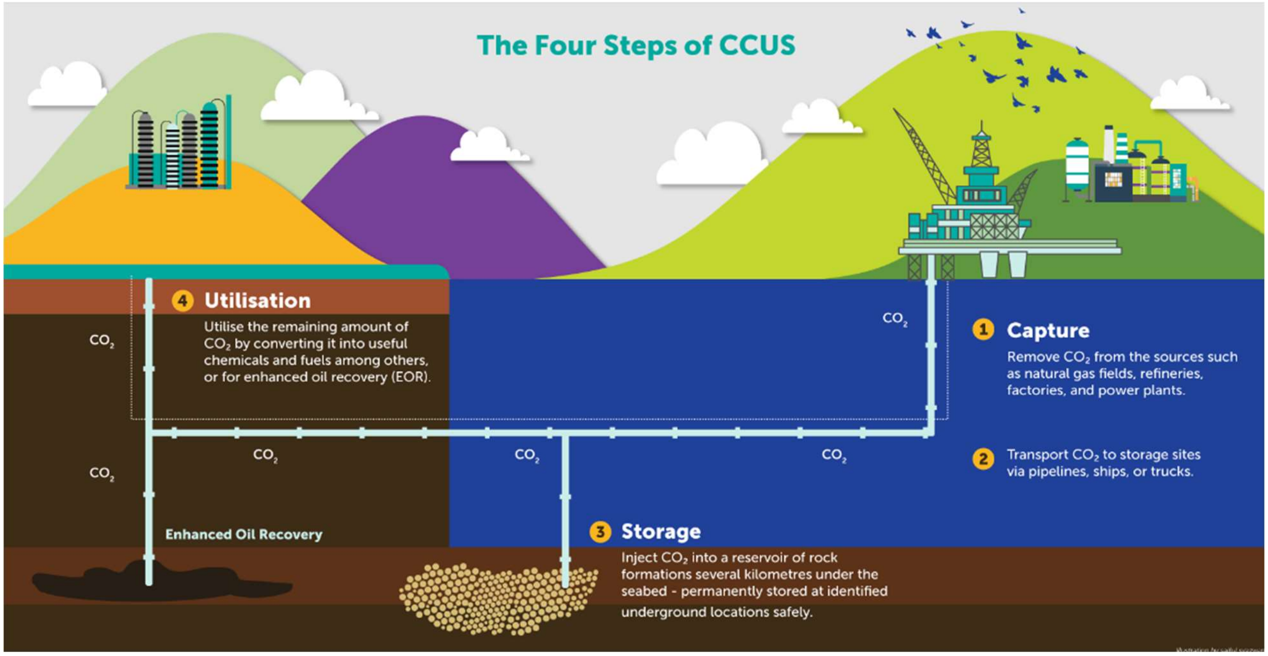


*Figure 19 The many names for carbon capture mostly derive from the post capture process where the carbon can be stored or used for Enhanced Oil Recovery (EOR) or other industrial processes. (Khalid, 2021)*

The first step is the actual capture process, as it is installed on a traditional source of carbon. Then it is either isolated and stored for transport or shipped through a series of piping to another location. That next location can use it in several ways. The two main uses are either to use it in an industrial process such as Enhanced Oil Recovery (EOR) where additional oil can be brought up from the ground or it can be geologically stored permanently deep into the earth.

Again, the focus here is on the power generation sector but it can be used in many areas that are interrelated. As the process is further practiced, researched, and publicly known there will likely be inter area benefits along the way. CCS can be applied to the industrial sector where emissions are a known major contributor such as the production of concrete and chemical production sector. CCS can help in the processing of natural gas, hydrogen production, and commercial fertilizers. In the power sector, depending on the specific version of CCS that is used, both natural gas plants, and coal power plants, can benefit from the technology. While the work done here is specific to power plants, there may be some benefit to modelers from other fields who could glean some benefit from these results.

### 1.3.1 Different CCS technologies

There are several different CCS technologies, but they can be broadly collected into 3 variations: post-combustion, pre-combustion, and oxy-fuel types. All 3 types have their benefits and drawbacks, which are either magnified or disregarded depending on the application. While in this study, they are generally lumped together and viewed by their electrical impacts on the generators, their topologies are still important.

The significant difficulty in discussing CCS is that while it is an old technology it is only now seeing commercialization and investment. Initial studies and experiments date far back into the 20's with basic separation techniques being investigated and found successful (IEAGHG, 2023) but little being done with it until recently. One way to look at the progress of a technology is to understand its Technical Readiness Level (TRL) (see Figure 20). Here we will explore the TRLS of the various initiatives, and a timeline of a high-level look at the technologies (see Figure 21).

| CATEGORY | TRL | DESCRIPTION |
|---|---|---|
| Demonstration | 9 | Normal commercial service |
| | 8 | Commercial demonstration, full-scale deployment in final form |
| | 7 | Sub-scale demonstration, fully functional prototype |
| Development | 6 | Fully integrated pilot tested in a relevant environment |
| | 5 | Sub-system validation in a relevant environment |
| | 4 | System validation in a laboratory environment |
| Research | 3 | Proof-of-concept tests, component level |
| | 2 | Formulation of the application |
| | 1 | Basic principles, observed, initial concept |

*Figure 20 The broad breakdown of TRL levels as they pertain to technological maturity. (Kearns, Liu, & Consoli, 2021)*

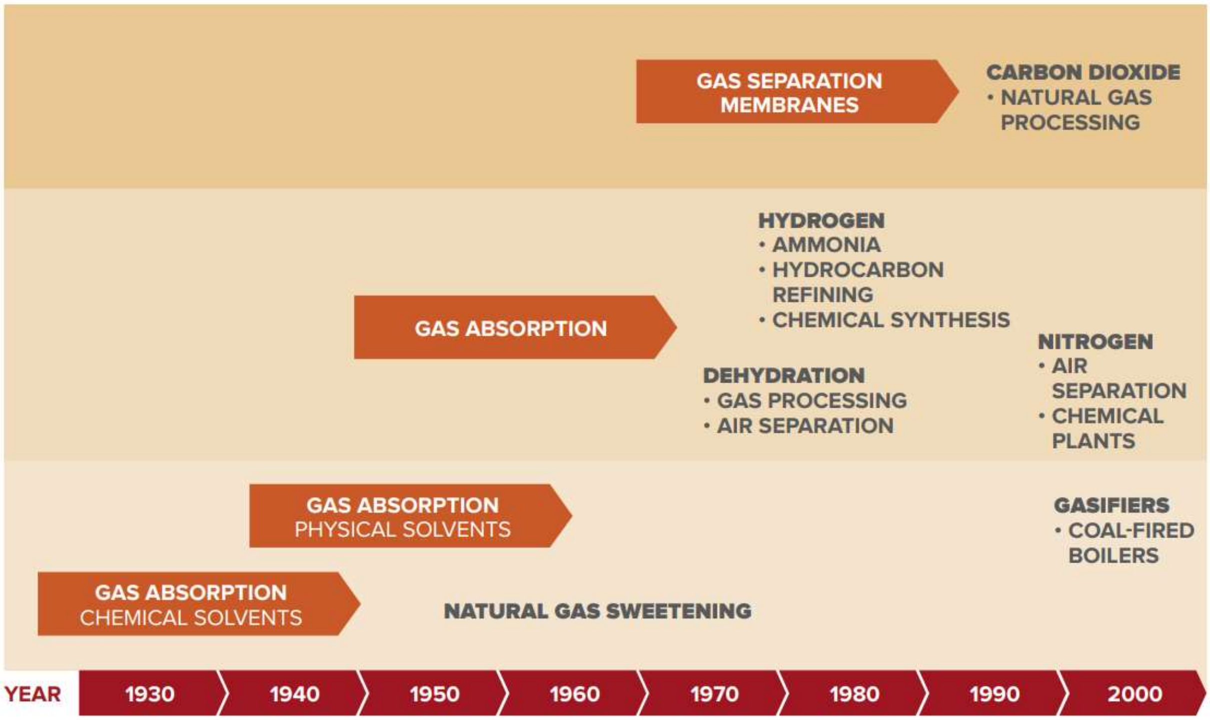


*Figure 21 Some use of CCS took place nearly a century ago while others have only recently been developed. (Kearns, Liu, & Consoli, 2021)*

Figure 20 and Figure 21 come from a technology readiness report discussing TRLs for CCS (Kearns, Liu, & Consoli, 2021). In the work done there, they summarize the whole process from the capture of the $CO_2$ all the way to the storage or use of the material and apply analysis to determine the TRL. They separated the technologies by sub-process, such as using liquid solvent or solid absorbent, and found that it spans the full range. While their findings are too extensive to fully include, below is the Membrane category of CCS which had one of the broadest ranges.

| TECHNOLOGY | | KEY VENDORS | TRL 2014 | TRL 2020 | PROJECTS |
|---|---|---|---|---|---|
| Membrane | Gas separation membranes for natural gas processing | UOP, Air Liquide | -* | 9 | Petrobras Santos Basin Pre-Salt Oil Field CCS |
| | Polymeric Membranes | MTR | 6 | 7 | FEED studies for large pilots |
| | Electrochemical membrane integrated with MCFCs | FuelCell Energy | -* | 7 | Large pilots at Plant Barry |
| | Polymeric Membranes / Cryogenic Separation Hybrid | Air Liquide, Linde Engineering, MTR | 6 | 6 | Pilot studies |
| | Polymeric Membranes/ Solvent Hybrid | MTR/ University of Texas | -* | 4 | Conceptual studies |
| | Room Temperature Ionic Liquid (RTIL) Membranes | R&D only | 2 | 2 | Lab tests |

*Figure 22 Note that they applied this methodology over several years, and some were unavailable in their original reports as new findings are being consistently developed. (Kearns, Liu, & Consoli, 2021)*

### 1.3.2 Post-Combustion Carbon Capture

Post-combustion carbon capture works, as its name's sake suggests, where the gases from the combustion process are diverted, treated, and captured for storage in several different ways or used in industrial applications to offset the costs of the process. This is the most common method when it comes to retrofitting, or new CCS, plants as it is a straightforward process to add additional machinery and begin refining the output. While the most common form of CCS, efforts are still in the early commercialization space so costs can be prohibitive.

Post-combustion can be further broken down by the specific methodology applied to capture the $CO_2$ itself, as diagramed in Figure 23.

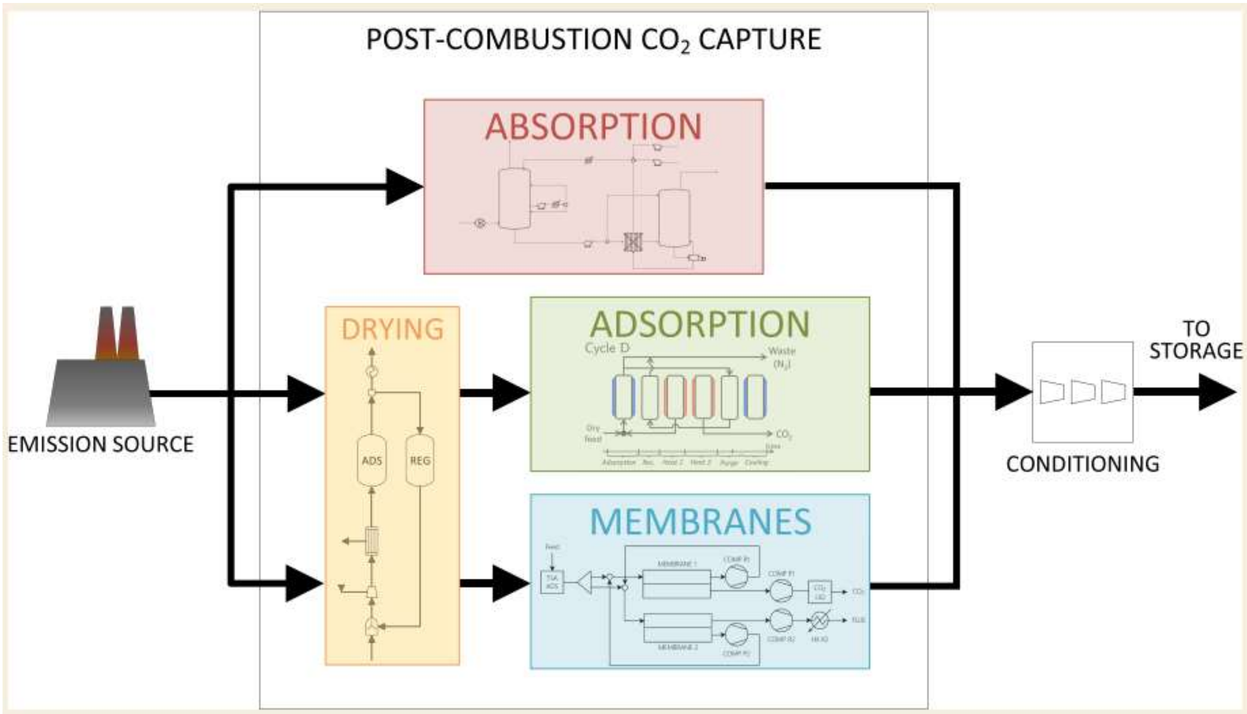


*Figure 23 Infographic shows three varieties of post-combustion capture. Notice that they all occur as the source completes its operation. (Zanco, et al., 2021)*

The work above in Figure 23 compared mature technologies in several sectors but was ultimately simplified down to performing CCS by using a piperazine solution solvent, an adsorbent of Zeolite 13x in conventional beds, and a membrane of polymeric material with multiple stages. The in-depth technical details aside, the important thing to note is that there is no single methodology to the process. This variety comes from the fact that significant research is still being done on the process as efficiencies and cost reductions are found.

### 1.3.3 Pre-Combustion Carbon Capture

Pre-combustion carbon capture is generally used in industrial applications such as the creation of chemical manufacturing or in concrete. In this method the carbon is removed from the fuel source prior to combustion so the effluents are naturally cleaner with an example set up seen in Figure 24.

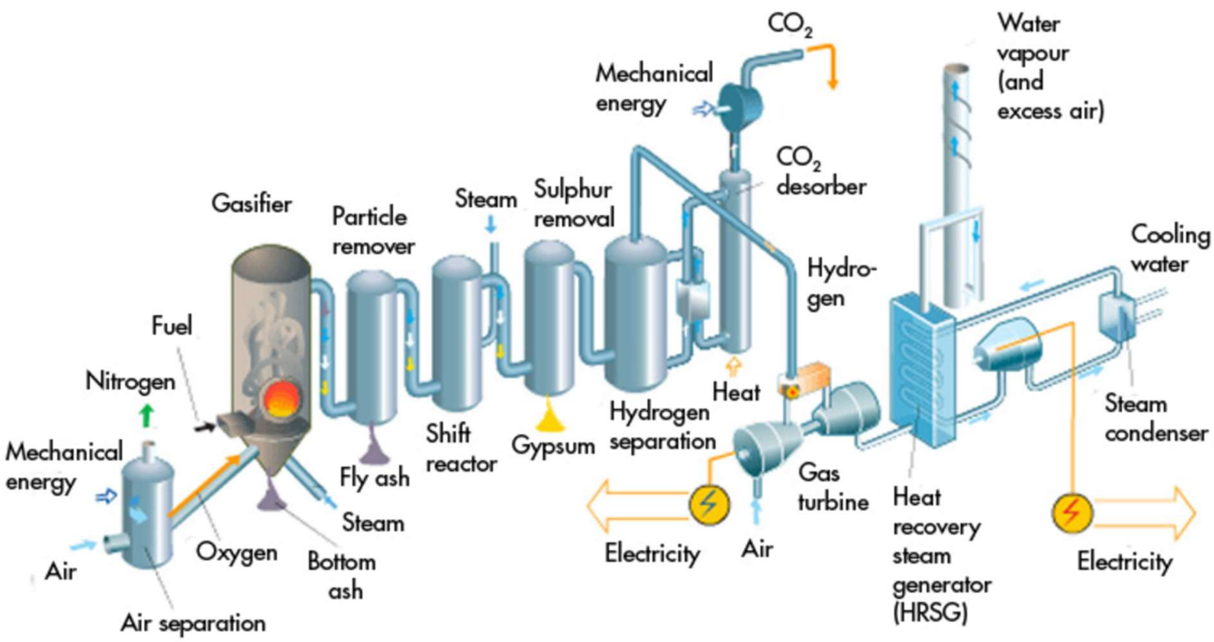


*Figure 24 A simplified diagram of pre-combustion CCS. (ZeroCO2, 2017)*

This process is even more expensive than the previous one, but that isn't to say it isn't still growing. Given the process of converting the fuel source over to various gases for capture, there are benefits for IGCC (Integrated Gasification Combined Cycle) plants. The DOE is targeting this method as the model to capture costs below $30/tonne, which it believes to be integral to industry adoption (DOE Fossil Energy and Carbon Management, 2022).

### 1.3.4 Oxy-fuel Carbon Capture

Oxy-fuel carbon capture is the most technologically demanding and is only being brought about in newer age plants, as retrofitting an existing plant would be cost-prohibitive. Instead of using general air, this process uses nearly pure oxygen to ignite its parts. While the youngest of the 3 options, in terms of technological maturity, it is nearly on par. This is due to several advantages in the process, such as savings in terms of flue gas treatment, ease of separation of pollutants, and overall heat efficiencies. With that ease in separation, it becomes increasingly easy to capture the carbon developed when power is being developed. Oxy-fuel, for example, is a very powerful option, but it cannot be easily retrofitted back into aging facilities as it would often require a significant plant redesign to support it. An example of the basic design is presented in Figure 25.

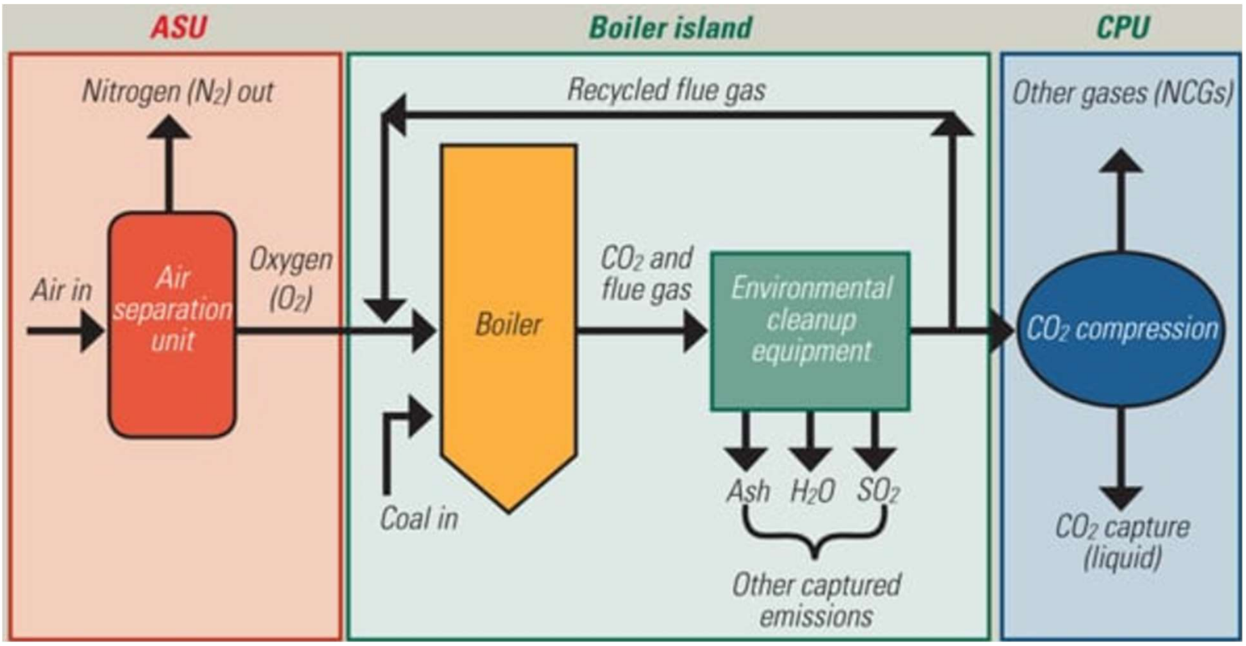


*Figure 25 A simplified diagram of Oxy-fuel carbon capture with the 3 basic building blocks. (Mcdonald, Moorman, Darde, & de Limon, 2011)*

While it was just said that oxy-fuel technology could not be easily or cost-effectively integrated into an existing plant, there have been designs in the past that said it could take up the same footprint as other technologies and could be more efficient in the capture process to offset the greater initial cost (Mcdonald, Moorman, Darde, & de Limon, 2011). The same report indicates the system could become operational at a reduced capacity and then upgraded over time. It does seem like this proposed project never came to fruition though, again highlighting the many unknowns about CCS and its capabilities in the power sector.

### 1.3.5 Carbon Capture in Power

The application is not free by any measurement of the term. First and foremost, this research is the studies impacts of the technology on its host plant. No matter the topology, capturing carbon will be an invasive process that will directly impact the operations of the power plant by interrupting the outflow of exhaust, changing the way the system burns its fuel, or taking a significant portion of the power from the plant to process.

This is the crux of this research. As various topics and opinions are discussed, some will go against each other, but the need for CCS is certainly there. The power grid is evolving rapidly, seeing new threats introduced while basic principles like the flow through the lines are being flipped. Based on politics and aging infrastructure, we see thermal plants retire at an increased rate, with an argumentative need for them to remain in place. CCS has the possibility of helping turn these problems over, and research has shown that to meet the demands of the Paris Agreement, conventional resources will remain critical to the world's energy demands even with renewable expansion (Kim, Kim, Kim, & Kim, 2019).

The downside is that the technology is relatively unproven in the world at large for commercialization, making it necessary for first-of-a-kind implementations (Comello & Reichelstein, 2014). As a project that could measure in the range of millions of U.S. dollars for a facility of small size, it is difficult to gather scientific evidence. While many are looking to the environment with renewed interest as time goes on, the fact is the operation of the grid is largely driven by economic decisions. On top of this, units also consume a large amount of power, and that changes how the plant can operate technologically and fiscally. The high cost of CCS commercialization will continue so long as engagement remains low and the challenges of low TRL tech are not solved.

This work will give a comprehensive look at a grid in operation which will show why we should examine this technology for its symbiotics and capabilities. The energy mix needs to remain diverse for a healthy and reliable grid and this is present in both our nation and others (Augutis, Martisauskas, & Krikstolaitis, 2015). For this to remain true, methodologies differ in how a power grid is invested in for the long term compared to the short term, where diversity plays a more significant role (Kosai &

Unesaki, 2020). Pertinent stories will be discussed in related fields, like the rising grid concerns due to unprecedented storms and the rise of grid attacks in recent years. This work will show why developing a mathematical model could help other researchers continue doing grid studies. While CCS will not be the end-all-, be-all solution to all these problems, “As every tonne of $CO_2$ emitted contributes to global warming, all emissions reductions contribute to slowing it down.” (European Commission, 2023).

## 1.4 Research Merits

### 1.4.1 Gap in Knowledge

There is a significant gap in knowledge about what exactly CCS will do regarding impacts on the grid. We know that it will lower the capability of a power plant installed on, which has obvious implications but is hard to capture numerically. Later in the literature review, it will cover the synergy between flexible power plants and this technology, but again those studies are not quantitative but rather qualitative. What is interesting is that we are discussing the flexibility of a power plant in terms of ramp capabilities while at the same time negatively impacting those same metrics by imposing a reduction in overall power that a unit can facilitate.

This research will provide a quantitative answer under several self-imposed limitations through scenarios and technical possibilities. It will not be able to provide an end-all-, be-all answer, but instead of general statements, it looks to provide a set of answers that others can build off and help see trends in the industry.

To do this, the work will need to make some generalizations about the plants and treat them at a high level, focusing less on the in-depth details like which condenser is used and day-to-day operation. We look at the high-level power plant ramp-up and down characteristics along with maximum capability. This will then be paired with a mini-grid model (namely the IEEE 37-node model) to include realistic scenario properties and maximum hosting capability under the new plant. Finally, the system will add renewable power generation to show a ratio of load balancing in contrast with the plant. In the literature review, CCS is not seen as the ultimate answer to the grid, which makes sense. Different grid makeups, loads, and scenarios lead to multiple answers being needed to host the modern power demand. CCS is believed to be a significant contributor to the solution of both environmental and grid modernization concerns, but it is being held back by low TRL which is compounded by a lack of investment, public understanding, and focused research.

With this research, the hope is to shine some light on these gaps and give the next-step to guide followers to build from. With that in mind, the model will also need to be available to others. Here we cover several different options with the idea in mind for others to be able to take this research and build off of it. PowerWorld (PowerWorld Corporation, 2023) and MATLAB (Mathworks, 2023) software platforms were initially promising options, but in practice, they did not pan out and could not meet the needs of the first question (to be described) of this thesis/research.

PowerWorld does not have the user-definable characteristics to allow these studies. In older versions of the software, the ramp rates of the power plants were able to be dictated, but strangely enough, the newer versions do not allow for this. Instead, the software limits plants by Megawatts (MW) and Megavolt-amps Reactive (MVAR) capabilities which have their uses but do not fit this research.

MATLAB is a wonderful toolset, but to get to grid-level simulation, a number of different toolsets are required to be used in conjunction with one another to build a functioning system. Additionally, you would still need to build whatever wanted next for the system. While the user distributive characteristics were initially promising, the workload side prohibited its direct use.

All of this will be covered in much more detail in the methodology portion, but it should be noted that these problems are part of why this capability is needed in the first place. There are good reasons for these programs to be as they are but that does not help answer the questions the field has or help promote wide distribution and collaboration. In the end Gridlab-D software (Pacific Northwest

National Laboratory, 2023) provided a good middle ground to build an adaptable platform as well as had a good customizable model.

Gridlab-D is a general modeling software developed by Pacific Northwest National Laboratory (PNNL) for the DOE with the intent to be as adaptable as possible. The system has the standards necessary for grid simulations but leaves the user with most of the heavy lifting. While the assessment of this research will be quantifiable answers that will show the capabilities of flexible CCS-enabled power plants, the novelty of the research that can be handed off to others will be the model network built within. This model will be mostly made up of Gridlab-D outputs as it simulates steps that are output to Excel files (or MATLAB files) where processing is performed, and then the next iteration of the simulation is built. These will be captured in flowcharts that the user and reader can easily follow along with to understand how to adapt the methodology to other platforms for further development.

## 1.5 Hypothesis

A notional qualitative relationship exists between power plant flexibility and the ability to host renewable energy systems. This relationship can be further strengthened when dynamic CCS units are introduced to the mix. At this stage, however, there is limited capability to analyze the situation quantitatively. CCS is a technology allows thermal plants to remain environmentally competitive and can symbiotically allow additional renewable energy resources to be brought online while simultaneously allowing a greater amount of power demand to be met in baseload power satisfaction. To show this relationship, this study can essentially be boiled down to addressing two distinct questions.

### 1.5.1 Question #1

Can a simulated system be built with modern, widely available academic tools to model a power plant with CCS, a dynamic load with grid parameters, and renewable energy?

### 1.5.2 Question #2

What are the relationships between Variable Renewable Energy (VRE) hosting, the dynamic CCS system, and the flexibility parameters of the power plant from a quantitative perspective?

### 1.5.3 Research Significance

CCS is a burgeoning opportunity for the power grid to adapt to environmental concerns while maintaining existing thermal plants (Anderson, Rode, Zhai, & Fischbeck, 2021) and creating a new fleet of flexible plants. However, the existing knowledge gaps do no one any favors in addressing the concerns (McLaughlin, et al., 2023). A power plant that can ramp up output quickly would be able to help adopt green renewable power like intermittent solar, but by how much? How complicated is the answer when discussing a distributed network that includes miles of transmission lines or loads with active components? Assuming the ability of CCS to be turned off during periods of high-power demand, how important might that feature be on days when solar is not as beneficial?

These questions are qualitatively easy to answer but quantitatively difficult without a model to input a systems parameter into to measure the case-by-case basis. A plant that can ramp up faster will support more variable solar power, but what is the difference between a 1% and a 15% ramp capability after it goes through a system? This research is developed to begin forming that answer for others to build off. The model developed here, to address Question #1, will be useful for others in this area to continue the work or adapt to their own devices, which would work to answer more specifics others would have in their own version of Question #2.

We have a power grid that is subject to a quickly changing energy landscape, an additional new technology that is relatively unknown and untested on the power grid at large, a significant number of unknowns about this technology, and a direct need, called out by some of the most well-known players in the world, for climate change. All of this together clearly shows a need for further understanding and the dissemination of more information so others can do the same and begin adopting these pieces. This is all easier said than done.

Of the past projects for CCS that will be covered, one of them showed negative results (Kemper), and another (Petra) gave results that are subject to controversy and discussion. Another project that will be highlighted (Tundra) could very well be the one that changes the dynamic of the technology; however, right now, the overall outlook is grim. On top of that, many of the papers discussed generalities and possibilities, but few have actively performed a study using numbers and applications. CCS can be expensive to implement, and the capabilities are unknown, so this makes sense.

Where this work will come in is that there is still a significant knowledge gap when it comes to analysis and modeling. This work will implement the literature review and use the most up-to-date variables. An example of this is the fact that there is a lot of talk of being able to build a CCS system capable of only a 5% parasitic load but the most concrete and sure number found was the one that went into detail on each variation of CCS but in general summarized to approximately 20% (Thorbjornsson, Wachtmeister, Wang, & Mikael, 2015). While certainly there will be advancing technologies and disagreements between theorists, this alone shows that so much still needs to be studied. The decision was made by the author for the reduction to be a 20% parasitic load, with the hope that future developments of the technology will decrease this number.

CCS systems are estimated to cost upwards of 500 million dollars (PNNL, 2023), depending on the size and the design of the system. That prevents most people from even considering the implementation of a CCS system, despite the clear need for it in the changing energy field.

With more science behind the technology, researchers can help businesses weigh the risks more intelligently. This is where the DOE’s Fossil Fuel branch comes in. While they are providing the aforementioned tax incentive, they are also investing in research and information dissemination.

Beyond simply educating the reader about this topic, the hope is to incorporate a number of analysis methods along with the work. Part of the parasitic load features of CCS can be mitigated in times of great need. The methodology is to use a look-ahead forecast method that allows us to "plan" for extreme need, allowing for a greater load to be supported than under normal operating conditions. The Arctic event (which will be covered in detail later) was an expected system stressor that was prepared for by increasing utility readiness and keeping generators on standby where possible.

The matter at hand is that you can do the same with CCS. If the look-ahead forecast calls for extreme weather patterns, CCS operations can be suspended to free up the loading capabilities of the plant to respond to this need. There will still be the option of reacting in the situation, which may come from other sources of disturbances, such as the malicious destruction of a local substation, but this stepping-stone implementation could be used to support that advanced simulation.

Ultimately, this work's significance can be measured in the ability to adapt to others' needs. Its reach can be measured in the idea that others can take this relatively unknown technology and play with the variables enough to define general parameters about their specific application. Through this, they can follow up with risk assessments and cost-benefit analysis.

### 1.5.4 CCS as a Solution

"Carbon capture can achieve 14 percent of the global greenhouse gas emissions reductions needed by 2050…" (Center for Climate and Energy Solutions, 2023). "If the world is to reach the goal of net zero emissions by 2050, we must remove between 7 and 9 billion tonnes of $CO_2$ a year. In other words, the need for CCS is enormous – and now the market is following suit because it is starting to pay off commercially." (Aasen, 2023).

CCS remains one of the few solutions allowing entities to continue using existing infrastructure, allow additional VRE hosting and/or maintain the thermal capacity to operate those resources and work towards their climate goals (Rahman, et al., 2017).

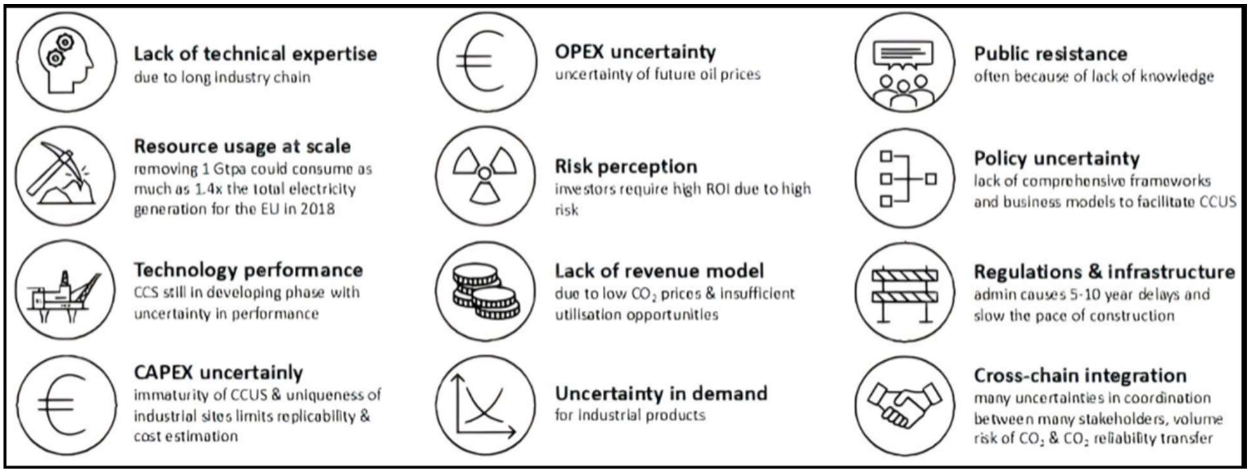


*Figure 26 There are many reasons as to why CCS is not being utilized as presented above. (European Commission, 2023)*

Figure 26 summarizes many challenges that face this climate solution. The work here directly addresses many of these findings and would allow others the opportunity to personalize the model and results to their application. From the list above, the models themselves and the results from this work will help address resource usage at scale, as there is no way to answer that without quantitative results bounded by parameters. Technology performance and Capex uncertainty can likewise only be evaluated by studies within the specifications of the design. Business cases require risk assessments, and models' performance helps show a system’s performance parameters and the benefits and drawbacks. Finally, it should be highlighted that the only way to begin addressing the public’s opinion of technology is with data and results along with clear representation (Denton, Chi, & Gursoy, 2020). It is fair to say that CCS’s application to power has had a checkered past, but to show the positives capable, if technological maturation takes place, can counteract those negative events.

# Chapter 2

## 2.1 Literature Review

The review here is broad and touches on more depth than the previous sections. As with any growing research subject, there are multiple viewpoints to cover and influencing factors to bring up. The factors impacting the adoption of CCS, as well as the various supporting technical studies, will be covered here. While direct studies may seem limited, there will be a discussion on the implementation of the technology, which will help further show the gap that exists and part of what influenced it.

### 2.1.1 ACE Rule: Its Impacts and Importance

The Affordable Clean Energy (ACE) Rule came about on June 19, 2019, from the Environmental Protection Agency, and was meant to replace the Clean Power Plan (CPP) (EPA Press Office, 2019). This broad action had many implications related to power generation, but mostly, it put forth efforts to reduce greenhouse emissions from coal-fired electric plants. The ACE Rule provided guidelines for the heat rate efficiency of a plant that directly influences its emissions with the belief that it could drop the energy sector's emissions to below 2005 levels by 2030. Tied to this, it would also perform evaluations for what it called the Best System of Emissions Reduction (BSER). These technologies would be critical to the plants that must meet the new guidelines that would come into place and would consider the age of the technology, the capability, and the business case of them so that plants could remain operational.

Several critiques came against the rule. The BSER went through several iterations, with the initial pass being a system that included heat rate improvements coupled with increased utilization of natural gas cycle units and increased renewable energy mixture. As it continued development, however, it became more reliant only on the heat rate improvements and left behind the other two parts of the system (Wentz, 2019). Some pointed out that while the rule used technology to ease emissions, the rule did not cap those emissions. Some of the worst critics argued that the rule essentially does not even meet the EPA's basic mission goals of protecting the environment, with one quote saying, "The Rule is a blatant abdication of EPA's statutory duty to protect the public from air pollution that the agency itself has repeatedly found poses grave and imminent dangers to health and welfare" (Beitsch, 2020).

Ultimately, the rule was struck down with it returning to its relation to the CPP and how it was initially brought about. “The ACE Rule expressly rests on the incorrect conclusion that the plain statutory text clearly foreclosed the Clean Power Plan, so that complete repeal was ‘the only permissible interpretation,’” the decision stated, adding that the agency “fundamentally ‘has misconceived the law,’ such that its conclusion ‘may not stand.’ ” (Court strikes down Trump coal power plant rule, 2021).

That does not mean that its legacy is not something to concern ourselves with. The threat of new guidelines and the necessity of new equipment changes the overall energy landscape beliefs. The Energy Information Administration (EIA) directly addresses this by fully admitting it influenced their retirement and energy mix forecasts for multiple years. The EIA attempts to follow quantifiable things like plant retirement dates, infrastructure improvements forecasted in state and local energy plants, and growing energy needs. They also attempt to add in the less easily assessed things like political changes, public opinion, and in this case, a rule that was looking to cost the coal plant fleet in the U.S. millions of dollars in structural changes to follow the guidelines or could also dramatically change power output and efficiency factors.

The AEO2020 reference case gave the option of taking it out of their outlook which had fairly large impacts in the shorter term. “In the No ACE Rule case, 9 GW less coal-fired capacity is retired in 2025 than in the Reference case, and 6 GW less is retired by 2050. This result has a larger effect in 2025–39, with 2%–3% more coalfired generation in the No ACE Rule case compared with the Reference case.” (EIA, 2020). This is a major influencing factor on why this legislation was so important. While the direct impact was removed, its ripple effect that extended into other research areas will continue.

### 2.1.2 Flexible CCS

Coming out of the UK from the International Energy Agency (IEA), specifically from the Greenhouse Gas R&D IEAGHG program, is the study of flexible CCS systems and how they can benefit their grid. Those authoring the study wanted to evaluate CCS and flexible versions of the technology to measure the overall system value gained by adopting the technology. They argue that while both the normal and flexible variants of the technology are expensive and have their drawbacks on a single generator level, the benefits they supply to the grid far outweigh those costs measured by their metric, Total System Cost (TSC). While other studies show that more flexible power plants are already market competitive on their own (Glensk & Madlener, 2019),this grid-level approach can help show the synergies available and has been shown in other studies (Braun, 2022).

TSC is a conglomeration of multiple variables and is the counterpoint to System Value (SV) wherein the added benefits override the negatives. These may include the addition of more renewable resources, the ability of thermal units to help grid operations, and the reduction in the need for a given region to require importing power and is supported by other studies that find that CCS has co-benefits to renewables it helps to host (Fennell, 2019). One of the outcomes from the study is presented below in Figure 27, where they took their results and plotted different technologies, and compared the capacity capability of their additions compared to their relative SV. Overall, post-combined cycle gas turbine technology proved to be superior to the other types, but all provided good system value.

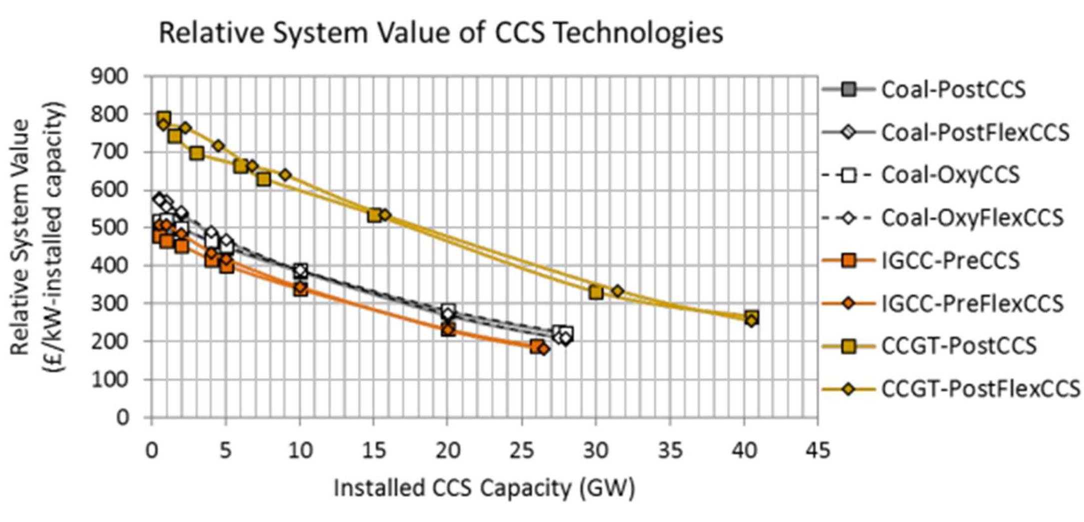


*Figure 27 System value provided to the UK grid comparing the various CCS technologies and their generation capacity. The graph shows that CCGT is significantly better than the others, but all provide a benefit (IEAGHG, 2017)*

To evaluate the technologies, a simulation based on the UK's electrical grid was developed and then evaluated against real values in the study year. When a consensus was reached, the results were used to extrapolate that system to 2030 and 2050 to see future scenarios. One of the driving factors behind the study (and behind this study) was that significant changes were expected to the energy mixes where more renewables are coming online, and the desire was to test what interconnection expectations may be required from these changes.

The results were that the system benefited greatly from the addition of CCS and flexible CCS. The below bullet points highlight the key findings.

- All variations of the technology show a reduction in TSC in the simulated years of 2030 and 2050.
- CCS allows a greater number of renewables to be added to the grid. This is important as cost optimal results require larger amounts of renewables.
- Flexible CCS technologies allowed more intermittent renewables than regular CCS.
- Flexible CCS operates under more frequent on-off periods, while its non-flexible type operates more continuously in shorter bursts.
- Flexible CCS reduces import power needs compared to non-flexible.

Some of these points repeat or relate to one another but show a good result overall. With flexible units, the costs are higher monetarily as well as operationally. This is offset by the greater freedom the unit enjoys, which allows it to start, stop, and intercept rapid changes in the grid from demand or renewable dropouts. Non-flexible CCS units still showed good results but are somewhat hampered by their inflexibility, where they would operate at higher rates for longer periods but were then offset by periods of hibernation where the economic startup was not justified.

The work done here bears multiple similarities to this one, where they simulated generation mixes in the future and compared the impacts of CCS on the grid, but each situation is different and justifies investigation. With the different regions of study, choice of simulation, and style of interpretation, there is plenty of value in proceeding with this work. This case study still provides significant merit to the need for continued study, though, and there are similar studies elsewhere at the high level showing positive CCS performance in the energy mixtures (Magnolia, Gambini, Mazzoni, & Vellini, 2023), but they rely on qualitative analysis instead of specific quantitative findings with respect to specific grid operations.

### 2.1.3 Arctic Event

While climate change was covered previously, along with the impacts it could have on the world and in reference to power grid operations specifically, the arctic event covered here demonstrates the immediate impacts in action. Other events, in recent history, could also demonstrate this, but to cover all of them would go well beyond the scope necessary here to understand the need for maintaining thermal power plants, the relationship to renewable energy, and the value that could be gained by having CCS act as an emergency variable during high demand grid events.

The report by MISO, covering the Arctic Event (MISO, 2021) that impacted large swathes of land in the southeast portion of the USA, brings forth many points to justify continued work towards CCS integration. The event itself is another name for storm Uri, which occurred between February 14 and 18, 2021. This storm took many of the balancing authorities by surprise. Balancing authorities are entities that work to ensure grid operations are status quo while allowing power generators the freedom to take advantage of energy market fluctuations. Systems that were thought to be prepared were overcome, and those that were weathering the impacts well were suddenly being hit with requests to support their neighbors. This event is not without precedence, as noted in Figure 28.

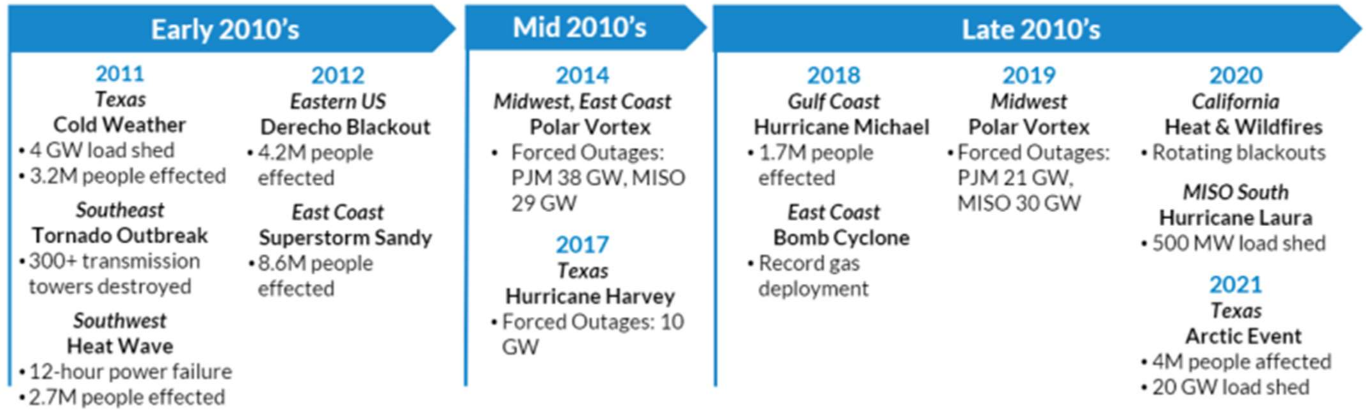


*Figure 28 This infographic shows some of the more noteworthy grid level emergencies in recent history (MISO, 2021)*

This polar vortex impacted large swathes of land. Locally the grid may have mild impacts but in the modern-day grid it is all interconnected so drops in renewable capabilities, like solar with its dependence on clear skies, must be made up somewhere. This event was particularly bad, as its impacts were felt across grid territory lines to Electric Reliability Council of Texas (ERCOT) made up mostly by the state of Texas (Kemabonta, 2021). The map in Figure 29 shows some of the major impacts of the storm and their extensive reach even outside of the storm's path. This is an important thing to note as the local grid needs to be resilient, just as much as surrounding ones, due to the interconnectivity (Das, Munikoti, Natarajan, & Srinivasan, 2020).

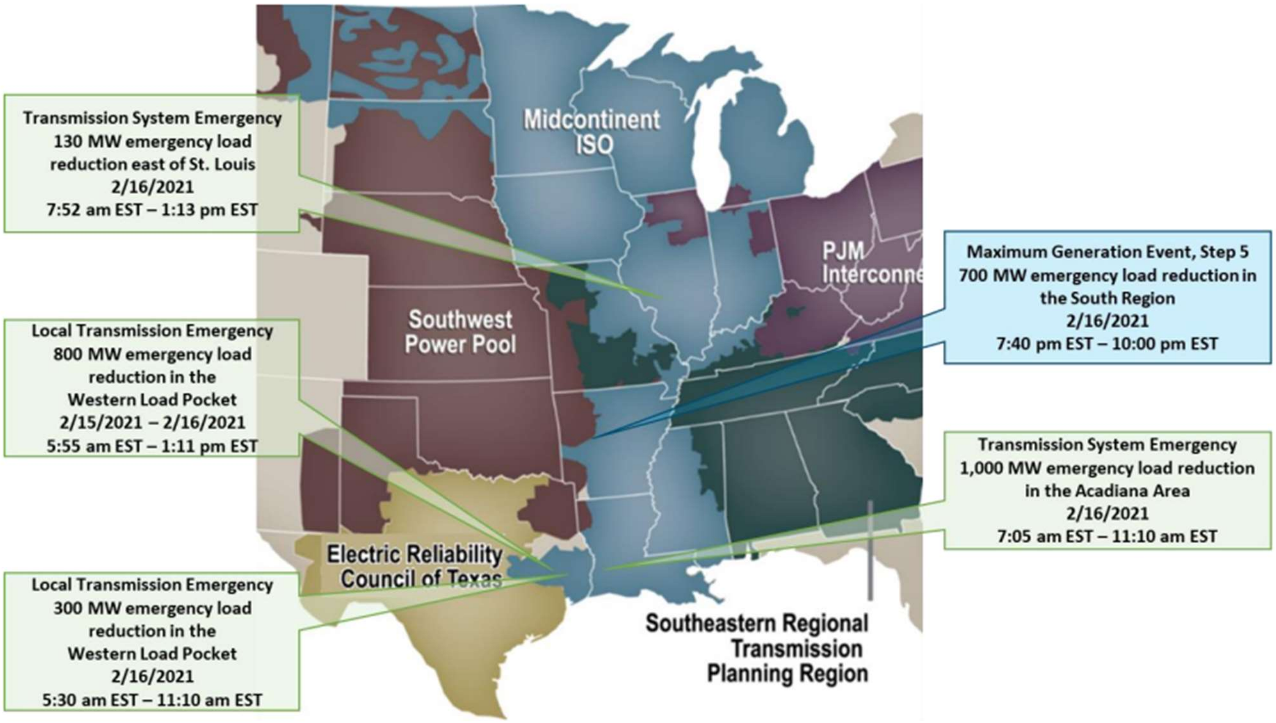


*Figure 29 A map of the EIC pointing out some of the more significant impacts of storm Uri. The report is by MISO, but many neighboring authorities were impacted as well (MISO, 2021)*

Multiple lessons were learned from this event, ranging from the installation of new lines to allow more power transfer during emergency conditions to changes in how the energy market is operated. Renewable power during the event was sporadic at best with high winds and cloudy skies. Thermal generation was impacted as well, with fuel transport and lines being interrupted with some freezing over. CCS would not have been a silver bullet in this case. Walton specifically noted in his report that “Coal provided a bigger overall percentage of the generation mix during the worst periods, but actually delivered a lower percent of its capacity than wind” (Walton, 2021).

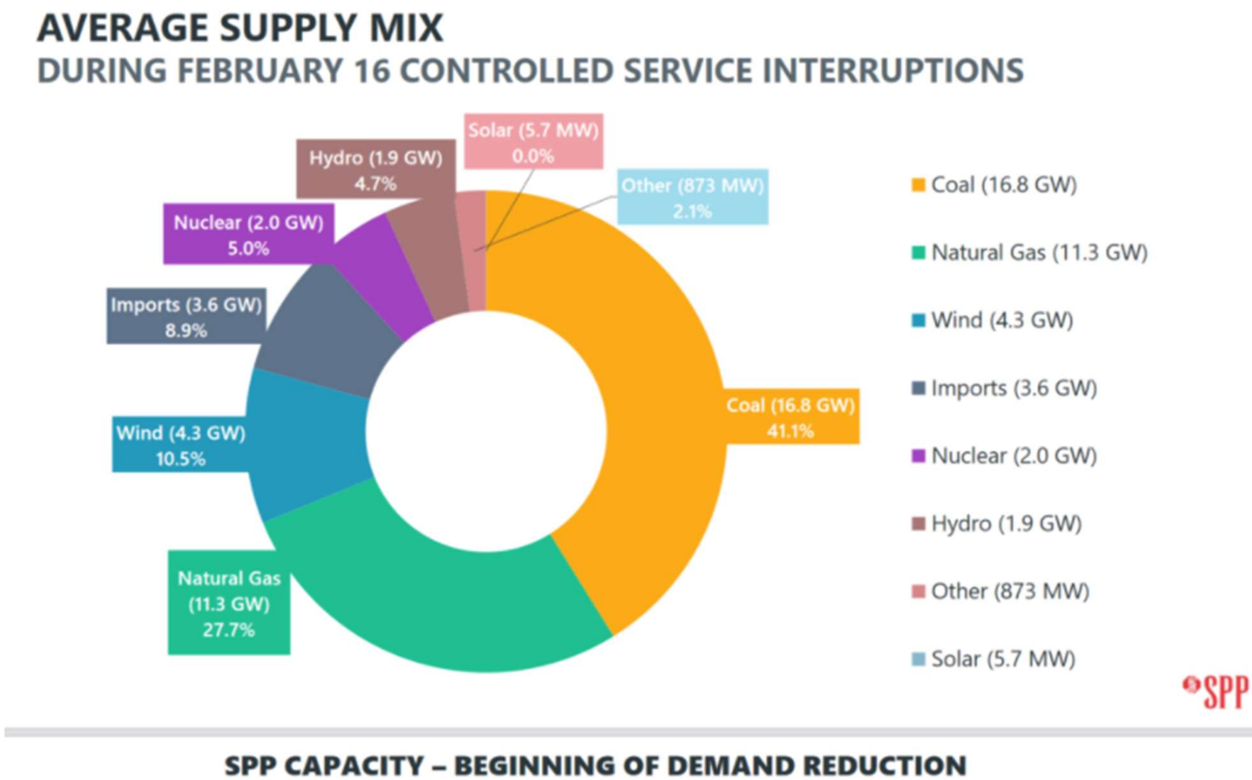


*Figure 30 Energy mix during winter storm URI on February 16 from SPP (Walton, 2021)*

Note, however, the importance that amount may have played in this event at 41% (as seen in Figure 30) of the mix for SPP. Without CCS, coal plants are being phased out in pursuit of greener agendas. This is not inherently wrong, but the impacts of leaving the grid without study represent a significant unknown at a time when the grid seems to be experiencing unprecedented numbers of extreme events and subject to more cascading failure events (Lian, Qian, Li, Chen, & Tang, 2023) (Wu, Chen, Chang, & Hong, 2022).

### 2.1.4 GridMat

It should be noted here that a significant amount of time was spent looking into and trying to use the program known as GridMat. GridMat was developed by Mohammad Abdullah Al Faruque and Fereidoun Ahourai (Faruque & Ahourai, 2014) and was built to be an enhancement of Gridlab-D, similar to what this work is now doing. A layout can be seen below in Figure 31.

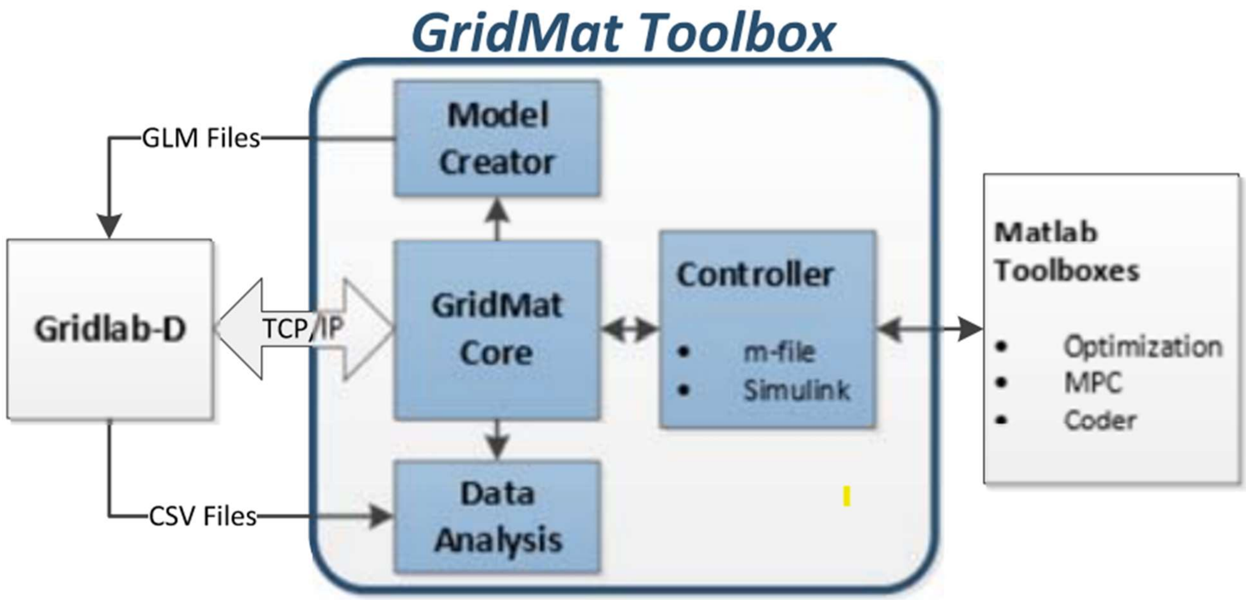


Figure 31 Hierarchy of GridMat (Faruque & Ahourai, 2014)

In their work, they highlight the advantages of Gridlab-D and note the distinct lack of controls and user-friendly use while highlighting MATLAB's capabilities. Their work focuses on fixing this problem by integrating the two software platforms and giving users a better interface to understand and troubleshoot operations. The main driver behind this work was in application to microgrid validation and operation controls.

While this seems like it would be great to build off from, GridMat seems to have been essentially abandoned since inception in 2014 with the original posting on SourceForge (a repository for software and code projects) remaining virtually untouched since then. Those that support Gridlab-D are often queried about their involvement with GridMat, but they are quick to admit that it is separate and not supported or tested by Gridlab-D developers. The reviews on the SourceForge posting from nearly a decade ago also seem mixed, with some stating that it no longer works. Their implementation of Gridlab-D with MATLAB was impressive, but in doing so, I believe they created something that would not be able to be easily adjusted as Gridlab-D was updated over time.

While there are similarities between their work and the work presented here, theirs delves far deeper into creating a user tool while this effort is focused on creating a general model. The aim is to have the models and algorithms be open enough to allow easy adaptation to other applications and methodologies, with the bare bones being essentially nested with the mathematical equations and logic trees in MATLAB and the grid simulation portion possibly adapted to other softwares. The aim of this study is that as this research ages, the structure of it will still be applicable.

### 2.1.5 CCS Studies & Simulations Overall

There are several existing studies and simulation works in the field concerning CCS technology. One such study discusses an algebraic approach to the system-wide distribution of thermal CCS plants with a focus on maintaining the demand curve,; but much like the Flexible study from above, the grid is simplified to whole single demand point values which are good but lack the fidelity necessary for application-specific instances (Sahu, Bandyopadhyay, Foo, Ng, & Tan, 2014). Another paper performs a similar large-scale study of plants in India and the possible location specifics in regard to carbon storage location parameters (Garg, et al., 2017). Another looks at Mexico and their desire to meet their 2050 climate targets and how distributed CCS could support that long-term goal (Fernandez & Baker, 2022).

Many economic studies support CCS (Singh, Ku, Macdowell, & Cao, 2022) and (Gooty, et al., 2023), overall. There are also a number of studies that go into CCS environmental impacts and possible environmental strategies (Gyanwali, Komiyama, & Fujii, 2021), (Amiri-Pebdani, Alinaghian, & Khosroshahi, 2023), and (Hu & Wu, 2023). There are a number of small-scale specific applications of CCS technology as well (Thomas & Mishra, 2022), (Ferrario, Stendardo, Verda, & Adrea Lanzini, 2023), and (Costamagna, 2021).

There is no shortage of technical documentation available for CCS. Many studies agree that CCS is a technology with ample opportunity available to it. However, there is a distinct lack of research in direct grid modeling with CCS-enabled plants. This work's Question #1 model and the subsequent relationships from that model that support Question #2 are distinct in that it will look at how a grid, with a plant limited by CCS during normal operation, can flexibly adapt to both its own newfound system as well as outside distributed VRE's.

## 2.2 Grid Reliability

Grid reliability is ultimately what this research is coming to address. The difficulty of this topic is that it means different things for different people and has been a changing subject as technology is introduced and different consequences are discovered. We can all agree that the delivery of power to those who need it and when they need it is the basic definition, but the problems can become evident when you look at the details. Are brownouts and blackouts of a significant magnitude seen in other countries enough to say that their power grid is unreliable? Would 99% consistent power availability be sufficient for a hospital with no backup preparations for those reliant on external life support machinery? How about simply having spikes that temporarily shock the system, possibly causing damage to more sensitive machinery but are otherwise consistent and traditionally considered reliable? This difficulty in setting a definition may seem trivial but it is pivotal in this research. The following section will further highlight the massive task before this work in addressing reliability in the power grid.

### 2.2.1 Grid reliability compared to resiliency

It's hard to talk about grid reliability without bringing up grid resilience. The two terms often get mixed together and, while they can have similar missions, there is an important distinction. Grid reliability is simply the ability of the power grid to deliver electricity to its customer. Grid resilience, though, is the ability of that power grid to both prepare for and adapt to dynamic situations. These situations could be natural in occurrence or come from internal or foreign actors (Pierre, 2021).

This is an important distinction, as CCS supports both reliability and resiliency. CCS could be a way to keep existing thermal power plants online amid changes in ecologically focused environments

(Xie, et al., 2023). As I have shown there is still a significant need for thermal power to act as a baseload supply in grids that host large amounts of intermittent renewable energy. This can become tricky as you want to invest in that renewable resource, but it is acting against you by driving down the use of the thermal source, so the thermal source struggles to remain economically viable. With a CCS unit installed, it could meet your ecological expectations by allowing the thermal plant to stay online in periods when renewables are available but quickly switch if there is a sudden demand in a rush.

In this way, CCS could be one of the tools that allows a grid to meet reliability demands better, but it could also help the grid meet resiliency points. While there is no one prescriptive way to enable a reliant grid, diversifying the energy mix portfolio is certainly part of the solution (Mihlmester & Choate, 2017). A diversified energy portfolio makes it difficult for any singular grid impact to knock out a diversified grid.

In considering diversified energy resources, consider the Uri storm. While the storm was certainly an extreme case that went above and beyond in taking out so many different resources, we saw a difference in how the resources were impacted. Solar was shut down without sunlight, the wind was not properly weatherized, and thermal was impacted through losses of resource delivery or pipeline shutdowns. Any one of these factors could be addressed and better prepared for the next storm, but there is no single fix that would impact them all, which may seem counter to the point, but at the same time, there was no singular cause that took them all out either.

This will be expanded on in the coming sections as there cannot be enough said on how different these concerns have become over time. There was a time when a simple connection and a source was enough to meet resilience and reliability concerns but that certainly is not the case anymore as the grid has become more complex and threats towards it have been gradually evolving as well.

### 2.2.2 Malicious Actors

“Malicious actors” is a term that was taken from the cyber realm and is a catch-all term that encompasses those that mean to harm your subjective network. This, of course, fits into the power grid as well. Malicious actors really were not something that was a concern to grid operators in the past but is growing more prominent over time as geopolitical environments become more prominent or the advancing interconnection of the grid opens unknown vulnerabilities. In fact, when a vulnerability is mitigated, it is often outpaced by other threatening technologies (Ratnam, Baldwin, Mancarella, Howden, & Seebeck, 2020). The following will demonstrate this with an example.

On April 16th, 2013, an attack occurred against an electrical substation around San Jose California (Smith, 2014). Around 1 AM, some communication lines owned by AT&T were cut, thereby disabling customer service to a small area around the Metcalf substation. About 30 minutes later, a surveillance camera picked up what investigators believe to have been muzzle flash from rifles, as well as flashlight signals, and the police received calls reporting what sounded like gunfire in the area. Shortly thereafter, PG&E (Pacific Gas & Electric) began receiving alarms around the substation reporting motion and another alarm as the first back of transformers failed from overheating due to a loss of oil. The oil had drained from the units through the many bullet holes having been shot into them at a range of about 40-60 yards. At about 1:50 AM, another image from the surveillance system is believed to have been a signal to halt the attack. Upon investigation by the police, more than 100 rounds of 7.62x39mm were expended.

Upon further investigation, PG&E stated that 17 transformers were significantly damaged, and the total damage exceeded 15 million dollars. Of additional concern were the local power outages. While some residential areas lost power temporarily, it was reported that this substation is a major power connection that feeds Silicon Valley. PG&E was able to reroute power and get the grid back online in short order, but such a massive disruption that occurs so suddenly could have had more severe, successive events had just a few more things gone wrong.

Following this event, millions were poured into the power grid, upping security to try and mitigate future events, but we are talking about a grid that was designed to span from coast to coast of the entire U.S. in an interconnected manner and, in some cases, even internationally. While there was always the possibility that a weather storm could cause massive sudden damage or someone could accidentally take out a tie line, this was one of the earliest and most prominent examples of what could have been a concentrated attack by a foreign entity or a homegrown terrorist group out to cause widespread damage. Recent history shows that it was not to be the last, either. In fact, CBS says that there has been a 71% rise in grid attacks in the last year (Sganga, 2023).

Some of these attacks are similar in nature to the above, where ballistic damage is evident, while others fall under “simple” vandalism. More worrying is that it is believed these attacks are focused by groups hoping to bring down society by destroying the power grid and plunging society into chaos. Other attacks are less physical and more electronic. The DOE secretary Jennifer Granholm stated that “enemies of the United States have the capability to shut down the U.S. power grid, and “there are very malign actors trying, even as we speak.”” (Walton R. , 2021).

Ultimately, what is important to know from this section is that there are a host of evolving threats to the power grid beyond a lightning strike or hot weather causing more AC usage. Grid leaders are working to address these concerns with more advanced studies to find vulnerability solutions (Xiang, Zhang, Shi, Diao, & Wang, 2020) and, more directly, the beefed-up security that PG&E put into place after the Metcalf attack back in 2013, but it is impossible to completely solve this issue, especially if we begin to talk about other nations coordinating attacks against us in unexpected ways. While the specific cause of a transformer going out may be different, where this ties into this work is that there is a level of uncertainty in all power grids no matter how secure, and the ability of this model to be adapted to these concerns would be beneficial to researchers and those that concern themselves with the customer satisfaction of power delivery.

So, in the end, we have traditional concerns to worry about, like meeting increased summertime demand or an unexpectedly bad storm, as well as emerging threats that are taking advantage of the growing vulnerabilities (Sun, Hahn, & Liu, 2018).

### 2.2.3 Variable Renewable Energy (VRE)

Along with this discussion is the advancement of renewable energy itself and how it has greatly changed the landscape of energy. While these resources do not inherently make a grid more stable or unstable the growing pain of their increased incorporation significantly impacts resilience, reliability, and simple operation (Jin B. , 2023) (Beyza & Yusta, 2022).

#### *2.2.3.1 What Makes a VRE*

A VRE is an energy resource whose output cannot be easily depended on due to its intermittency and inability to store its power. This could be a daily or seasonal occurrence, as depicted in Figure 32.

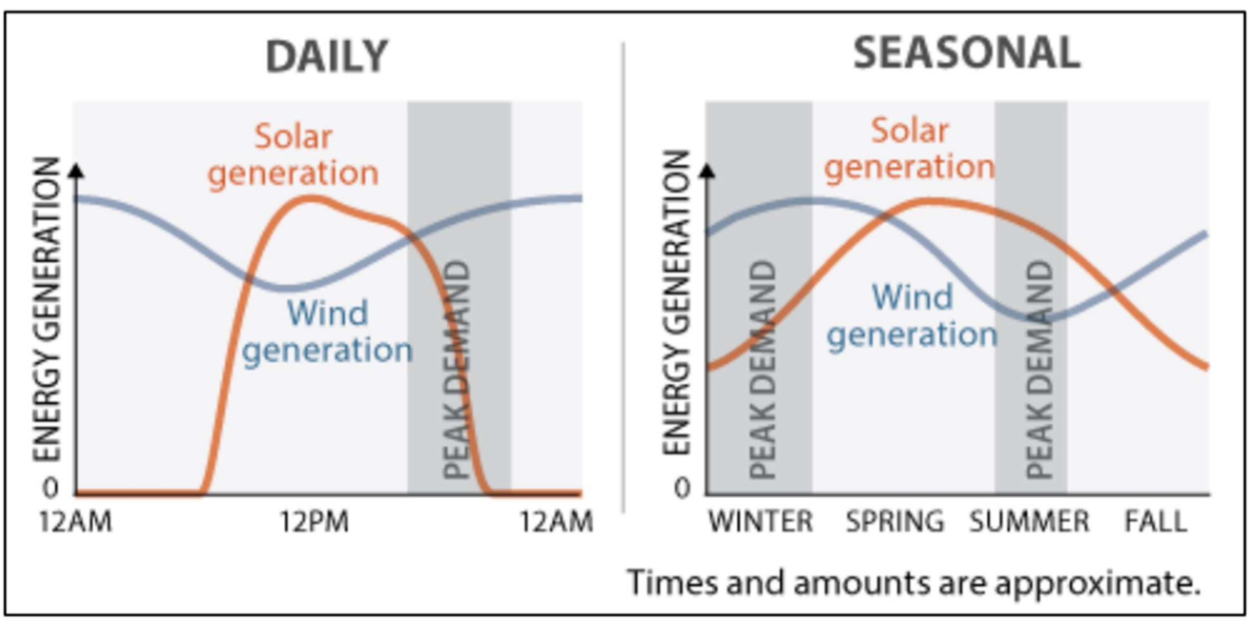


*Figure 32 Here the resources fluctuate by both the season and the time of day. (Lawson, 2019)*

With this intermittency being inherent to the resources, it becomes difficult for grid operators to dispatch base load power sources reliably, with changes in methodology becoming necessary (Wang, et al., 2023). A certain amount of power needs to be held in reserve should the renewable resources suddenly cut out. This causes the needed amount of renewables to far exceed the maximum demand as the renewables need to have an operational range beyond the maximum demand as well as a degree of flexibility from the grid itself to allow base-load reserve to increase their penetration levels (Impram, Nese, & Oral, 2020).

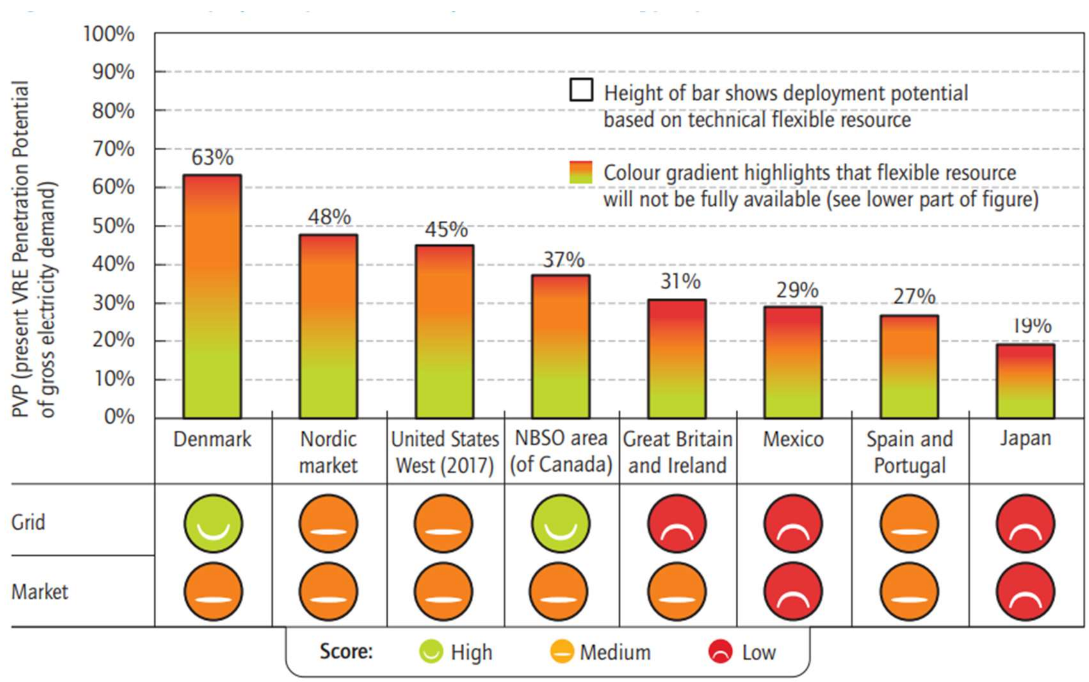


*Figure 33 The penetration rate (ability of a system to accept a percentage of VREs into it) varies depending on market, grid, and economic factors. (Internation Energy Agency, 2011)*

CCS could supply this needed capability by allowing these VREs to operate during periods of high output while remaining in reserve and then switching modes and turning down or off the CCS apparatus to supply maximum thermal capabilities during times of increased demand. Figure 33 above shows the variability of some grids require more flexibility to allow more renewables to be hosted.

### *2.2.3.2 What is a VRE*

Most could probably name the renewable energy sources that fall under this category already as they are well known. Not all renewable energy sources are VREs, though. Hydro and geothermal are both considered to be dispatchable and have enough energy reserve that grid operators generally place them in the same baseload category as other thermal plants like coal and gas. Solar, wind, and, to some extent and application, tidal remain as VREs, though.

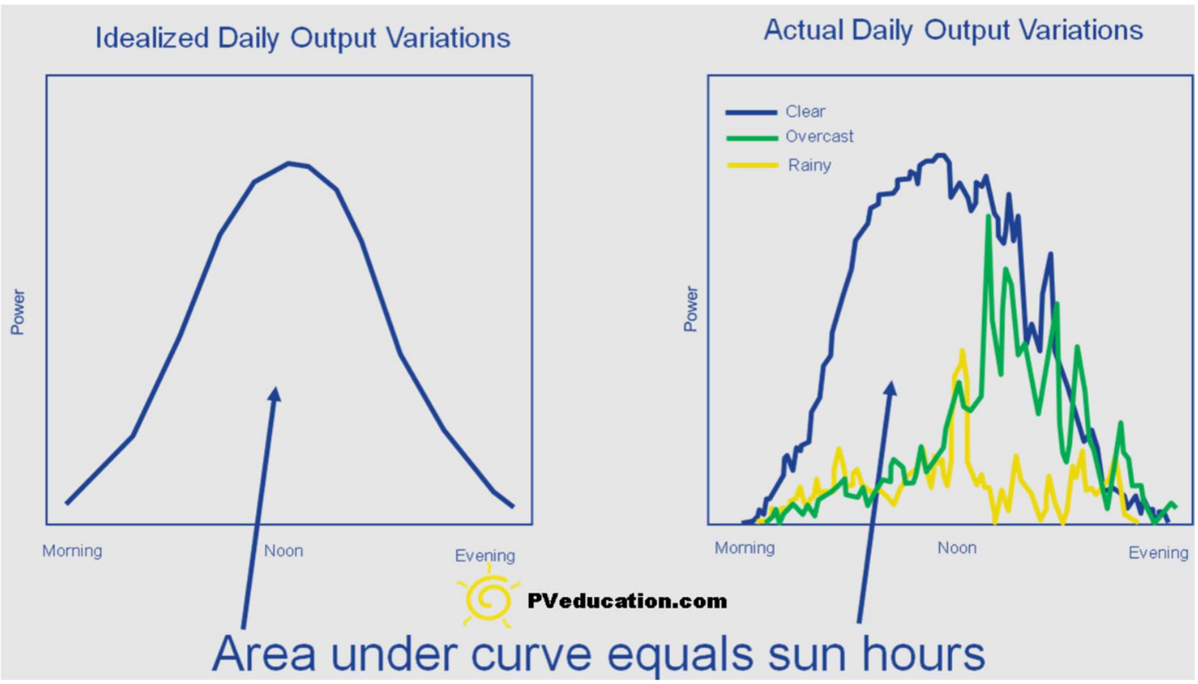


*Figure 34 This graphic shows a generic solar curve and influencing factors that can make it variable day to day. (PVeducation, 2023)*

The curve in Figure 34 shows the significant differences between day-to-day operation of a solar array depending on the weather. The idealized curve shows something that can be easily planned around, but as the weather becomes a factor, the difficulties start to show through.

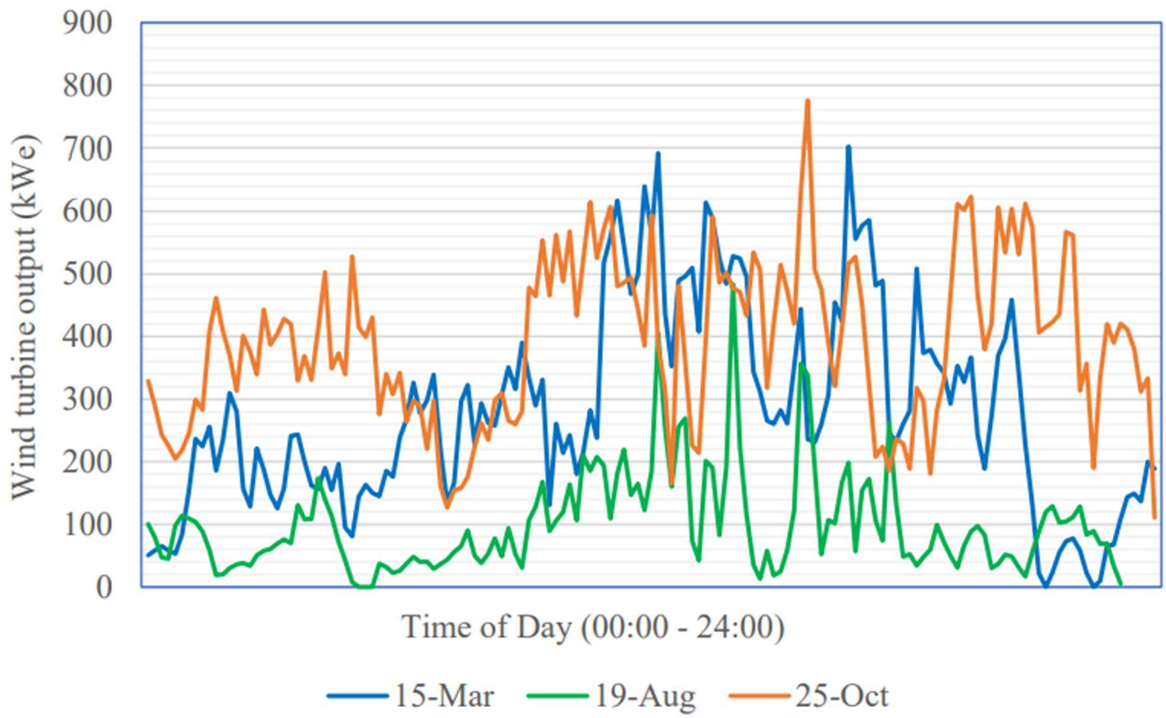


*Figure 35 Example of the different outputs of a single wind turbine. (Huang, 2018)*

Figure 35 shows the output of the same wind turbine but on different days, subjected to different wind patterns. While some argue that wind power is more reliable than the sun and go so far as to say that the resource should not actually be considered intermittent but only variable (Wind Energy the facts, 2023), the resource is still subject to fluctuations that make it difficult to plan around.

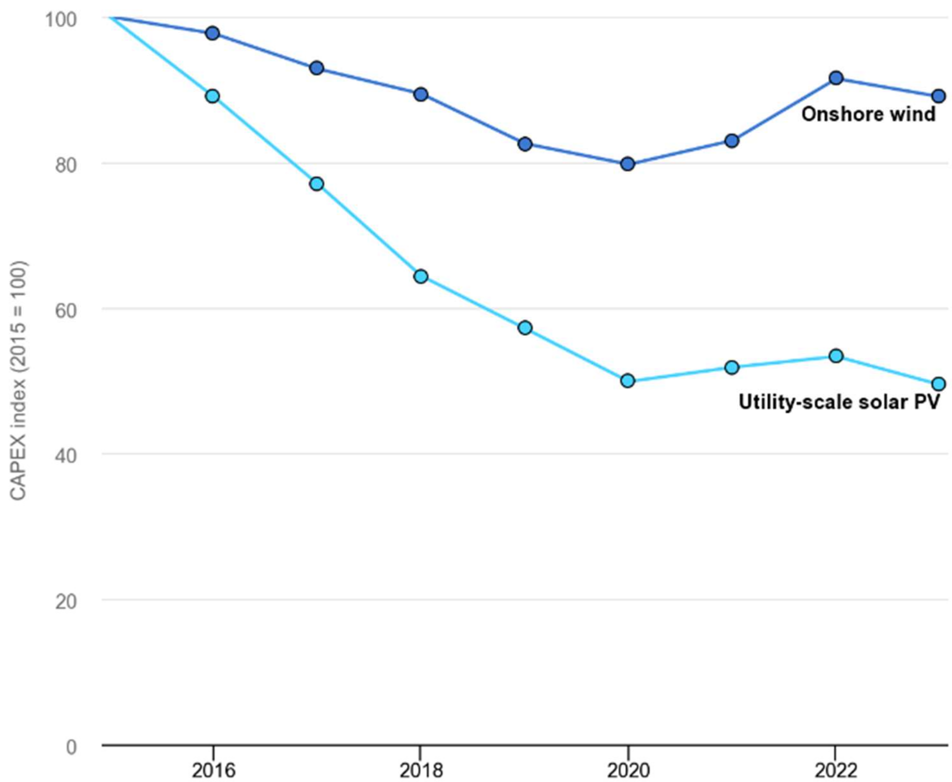


*Figure 36 Despite the problems with the resources both wind and solar have been consistently trending down in cost over time. (IEA, 2015-2023)*

Both wind and solar have become increasingly more competitive cost-wise (as shown in Figure 36) leading the charge to greater adoption on both the grid and in personal systems.

*2.2.3.3 Energy Storage*

VRE's have already found their theoretical solution in energy storage systems, which would solve the intermittency issue. This comes in a few different forms but is primarily made up of pumped-hydropower, with the hopes that grid-scale batteries will quickly surpass it in the future (see Figure 37).An IEA report shows in Figure 38 that while the technology has gone through significant improvement in recent times, there is a significant concern that scaling the technology will take a considerable amount of time to meet climate goals. This addresses the installation and anticipated need but does not speak to the mineral limitations both geographically as well as the necessary methods to extract the resources being environmental and cost prohibitive.

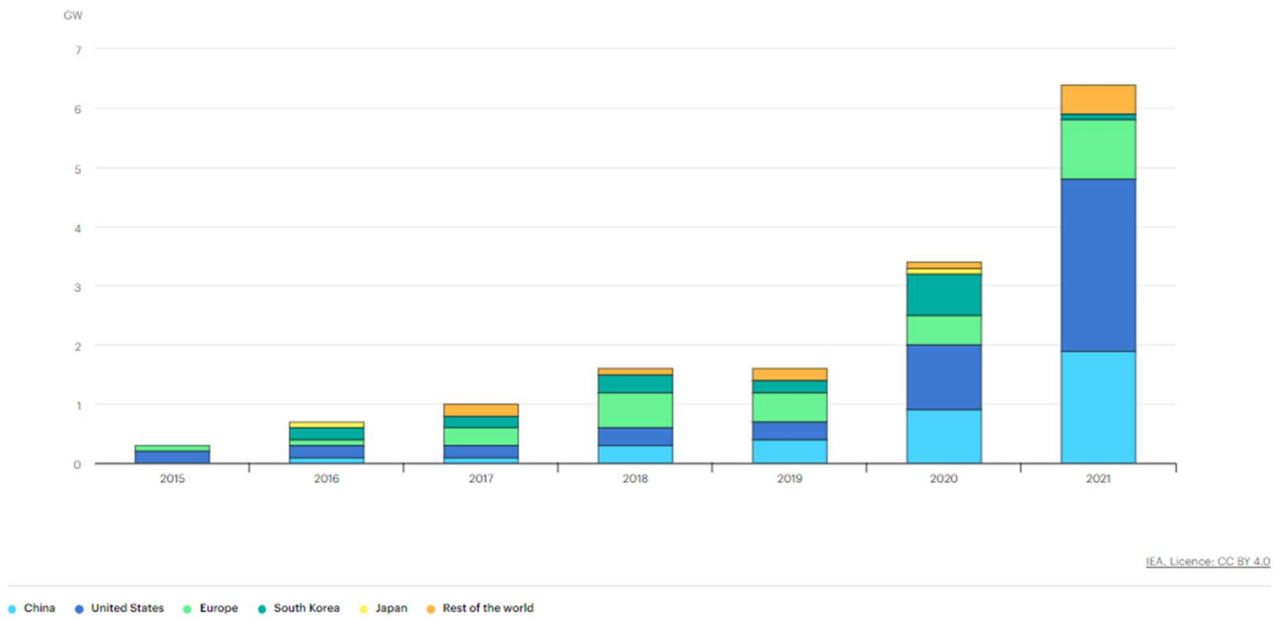


*Figure 37 The amount of grid-installed batteries the world over is growing quickly but is still very small compared to the need for them. (IEA, 2016-2021)*

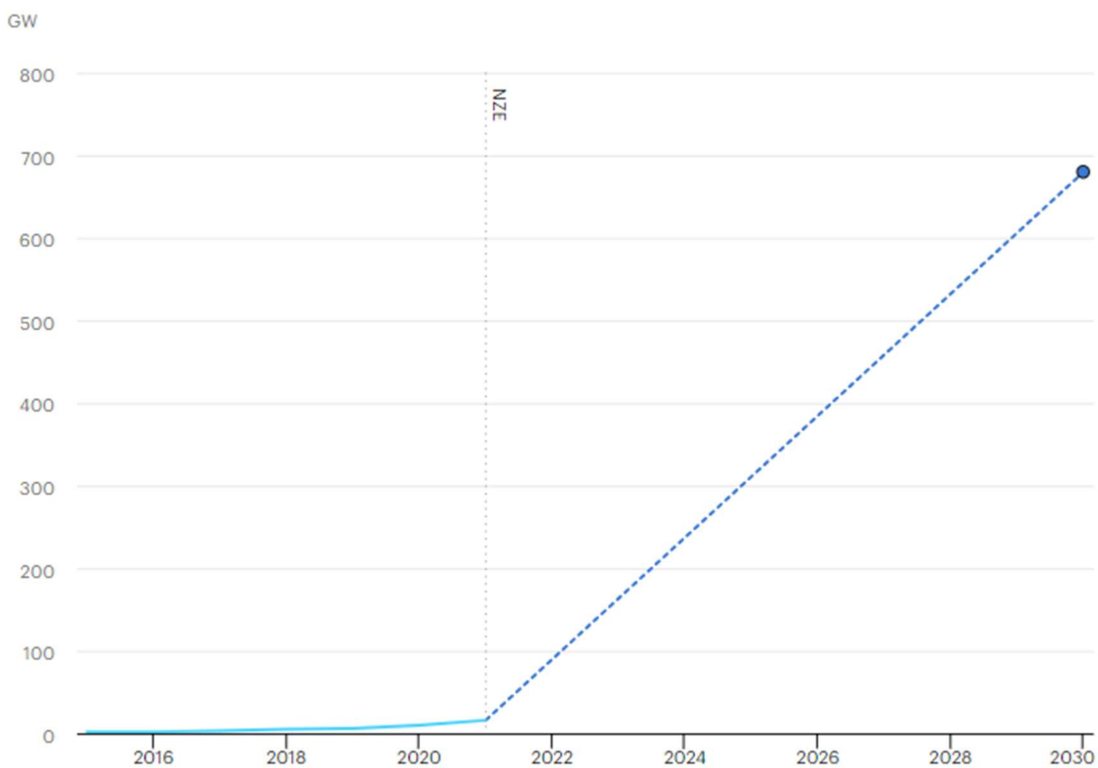


*Figure 38 The necessary scaling needed for grid storage options to meet net-zero scenario goals. X-axis is in years. (IEA, 2016-2021)*

## 2.3 Efforts to Adopt CCS

### 2.3.1 Existing CCS projects

Just as important are both the historical and existing CCS projects that are taking place in the US. Without this proof of concept, the adoption of the technology is likely never to come to fruition. The following snippets will show the more well-known related events but are not all-inclusive. Some of the above literature comes from around the world, with a big chunk of it taking place across the pond in England, which heavily invests in the idea. The next decade will likely see even more pop-up installations as lessons are learned, and the investments begin to mount progress.

*2.3.1.1 Project Tundra*

Project Tundra is an effort in the very backyard of my studied region using one of the coal plants (featured later in my simulations) using the generators of the Milton R. Young coal power plant. This project will build the largest carbon capture facility to date should it come to fruition (Minnkota Power Cooperative, 2022) and will bring together many different stakeholders, including the operators of the plant, the owning body (Minnkota Power Cooperative), and the Energy & Environmental Research Center (EERC).

The plant comprises two lignite coal units that started service in 1970 and 1977 with generation capacities of 250 MW and 455 MW. This plant is nestled near the center of the state of North Dakota and has been a contributing member to the power grid in its area since opening. The coal mine that feeds the units is the BNI coal mine and its close proximity helps ensure reliable and continuous operations when other plants are vulnerable to fuel disruptions.

Construction of the add-on CCS facility is pending the results of the research and design phase results but is expected to begin in 2023. CCS operations will run the full lifecycle with coal mining, to capture in the power generation facility, and then finally, the sequestration of the captured $CO_2$.

Relating to the project work done here should be obvious. The project is still within the design and research phase, where those working on the efforts are using these outcomes to influence decisions before action. The project costs are expected to exceed 1 billion dollars, so the influence of studies such as mine will help justify or change the decisions that are being made. Research is a cornerstone of technological developments and is known to continue well beyond the first iterations of application as impacts are still being learned and methods are being refined.

*2.3.1.2 Petra Nova project*

Project Tundra is an upcoming project, while the Petra Nova facility is, for all intents and purposes, complete. It was a retrofit that was applied to one of the boilers at the NRG Energy WA Parish generating station in Thompsons, Texas. This post-combustion system was adapted to the 1977 equipment and was designed to annually capture 33% of the $CO_2$ that was generated from unit #8 (EIA, 2022).

The captured $CO_2$ was then used in EOR operations at a nearby oil field where the added pressurized gas could contribute to that field's output. While the project was completed on budget and on time, the project's lifetime was cut short. On May 1st, 2020, the NRG shut the project down, citing low oil prices during the COVID-19 pandemic. Originally this project was expected to operate for another 20 years, so the 3-year operation window was cut back.

During its time of operation, the facility performed several operations for research applications including ramp up, ramp down, full load, and emergency shutdown operations (Petra Nova Parish Holdings LLC, 2022). How much of this was cut short due to its sudden shut down? Hard to say from the final technical report. Going beyond what was done, this was a very specific application of CCS that would differ from the study done here and the technical community would find useful.

One key aspect is that this system was supported by a separate dedicated gas system to power it. This by itself changes the dynamics of the project from less of a grid application of the technology and more of a research project for the operation and use of the captured material and it showed that it had some advantages when compared to other CCS projects such as Boundary Dam (Mantripragada, Zhai, & Rubin, 2019). Still interesting from an application and cost perspective, but the impact on the surrounding grid would be hard to count on.

*2.3.1.3 Kemper Project*

The Kemper project never fully came to fruition but lends itself well to the continued unknowns of CCS. The project broke ground in 2010 at the Kemper County energy facility in Mississippi and was supposed to be the largest gasification and CCS commercial application.

There were several contributing factors to its ultimate end, but the major point was the massive construction cost overrun and delays. Towards the end of the project, the project oversight suspended coal gasification with plans to operate as a natural gas plant, and then, the full infrastructure was demolished in 2021, ending its timeline for the project (Geuss, 2017).

The Kemper project is generally considered a failure for CCS (Swartz, 2021). While the losses incurred at the individual location are bad on their own, the damage to the technology's reputation may be worse. When something gets known for such a loss in capital, it can be harder to get investors onboard in future projects. As it is already an uphill battle, the importance of this work is magnified.

*2.3.1.4 Boundary Dam*

Boundary Dam is a functional CCS system in Canada near Estevan. They began CCS operations in the fall of 2014 and reduced up to 90% of $CO_2$ emissions (SaskPower, 2023), although the actual operational numbers vary depending on maintenance and schedule. Joel Cherry stated, "Just because it's capable of that doesn't mean it makes sense operationally to run the facility to max capacity…. Our actual capture target rate is between 75% and 80%." (Rives, 2022). The same article highlights that the project is the longest running and sole CCS project in the world.

This 115 MW proof of concept on unit #3 is estimated to have a 30-year lifetime and was a refurbishment for an older aging unit (The Star Phoenix, 2014), but operationally only performed at 110 MW for a 12-month period and the uninhibited design. This is a key piece of information for this work as the designed nameplate capacity of the unit after refurbishment was 139MW, but even this can be a little difficult to work with.

This quote from Mike Marsh, the SaskPower CEO, helps illustrate the point: "We had net megawatts of 139 off of a gross megawatt rated unit of 150 [before the retrofit]. When we refurbished this unit, we upgraded the design so with the same amount of coal that is used we can now achieve better efficiency. We can achieve 161-162 megawatts when we're not running the carbon capture facility. When the carbon capture facility is running, we'll have a net megawatt of 120, so essentially 40 megawatts of parasitic load." (Harvey, 2015).

If you were to take the numbers quoted at their best of 162 MW with a parasitic of 40 MW, you find that the draw of the facility is approximately 24.5%. This is higher than most papers have assumed the facilities would draw, but since this is the first large-scale power application, improvements and lessons learned could have already been found. Calling back to the TRL paper, there is already a steep decline expected in the cost of $CO_2$ captured per tonne and is directly attributed to a "learning by doing" effect where the best way to find more efficient designs and improvements is to follow through with the projects as shown in Figure 39.

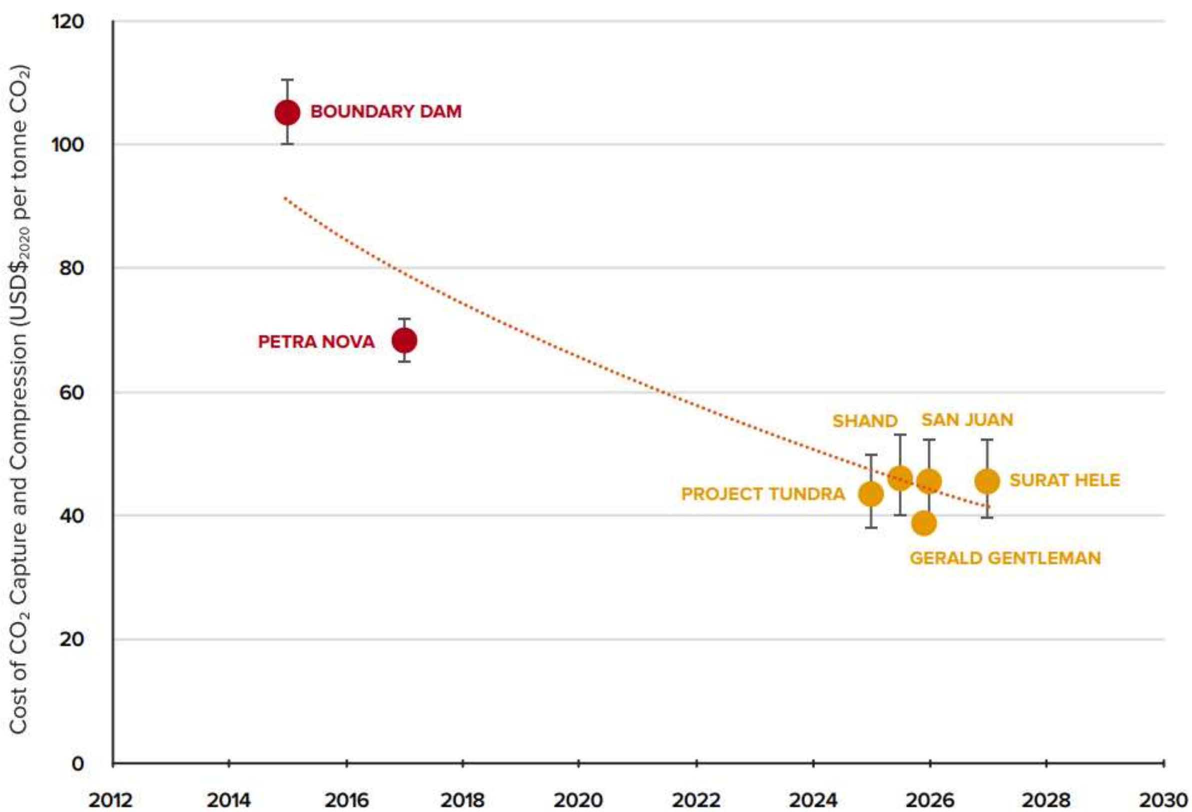


*Figure 39 The graph relates the cost of $CO_2$ capture in tonnes over time and relates the various projects that were highlighted here. Note the timeline of notable projects is mostly future based. (Kearns, Liu, & Consoli, 2021)*

Since Boundary Dam has such a long history, and SaskPower hopes to install additional units, it must be considered a success, correct? Not necessarily. Emission numbers have not met the designed 1 million tons a year shown in Figure 40.

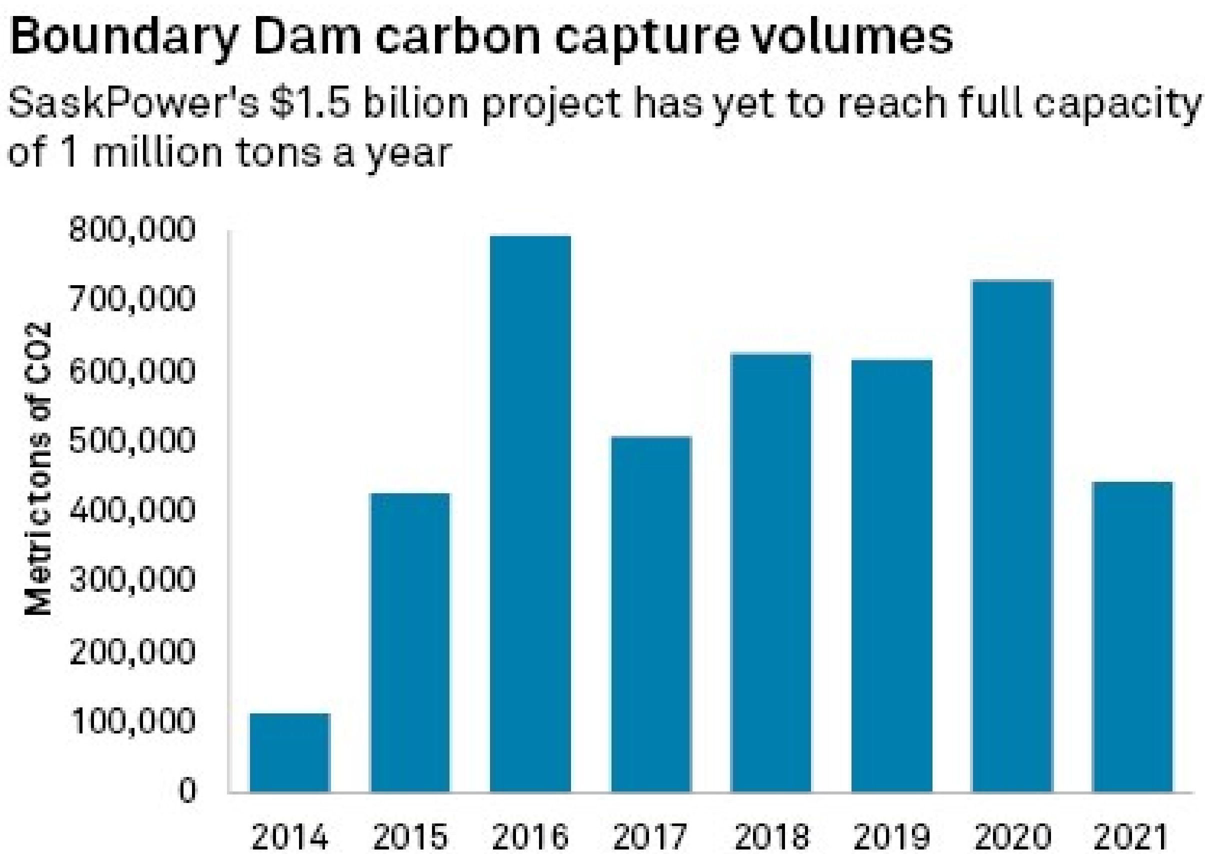


*Figure 40 Reported emissions have shifted year to year based on maintenance, interruptions, and other issues. (Rives, 2022)*

Given its significant cost (CAD $1.5 billion) some are saying the lack of meeting the targets is not worth the extreme cost, and some are highlighting it as a lesson learned. "The fact that Petra Nova and Boundary Dam both experienced frequent outages during just a few years of operations should serve as a red flag for policymakers and investors considering coal carbon capture proposals", said Joe Smyth, a research manager at Energy and Policy Institute (Anchondo, 2022). However, the only way to increase the TRL of a technology is to continue learning by doing. To that end, this work presents models and quantitative analysis in support of that goal.

### 2.3.2 45Q tax credits

With all this said, the US government is doing something to directly influence this by introducing the 45Q tax credit. The tax credit is an incentive for the adoption of the CCS technology by allowing a user of CCS to claim a rebate from the government, depending on the amount, type, and implementation time. See Figure 41 for additional details.

**Table 1. Key Elements of the Section 45Q Credit**

| Equipment Placed in Service Before 2/9/2018 | Equipment Placed in Service on 2/9/2018 or Later |
|---|---|
| **Credit Amount (per Metric Ton of $CO_2$)*** | |
| *Geologically Sequestered $CO_2$* | |
| $23.82 in 2020. Inflation-adjusted annually. | $31.77 in 2020. Increasing to $50 by 2026, then inflation-adjusted. |
| *Geologically Sequestered $CO_2$ with EOR* | |
| $11.91 in 2020. Inflation-adjusted annually. | $20.22 in 2020. Increasing to $35 by 2026, then inflation-adjusted. |
| *Other Qualified Use of $CO_2$* | |
| None. | $20.22 in 2020. Increasing to $35 by 2026, then inflation-adjusted. |

*Figure 41 The tax credit system is a direct attempt to assist implementation of CCS technology (Congressional Research Service, 2021)*

You can also see that this work has been taking place over the years, with incentives out as far as 2026, and it has been updated in the past with more funding. It was first introduced in 2008 and is considered by the IEA to be a significant stimulus package (IEA, 2022) and is supported by several studies that find it to be one of the key opportunities for meeting the necessary environmental impact (Victor & Nichols, 2022) (Snyder, Layne, & Dismukes, 2020) (Nagabhushan, et al., 2021). The IEA discusses additional updates to the initial ruling that projects have until 2033 to begin construction, extending the reach of the credit into the decades range.

Government-funded support is one of the primary ways technology can become adopted (Jin & Lee, 2020) and is considered strategically important to the US. While there are numerous reasons behind this, some of the highlights are the necessity for economic competitiveness, general prosperity, and (of particular import here) national security (US government Accountability Office, 2022). Later in this work, it will be shown that, while it may not be obvious at first glance, the need for a robust and resilient grid greatly impacts national security.

This literature review has covered several topics, but to touch on it here, we are seeing a rise in renewable energy, a need for base load generators that is drastically thinning, a documented known need that emerging economies will depend on coal and an emerging technology that can directly address the major concerns of the first three points, but that requires proving and systemic adoption. The IEA sees CCS as “one of the most cost-effective solutions available to reduce emissions” (IEA, 2022) and sees it applicable to not just energy generation but also other industries like chemical plants and cement manufacturers. It is a technology that features prominently in their low-cost climate change scenarios.

The trick to this all is that CCS is in its infancy with very few actual applications of the technology. Without research and data, the high capital costs of new technology will never be overcome for later cost-saving knowledge to take the lead. The merits of this research here are that it is one step of many necessary to gradually understand what can be done and what future work is necessary to continue along the path. These results will help the aforementioned issues and provide a basis of understanding for future market and generation opportunities and when studied have been found to be beneficial if implemented elsewhere, such as in China (Fan, et al., 2018).

#### *2.3.2.1 Other Initiatives*

Not covered directly, the 45Q incentive is one of the policy implementations that are talked about to decrease carbon emissions. It is often found to have a greater impact when implemented with other initiatives, such as a carbon tax, so there is a symbiotic saving in that emissions are lower, and the subject is also refunded for capturing emissions that remain (Gowd, et al., 2023). While there are any number of possible political policy drivers that could be put into place, 45Q remains one of the solely implemented direct initiatives towards the capture process and would benefit greatly from other policies because of the possible symbiotic nature (Tcvetkov, 2022).

# Chapter 3

In this section, the study as it was performed will be broken down, how it was performed, and most importantly what tools were used to complete it. The beginning will discuss the overall methodology and how the results will be used to formulate the potential for flexible power plants given a realistic load and system to model it. There are opportunities for others to build upon this work so long as the limitations of the answer are understood. This directly supports Question #1 of this paper as the model is developed and explained.

## 3.1 Overall Methodology

There is a clear lack of understanding in what a flexible power plant can do quantitatively and few ways to model it relating to Question #1. While plenty of generalities are possible, there is little-to-no information in application from both a real perspective and simulation view, which limits the understanding and instates limitations between the variables in Question #2. Adding CCS to this equation makes this more nebulous as the technology is only recently starting to see results from practical uses. This study will show at least the beginning stages of what the difference between a flexible and non-flexible plant is capable of in conjunction with CCS operation. It will do this by measuring the capability of these units under 3 separate criteria that increase in complexity to vet the Question #1 model.

1. Ability to host and adapt to a dynamic load.
2. Ability to host and adapt to a dynamic load in the presence of distributed solar power influence.
3. Ability to host and adapt to a dynamic load in the presence of distributed solar power influence and assuming the capability of CCS to provide additional flexibility in on/off contributions.

These abilities will be tested under multiple variations in flexible and non-flexible power plant varieties and will then compare between them. While these variables will be taken from industry standards, their operations will be decided between the developed algorithm and the chosen simulation software Gridlab-D. To put this another way, parameters for a thermal power plant with CCS will be diluted down to things such as their ramp rate, start times, down times, and minimum load, which will be used as raw values for inputs into the simulation. For the simulations that are performed, these are the important factors that will influence outcomes and other topologies like lignite, Combined Cycle Gas Turbine (CCGT), and Open Cycle Gas Turbines (OCGT) will get a similar treatment. In this way, this study becomes less a measurement of a plant genetic makeup and more a study on its flexibility.

In addition to these three main testing points and in the evaluation of the data they provided, two additional measurements would be made to show the model's capabilities to be adapted to others and test the limitations of the model and its results. The first is that two plants will be staged against one another to measure the difference operationally in how a flexible plant and a nonflexible variety would be fair in support of one another. The second is that these tests are being done on a scale. There was a desire and a need to see if the model would continue to operate when the test system was scaled up to a more reasonable level and added in a limited capacity later on. This test would show the model's validity and expand the findings to ensure the scaled test performed similarly.

To measure the hosting capability of a power plant to a dynamic load, a simulation system will be built to model a small sub-system entirely independent of outside grid infrastructure. All details for this will be covered below, but in general, a known IEEE test feeder will be utilized to build the grid of study and will be simulated for several months. A real load will be shaped to fit the area while maintaining the IEEE feeder characteristics. A power plant will be placed in service to feed the demand of the area, which will be initially under-sized to ensure operation on the 37-node system but will then be iteratively expanded until either the limitations of the plant prevent successful operation or a violation in the system would prevent continued operation like a power line operating well outside allowable voltage regulation areas. This will show us the hosting abilities of the plant. For example, a plant with a ramp rate of 15% could better adapt to a dynamic load than one with 2%, but it is hard to quantify beyond generalities, and by bringing in other factors, we can see the limitations more clearly, as well as the strengths.

After these "maximums" are found, the load will be further complicated by hosting distributed solar power, which many studies have shown make the grid more difficult to work with in modern times. These solar farms will iteratively grow until the maximums of the plant are unable to host the size and another limitation is found.

Finally, the ability of CCS to be turned on and off with the minimum load and start up and shut down times of the CCS will be added into the algorithm to influence the previous two maximums. The CCS unit will provide a dynamic load relief mechanism that can significantly impact the performance of the plant it is hosted on.

With these three criteria, it will be qualitatively shown how these facets of flexibility will influence grid capabilities as a whole, as well as the influence of CCS. Qualitatively it has been shown many times over that all these factors will synergize well, but quantitatively we remain in the dark. The ability of a more flexible plant with faster ramp rates and lower minimums will allow more renewable energy to be hosted, but it is expected that the range will remain consistent over the step sizes, such as a 5% reduction in minimum equates to 10% greater renewable energy being brought in. Likewise, we can easily determine that the variable CCS unit will allow more load to be hosted since the unit represents a 15% loss of operating power capacity. It is assumed that it would equate to significant improvements in average power as the maximum would allow the average to float more freely at an increased size.

### 3.1.1 Gridlab-D

Gridlab-D was the chosen platform for this work for its open-source capabilities, as well as its included libraries. Since the CCS technology is still developing and there is still a significant learning curve behind both its use and its capabilities, it is imperative that the research performed here be able to be disseminated to other researchers for their input and changes. The Gridlab-D code was developed by Pacific Northwest National Laboratories (PNNL), which performs work for the DOE. The code is a modified form of C and was primarily developed to help the research being performed on smart grid studies, evolving grid demand studies, and other grid-level research that has traditionally been difficult to develop due to the dependence on expensive software or scopes of work.

What makes Gridlab-D unique is its efficiency and open-source capabilities. It builds a network based on a GLM file which describes nodes, loads, connections, and other characteristics. Initial values can be set within the code or read from separate files for dynamic editing. It then solves these initial values using a couple of different methodologies: Newton Raphson and the Forward Backwards style (FBS). For this study, the FBS method was chosen as it is more mature, vetted, and studied with more backing behind its implementation. Again, Gridlab-D is an open-source code that is evolving with use and is nearing two decades of implementation. As such, several things about the code are still under development and maturing.

```
object node:799 {
    phases "ABC";
    name N799;
    bustype SWING;
    voltage_A 2400.000000-1385.640646j;
    voltage_B -2400.000000-1385.640646j;
    voltage_C 0.000000+2771.281292j;
    nominal_voltage 4800;
}

object meter {
    name meter799;
    parent N799;
    phases "ABC";
    voltage_A 2400.000000-1385.640646j;
    voltage_B -2400.000000-1385.640646j;
    voltage_C 0.000000+2771.281292j;
    nominal_voltage 4800;
}

//Create extra node for other side of regulator
object node:781 {
     phases "ABC";
     name N781;
     //bustype SWING;
     voltage_A 2400.0000-1385.640646j;
     voltage_B -2400.0000-1385.640646j;
     voltage_C 0.0000+2771.281292j;
     nominal_voltage 4800;
}

object node:702 {
     phases "ABC";
     name N702;
     voltage_A 2400.000000 -1385.640646j;
     voltage_B -2400.000000 -1385.640646j;
     voltage_C 0.000000+2771.281292j;
     nominal_voltage 4800;
```

*Figure 42 A sample of Gridlab-D code showing the creation of both nodes and meters along with some of the supporting details.*

An example of the code, in Figure 42, includes the building of a node and the defining of the type of generation that is being used. In the next section, specifics about the system that was studied will be covered, but an example will highlight how this system works with Gridlab-D. Unlike a lot of the software out there on the market, Gridlab-D is nearly entirely text-based, so troubleshooting and manipulation can be more difficult than when compared to contemporary software like PowerWorld. In PowerWorld you can see power flow in real time and quickly update a schematic with changes to see how things become impacted. In Gridlab-D you generally have to set up meters to read out how things operated under your analysis, reading out power or voltage that needs to be handled from a CSV file to be read meaningfully.

So then, why would you want to operate this software if it can be so onerous? In the case of the comparison to PowerWorld, a few strengths immediately become obvious. PowerWorld simplifies the simulation of cases by assuming that all systems are balanced and can be analyzed in a one-line fashion. This means all phases share the same load, imbalances, and changes, and while this is fair for a vast majority of cases for this study looking at the abilities of a flexible enabled power plant, it was desired to highlight what would happen with a realistic unbalanced network. Additionally, while previous versions of PowerWorld allowed you to modify ramp rates of plants, version 22 no longer can. Attempts were made to get in contact with PowerWorld, but there was no additional information found on the matter.

Gridlab-D does have some very major positives, though. Since there is nothing to present in a graphical sense, the system operates very "quickly" given the number of data points it needs to process. This study was performed over a series of months, with calculations being updated hourly in that timeframe, which translates over to single run command consisting of approximately ~20,000 timestep calculations, with each one having 37 nodes and usually 3 phases. The system outputs hundreds of variables into CSV files, as well as reads others for updated information during operation, but all this still results in runs being completed within tens of minutes. Since the study requires such an iterative methodology, this means that even gradual progress will allow accuracy quickly once the variables are straightened out.

The reality is that Gridlab-D does have difficulties in operation. So, to combat that, as well as add to the study methodology, it was paired with MATLAB. The next section will cover more of what was added, but this is another point in the software's uses in that it has been built to interact with MATLAB in the first place. Pairing the two together will allow the system to quickly diagnose, analyze, and reiterate the runs to study changes and home in on the desired solution.

### 3.1.2 MATLAB

MATLAB likely needs no introduction, but it is software that has been used in the engineering industry since the 1970s. While it is less open-sourced than Gridlab-D, as it is a product of MathWorks and requires a paid license, there is a form of an online workshop that you can access to see other projects and solutions and see if you can quickly adapt it to your operation. Initially, the implementation was planned to entirely depend on MATLAB for the study, as it has such a wide market adoption. When looking at the options for simulating power grid studies, multiple toolsets were found that covered parts of grid simulation but no single source system. Cobbling together the smaller pieces would not be beneficial enough in the long term rather than looking around for a system more readily available. What it was used for is overall control and automation as shown in Figure 43.

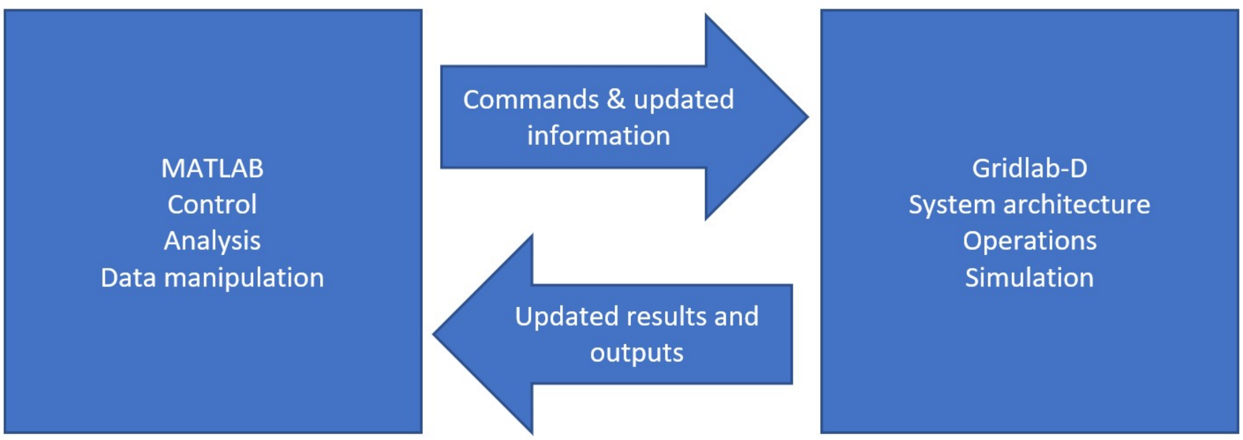


*Figure 43 The diagram illustrates the relationship between MATLAB and Gridlab-D*

MATLAB was used to fill in the larger blanks that Gridlab-D left in its use. MATLAB interacts with Gridlab-D through its usual interface, calls the program to run from the terminal. After the call is performed, Gridlab-D performs as usual as if its usual terminal window interface ran it and updates anything it needs to, such as the attached CSV outputs. An example of the system communicated is seen in Figure 44. MATLAB is then used to analyze those outputs and give the user a graphical interface to interact with. This becomes necessary given the number of runs that were performed to iteratively find the answers that were being investigated.

```
[status,result] = system('gridlabd base.glm')
```

```
WARNING  [INIT] : class_find_property(CLASS *oclass='diese
WARNING  [INIT] : last warning message was repeated 18 tim
WARNING  [INIT] : Daylight saving time (DST) is not handle
WARNING  [INIT] : Only WYE-WYE configurations are working
Model profiler results
======================

Class             Time (s) Time (%) msec/obj
---------------- -------- -------- --------
climate             0.181    91.4%    181.0
player              0.015     7.6%     15.0
underground_line    0.002     1.0%      0.1
================ ======== ======== ========
Total               0.198   100.0%      2.2
```

*Figure 44 Early example of MATLAB calling and operating Gridlab-D from its live code interface. The right-hand side is Gridlab-D responding to the request saying how the run performed.*

Since we are looking at so many variables at a given time, MATLAB allowed the system to categorize and analyze them quickly to identify issues but, more importantly, analyzed them to determine if the runs are complete or if more runs are necessary. This is done by reading in the outputs of Gridlab-D and ensuring that no power violations occurred or, if they have, deciding if the last iteration was sufficient to consider the run complete.

### 3.1.3 Diagnostics Performed

This subsection will go further into detail on the processes internal to the model. This is done so that others may improve and modify processes to fit their application or evolve the implementation to meet newer methodologies.

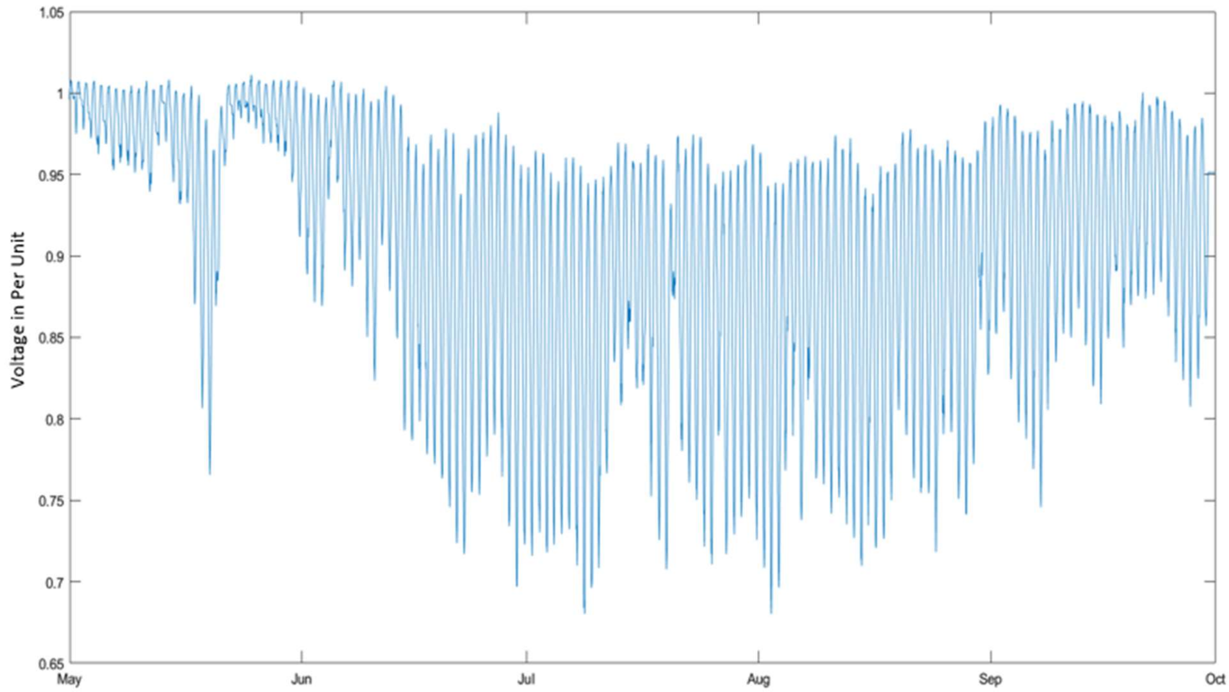


*Figure 45 PU voltage for Node 741 phase A under extreme load testing to check feasibility of upscaling the injected energy.*

Figure 45 demonstrates an example of the output voltage of one of the node phases of a network understudy after being put into per unit (P.U.). Since all of the nodes operated at the same voltage, all of them were divided by the line to neutral voltage of 2771V. Inside the Gridlab-D file, these node phases use the 4800V line to line reference system:

$$V_{p.u.} = \frac{\sqrt{\left(V_{Real}^2 + V_{imaginary}^2\right)}}{2771}.$$

To ensure that the system was acting appropriately, all the node voltages were monitored and measured. Power (both real and imaginary) was analyzed before and after the regulator. Using those power measurements, all the parameters were checked against the system limitations to ensure appropriate levels. The power factor for both the solar resource and load demand were monitored to ensure appropriate operations and that no unexpected impacts were taking place. For both the power of the system and the power of the solar, it was expected that the natural processing of the system would influence the Power Factor (PF) and drive it towards unity. PF was calculated on a point per point basis and then averaged over the length of the full test:

$$Power\ Factor = \frac{Real\ Power}{\sqrt{(Real\ Power^2) + (Imaginary\ Power^2)}}.$$

While not a direct diagnostic, the regulator attempts to keep the system's voltage within specifications and was not modified during the testing. This means the base numbers that are inherent to the IEEE 37-node system remained unchanged. Had the voltage become an issue, it would have been more actively integrated into the testing, but, since the system was scaled compared to the initial values with the plant size and operations, the regulator was able to keep up with the demand.

## 3.2 IEEE 37-Node Residential System

The IEEE 37-node test feeder was chosen for several reasons for this study. The first is that it is a real feeder unit based upon a real system in California, and it was introduced in the year 1992. While this puts it at a few decades old, the topology is not so old as to be outdated, and, if nothing else, its age contributes to the difficulties of adapting an older grid model to new age grid bidirectional power flows. It is highlighted in most literature that 37-node system is fairly uncommon (IEEE, 2022) but that it is made up of multiple spot loads and is very unbalanced, which should provide a good proving ground for our flexibility studies wherein the plant will need to balance multiple parameters at once among its phases.

Gridlab-D uses a file format known as a GLM file. The file contains all the objects and run setting for Gridlab-D to operate. When prompted, Gridlab-D will read through the file to get its instructions and objects and then begin to perform the necessary calculations which may also include reading values from other supporting CSV files as dictated by the GLM file. This file can be modified using simple text editors and the language is Gridlab-D’s own but is very similar to C languages.

At the end of this work, there will be attached the modified GLM file used in the simulations, which was based upon a publicly available file developed by Battelle Memorial Institute under DOE contract while working on Gridlab-D (Battelle Memorial Institute, 2022). This was a modified version available from the SourceForge Gridlab-D repository. Some of the node naming conventions are (at the base) modified from the layout in Figure 46. Additionally, based upon how Gridlab-D operates, there are additional inserts that had to be added for both diagnostic and operational use. The intent was to change as little as possible to capitalize on the industry-known standards that the model represents, but similar to how you probe a system in real life, you have to code in and sometimes even through the "wiring" of the system to get the data needed.

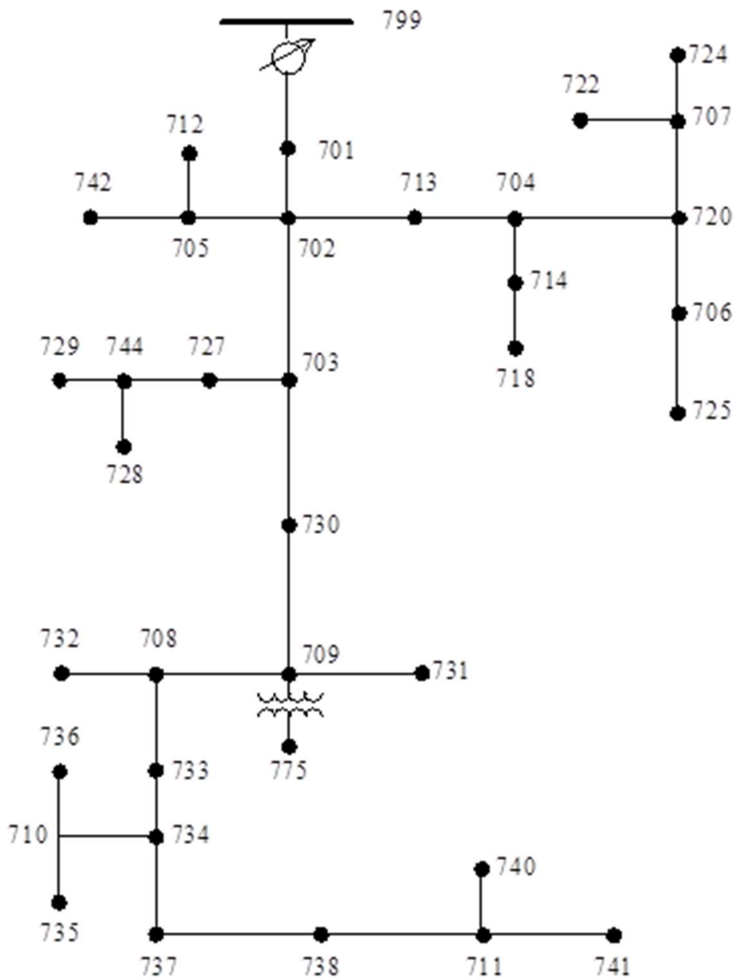


*Figure 46 One of the many graphical representations of the IEEE 37-node system (IEEE Power Engineering Society, 2023)*

### 3.2.1 Test load

Another large influencing factor in the study is the load used. The load is applied to the test feeder in a fashion to attempt and retain the original pattern from the IEEE 37-node system as set up from below but still have a realistic load shape and curve from real data that was measured from the Las Vegas Summertime neighborhood. This was done by analyzing the static pattern of the original setup and then scaling the data to the system using the percentages. The load from the real neighborhood data was further shrunk or multiplied by a single scalar value as the power plant under study could handle. If the simulation came back and the plant was able to service, the applied load for the full summertime frame the simulation was run again with the load curve being scaled larger until a failure was induced.

*Table 1 Original unedited values per spot load as introduced.*

| Node | Load Model | Phase 1 kW | Phase 1 kVar | Phase 2 kW | Phase 2 kVar | Phase 3 kW | Phase 3 kVar |
|---|---|---|---|---|---|---|---|
| 701 | D-PQ | 140 | 70 | 140 | 70 | 350 | 175 |
| 712 | D-PQ | 0 | 0 | 0 | 0 | 85 | 40 |
| 713 | D-PQ | 0 | 0 | 0 | 0 | 85 | 40 |
| 714 | D-I | 17 | 8 | 21 | 10 | 0 | 0 |
| 718 | D-Z | 85 | 40 | 0 | 0 | 0 | 0 |
| 720 | D-PQ | 0 | 0 | 0 | 0 | 85 | 40 |
| 722 | D-I | 0 | 0 | 140 | 70 | 21 | 10 |
| 724 | D-Z | 0 | 0 | 42 | 21 | 0 | 0 |
| 725 | D-PQ | 0 | 0 | 42 | 21 | 0 | 0 |
| 727 | D-PQ | 0 | 0 | 0 | 0 | 42 | 21 |
| 728 | D-PQ | 42 | 21 | 42 | 21 | 42 | 21 |
| 729 | D-I | 42 | 21 | 0 | 0 | 0 | 0 |
| 730 | D-Z | 0 | 0 | 0 | 0 | 85 | 40 |
| 731 | D-Z | 0 | 0 | 85 | 40 | 0 | 0 |
| 732 | D-PQ | 0 | 0 | 0 | 0 | 42 | 21 |
| 733 | D-I | 85 | 40 | 0 | 0 | 0 | 0 |
| 734 | D-PQ | 0 | 0 | 0 | 0 | 42 | 21 |
| 735 | D-PQ | 0 | 0 | 0 | 0 | 85 | 40 |
| 736 | D-Z | 0 | 0 | 42 | 21 | 0 | 0 |
| 737 | D-I | 140 | 70 | 0 | 0 | 0 | 0 |
| 738 | D-PQ | 126 | 62 | 0 | 0 | 0 | 0 |
| 740 | D-PQ | 0 | 0 | 0 | 0 | 85 | 40 |
| 741 | D-I | 0 | 0 | 0 | 0 | 42 | 21 |
| 742 | D-Z | 8 | 4 | 85 | 40 | 0 | 0 |
| 744 | D-PQ | 42 | 21 | 0 | 0 | 0 | 0 |
| | | 727 | 357 | 639 | 314 | 1091 | 530 |

*Table 2 The spot loads were converted to percentages relative to the full system to maintain the original feeder distribution.*

| Node | Phase 1 kV | Phase 1 kV | Phase 2 kV | Phase 2 kV | Phase 3 kV | Phase 3 kV |
|---|---|---|---|---|---|---|
| 701 | 3.83% | 1.91% | 3.83% | 1.91% | 9.57% | 4.78% |
| 712 | 0.00% | 0.00% | 0.00% | 0.00% | 2.32% | 1.09% |
| 713 | 0.00% | 0.00% | 0.00% | 0.00% | 2.32% | 1.09% |
| 714 | 0.46% | 0.22% | 0.57% | 0.27% | 0.00% | 0.00% |
| 718 | 2.32% | 1.09% | 0.00% | 0.00% | 0.00% | 0.00% |
| 720 | 0.00% | 0.00% | 0.00% | 0.00% | 2.32% | 1.09% |
| 722 | 0.00% | 0.00% | 3.83% | 1.91% | 0.57% | 0.27% |
| 724 | 0.00% | 0.00% | 1.15% | 0.57% | 0.00% | 0.00% |
| 725 | 0.00% | 0.00% | 1.15% | 0.57% | 0.00% | 0.00% |
| 727 | 0.00% | 0.00% | 0.00% | 0.00% | 1.15% | 0.57% |
| 728 | 1.15% | 0.57% | 1.15% | 0.57% | 1.15% | 0.57% |
| 729 | 1.15% | 0.57% | 0.00% | 0.00% | 0.00% | 0.00% |
| 730 | 0.00% | 0.00% | 0.00% | 0.00% | 2.32% | 1.09% |
| 731 | 0.00% | 0.00% | 2.32% | 1.09% | 0.00% | 0.00% |
| 732 | 0.00% | 0.00% | 0.00% | 0.00% | 1.15% | 0.57% |
| 733 | 2.32% | 1.09% | 0.00% | 0.00% | 0.00% | 0.00% |
| 734 | 0.00% | 0.00% | 0.00% | 0.00% | 1.15% | 0.57% |
| 735 | 0.00% | 0.00% | 0.00% | 0.00% | 2.32% | 1.09% |
| 736 | 0.00% | 0.00% | 1.15% | 0.57% | 0.00% | 0.00% |
| 737 | 3.83% | 1.91% | 0.00% | 0.00% | 0.00% | 0.00% |
| 738 | 3.44% | 1.69% | 0.00% | 0.00% | 0.00% | 0.00% |
| 740 | 0.00% | 0.00% | 0.00% | 0.00% | 2.32% | 1.09% |
| 741 | 0.00% | 0.00% | 0.00% | 0.00% | 1.15% | 0.57% |
| 742 | 0.22% | 0.11% | 2.32% | 1.09% | 0.00% | 0.00% |
| 744 | 1.15% | 0.57% | 0.00% | 0.00% | 0.00% | 0.00% |

In Table 1 & Table 2 above you can see the spot loads were converted from vars and watts to percentages to be used as scalar factors against the real-world load shown below Figure 47. This was done by summing all of the values together and then finding out how much each spot load contributed to the total in percentile form for ease in parsing out full load curves. This real load was taken from the Summerlin neighborhood in Las Vegas during the summer timeframe and so will include many dynamic variations over time such as a massive contribution of a residential area in a hot environment and their AC units fluctuating over time. This data set was included in the appendix and was provided by Dr. Yahia Bagzhouz (Baghzouz, 2016).

Note that Table 2 sums 100%. As this table is applied to the real results, there will only be a partial application of the load curve shape. This is not a problem, but it needs to be noted as, for example, all the real components added up will only account for about 67% and will, therefore, only transfer 67% of the scaled load as it is parsed out to the CSV files and uploaded to the simulation.

As highlighted, it was desired to use an industry-standard 37-node system to control the variables in the system to the best of the models' capabilities. Using a residential load on a residential system, the hope was to match the framework set up by the IEEE standard to real-world implications.

As the real-world load fluctuates based on external temperatures, different houses will react differently based on those that live within them, but as you climb the hierarchy of the power system, the overall becomes subject to an averages game.

A second issue came up later in the work as it was found that this load that was being manipulated was given in hourly time steps. The original load curve can be in Figure 47 without any additional changes.

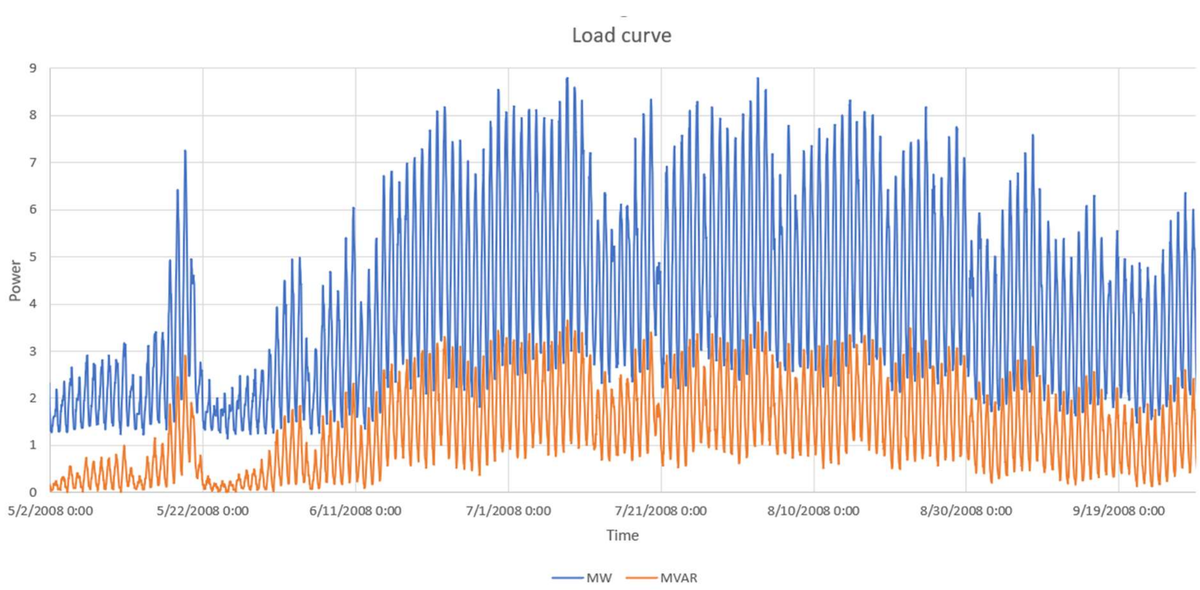


*Figure 47 Example of the load curve under use during the tests unedited and with original time steps.*

This is a problem as one of the major points being looked at in this study is the capability of the plant to adapt to changing loads using its inherent ramping capability. If the time steps are in hourly segments, then that limits the data fidelity beyond the ability to be properly assessed. To fix this, the system implemented a form of data interpolation inside of MATLAB where the original data was broken up from starting hourly time steps into minute-to-minute time steps. Then the system uses the "interp1" command with cubic settings to create the data with more granularity. See Figure 48 for the interpolated data.

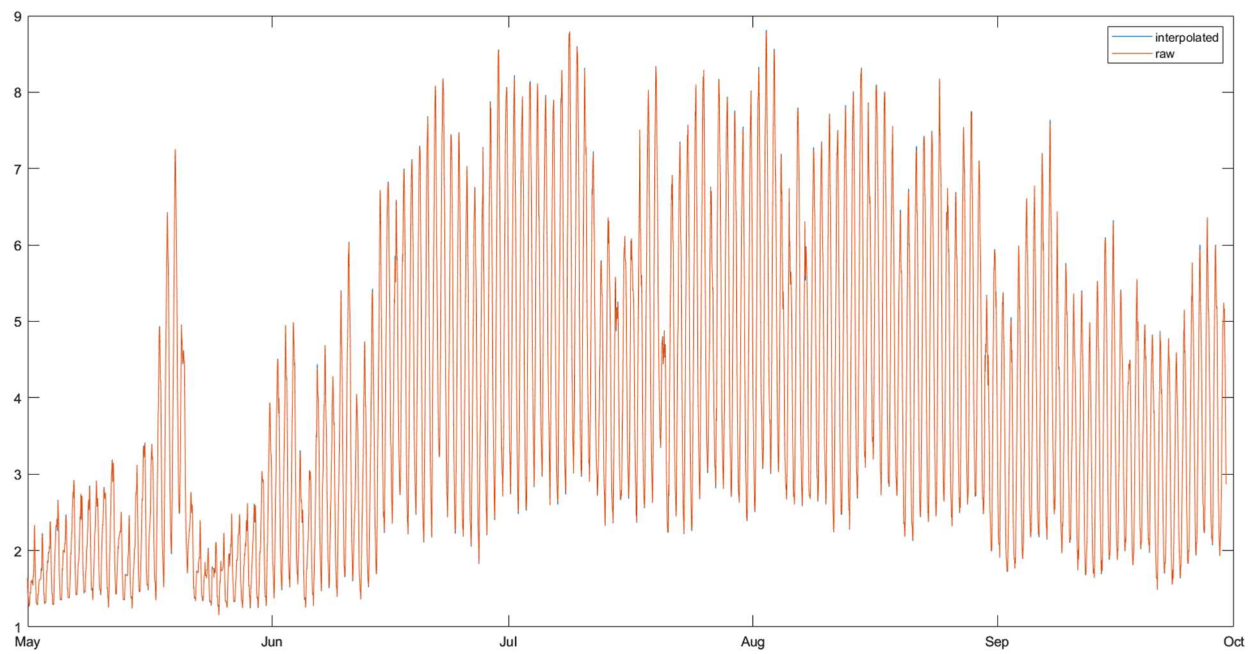


*Figure 48 The interpolated data and raw data placed over one another. Little difference can be seen at this scale, but you can see hints of over and undershoots.*

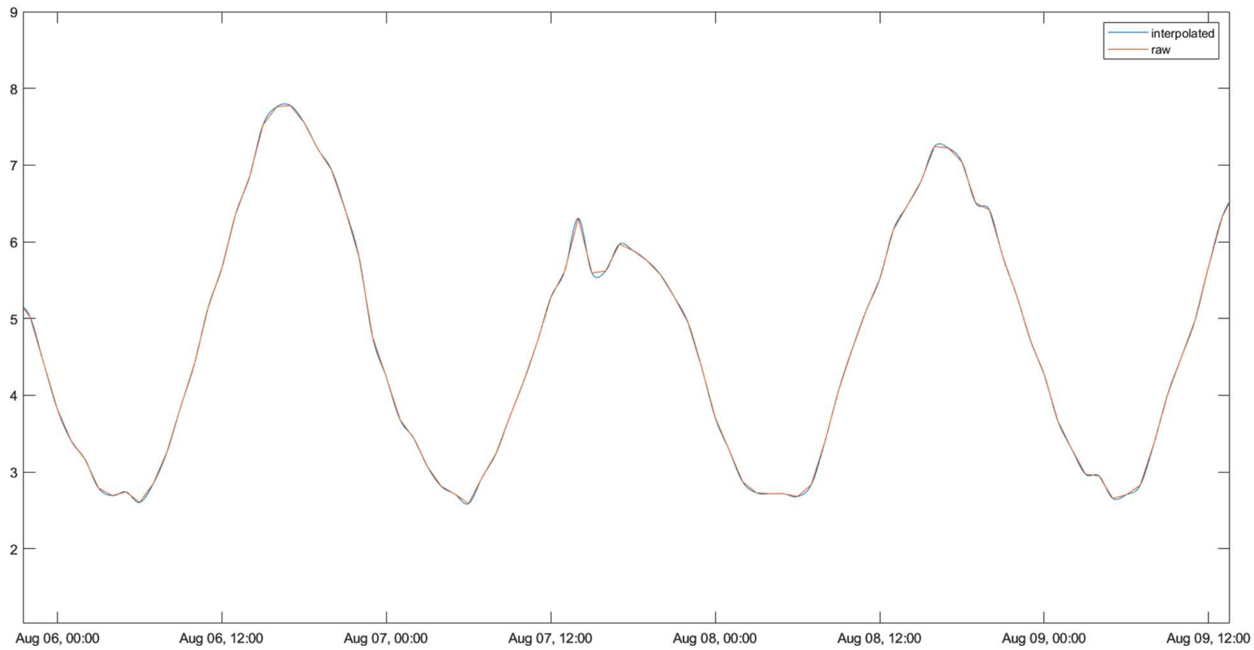


*Figure 49 Zooming in, you can see some variations between the interpolated and raw load data sets, as expected.*

There are multiple methods of interpolating between the data points, and many were tried before the final selection of the cubic version. In Figure 49, you can see that there is some variation between the input and output sets, and pulling this a little further out, we can see how this might lead to inflated peaks and valleys, but they are not what would be deemed significant. From the viewpoint of a "scaled" curve, the slightly different results that the interpolation gives fit within the intent of the tests. Where the reader may wish to differentiate their work is that it was assumed that there would be a gradual change between data points. As the diagnostics are mostly only testing the grid at a single conglomerated point, unless a minute-to-minute change is severe and widespread enough, it would become smoothed out by the transition upstream. Figure 49 only shows the real component of the data, but the non-real component went through similar methodology.

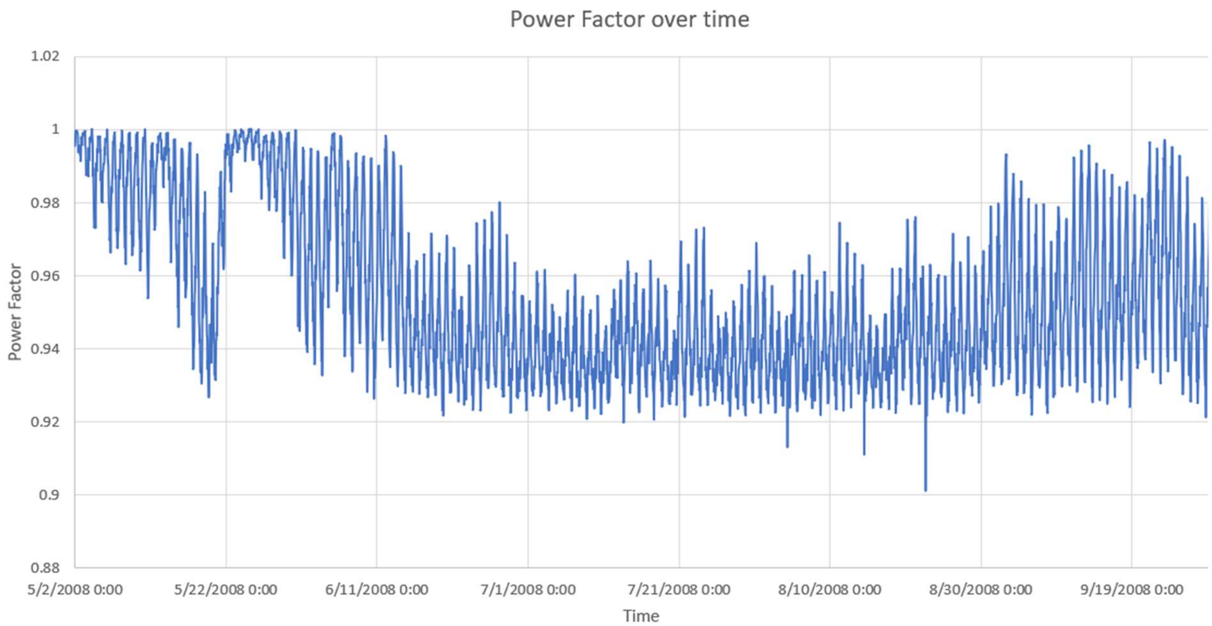


*Figure 50 Raw data power factor over time.*

It should also be highlighted that the raw data, being from a residential load, has a fairly good power factor as seen in Figure 50. On average, the power factor came out to be about .955, and you can see that it changes over time but never goes below .9. Subsequent work may wish to subject this model to more dynamic events with lower power factors. This will also be impacted by the fact that the CCS unit will be modeled as a real power load with no imaginary components and will, therefore, "improve" the power factor by naturally increasing the real power the system sees.

### 3.2.2 Solar Resource

With all that said for the load parameter, it turned out it was good practice for how the solar parameters also had to be adjusted. Later more details will be given about the general makeup of the solar Typical Meteorological Year (TMY) data, but this is a good point to bring up that it is inherently only reported in hourly timesteps. The TMY data used here was found in the National Solar Radiation Database (National Renewable Energy Laboratory, 2023).

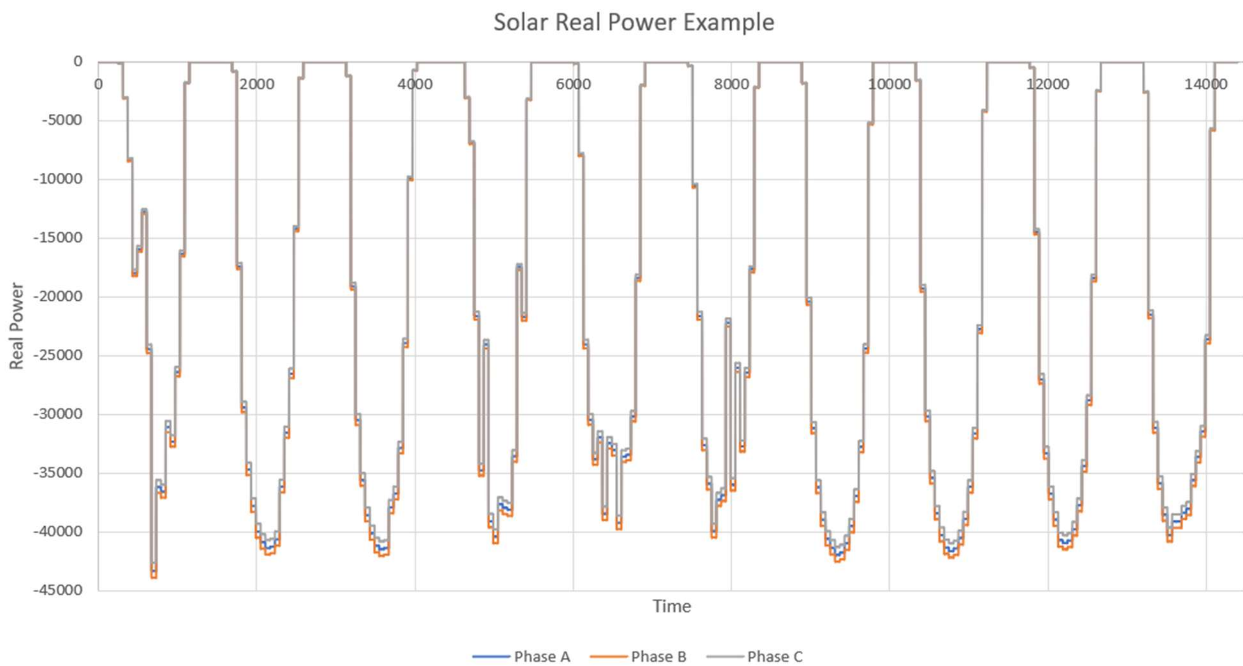


*Figure 51 An example of the early outputs of the solar TMY data used in the simulation.*

As you can in Figure 52, the outputs of the solar arrays are very discrete. This data came from Gridlab-D by loading in the local TMY data and allowing the system to operate. The curve was pulled out, analyzed, and manipulated in MATLAB. Figure 53 shows an even more zoomed in variation to better see the issues induced by the hourly timesteps in the TMY data.

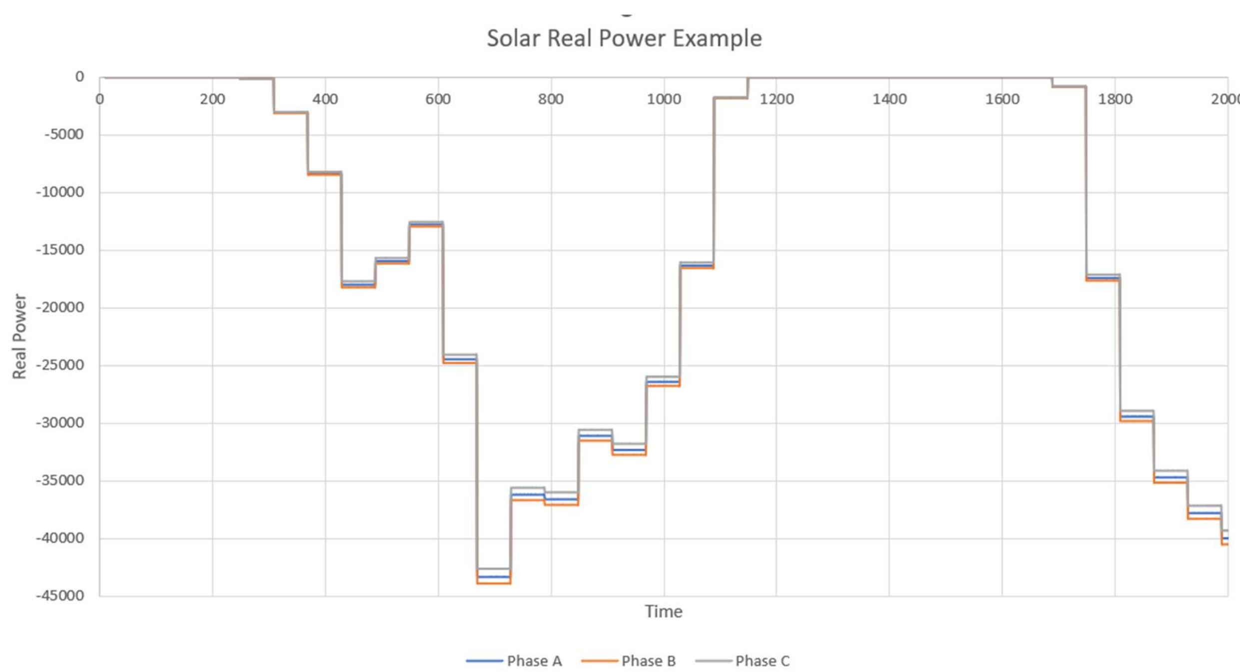


*Figure 52 A more zoomed in example of the issue with the time steps.*

Gridlab-D will operate at almost any timestep you give it, including sub-second time steps if the appropriate additional toolboxes are installed. However, there is no data interpolation in the system. If you give it a time step in minutes (as the Figure 52 shows) but provide it with data in hourly time steps (as is inherent in the TMY data) it simply repeats the value until it gets a new one which leads to the above results in Figure 52 where instead of a smooth solar curve, we get these consistent flattops, much like the issue experienced in the development of the test load.

To solve this problem, the MATLAB code developed a "base case" load profile for the solar system. Using a single node as a test subject a solar object was connected to that node and operated over the simulation time. That solar object was monitored for its 3-phase output, a snippet of which was presented above. That output was then used as the unitless solar curve which would allow the research to have a scalable dataset to apply to other nodes that accounted for TMY inputs but would allow the research to perform the needed dataset manipulation that couldn't be done within the Gridlab-D environment.

The MATLAB system then used the same scalar percentages that were developed for the load against the resultant with the logic that array sizes would be approximately sized to that of the load. If the load were 100 houses, for example, based on the 3% scalar, the solar arrays would be approximately the same size as well. While this does mean all the arrays will be the same wave shape, that in practice is not an issue. Based upon how Gridlab-D handles the development of solar outputs (the TMY data file) they would have all been the same anyway, and the only thing this will change is that now we will have a more granular timestep. There was an additional complication in this case, though.

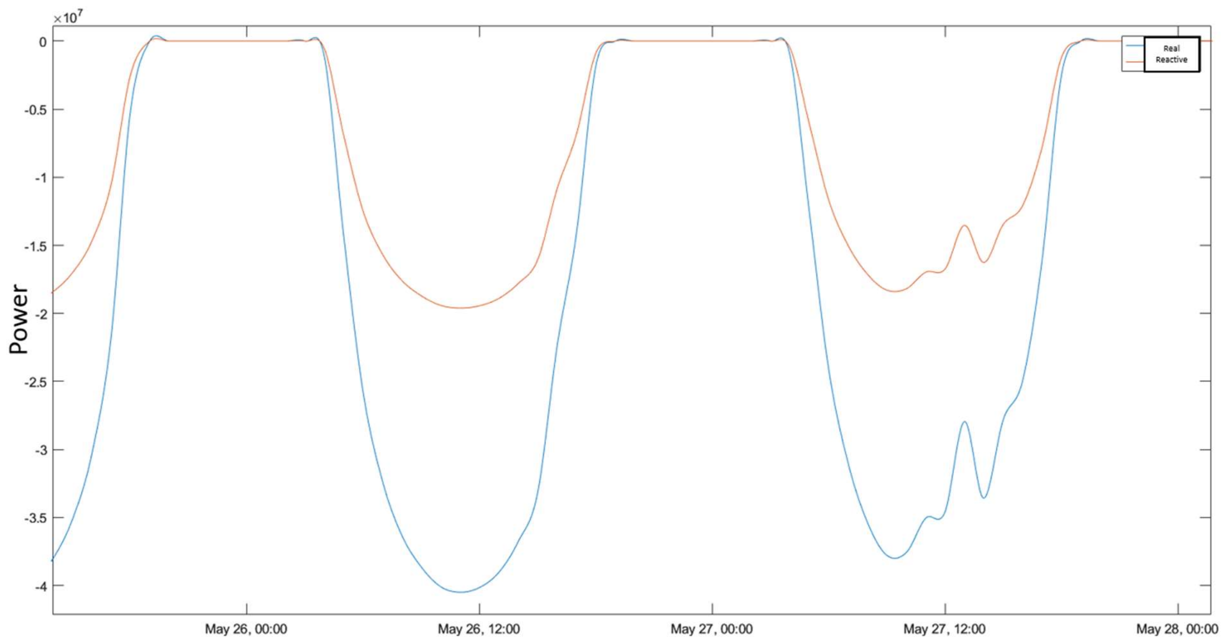


*Figure 53 A quick graph showing the overshoot occurring due to the interpolation. The lines are the real power in blue and the imaginary power in orange. The Y-axis is in Watts and Vars.*

As with the load development, the system was experiencing some overshoots occurring in the data as evidenced in Figure 54 as the graph line goes over 0. When put into the system that means the solar array would actually draw power instead of supplying it for a short period. This occurred in the load development as well but was not an issue there as it was more in line with how a load would operate and the data never reached complete zero. To correct this, another line was added in MATLAB to zero out the final iteration, resulting in Figure 55.

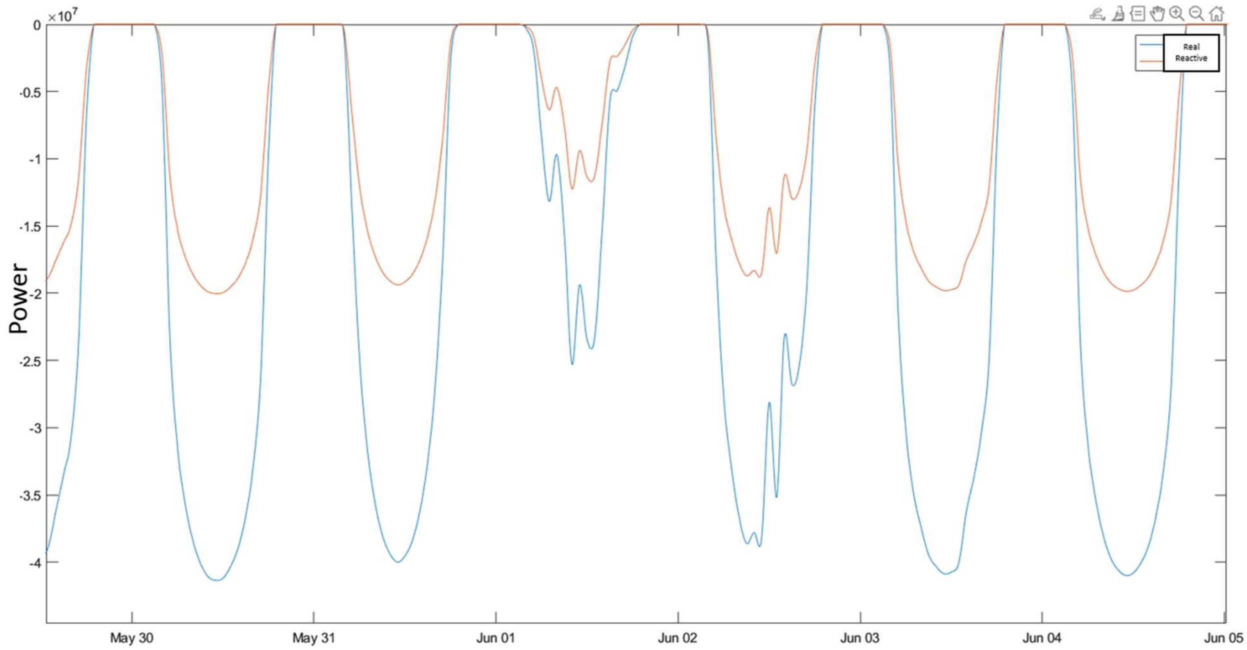


*Figure 54 Another quick graph showing the real power in blue and the imaginary power in orange. The note to take from this is there is no longer any overshoot above the 0 line.*

The solar array is modeled as if the inverter and other supporting hardware and inefficiencies are already baked in. While there is a movement to a need for arrays to operate at greater than a 0.9 PF for the system to be hooked into the grid, there is still legacy hardware out there and other factors that influence what is actually in place (Continental Control Systems LLC, 2023). The array architecture here was calculated for its initial values to be 0.9PF. It then would be influenced more by the scalar percentages from the table like the load was. The arrays were then modeled as negative loads and put into the system in parallel to the loads at the individual nodes.

Given the ultimate implementation of the solar resource curve with interpolation and the use of an inverse load node in Gridlab-D this model could be fairly easily adapted to use wind power. A user would need to find a power curve or develop a desired one to use in testing and then follow the same process. If the data is already in the correct time steps for the simulation, then you could jump straight to distributing the load curve using the same parameters here.

### 3.2.3 Scaled Test

This is a good time to highlight that this simulation is a "scaled" approach. There were many factors that made this initial research quantifying the CCS unit and plant flexibility bounded on this scale. Before we go into some of those, we should expand on the idea of scaled power testing and why this is not outside the norm of grid studies.

At its core, simplification is such an inherent part of electrical engineering that it is taken for granted. Transmission lines are approximated to lump sum parameters depending on the length of the line. Houses and even neighborhoods are summed up to large-scale spot loads, such as in the case of the IEEE 37-node system, which is a real California suburb but doesn't show the individual houses that make it up. In almost every software package that was looked at, city block-sized power plants are simplified down to output parameters. PowerWorld prides itself on the fact that it simplifies systems down to one-lines going so far as to claim 3 phase systems are balanced and can be "very well modeled as an equivalent single-phase system" (PowerWorld, 2023) based on the fact that at the large scale most are very well balanced.

This goes beyond the simulation aspect as well as many power labs that scale down many large-scale components. The image in Figure 55 is from an extensive catalogue where schools can buy a module and rack to perform simulations on the grid level. This can include modules that simplify wind turbines and power generators down to simple fans and motors or transmission lines down to boxes to plug cabling in and through to cause delays and phase shifts.


*Figure 55 Example educational workstation from Edibon (Edibon, 2023).*

In the end this goes back to modeling and simplification in general and a quote that was found sums it up best: “Simplification is considered a fundamental part of modeling and simulation. Model simplification is instrumental in creating models that are useful - by focusing on system elements that matter, and feasible - by reducing study efforts.” (Van der Zee, 2018). In this work the desire was to limit the number of unknowns that had to be quantified, and, by using an industry standard, it helped to inherently keep those situations under control.

That industry standard (IEEE 37-Node system) is one of the largest radial feeders that exist. Much larger, and they suddenly had multiple generators muddying the simulation results, and complexity increased. The load was one that had been previously tested and used before to achieve good academic results (Misch, 2017).

As we have talked about the availability of software, we can speak on the fact that Gridlab-D and MATLAB performed very well together, and both are intensive coding languages for even experienced users. Simulation times varied depending on which test was added in a variety of variables but were clocking in beyond 20 minutes towards the end for one completion. The number of raw output points came in at over 38 million.

The system was designed around the concern of a scaled test. The maximum power of the plant, ramp rates, min/max are all only a couple of inputs. The analysis code is based upon those same values as well and should scale well. The system was also exercised towards a stretch goal of building and designing a much larger system to exhibit this flexibility at scale.

## 3.3 Flexibility parameters

Flexibility, when it comes to power plants, can mean many things. It could refer to the people manning the systems and their ability to switch up operations quickly. It could refer to the system's ability to accept a wider range of fuel types. For this study and the focus on how the parameters influence Variable Renewable Energy (VRE) and dynamic CCS operations, the model for Question #1 will be built in such a way as to focus only on the quantitative results found in Question #2.

This work covered some of the more common flexibility parameters you would expect, and for these specific tests, we will be using the characteristics of ramp rate, start-up time, and minimum load, and the ability of the CCS to be coordinated with a look ahead and shut off when necessary and only turn on in a controlled manner. Among these variables, maximum loads are often listed as well; however, in this case, we kept all tests on the 37-node system the same to remove that variable. While the maximum a plant can host is certainly important, the desire was to focus on the other parameters, such as the ramp rates, specifically as they become more and more important to an evolving grid that hosts intermittent renewables and may need to cope with massively reduced loads or to even shut down for periods of time and then recover for the night swing.

The ramp rates and plant minimums were found from the International Renewable Energy Agency's (IRENA) study on flexibility in conventional power plants (IRENA, 2019) wherein they discuss different topologies and their comparisons between flexible and non-flexible power plants. The drive behind this study was the evolving grid and how older plants could be updated or how newer plants could contribute to an existing power system. They specifically highlighted that these plants would be part of the answer to bridge the gap as the grid goes towards VRE integration while other technologies catch up to implementation such as energy storage units.

*Table 3 The table below shows a wide range of power plant capabilities and is taken directly from the IRENA report. (IRENA, 2019)*

| Type of point | | Start-up time* | Start-up cost (USD/MW instant start) | Minimum load [% $P_{nom}$] | Efficiency (at 100% load) | Efficiency (at 50% load) | Avg. ramp rate [% $P_{nom}$/min] | Minimum uptime | Minimum downtime |
|---|---|---|---|---|---|---|---|---|---|
| **Hard coal** | **Average plant** | 2–10 h[a] | > 100 | 25–40%[a] | 43% | 40% | 1.5–4%[a] | 48 h | 48 h |
| | **Post flexibilisation** | 80 min–6 h[a] | > 100 | 10–20%[b] | 43% | 40% | 3–6%[a] | 8 h | 8 h |
| **Lignite** | **Average plant** | 4–10 h[a] | > 100 | 50–60%[a] | 40% | 35% | 1–2%[a] | 48 h | 48 h |
| | **Post flexibilisation** | 75 min–8 h[c] | > 100 | 10–40%[b] | 40% | 35% | 2–6%[c] | 8 h | 8 h |
| **CCGT** | **Average plant** | 1–4 h[a] | 55 | 40–50%[a] | 52–57% | 47–51% | 2–4%[a] | 4 h | 2 h |
| | **Post flexibilisation initiatives** | 30 min–3 h[a] | 55 | 20–40%[c] | 52–57% | 47–51% | 8–11%[c] | 4 h | 2 h |
| **OCGT** | **Average plant** | 5–11 min | < 1–70 | 40–50% | 35–39% | 27–32% | 8–12% | 10–30 min | 30–60 min |
| | **Post flexibilisation/ advanced plant** | 5–10 min | < 1–70 | 20–50% | 35–39% | 27–32% | 8–15% | 10–30 min | 30–60 min |
| **ICE[c]** | **Average plant** | 5 min | < 1 | 20% (per unit) | 45–47% | 45–47% | > 100% | < 1 min | 5 min |
| | **Post flexibilisation/ advanced plant** | 2 min | < 1 | 10% (per unit) | 45–47% | 45–47% | > 100% | < 1 min | 5 min |

* Start-up times are longer for cold start-up (plant shut for more than 48 hours) than for hot start-up (plant shut for less than 8 hours).

**Notes:** h = hour; min = minute; MW = megawatt; Pnom = nominal power.

While Table 3 has a very full range, many of the numbers repeat, overlap, or simply fall within other ranges and can therefore be simplified down. For the testing done here, the power plant minimums would range from 10%-60% and the ramp rates will range from 1%-15%. Smaller data steps will show the evolution of these values against the increased load and renewable integration. The CCS unit also helps to exercise the consistent maximum that all the plants will share as supported by the ramp rate capabilities.

# Chapter 4

## 4.1 Limitations

As with all research, there are several limitations to the research performed here and, therefore, the results from that research. These limitations represent opportunities for future work for other researchers to adapt from and, as well as points of contention from others. The intention is to provide a good foundation for others to build from, and, as such, the design was to highlight some of the larger limitations that are present specifically. This section also supports Question #1 and its developed model to show the limitations of the work. As the model mostly resides in MATLAB and Gridlab-D, the opportunity present here is that it would be fairly easy to modify to a user's need should they feel differently about the study. An example of this can be found in Test #5, as a different grid and load are developed to evaluate the model.

### 4.1.1 CCS capabilities

One of the largest gaps in the work here is the unknown of CCS. On almost any given day, you can look up new information on the subject, and often that information can be contradictory for several reasons, such as different manufacturers or goals for the system itself. The aforementioned ACE Rule, and how that impacted the information for energy capabilities in the US and the world over, is a perfect example of this in action. The ACE Rule directly changed the results coming out of various research institutes whose information was then used elsewhere, cascading its impact as the thermal fleet was suddenly expected to not be as long lasting and therefore not as viable a research subject. We also covered several institutions that consider CCS of integral importance to climate change, such as the popular Paris Climate Agreement. With all that said, the choices to make CCS be a 20% load on the power plant bus, or the fact that it was assumed that a power plant could immediately begin to recover from that load after shut down properties, or even whether or not that CCS could be shut off in a coordinated fashion to such dynamic load operations (i.e., not responding to emergency conditions like those of a storm but instead more of a daily operation case), are all based upon publicly available information and the interpretation of it.

This study was built with that in mind. All those parameters are easy to update and rerun to see their results once you understand the architecture of the build. There has been talk of some CCS designs bringing down their impact to 10% on a plant, which would be 50% better than the assumption operated on here, which would, in turn, dramatically change the outcomes.

### 4.1.2 Solar Power

Solar power was chosen as it is one of the most mature implementations in Gridlab-D, as well as one of the most dynamic and impactful (relative to the study parameters) compared to things like wind, tidal, geothermal, etc. The intermittency of the resource is up for discussion as some consider wind to be more reliable given that there is usually some output from the unit while solar fully shuts down at night (Verde Team, 2021). Whatever the case, if this study were to be reperformed using another variation of the technology, you would expect to see a fair impact on the results given the make-up of the system and chosen type.

Traditionally the dispatchability of VRE resources has been one of the most important variables in its adoption and certainly one of the first to be asked about in implementation (Congressional Research Service, 2022). Wind and solar are both considered to be difficult in this fashion and wind was considered for the study, but limitations in software, as well as breadth of scope, stopped its addition, let alone other VREs. It is expected, though, that given the climate chosen and the system of study that "worst case scenario" was at least closely looked at if not directly studied.

### 4.1.3 Grid Operations

Grid operations were performed purely from the standpoint of load satisfaction and nodal limitations. Modern-day grids often perform, instead, in more of a fashion to satisfy economic needs, and that can be in conflict with more efficient methodologies, as addressed in this quote: “Although economic dispatch will usually run higher efficiency gas-fired units before lower efficiency units, that is not always the case, for several possible reasons (US DOE, 2022)”.

Economics can often come into conflict with the “efficient” solution, whether that be the capability of a closer unit to satisfy a power need or environmental impacts that are much better satisfied by a more expensive unit with lower emissions. There are thousands of studies done on the subject and a myriad of opinions about the proper way to operate a grid, but the point here is that this study was performed from a pure calculation perspective with little-to-no interconnections to a larger grid and that there are no outside impacts such as weather or economic policy to influence the operation of these power units besides those necessary for solar operation based upon TMY data.

Along with this is that a “look-ahead” form of scheduling is done in the most rudimentary of ways. When the load was expected to exceed a trigger point certain actions were taken, such as shutting down the CCS unit. In more traditional grid operations, you have to consider operations and maintenance demands, the energy market at work, and even surrounding areas operations in the case of storm Uri. The model is a fair simplification of a traditional methodology but there are factors that could not be taken into consideration.

### 4.1.4 IEEE 37-Node test feeder

The IEEE 37-node test feeder was covered fair bit in its introductory section, but it remains a large limitation in this study that the chosen topology will influence the outcomes from the work. The complicated and large test feeder was chosen to fairly introduce operational variables, like distant nodes and location of the solar generators; however, if this was installed on a smaller grid or interconnected to other systems, results will vary. Keeping things in a controlled environment should highlight singular contributions to the problem and provide a sandbox to emphasize those contributions more clearly.

This was somewhat alleviated with later additions of the self-developed 10-node system. This gives future modelers a methodology to adapt this work to other systems or modify the one presented here. While the 10-node system was a scaled unit against the power plant, since it was the outcome of the research here instead of an industry standard like the 37-node system, improvements are bound to be made there as well.

### 4.1.5 Typical Meteorological Year Data

TMY data is an industry-standard data type that gives you the climate information for a given geographic location chosen by the user. In this study, since the load was used from a Las Vegas neighborhood, the dataset was also found for Las Vegas, which is how the outputs of the solar arrays were calculated for the times studied. This means the performance of those arrays depends entirely on this data and will change dramatically if another area (especially a cloudy one) were chosen. Again, since the original load data set is from Las Vegas, it made sense to keep with the geographic location for the TMY data, but further work can be done to reevaluate at different locations. In the end, this data was used to generate a load curve that was distributed similarly to the neighborhood example load presented. Doing this, it gave more control during iterations and made editing easier if others desired to do so. The interpolation performed on the data is covered elsewhere but extends the same idea.

### 4.1.6 Plant Topologies

As was covered above, plant topologies were simplified down to operating parameters. As such, a coal power plant could conceivably have the same information as a lignite plant and vice versa. While this is also a strength of the study, in the sense that it highlights the performance data instead of the economic or environmental impact, there are some simplifications that come along with those choices that could be better studied, such as maintenance factors or cost of these operations that are not accounted for in this work. This work covered a lot of different technologies in this paper that could work with one another in unique ways. By simplifying them down to their outputs and their capabilities in only the way it would impact the simulations, it should allow a researcher to focus better on these specifics instead of the minute details. As CCS and its applications towards existing and future thermal plant topologies evolve, there will be more efficiencies found, which will vary the results garnered herein.

### 4.1.7 Non-real Power

Throughout this work, there will be mentions, and tracking, of the VARs of the system. The power factor (whether leading or lagging) can greatly influence how a grid operates or fails. It is necessary to include all this information because, depending on the application elsewhere, this can be a major change for future work as others work to include their lower power factor systems. In this work, though, it never became a significant variable. The initial load of the system already had a good power factor, and the injection from the renewables only helped that in the long run and offset the real load CCS unit. It was not considered a major issue for the power plant as there are multiple solutions like capacitor banks, static compensators, and a clutch-connected secondary generator, with estimates coming in at around $50,000 for a 5-MVAR capable system (Power, 2007). $50,000 is not cheap, but CCS units range in the millions of U.S. dollars, so relative to one another, it was not believed to be a limiting factor in the generation or as a variable.

# Chapter 5

## 5.1 Research Results

The following sections describe the experimentation outlined above. A simplified hierarchy is presented below. The first few tests build off each other to develop the model in a controlled testable manner, while the last two tests expand those results to help test the model’s ability to adapt to wider test parameters. While this section uses the model developed for Question #1, the results are in support of Question #2.

- Test 1- Initializing the system and establishing the appropriate operation and reporting. The dynamic load is modeled, and the beginning limitations of the system are found from the hosting of the carbon capture-limited power plant.
- Test 2- Add in renewable energy systems in a distributed manner. The amount will be directly tied to the minimums of the power plant and the ramp capabilities.
- Test 3- Enable the dynamic CCS unit to find the increased load hosting capabilities and the impact the ramp rate differentials can support.
- Test 4- Split the single power plant into two and operate a flexible and non-flexible variation against one another, from a priority standpoint, to show the different hosting capabilities possible with the different strategies.
- Test 5- Increase the size of the hosted grid to more realistic scales. The plant maximum will now be 700 MW, and the makeup of the grid will change to reflect a larger platform to see operations under the model at scale.

### 5.1.1 Test 1

Under the Test 1 condition, the power plant is treated as a swing bus to the rest of the system. The initial test is simply getting the power grid operating and ensuring it follows the design. A general algorithm is presented in the appendices as a flowchart.

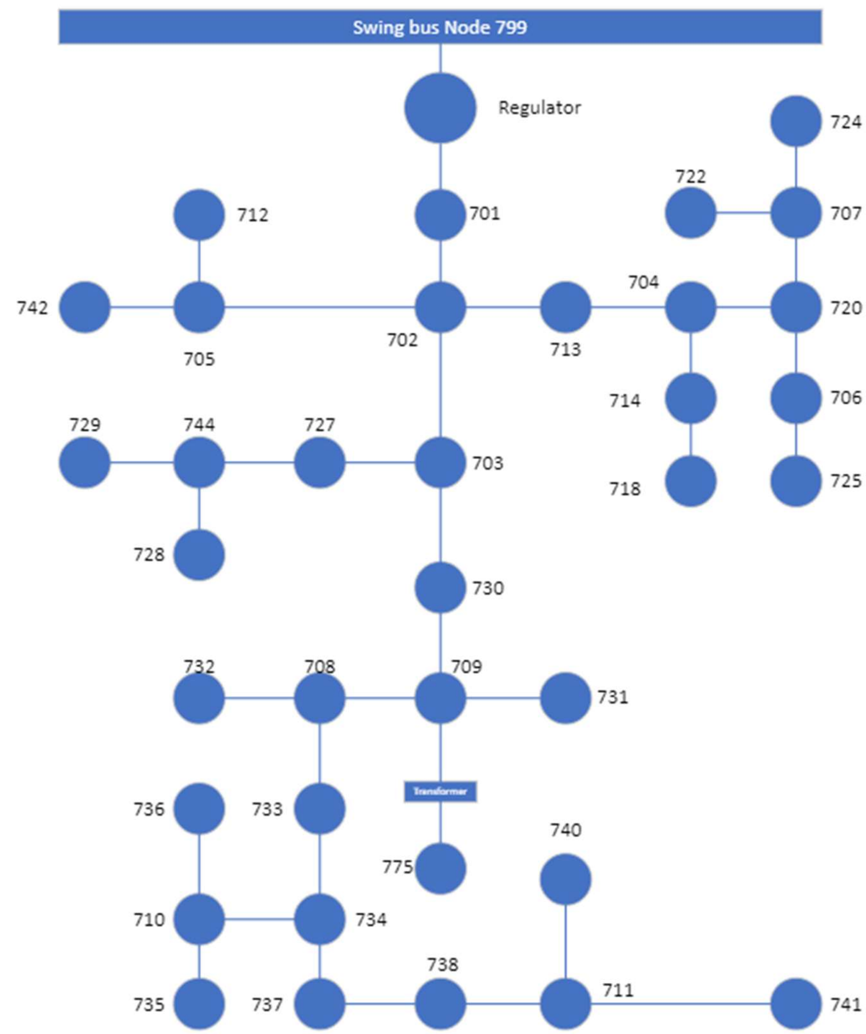


*Figure 56 The updated IEEE 37-Node system with the additional CCS node inserted after the regulator.*

Figure 56 shows how the system was modified to include the CCS system. Otherwise, all other parameters were kept as close to the originally reported IEEE standard. The CCS system was added on after the regulator forced the system to account for its loading profile in the voltage regulation. This also made it so that the system could be monitored on the swing bus side to account for the whole system operation instead of piecemealing it elsewhere. The CCS unit was modeled as a 20% parasitic load evenly distributed over the 3 phases. This came out to 500 kW total with individual phases being ~166 kW per phase and were kept static until later controls were implemented.

It became obvious that the main limiting factor under this loading scheme would be the capability of the power plant to host a minimum load as the system rapidly approached the maximum. Figure 59 shows the result from the final test in the initial run series, which happened to be run 13.

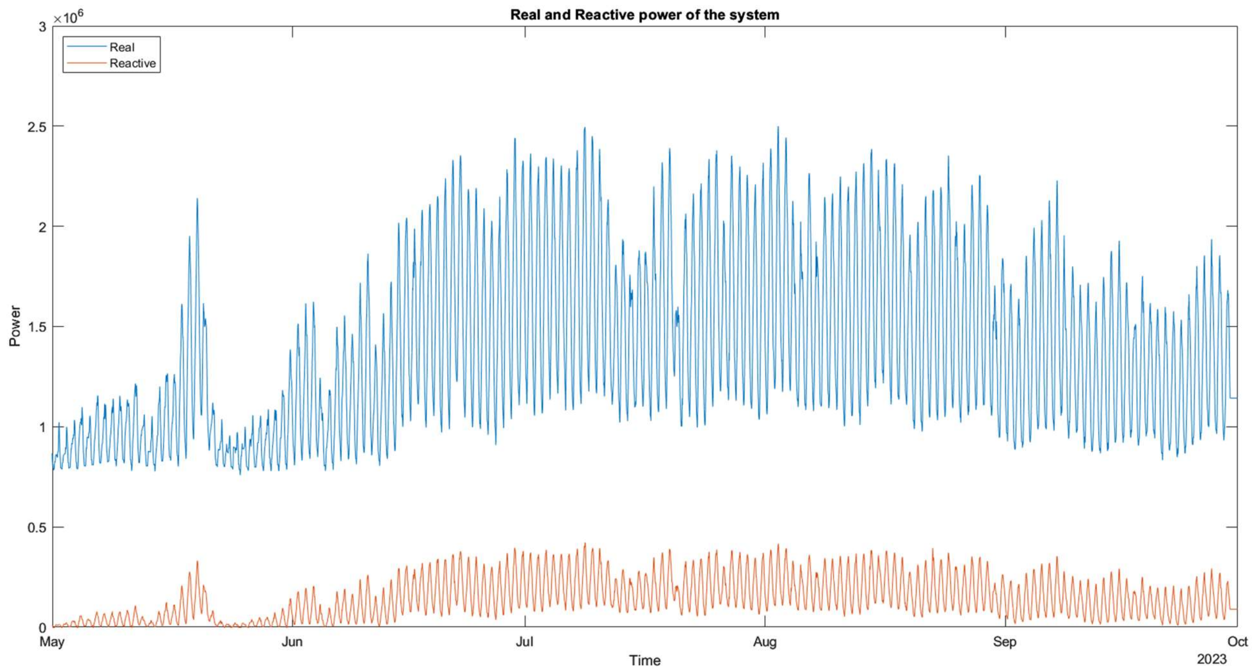


*Figure 57 Test 1 run 13 results. The blue is the real power of the system as measured leading to swing node 799 (bus node) and the orange is the reactive component of the system.*

This is fair given the dynamics of the system and the intent of trying to quantify the capabilities of a flexible power system. This is still based on a real load curve and is being scaled against a real residential power grid. This first test therefore quickly eliminates those higher end minimum capabilities greater than 30% but it still gives us a lot of room to evaluate the system as it ranges from 10-30% in the future tests. Additionally, in developing the model there is nothing that cannot be adapted to other systems as is done in a later test. You could take the above data and edit the swing of the day-to-day operation, minimizing the peaks and valleys, but through iterative testing it was found to already be happening.

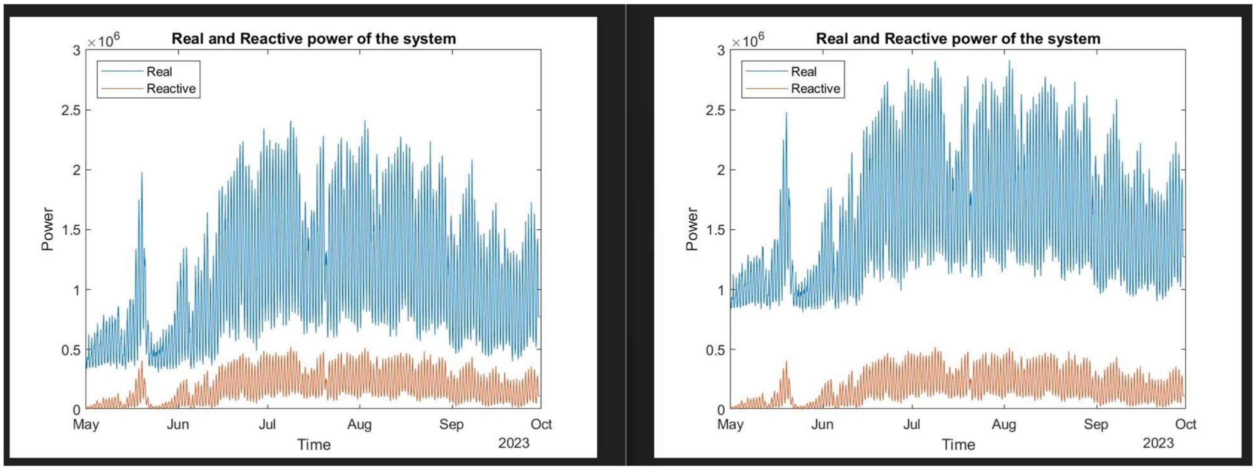


*Figure 58 Early troubleshooting noted that the CCS unit was improperly coded and not impacting the system. This is evident in the very large increase in the real power of the system, as the CCS unit is a large baseload influence. The Left is without the CCS unit, right includes the CCS unit.*

Early in the research it was found that the CCS unit was improperly coded and not actually drawing the power it should have been. This is highlighted here as it gives the opportunity to show the significant influence of the unit in shifting the baseload power draw. In Figure 58 on the left, the code was not implemented properly, while on the right, once it was fixed, it shifted the real power up significantly by the designed 500kW.

```
test information
03-Apr-2023 17:38:42
scalar,plantsize,averagepf,averagepower,maximum seen,minimum seen
332500,2500000,0.994811374130223,1384221.17648047,2499679,758045
ramp rate setting,ramp setting %,min load of plant,min load % setting
100000,0.04,750000,0.3
test passed
```

*Figure 59 Example of system output. Specifically, this is the information for run 13.*

In wanting to document the results and make it easier to recall past runs and keep the variables run to run consistently, the MATLAB portion of the code outputs several results to a small text file based upon the user's file name input desires that can be seen in Figure 59. The scalar of the system for this run was 332,500, which in and of itself means little, but since the scalar remains consistent against the math parameters, inputting the same scalar later would give us the same results. This can be found on the 4th line of Figure 59. The scalar is a user parameter set before the run that the MATLAB code uses to multiply against the power demand curve. It is multiplied against the individual values of the real neighborhood data set. Plant size was 2,500,000 W in line with the scaled test design.

Knowing that the scalar, to others, essentially means nothing, the system was also analyzed in other ways to better quantify the results. The average power factor is of the full run and came in near 1. While this is higher than our initial input power factor, that makes sense since first, it is a residential load and second, we are heavily influencing that with our very large CCS real component load. The average power over the run was 1,384,221 W. The maximum was just under our plant's maximum at 2,499,679 W. It became time prohibitive to get this to too exact of a number again due to the length of time each run was taking. The minimum was 758,045 W, which was just over our 30% minimum at 750kW.

The next row in Figure 59 is the user-set variables. The ramp rate per minute was 100 kW, which was calculated from the 4% setting. The minimum was 750 kW and was calculated from the 30% rating. The last line of the output in Figure 59 indicates 'test passed', which indicates all the variables were considered and checked against the data to ensure that the system meets spec and is operating correctly. This includes the node-to-node voltage PU check which ranged from .95 to 1.05 based upon the documentation of PG&E where they call upon National Electrical Code's ±5% expectation for the service grid (PG&E, 2023).

From these results, the decision was made to move forwards with minimum load rating step sizes of 5%, resulting in 30%, 25%, 20%, 15%, and 10%. The ramp rate of 4% was more than sufficient to meet the demands of the test, with run 13 only requiring about .2%, as minute to minute there were no significant changes. This ramp rate was later reduced further to more broadly study ramp rate impacts.

While the results are surprising, this will be tested more directly later as we add more dynamic elements like the solar and CCS toggle.

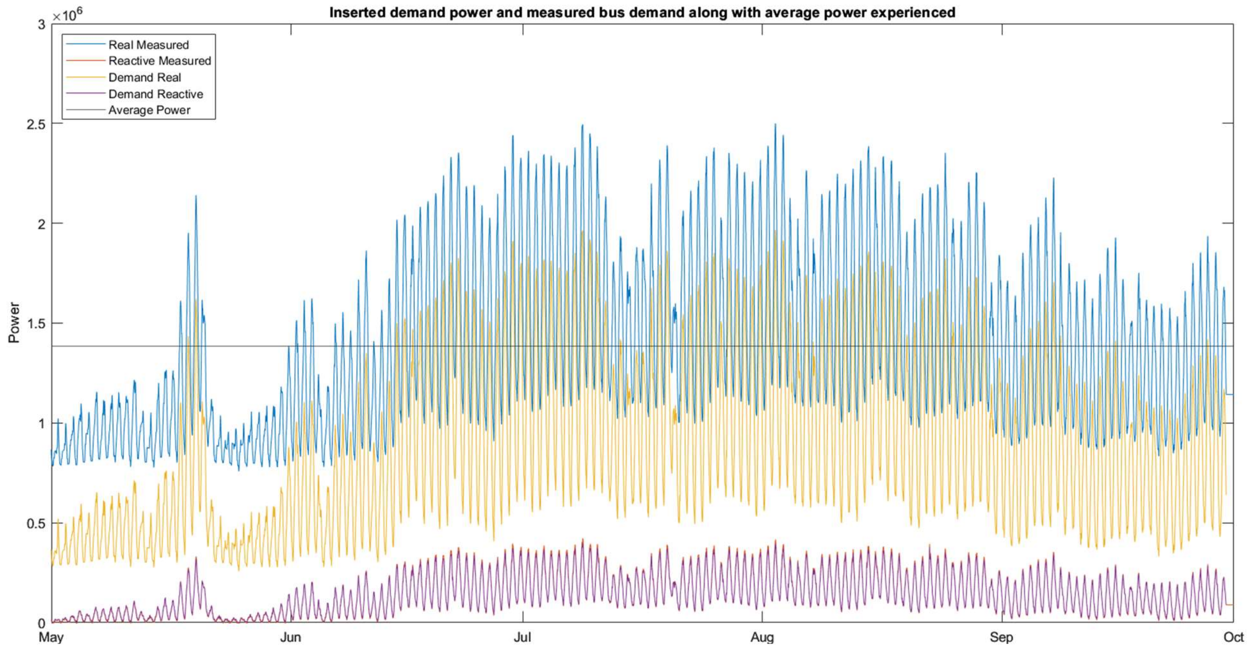


*Figure 60 Graph above shows run 13's applied load, measured load at Node 799, and a line showing the average power of Node 799 over the test period.*

Figure 60 shows the power that was injected into the system along with the measured power at Node 799. This is dominated by the CCS system, but you can see some differences induced by the system at large with the slight overlapping in the reactive power. Also shown is the average real power that was measured at node 799 with the black line at about 1.3MW.

For these tests, the full process is detailed in created flowcharts that show their general processes in more detail; these can be found in the appendices'.

### 5.1.2 Test 2

The big change coming into Test 2 is the addition of additional solar arrays distributed around the 37-node system and their influence on the point-to-point changes as they come online and shut down. Since this is based on a neighborhood with a common climate and area in the Las Vegas Valley, all units will share similar curve shapes but not sizes.

```
object meter {
name solarmeter712;
parent load712;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
    phases "ABCD";
    name sload712;
    parent solarmeter712;
    voltage_A 2400.000000 -1385.640646j;
    voltage_B -2400.000000 -1385.640646j;
    voltage_C 0.000000+2771.281292j;
    nominal_voltage 4800;
    object player {
        property constant_power_C_real;
        file Nodeloaddata/SN712CR.csv;
        loop 1;
    };
    object player {
        property constant_power_C_reac;
        file Nodeloaddata/SN712CI.csv;
        loop 1;
    };
}
```

*Figure 61 An example of the additional code that was added to the GLM file. Here is shown solarload712 being added into load 712. The naming convention was adopted from the IEEE standard and kept consistent for ease of use and troubleshooting.*

Figure 61 shows an example of the additional code that had to be added into most of the loads in the GLM file. While we could have simply subtracted the solar input from the load input, there was a desire to keep them separate for troubleshooting reasons, as well as give Gridlab-D the chance to recognize them as an additional input in case there was something in the backend, that we were not aware of during its solution generation. This turned out to be true, in some sense, as the scalar for power input had to be tweaked slightly going into this test. It is assumed some of the interactions between the nodes caused a slightly higher power draw, so I had to dial it down to account for it. The player files were added in on a phase-by-phase basis as well as a real and non-real component basis.

Since the MATLAB code now had many additional files to develop and the Gridlab-D side had nearly twice the number of files to read from at any given time, the simulation times really started to add up. The "player" node that Gridlab-D keeps track of was now accounting for a large portion of the simulation time. While this is problematic, little can be done about it, and including multiple arrays polling the TMY data fields would have also slowed down the simulation. Runs were now taking approximately 15 minutes at a time.

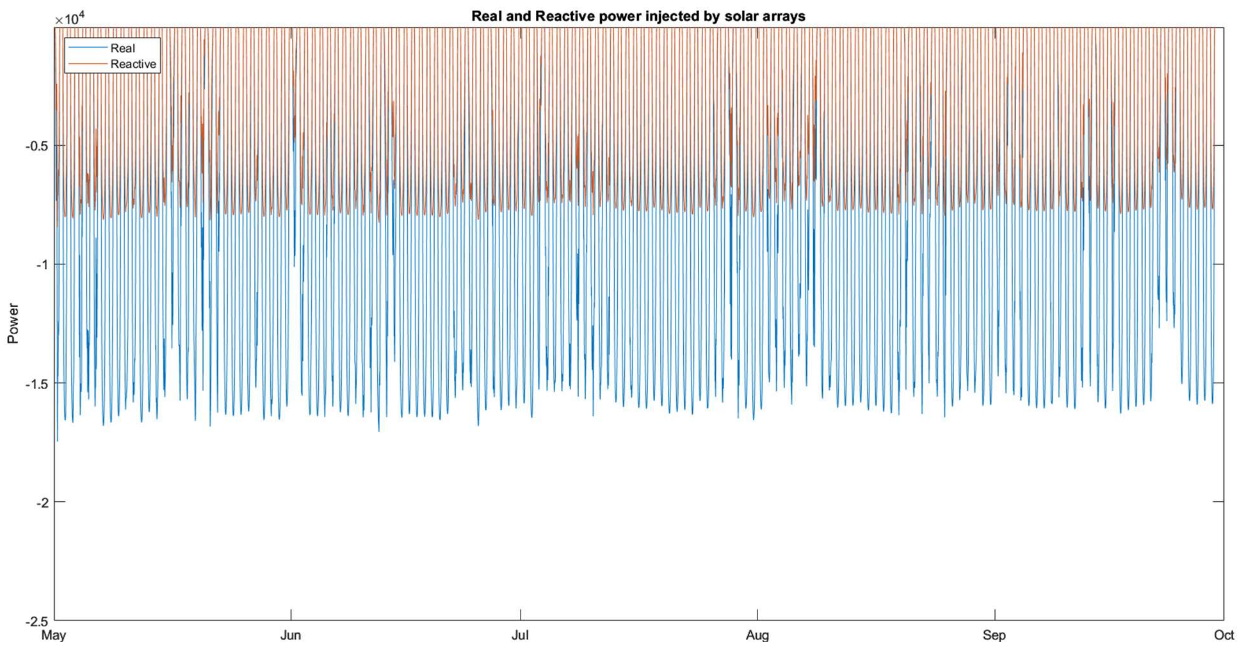


*Figure 62 An example of the full solar array calculation.*

Figure 62 shows the solar array calculation file before being cut up and inserted into the various nodal CSVs that Gridlab-D will use. You can see immediately the influence of the TMY data points on the output, which gives us our dynamic renewable energy that cannot be easily accounted for by hand. Figure 63 gives a zoomed in view so that the day-to-day variations can be more easily seen.

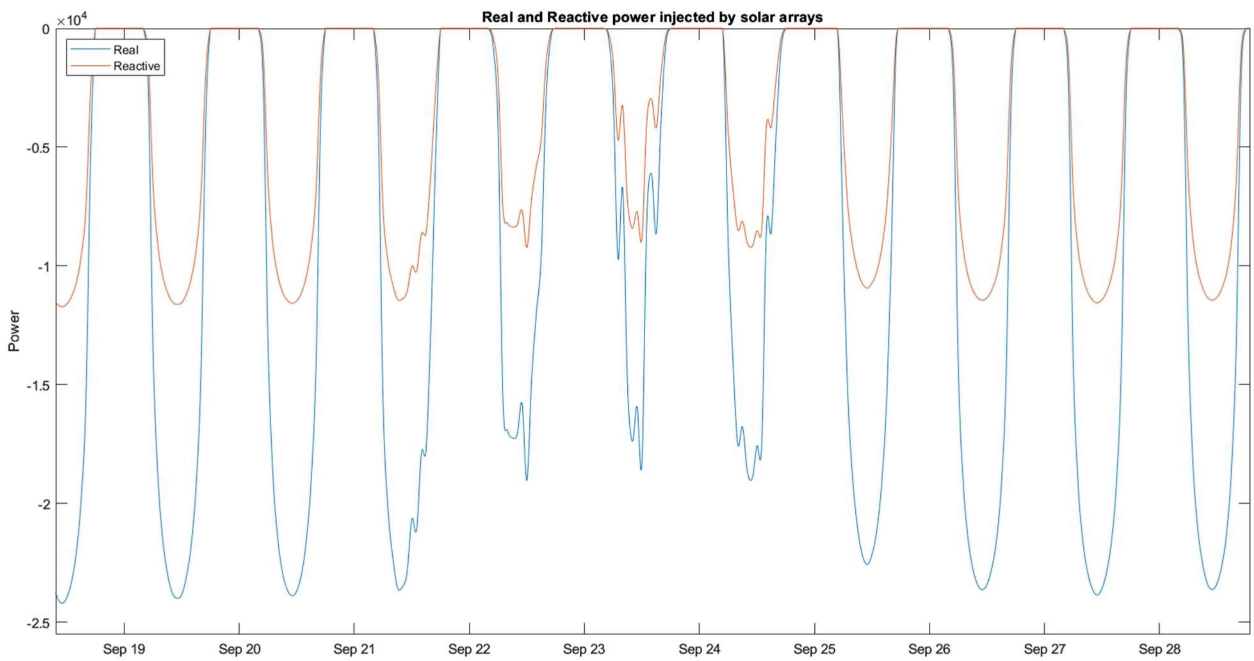


*Figure 63 Zoomed in look to show variations occurring day to day. The very dynamic curves in the center of the graph are of particular importance. These variations are what give VRE's their bad reputation.*

```
test information
05-Apr-2023 19:48:10
scalar,plantsize,averagepf,averagepower,maximum seen,minimum seen
330000,2500000,0.994878542933172,1373112.70024374,2479533,748405
ramp rate setting,ramp setting %,min load of plant,min load % setting
100000,0.04,750000,0.3
averagesolarpf,averagesolarpower,maxsolar,solarscalar
0.899999999999985,-6504.4235848976,-17458.9885341667,0.4
test failed check matlab
```

*Figure 64 Example of the updated output logger in the new test configuration.*

Figure 64 an example of the first failure for the 30% minimum rating on the power plant. Several additional checks were needed to ensure everything was operating correctly, so you see the average solar PF comes in at about 0.9PF. This was before slicing it up and inserting it into the system by the CSV table percentages. The average solar power was about 6.5kW, and this run's maximum solar power peaked at a little under 17.5kW. Notice the significant variation between the two numbers as it is averaged over nighttime hours, but its peak can get significant and would be taxing the system accordingly. While this initial failed test looks small to be fair, a failure only must happen once, for it to be counted out under this test's conditions.

There was an additional failure during testing, where there was also an insufficiency of the ramp rate of 1%. In parts of the test, 1.7% was needed to satisfy the test conditions. Thus, future tests will begin at a 2% ramp rate. The rising and falling of the VREs in the system were significant enough to have caused this, which helps to explain the dynamic nature of a modern grid under operation.

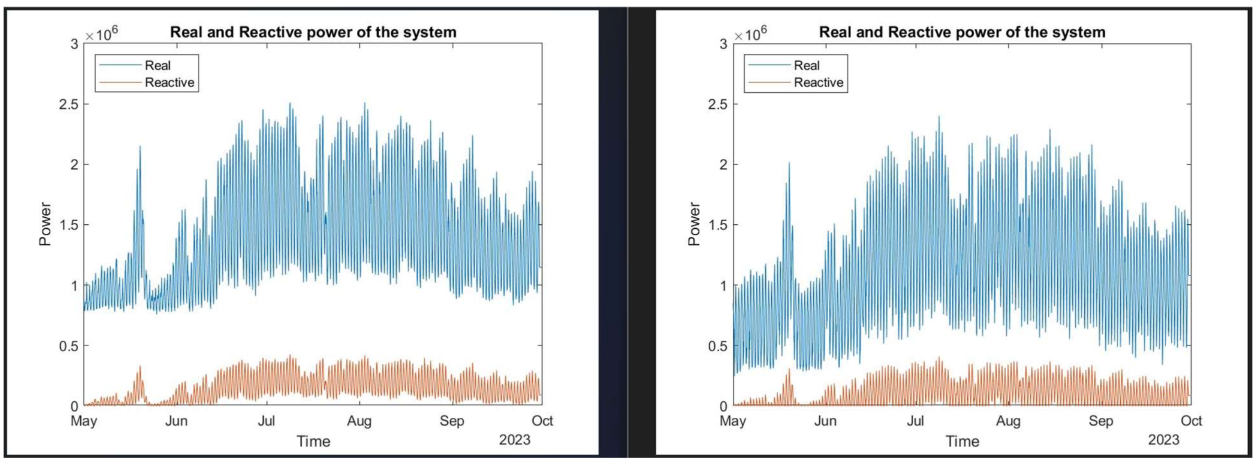


*Figure 65 Comparison between run #1 (on the left) and run #24 (on the right) showing significant difference in the demand on a plant from the increased solar activity being injected into the system. The load curve is brought down greatly, and some power factor correction occurs naturally.*

Figure 65 is a side-by-side comparison between the beginning of Test 2 and towards the end of it where the solar arrays have significantly more influence on the system. While the overall shape is essentially the same, we can see that the lows of real power are dipping further and further down. We can also see a slight amount of corrective action from the non-real component of the solar array injection. This comes from the inherent non-unity power injection as the solar inverter and arrays objects were set to have a 0.9 PF. In some areas it was likely to switch from a lagging power factor to a leading one for short periods of time. This is still a burden on the system as it forces the tap and the plant to adjust to these changes. A good example of this is the ramp rate failure that occurred in during testing.

In Test 1, there was significant room for the ramp rate as it was barely taxed beyond the point of about 0.2% throughout the test. In Test 2, it was put under much more extreme measures as the solar arrays changed depending on the TMY data inputs. This pushed it as far as about 1.7%, increasing the ramp rate to 2% for the remainder of the test.

### 5.1.3 Test 3

Test 3 departs from the past 2 tests because solutions must be recursive. This is mainly due to the need to create a generator that obeys the rules of our limitations. In the previous two tests, we used the swing bus and monitored that it remained within the bounds created for it. When it did go outside of them, the system considered a failure as, at that point, the plant would not be able to support the load characteristics as they stood.

Where Test 3 differs and critically changes how we look at the results is that the system will be forcing a situation that will not be able to be immediately solved by the generator. This work, it was assumed a CCS system would make up 20% of the maximum a plant could produce. Switching the unit off, unless the plant has a ramping rate of at least 20%, it will naturally be forced out of bounds. This difference in minute-to-minute calculation will need to be picked up by a slack bus. In this way, the system will need to recursively see the solution of the specific grid instance and follow it up with a second simulation creating a load profile that fits within the first simulation's output and then allowing the slack bus to operate where the load lacks. This difference and slack bus utilization will be one analysis point in differentiating flexibility standards.

While you could consider the immediate difference a failure, you must be fair to the unit under test. This could be comparable to a substation being taken out unexpectedly and in a real network there would be an interconnected network that would help to balance the system. The same could be said about Tests 1 and 2, but a line is drawn here by analyzing the difference between what the plant can provide and what would be needed. This difference will be used here as a point of flexibility measurement. Flexible plants will have fewer of these imbalances both in the times they occurred and the amount of power necessary.

While this is occurring, there is also a need to intelligently schedule the on/off times for the CCS unit. It will be done again using a recursive technique by looking at the first simulations load profile and treating this as a “look ahead” scheduling variation. With the CCS unit becoming dynamic, we can allow the host load system to grow up to the point of the maximum initial power plant. This could have also included iteratively increasing the solar resource profile, but we are treating those variables as failed so the remaining ones can shine better.

The sliding look-ahead window is subject to the interpretation of itself. The ramp rates of the plants are significantly faster than I had initially understood, so you could conceivably treat CCS as a minute-to-minute adjustment knob. However, it was shown that nearly all CCS units are of significant size and complexity. Unit to unit, they will also differ quite a bit as the technology matures and different applications allow unique topologies.

The operation of the CCS would be subject to market needs, grid needs, and even the plant’s staffing. In reality, you could likely ease and massage these numbers significantly to limit the impact transferred to the grid by hiring more staff or taking less drastic changes, but in exercising flexibility parameters, we want to focus on the most dramatic of approaches.

This work will primarily use the results from another in-depth UK study (BEIS, 2023). In their work, they study several technology limitations for CCS and power plant improvements and how they play into each other. An inherent issue with using this work is that they have intrinsically tied the CCS to the power plant and in doing so, it is not clear the ramp loading induced by the CCS unit. The system will use their values of minimum up and down time of 2 hours and it will assume the extreme case of a bypass being implemented to quickly turn on and off the CCS unit.

The typical application of these bypasses is tied to the desire to take advantage of high profitability windows in the energy market (Abdilahi, Mustafa, Abujarad, & Mustapha, 2023), but in this application here, we are assuming a worst-case scenario in that the parasitic loads will be assumed to be digital. Subsequent work can explore ways to ease operational impacts.

So, to reiterate, this work will first simulate the grid to develop a look ahead forecast, then the system will ramp the load until it again reaches the plant maximum, which will likely expand the amount of times the CCS is toggled, then the model will take the bus demand and pass it through a grid to develop a dispatch schedule which will either meet the bus demand exactly or differ in ways that must be carried by a slack bus. The updated layout is presented below in Figure 66. The ramp rates of the plant will drive those differences. The analysis will consider those values and be able to show differences among the plants.

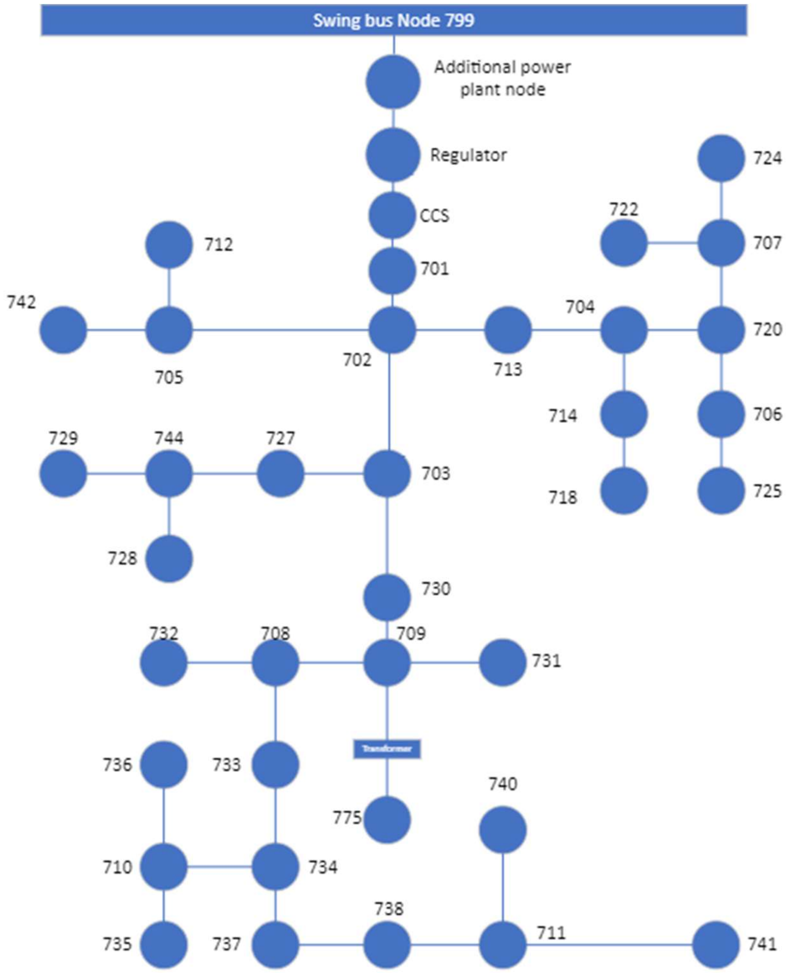


*Figure 66 Updated IEEE 37-Node system with another node added for the power plant inverse load node.*

### *5.1.3.1 CCS control*

Due to the complexity of the CCS control philosophy, the development of both the CCS controller and the subsequent power plant load following algorithm took a considerable amount of time and iteration. Very early on, the CCS control system began working and it was immediately noticed that without even working on ensuring it meets the on and off time constraints it was already turning itself off about 15% of the time simply because it was exceeding the initial limit of 2 MW. Without ensuring that the plant meets its 2 hour on/off time requirement, real systems would not be able to match this control pattern. This is still important to note though, as the power grid demand was exceeding its 2MW trip point a significant number of times as seen in Figure 67.

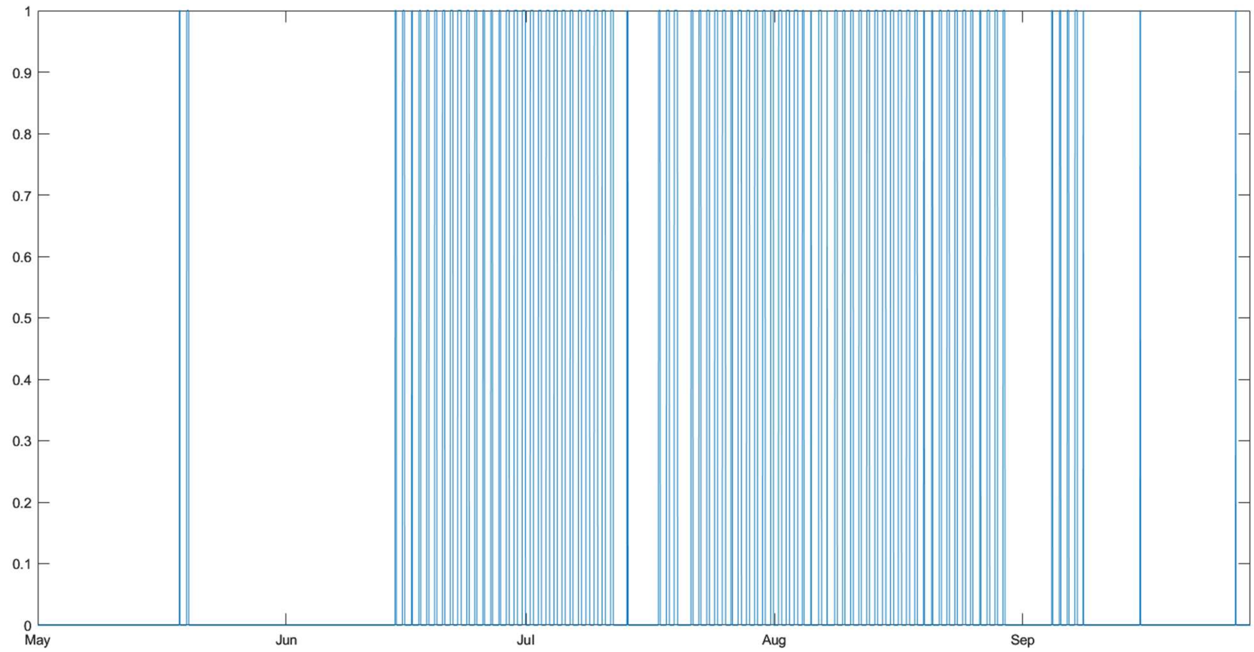


*Figure 67 The above early output of the CCS switch. When set to "1" the unit would turn off when the overall power demand of the grid using the look-ahead logic exceeded 2MW prior to the simulation application. This logic would then be expanded to toggle the 500kW draw of the CCS unit in later iterations.*

Again, the actual operation of a CCS facility will be subject to many constraints beyond simply ensuring there is adequate demand in the system. There are also the economic and ecological impacts to juggle and those cannot be understated. It quickly becomes imperative to ensure that however the unit is applied it has enough knobs to be fine-tuned as others come upon similar problems and choose different outcomes for their different objectives.

A second difficulty presented itself in that the system was toggling too quickly. By forcing the system to analyze the curve point by point and ensuring it did not violate the time constraints before worrying about what the value of the curve was performance increases were able to achieve CCS up times above 95% under my conditions. This was more in line with the original design's intent of maximizing time up and only shutting down to allow a greater load profile. An example can be seen in Figure 68.

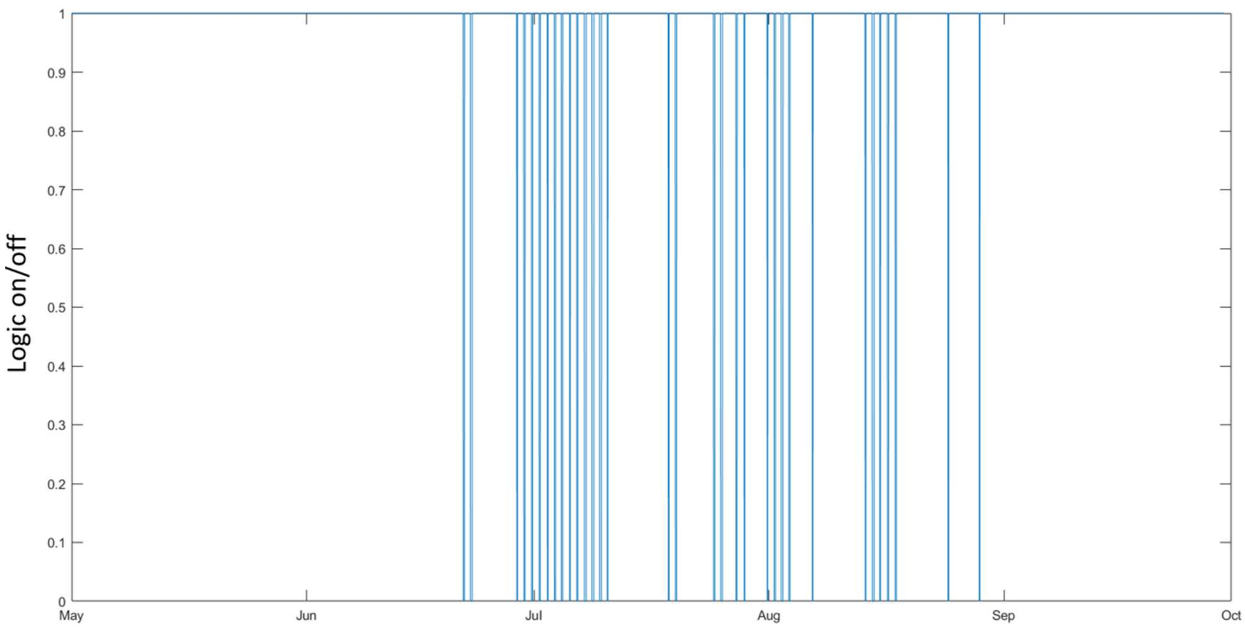


*Figure 68 In the final case logic, "1" signifies that the CCS unit is on, and it drops to "0" based on user set inputs. This iteration was able to achieve 96.6% "on" time when the look-ahead logic was set to trigger off 2.4MW of grid demand.*

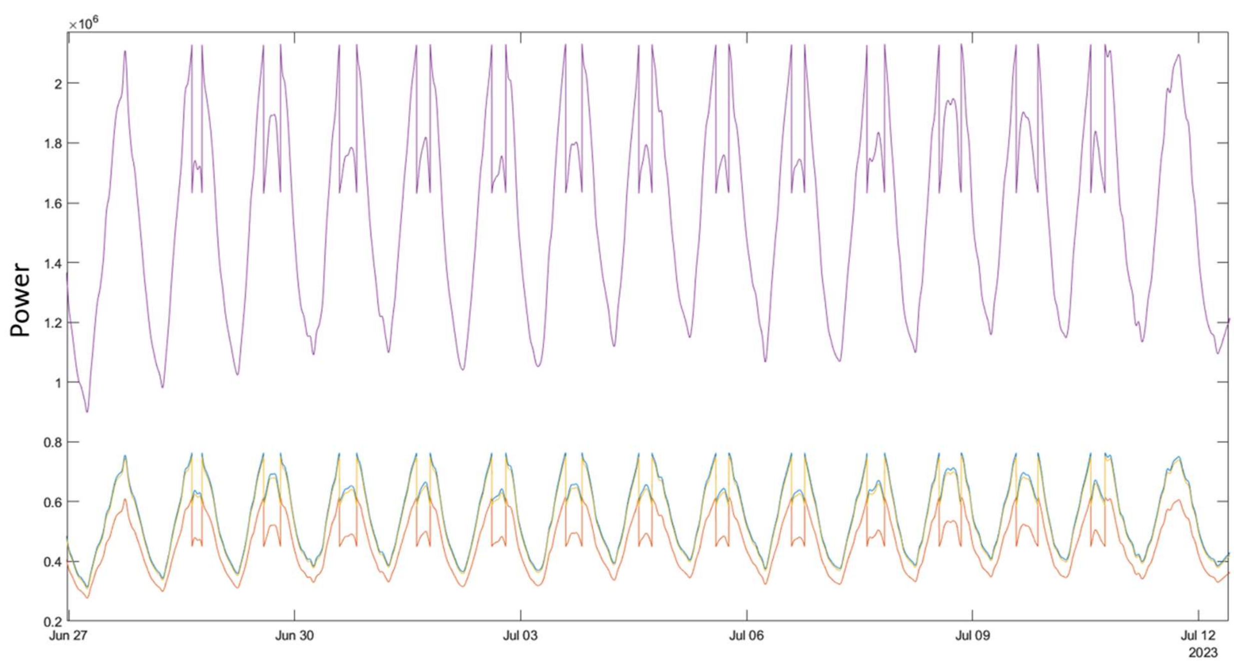


*Figure 69 This is an exaggerated look at the CCS unit activity and its impact on the total load curve.*

In Figure 69, the bottom 3 traces are the real power of phases A, B, and C of the load demand that Node 799 is seeing, while the purple trace is their summation. As you can see, the cut-off of the CCS unit can dramatically influence the "peak" seen by the power plant, but it does not change the other load parameters. We can see this because in the valleys of the peaks we continue to see the rise of the load. This is an important distinction to understand as the CCS unit represents 20% of the parasitic power draw of the plants maximum, but depending on the load curve, this can make the ramp rate necessary more or less than 20%. Since none of our plants can achieve this, it would be unfair to immediately assume a total failure as this becomes a load-following problem, so instead, it will be analyzed by other means, such as the gap this will create in the needed power for importing into the system and exporting excess power.

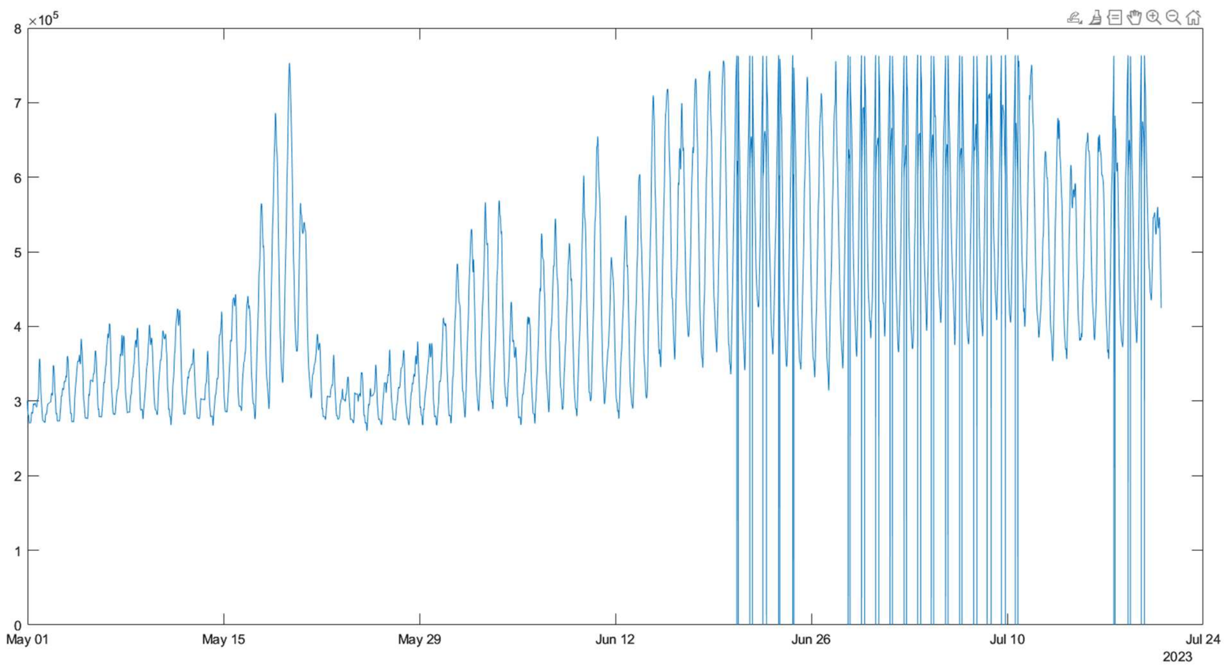


*Figure 70 Development of the phase control system to follow simulated data.*

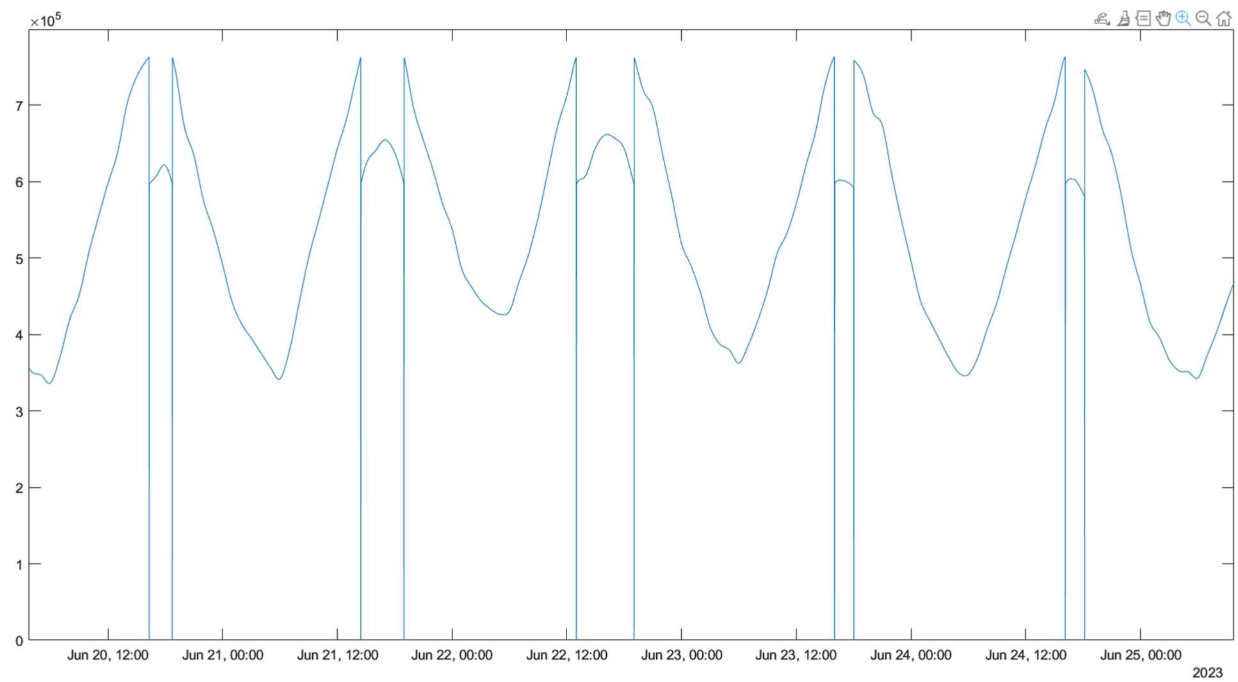


*Figure 71 Zoomed-in look shows the change points beyond the ramp rate.*

These two early looks at the control section of the code really highlight how well the power plant could have followed the load demand. Under these test sections, the MATLAB software used the plant parameters to match the simulated data that came from Gridlab-D, and should it have reached the threshold value, it would have output 0 power as seen in Figure 70. As there are not many points in Figure 71 where it went to 0, the system is already well matched to the ramp rate. While not what was needed for the model's work, it is illustrative of the few shorter points where the ramp rate of the power plant was actually taxed.

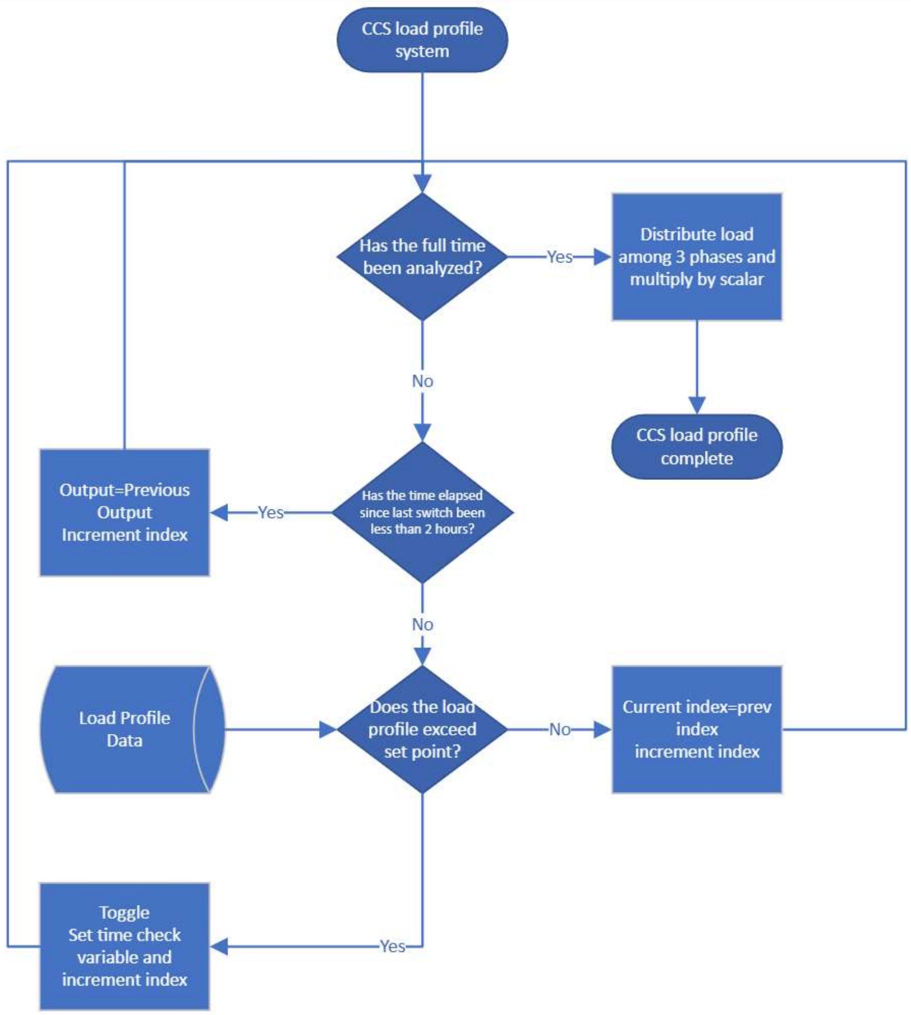


*Figure 72 Simplified flowchart for the CCS control implementation, also called a demand control scheme.*

Figure 72 is a simplified flowchart showing the general control system. The minor points that have been left out are the checks to ensure the system does not turn on or back off in the middle of a needed load curve potential. During Test 3's load profile development, this was not a concern as the peaks seen in the residential profile are thin and of short duration. Some of the durations of CCS on/off times therefore could have come out to 122 minutes, which are ever so slightly longer than the 2 hour set point minimums during the earlier tests. The following pages now detail the second part of this process which is developing the power plant output system.

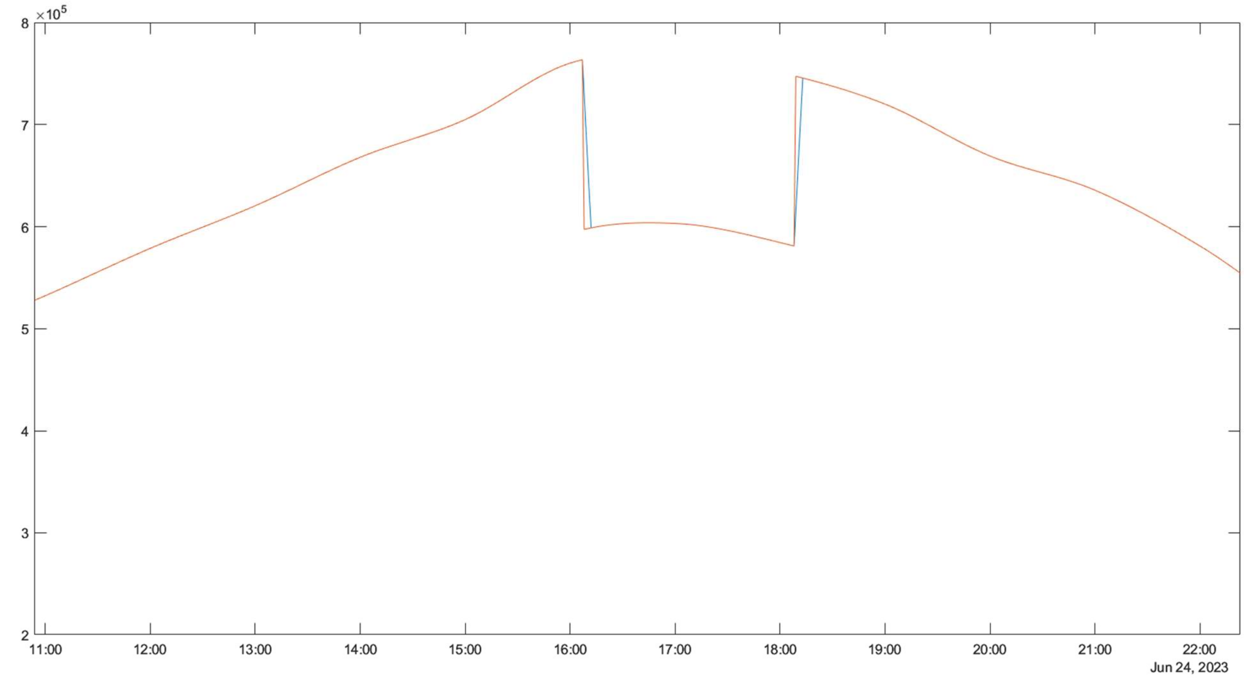


*Figure 73 The orange is phase A load demand from the simulated power plant, and the blue is the ramping the plant can perform.*

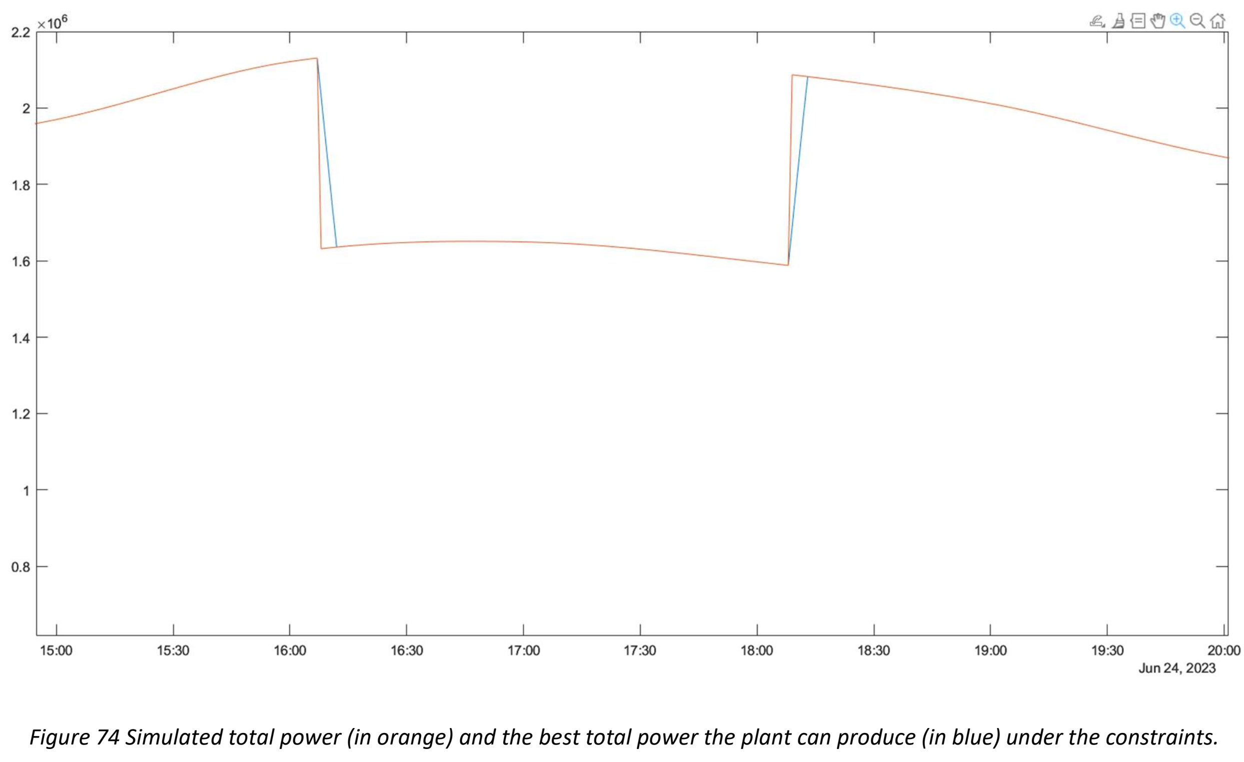


*Figure 74 Simulated total power (in orange) and the best total power the plant can produce (in blue) under the constraints.*

The two dips shown in Figure 73 and Figure 74 each lasted for about 4 minutes. In total over that amount of time, the difference between the system demand and the plant's capability to deliver was just short of 1 MW in both cases (~988 kW). The final iteration of the control code can be more easily understood with a more in-depth flowchart representing the if statements below, along with some mathematical equations. The flowchart is presented in Figure 75.

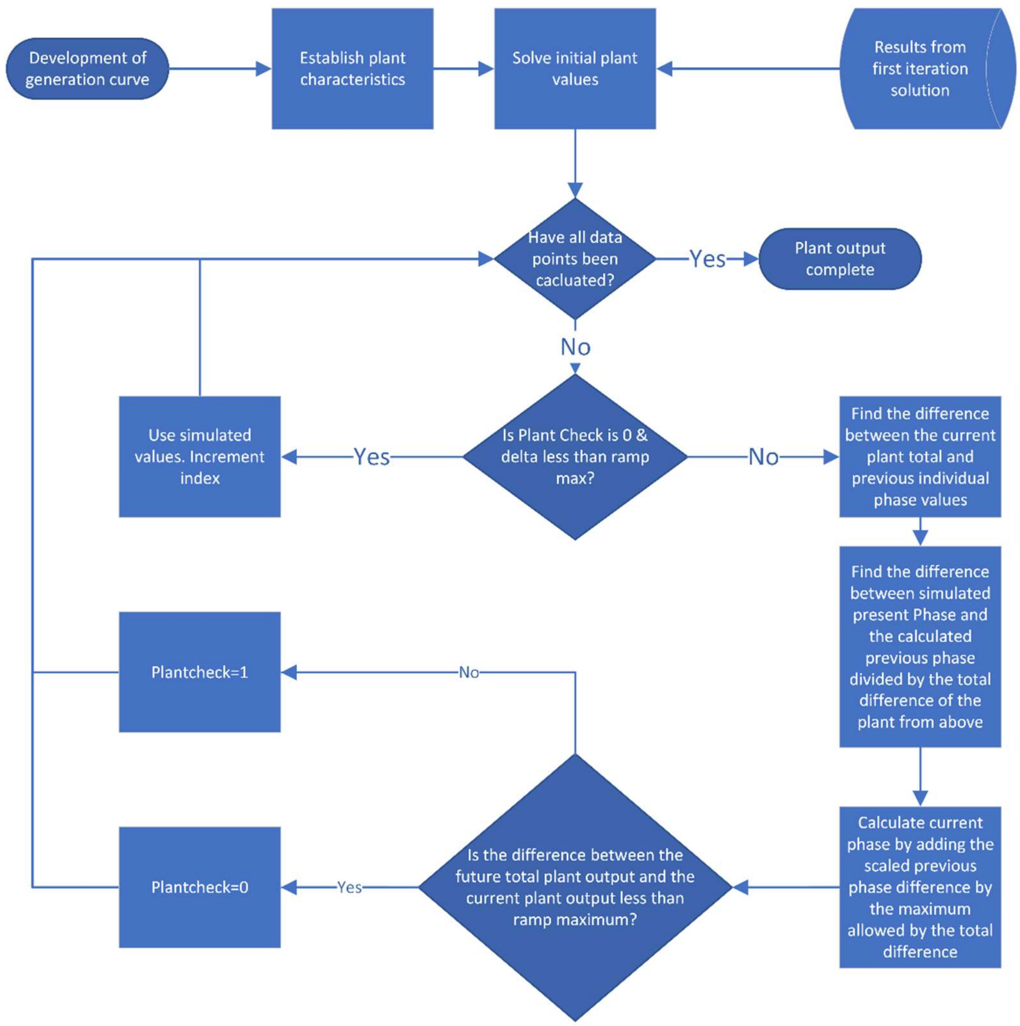


*Figure 75 The above flow chart shows the calculations done to find the limited plant output subject to its ramp rate capabilities.*

As we are solving this problem iteratively there will be the simulated data output and then there will be the follow-on calculated output that will be restricted by the ramp rate that would actually be possible. Simulated data would be the ideal solution but there will be times that the restrictions of the plant can't meet those demands. Where this can become a problem is that if the calculated values do not load follow "well" by rebalancing phase A too far or simply overshooting the calculated values can veer off and never reconcile back to the "true" simulated data set, which is the target.

The development of the plant output can be simplified down to two different cases. In the first case, the maximum ramp rate is greater than the delta between the previous and current total simulated output. The distinction between the simulated and calculated outputs will become more important shortly.

$Max\ Ramp\ Rate \geq \sum Plant\ power - \sum Previous\ plant\ power$;

if this is true, then we can simplify the output of the calculated plant output by simply equating it to the simulated output. The minimum and maximum are bounded by the first iterative solution that was performed. The ramp rate is the remaining influencing factor, and, so long as it is greater than or equal to the delta between the current and past values, the plant can meet its demanded power curve.

Where this can become a problem is when the plant cannot meet the point-to-point demand. When that occurs, we instead need to shift to using the following equations which will take the load demand and try to meet it with what the power plant is calculated as possible:

$Plant\Delta = \sum Plant\ Simulated - \sum Phase\ values\ of\ past\ calculated\ output$;

$Phase\Delta = (Present\ Simulated\ Phase) - \frac{Prev\ Calc\ Phase}{Plant\Delta}$; and

$Phase\ output = (Prev\ Calc\ Phase) + (Phase\Delta * Ramp\ Rate)$.

The first step of the above formula differentiates from the prior formula by specifying the calculated values instead of the simulated values. If the system gets into this branch of the decision tree, it knows to now be mindful that we can no longer rely on the simulated values, as we have likely deviated from them. This is where the ramping capabilities of the power plant will start to influence what the actual output of the plant could be. Plant delta will be the delta between the ideal simulated total demand and what is calculated as possible. The second line begins to check the difference between the phases. The load is imbalanced, and we cannot take for granted that the differences between the points are consistent among the phases. However, we use the simulated value as a target to achieve scaled ramped phase output to the best of the plants ramp abilities when it cannot match the simulated true target. So, by dividing out the total difference and subtracting it from the simulated value we create a scalar value to scale our ramp rate.

In the final formula we put that scalar value to work by taking the previously calculated phase delta and adding to it (the value could be positive or negative) after multiplying it by the ramp rate. While the system may not be perfect, it is attempting to iteratively catch up to the total power needed while at the same time maintaining the growth rate of the individual phases. While the system will still need outside help to either import or export these calculated values that do not meet the target simulated values, the plant will at least have tried to maintain the status quo.

The final formula necessary for this process is

$$Max\ Ramp\ Rate \geq \sum Future\ Plant\ power - \sum Current\ Calculated\ Power.$$

This final check on this more complicated side ensures that, should the system not be able to recover at the next data point; we would remain in these even following paradigms with a check value. Should the above be true, the check value is set at 0, and the subsequent phase and total output will again match up to the simulated values. Should it be false, the check value is set at 1, and we will continue to follow to the best that the ramp values will allow the system to do so.

Test 3 undergoes a number of significant changes compared to past tests. Between the CCS unit operation and the iterative solution of the power plant output, the amount of data and analysis coming from this test is greater than in previous tests. One of the major points of this test is finding where this delta in power comes from that the plant could not provide.

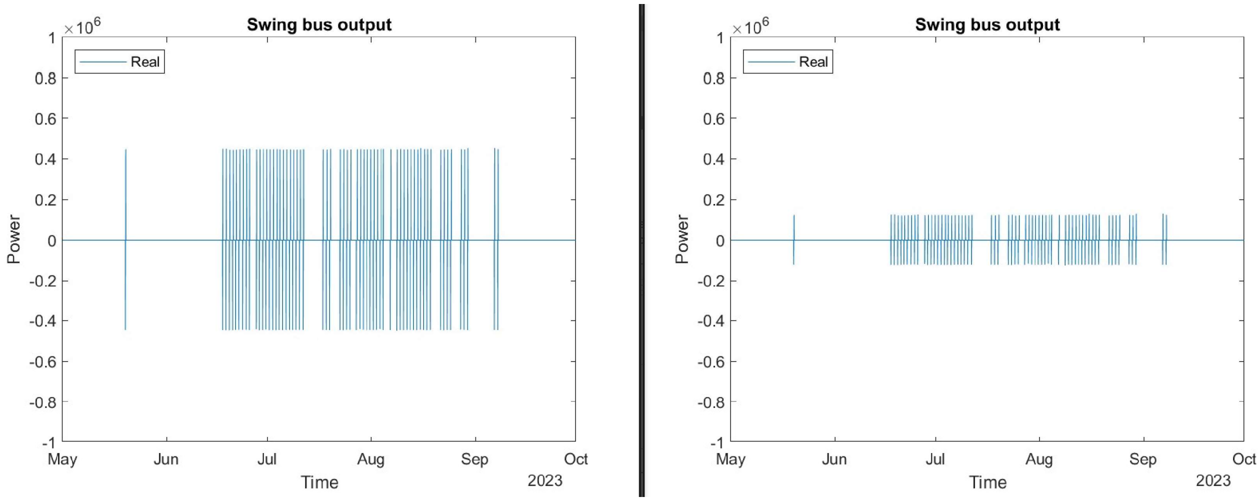


*Figure 76 Side by side comparison of the 2% ramp rate (on the left) swing bus to the 15% swing bus (on the right) demand*

To that end, an additional diagnostic was added to look at the power differential from the behavior of the limited plant. Since Gridlab-D does not allow islanding without substantial changes to both the timescale of operation and the methodology, it is assumed this is no longer a radial feeder that operates alone. Instead, the difference in power is assumed to come from a swing bus further out in the power grid. Figure 76 is a side-by-side comparison of the significant differences between what a 2% and 15% ramp rate would require for the system to be in balance brought in by the aforementioned swing bus. Not only are the magnitudes of the spikes significantly lower with the greater ramp rates, but the widths are smaller, showing that the amount of time under out-of-balance conditions is lower.

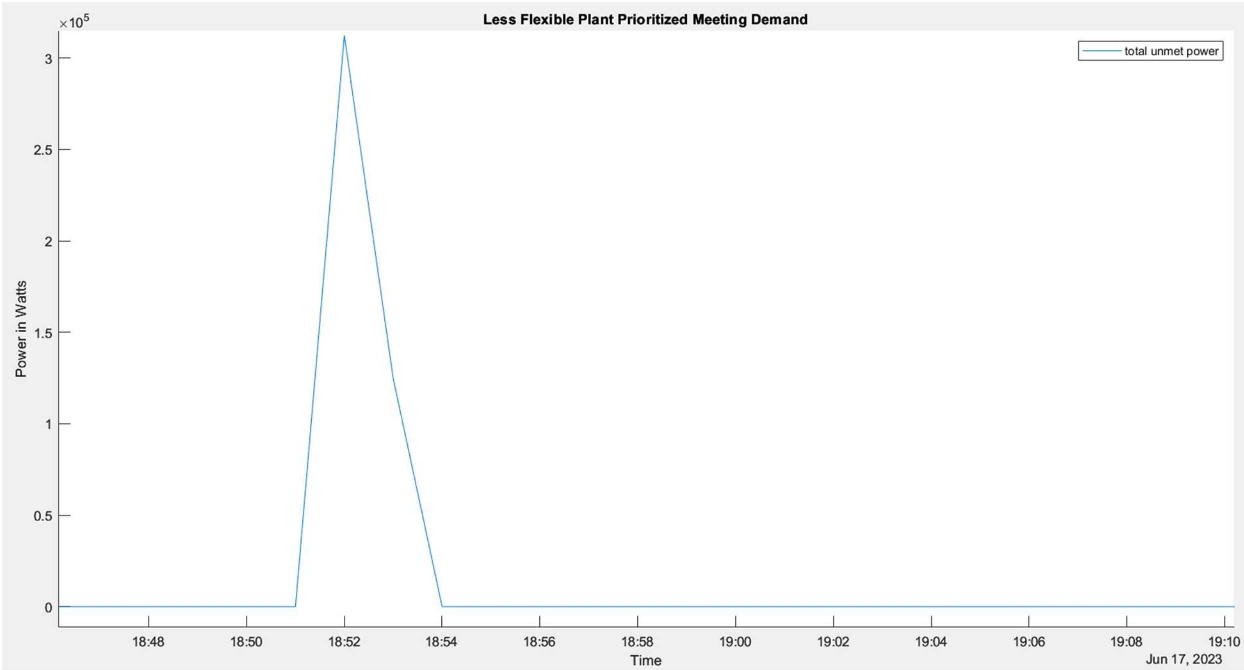


*Figure 77 A zoomed-in look of an example of the spikes shown in Figure 76.*

Figure 77 shows a zoomed in look on the spikes that are shown in Figure 76. The large field view makes them appear as impulses, but when zoomed in close you can see there is a rising and falling edge as the plant attempts to meet the sudden demand change and the difference is brought in or exported out. These discrepancies only last minutes long but are of significant size and therefore impact the operation of the grid. The example lasts about 3 minutes and peaks above 300 kW, and the falling edge can be seen to a slight shift in slope as the initial drop from the peak was as steep as possible, but the following (time step 53-54 minutes) branches out slightly as the plant is no longer maximizing on its ramping capability.

The discrepancies the CCS unit will impose on the system have been shown to be possible in the real world as a plant hurries to capture favorable market conditions and switches the system off quickly to free up generation capacity. This can also be viewed as a sudden disconnect from the grid of a large portion of serviced demand. The limitations of Gridlab-D are such that we cannot analyze the system for responses in the sub-steady state, but the system would still need to recover voltage regulation and power response if a substation were to fail.

While an outage is not the direct result of these tests, there is merit to the data in that should an outage occur of this variety, there is some similarity to this system. Flexible plants and increased capacity could have helped during Storm Uri, and it is similar here that a system could prop up sudden changes of a 20% load shift with these parameters.

### 5.1.4 Test 4

The system for Test 4 was developed on the same framework that the previous iterations were built upon. The difference here is that the plant under test was split into two, with one being a flexible variation with a minimum load of 10% and a 15% ramp rate, while the other was a non-flexible variation with a minimum load of 30% and a ramp rate of 2%. Under these conditions, the desire was to show if two plants were directly competing.

The immediate problem is that there are no shortages of what would define that relationship. Often plants are operated in ways that maximize economic dispatch and limit plant operational costs in response to energy market conditions. In this work, operations are dependent on demand only and are more in line with power generation under emergency conditions as there are no maintenance periods, no down-time, and the system entirely dictates efficiency or the lack thereof.

This subsequent test continues by dictating that the plants be beholden to the demand of the load to the best of their abilities. This is further expanded to account for their competition by prioritizing one plant over the other by first their ramp rates and then their maximum and minimums to see what portion of the load would be served by the nonprioritized plant.

This would show the bounding performance limitations of what could be possible under this scenario. If the plants were operated in a fashion that was more inclusive of other factors such as efficiency, limitation of O&M cost, or trying to keep the systems operating around a midpoint, then the results would come somewhere between the results found here in this test.

A detailed flowchart for this test can be found in the appendix labeled detailed flowchart for test 4. The 37-node load and renewable power curves applied to the test were the same as the maximum experienced in the final parts of Test 3. Splitting the single plant into two smaller versions would guarantee that the system could not meet the demand for it. This would supply the opportunity to see clear-cut differences in the performance of the study.

### 5.1.5 Test 5

The system for Test 5 was built to test some of the parameters of the past modeling work at scale. Gridlab-D remains a bounding factor in that it was not designed with "islanded operation" in mind. However, this system was built as a 700 MW test feeder, which would be more indicative of a traditional thermal plant size.

Load characteristics were found from another research paper (Evans, Zolezzi, & Rudnick, 2003) and are presented in Table 4 below (Evans, Zolezzi, & Rudnick, 2003). Using the values in the following table as overall curve scalars, allowed the influence of types of loads that are best explained by Table 4.

*Table 4 Load curve characteristics from a study on cost assignment modeling. (Evans, Zolezzi, & Rudnick, 2003)*

LOAD VALUES

| Hour | Hour load in p.u. | | |
|---|---|---|---|
| | Res. | Com. | Ind. |
| 0 | 0.70 | 0.25 | 0.60 |
| 1 | 0.61 | 0.23 | 0.57 |
| 2 | 0.52 | 0.20 | 0.55 |
| 3 | 0.48 | 0.19 | 0.53 |
| 4 | 0.47 | 0.18 | 0.50 |
| 5 | 0.45 | 0.18 | 0.53 |
| 6 | 0.47 | 0.17 | 0.55 |
| 7 | 0.58 | 0.40 | 0.70 |
| 8 | 0.70 | 0.60 | 0.85 |
| 9 | 0.59 | 0.79 | 1.00 |
| 10 | 0.55 | 0.97 | 0.93 |
| 11 | 0.54 | 0.97 | 0.91 |
| 12 | 0.52 | 0.97 | 0.90 |
| 13 | 0.51 | 0.95 | 0.91 |
| 14 | 0.50 | 0.90 | 0.92 |
| 15 | 0.55 | 0.96 | 0.90 |
| 16 | 0.59 | 1.00 | 0.89 |
| 17 | 0.73 | 0.90 | 0.87 |
| 18 | 0.82 | 0.80 | 0.85 |
| 19 | 0.90 | 0.71 | 0.82 |
| 20 | 0.98 | 0.62 | 0.80 |
| 21 | 1.00 | 0.53 | 0.81 |
| 22 | 0.99 | 0.44 | 0.83 |
| 23 | 0.85 | 0.38 | 0.71 |
| 24 | 0.70 | 0.25 | 0.60 |

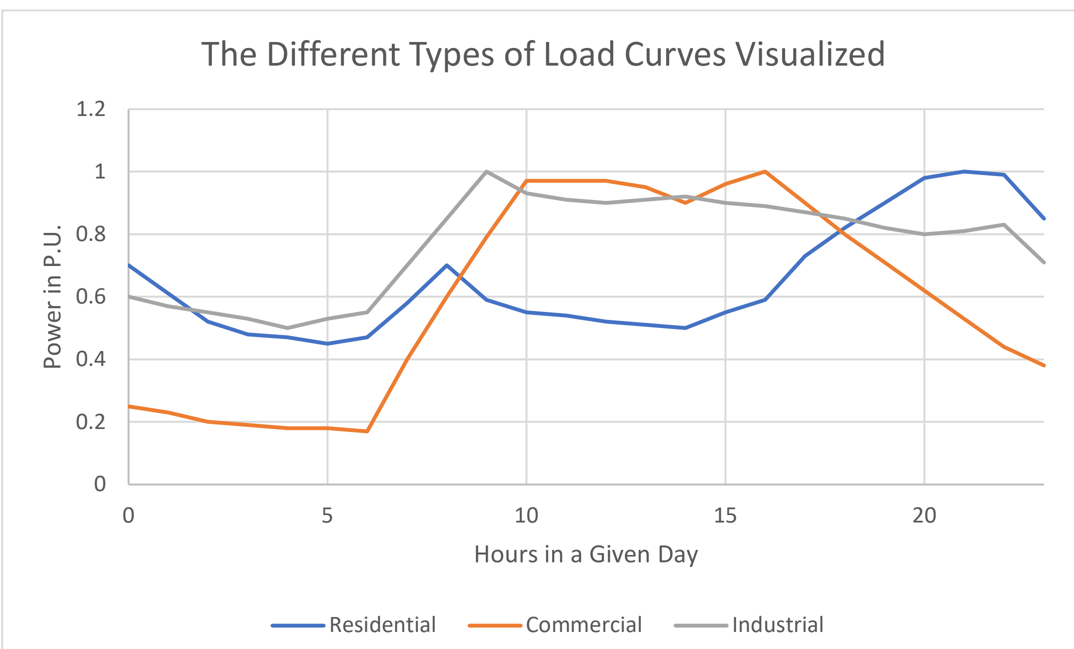


*Figure 78 Load data graphed out to better show the general curve shape throughout the day.*

Figure 78 better shows the load curves of residential, commercial, and industrial influencers as they evolve throughout the day and, subsequently, their influence on the total load experienced when those components are summed up for a power plant when it acts to meet that demand. Different types of loads peak and fall off at different periods as you would expect. The residential curve follows a similar pattern to what was used in other tests as peaks are defined later in the day as people come home and utilize their home systems. Commercial load peaks early in the morning and then gradually drops off over the course of the day before closing for the night. Industry load follows a similar trend to the commercial sector but has a higher, more profound rise, fall, and peak. All of these different load curves will react differently to the model and are important to work into the system.

Similarly in the earlier test, the system's power factor was designed to be "poor" as defined by sources (DTE Energy) (Evans P. , 2018) and set to 0.9PF for the duration of the test. Again, like the earlier results, the CCS unit generally performed a level of power factor correction by being such a large real load with a unity power factor.

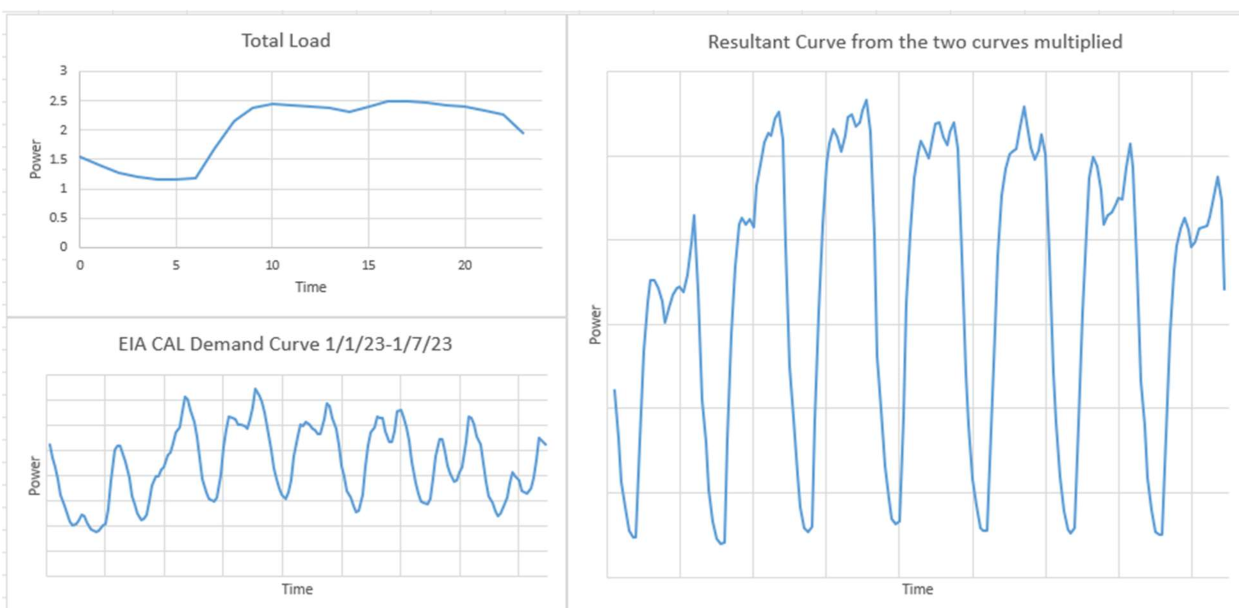


*Figure 79 Development of an example load curve using information from real results and scaling factors.*

There was not only a call to increase the system's size but there was also a need to show the model performing against the other curve characteristics. Figure 79 shows the details of how this was done using the results from Evan's work and real data from the EIA (EIA, 2023). The curve from Evan's work was developed by summing the hour-by-hour Per Unit (P.U.) values and plotted over a 24-hour period. The EIA data was pulled from their historical data set for a given region – in this case, it was from the CAL area (California). While either source would have been sufficient by themselves, a melding of the two allows the user to get a week's variation curve and real data influence from editable static values. Should you want to model an area with more industrial influence, you could increase the p.u. values in the base curve, or should you want to model something in the springtime, you could pull a later dataset.

In this instance, the values were kept static, so the assumption is that the system under test is evenly spread among industrial, commercial, and residential sectors. California's load demand influences the weekly curve in the mid-wintertime frame.

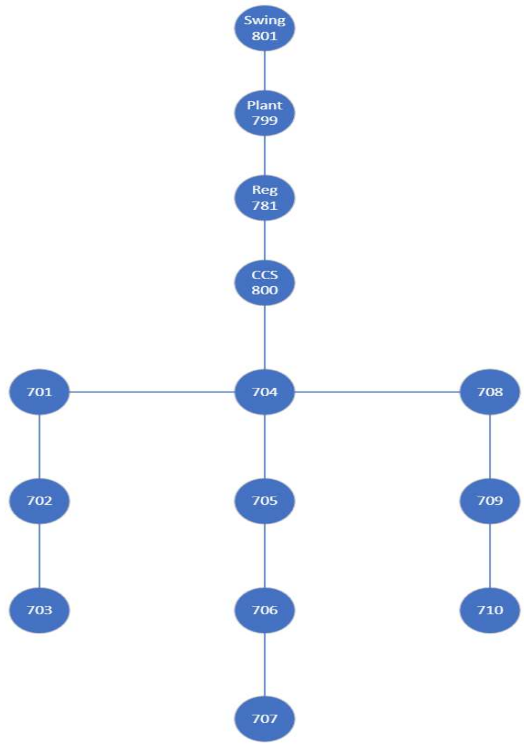


*Figure 80 The layout of the 10-node system developed is above. Numbering convention was adapted from the IEEE 37-node system to speed up development, but all other characteristics were updated.*

The feeder system under test also needed to be rebuilt and is shown in Figure 80. While the IEEE 37-node system was a valuable test feature, its power hosting ability was limited. The new system was designed with the plant size having a 700MW nameplate capacity. Values for transmission lines were based on the Kiwi transmission line settings (I A State). Line spacing for those lines was based on a typical 500kv spacing (Qais & Khaled, 2016). The lines were set to be 100 miles long between nodes past the CCS unit. This means the transmission lines are significantly oversized for the application but will still provide an influencing factor against the results while not risking line limits being reached.

Likewise, the nodes were resized to the 500kV standard, and the load that was developed above was redistributed by the table values below in Table 5.

*Table 5 Breakdown of percentage of overall power curve and how it is was applied to the phases in both real and non-real components.*

| | Distribution of Percentages | | | | | |
|---|---|---|---|---|---|---|
| | A real | A Imag | B Real | B Imag | C Real | C Imag |
| 701 | 0.03000 | 0.00333 | 0.04000 | 0.00444 | 0.01000 | 0.00111 |
| 702 | 0.04000 | 0.00444 | 0.04000 | 0.00444 | 0.02000 | 0.00222 |
| 703 | 0.05000 | 0.00556 | 0.03000 | 0.00333 | 0.03000 | 0.00333 |
| 704 | 0.03000 | 0.00333 | 0.03000 | 0.00333 | 0.04000 | 0.00444 |
| 705 | 0.01000 | 0.00111 | 0.02000 | 0.00222 | 0.01000 | 0.00111 |
| 706 | 0.03000 | 0.00333 | 0.04000 | 0.00444 | 0.04000 | 0.00444 |
| 707 | 0.04000 | 0.00444 | 0.05000 | 0.00556 | 0.02000 | 0.00222 |
| 708 | 0.05000 | 0.00556 | 0.02000 | 0.00222 | 0.02000 | 0.00222 |
| 709 | 0.03000 | 0.00333 | 0.02000 | 0.00222 | 0.02000 | 0.00222 |
| 710 | 0.05000 | 0.00556 | 0.02500 | 0.00278 | 0.01500 | 0.00167 |

The Table 5 above shows the percentage breakdown of power applied to the system nodes and phases. As the system under test is significantly larger and more inclusive of different types of loads, the phases of the system are more closely balanced but still contain some differences. Phase A was more heavily loaded than the other phases and then some nodes draw more power than others, but none are left blank.

The system's overall structure is still set up to be a radial test feeder but of a significantly larger size. Again, the limitation of traditional systems is that as systems grow larger, they usually have other plants help to share the load. A more complicated load relies on more complicated distribution systems to feed it. The problem remains the same as the original reasoning. If you want to see the capabilities and limitations of the system with only the system acting upon it, then isolation is needed.

During Test 5 the peaks were the result of commercial and industrial applications and subject to mid-point variations. The aforementioned checks that took place during the development of the CCS load profile were able to catch those system load profile set points that occur at the end of the minimum toggle set points but, should the load profile dip down and then back up within the toggle period, the system did not account for it. The plots in Figure 81illustrate this point.

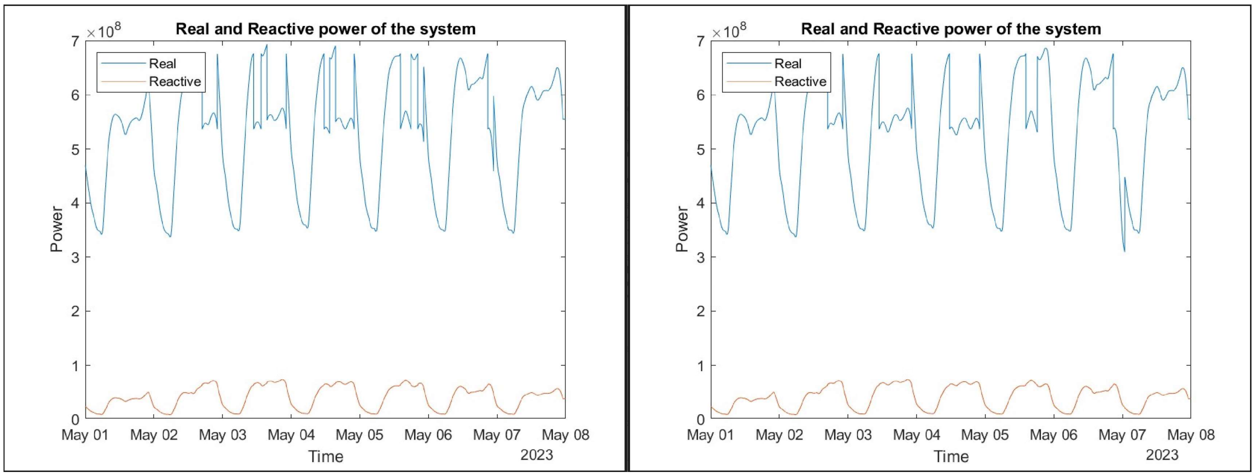


*Figure 81 The above graphs help illustrate the difficulty of working with a wider more dynamic load profile with the CCS control system. The left is with a 2-hour toggle set point. The right is with a 4-hour toggle set point.*

The plots in Figure 81 show the full load profile as measured at the swing bus nodes and is representative of the full system load. The original set points of the CCS system did not allow the unit to toggle on/off for time periods less than 2 hours in length in accordance with expected system capabilities in the industry. Additional checks ensured that if minute 121 of the check was above the maximum look ahead set point, the unit would stay off until the load profile dropped below allowable levels. This worked well for the original residential load as the periods of high demand were shorter in duration and less dynamic.

With this newer load profile, the tops of the curves were wider and shifted up and down more, so we get this result on the left, where the profile dips down but swings back up later in time. The CCS unit then toggles on/off a couple of times during these swings it can. This represents a difficult problem for the model.

Should you extend the toggle maximums and minimums to encompass the wider base? Should you extend the look-ahead system to measure the full curve to ensure it is always off during general high peak demand? Should you add a weight to how environmentally or economically valuable the CCS system is operated?

Here it was chosen to increase the toggle limitation to 4 hours which gave a more generally favorable result of limiting peak demands and increasing the CCS on times. The peak between May $5^{th}$ and $6^{th}$ remained problematic but is a good counterpoint to general operational concerns as it is very short in duration (relatively), but significantly costly in almost every other parameter to solve around.

The choice here was made with the expectation that real world operations would expect external energy markets to solve the need. While it is a limitation of the model, it is also an example of its capability to react and change relative to system requirements. It could have been solved entirely for that short, small peak but then the whole week's operation would have been weighted heavily by that singular need.

# Chapter 6

## 6.1 Results Discussion

The following hierarchy piece is presented again for ease of use for the reader. This section supports Question #2 while using the model developed for Question #1.

- Test 1- Initializing the system and establishing the appropriate operation and reporting. The dynamic load is modeled, and the beginning limitations of the system are found from the hosting of the carbon capture-limited power plant.
- Test 2- Add in renewable energy systems in a distributed manner. The amount will be directly tied to the minimums of the power plant and the ramp capabilities.

- Test 3- Enable the dynamic CCS unit to find the increased load hosting capabilities and the impact the ramp rate differentials can support.
- Test 4- Split the single power plant into two and operate a flexible and non-flexible variation against one another from a priority standpoint to show the different hosting capabilities possible with the different strategies.
- Test 5- Increase the size of the hosted grid to more realistic scales. The plant maximum will now be 700MW,700 MW and the makeup of the grid will change to reflect a larger platform to see operations under the model at scale.

### 6.1.1 Test 1

Under the conditions here, it was expected that the ramp rates would provide a larger influencing factor than they did. Despite the significant efforts on interpolation and fine tuning of the analysis and control software, the ramp rate was not significant until later in this work.

The main limitation to the system under Test 1's conditions was the minimum load the power plant could support. As the load gradually increased, it got to a point where the load fit inside the envelope of the maximum and minimum. In testing, it was not until a minimum load rate of 30% was achieved that the results would stay within bounds. This comes about due to the extreme swing of the load curve over the months.

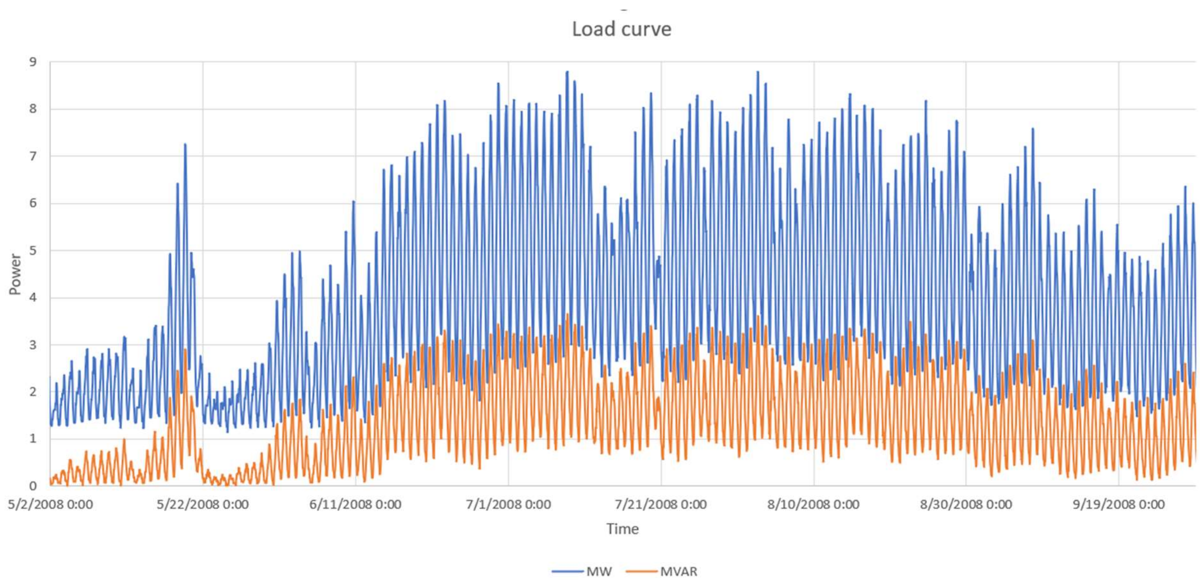


*Figure 82 Another example of the load curve applied to the system. This curve had not been appropriately sized and distributed yet.*

Figure 82 above shows an example of the load curve applied to the system. There is minimal swing across the hours in the early days of May. Towards the end of the month, we see a large swing, most likely caused by an unusually hot day. The residential houses react by turning on their central cooling systems, massively increasing the power demand. This becomes a major contributing factor later in time, though, such as during July and August. Figure 82 above is unitless as it is used only for its shape and multiplied to scale into the system, but, even from the curve, we can see that the most extreme day in May is still roughly 25% less than the day-to-day swings in July.

As discussed in the winter storm Uri section, weather can have a very significant impact on the demands that the power grid must account for. During the storm, there were a host of various plants working together to try and maintain power delivery, but it came to a point where load had to be shed. The same principle is applied here. 30% (750 kW) was the minimum power production that could support the load that was peaking at 2.5 MW during the extreme days. The average power over that time frame was approximately 1.4 MW, coming in at about 55% capacity factor for the unit.

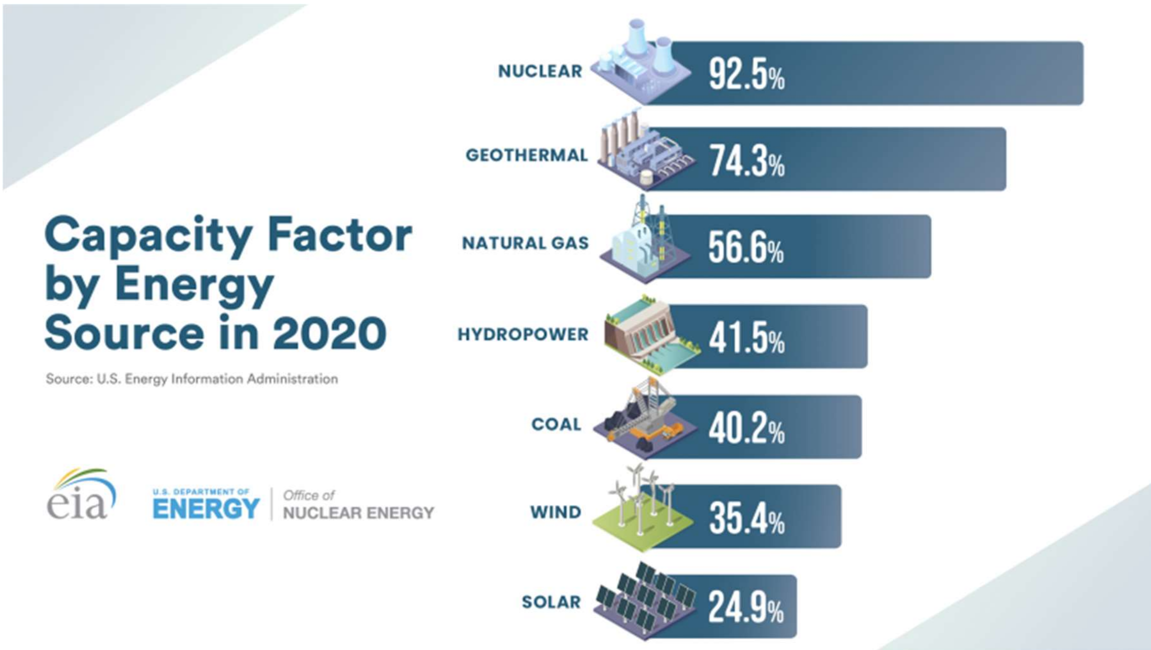


*Figure 83 Average capacity factor based on technology (Office of Nuclear Energy, 2021)*

There are a lot of different sources that say what the average capacity factor of a power plant should be, but Figure 83 shows that the value of the tests came in between a natural gas plant and a coal plant. Again, in this test, we are not modeling any specific technology. Only the values of their flexibility parameters, but it is important to note that, so far, the behavior is in line with expectations.

The capacity factor helps to tell the utilization of the power plant and can be critical in determining the health of the system. Different technologies of plants rely on operating within certain regimes to stay economically competitive. Not all these factors are immediately obvious, either. The same report Figure 83 came from notes that, depending on how the capacity factor is calculated, it could account for the downtimes when maintenance is being performed. This was one of the bigger influences for the nuclear power plant as it historically operated with lesser invasive or obstructive down periods to impact its capacity factor.

The capacity factor can also allow someone to analyze a system's reliability or robustness factors. A system that always operates in the 90% regime will not be able to adapt to sudden influxes of demand from a hot day. This all ties back to the variability of the CCS unit. It can operate and provide ecological benefits during periods of lower or more nominal power demands. In periods of higher demand though, it can shut down and allow the plant access to its full capability. This will be better covered in Test 3 results.

### 6.1.2 Test 2

Test 2 is where the model really began to grow in complexity, as there was both the base load and the solar resource causing disturbances within the system. The distributed solar resources positively and negatively impacted the plant's operation. The failure points are also included to show how fine-tuned the system was under these conditions. Again, calling back to the time it takes for solutions and the difficulty of performing iterative solutions, a range of acceptance was employed.

*Table 6 The table below summarizes the basic results from test 2.*

| Minimum load percentage | Average solar over period in W | Maximum solar in W | Failed point | Set point of percentage | Average power of plant | New Maximum Power | Run number |
|---|---|---|---|---|---|---|---|
| 30 | 4,355 | 11,723 | 748,405 | 750,000 | 1,373,112 | 2,479,533 | 4 |
| 25 | 68,245 | 183,182 | 623,004 | 625,000 | 1,278,339 | 2,407,200 | 11 |
| 20 | 127,209 | 341,453 | 497,640 | 500,000 | 1,219,132 | 2,404,662 | 14 |
| 15 | 174,708 | 468,948 | 372,017 | 375,000 | 1,163,106 | 2,402,963 | 19 |
| 10 | 221,115 | 593,512 | 247,856 | 250,000 | 1,116,668 | 2,401,718 | 22 |

The Table 6 immediately shows us a lot of expected results. The distributed solar power modules did not take much to create a failure point at 30%. This was expected, as it barely scraped by during the first test. In moving in 5% steps and retesting the system, we see more dramatic results better, seen below in Figure 84 and Figure 85.

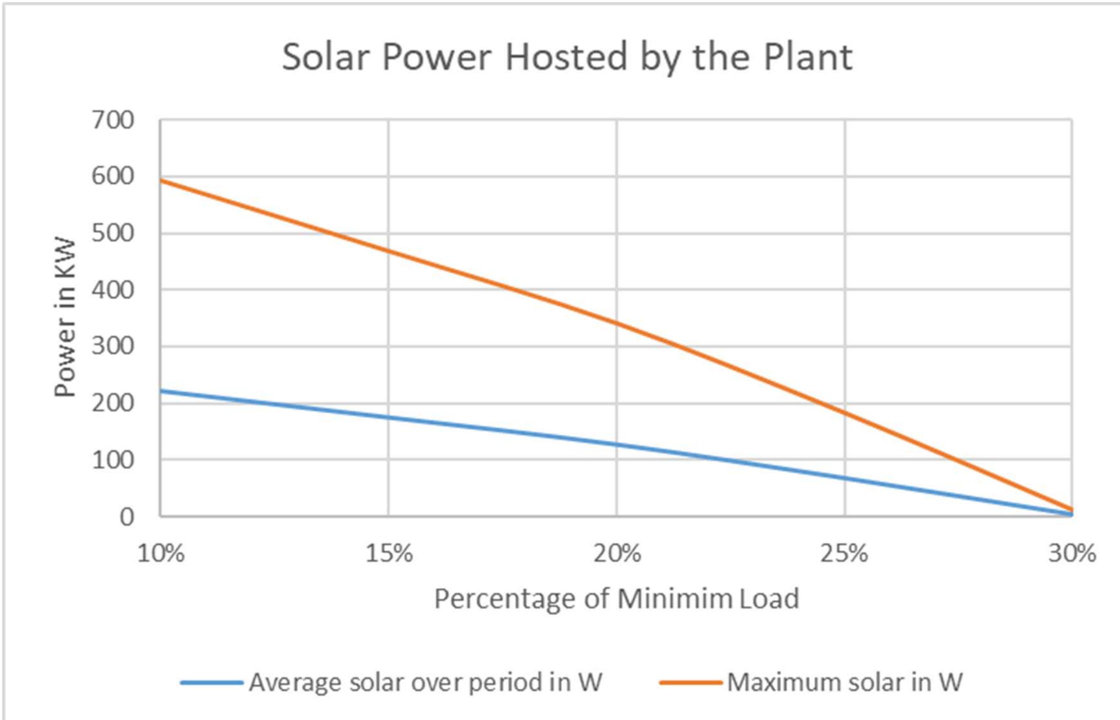


*Figure 84 Graphical representation of the first 3 columns of the above table.*

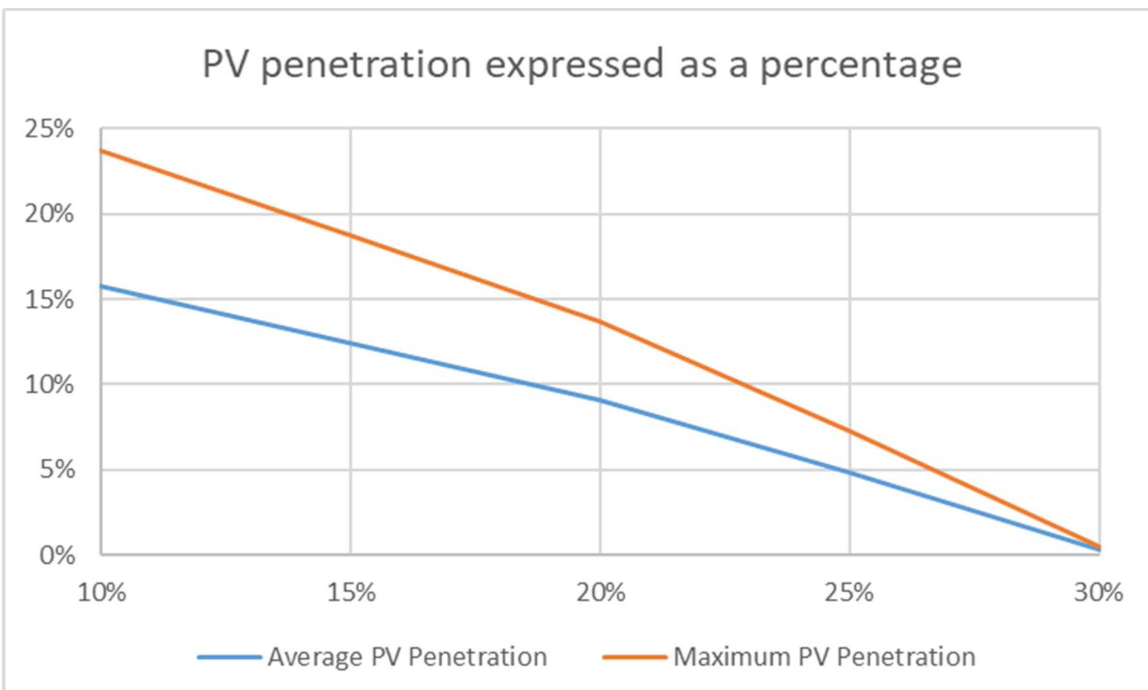


*Figure 85 The same graph again but expressed by using the average load from Test 1 and the maximum load to scale the results as a percentage.*

The hosting capability of the power plant is heavily dependent on the plant's ability to run in low capacities. Each step of 5% resulted in approximately a 50-60kW additional average power increase coming back into the system. The maximum seen from the solar at each 5% step also increased the peak power from the solar power by over 100kW, with some reaching as much as 150kW additional into the system. This also illustrates why distributed solar resources begin to impact grid operations significantly. The individual components of the solar arrays are negligible, but the summed portions can begin to wreak havoc on grids ill prepared for them.

In Figure 85, the outputs are scaled by the average and maximum power of the system to describe the Photovoltaic (PV) penetration of the system, which is a measurement of the solar resource coming into the system. PV penetration is very subjective to the system's makeup. Many high penetration studies come down to the system’s ability to regulate voltage and frequency. At higher levels of penetration, limitations are imposed by the voltage and frequency failing. In Gridlab-D, frequency regulation is not calculated, but our voltage regulation is. The feeder used here is lightly loaded, so the failure point for this test was the system’s ability to maintain a minimum load. It should also be noted that there are no penetration limits and that it should be taken with a grain of salt since it is such a system dependent (Ellis, 2010) as mentioned in Figure 86.

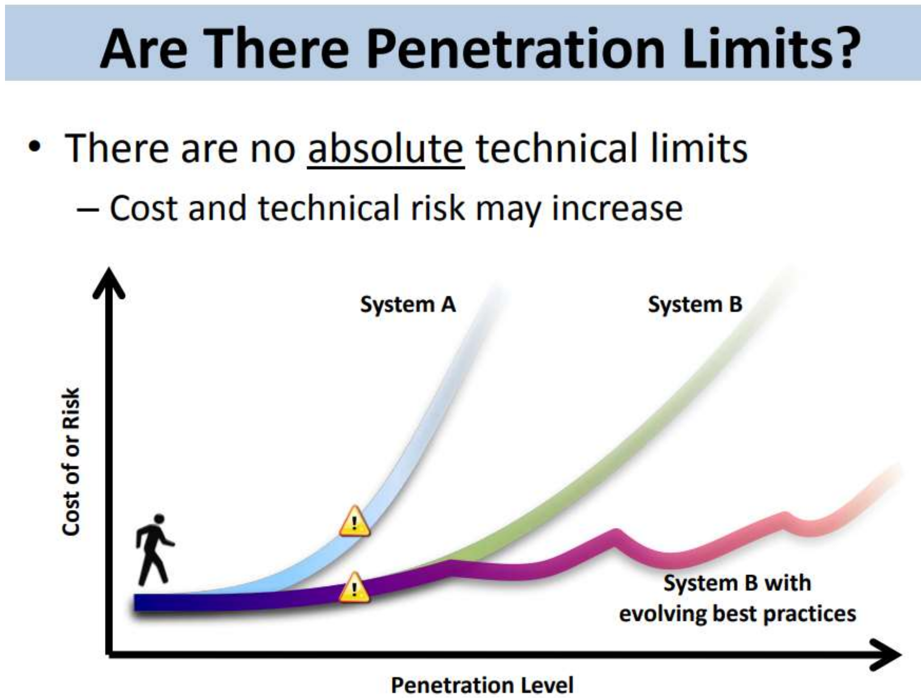


*Figure 86 This relates to the idea that there are no penetration limits on VREs. Only additional risks and costs are associated with handling those resources. (Ellis, 2010)*

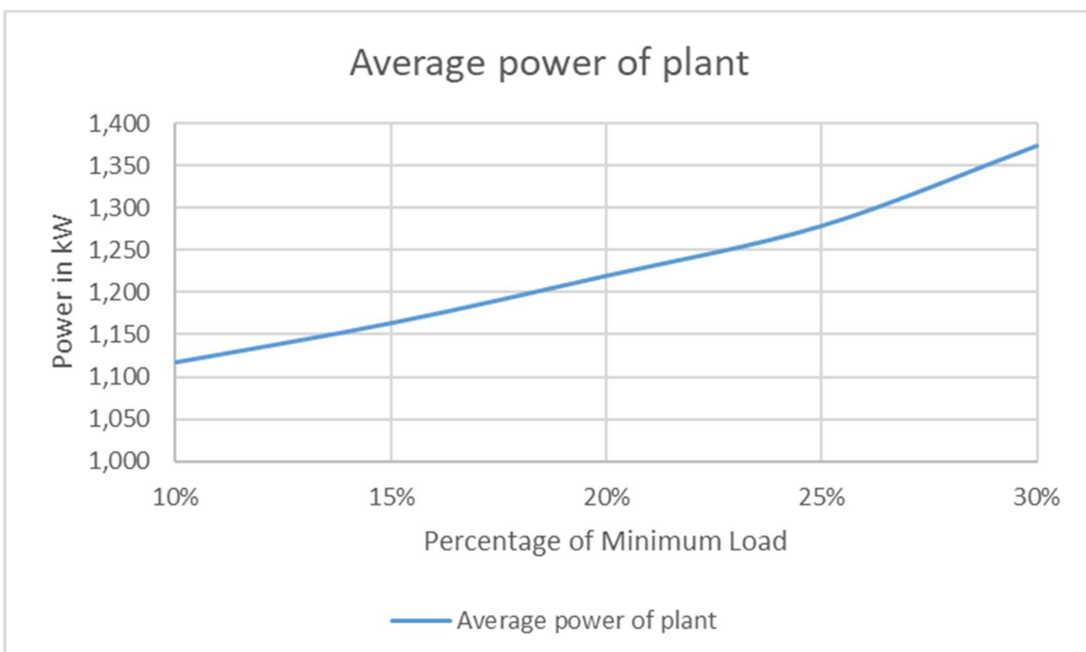


*Figure 87 Graphical representation of the change in the average power the plant supported under the distributed solar resource.*

Figure 87 illustrates the point of the limitations being experienced. As the solar resource lowers the minimum load, the average power the system supports is also lower. This is a result of the solar arrays being allowed to inject more power into the system. There is some constructive injection as well since the maximum of the solar in some areas helps to bring down the maximum that the plant produces. What dominates, though, is that the solar arrays take periods when there is lower demand and bring it even lower than the baseload the plant supports, which is also where we see these failures. This is partially where Time of Use (TOU) strategies come into play.

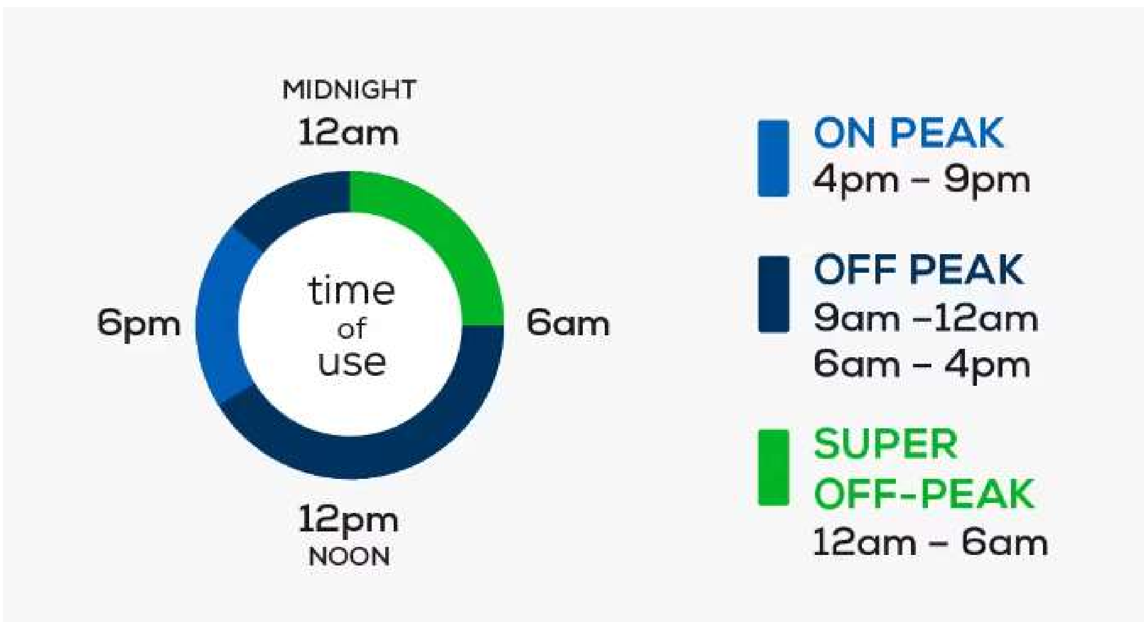


*Figure 88 Infographic about the general time of use clocks. (Palmetto, n.d.)*

Figure 88 highlights the different times that are best targeted by those trying to maximize their solar benefits. Solar power tends to peak between the hours of 11 a.m. to 4 p.m. (Regen Power, n.d.). This is out of alignment with peak power draws that generally occur between 4 p.m. to 9 p.m. This is under some discussion based on region and markets. The power grid operators know this and charge accordingly (NVEnergy, n.d.). Bundled altogether, what this means is that solar power tends to come in during periods when the demand on the grid is lower. Solar owners would want to shift their power injection into the grid to later times to maximize the rebate the grid operators give them for their generated power but that would require BESS units and could still then be cost prohibitive. Where this relates to the data at hand is that solar is not being shifted and is instead peaking at points when demand is low, further driving down the power draw that the plant see's and therefore violating our minimum load capacity the plants are operating under.

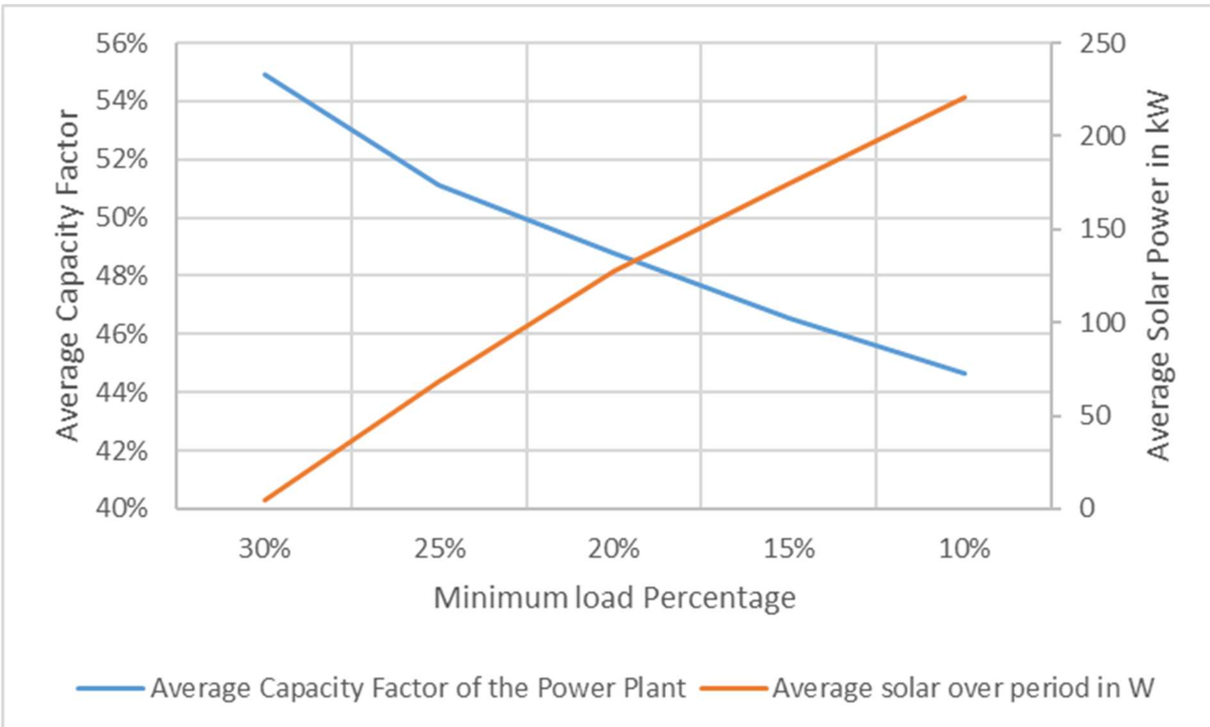


*Figure 89 The above graph shows the average capacity factor of the plant versus the minimum load percentage along with the hosted average solar power.*

Figure 89 shows the difficulty the evolving grid must operate under. The power plant's ability directly allows additional renewables to be hosted, but, economically, that will be difficult for a thermal plant to compete with. Figure 89 shows the direct correlation between the average capacity factor the plant would operate along with the additional solar resources brought in. Under these test conditions, no economic analysis has taken place. The operation of the plant purely dictates the system's load demand, but the results are reminiscent of the multiple studies highlighted before where cheaper renewables are forcing out thermal plants.

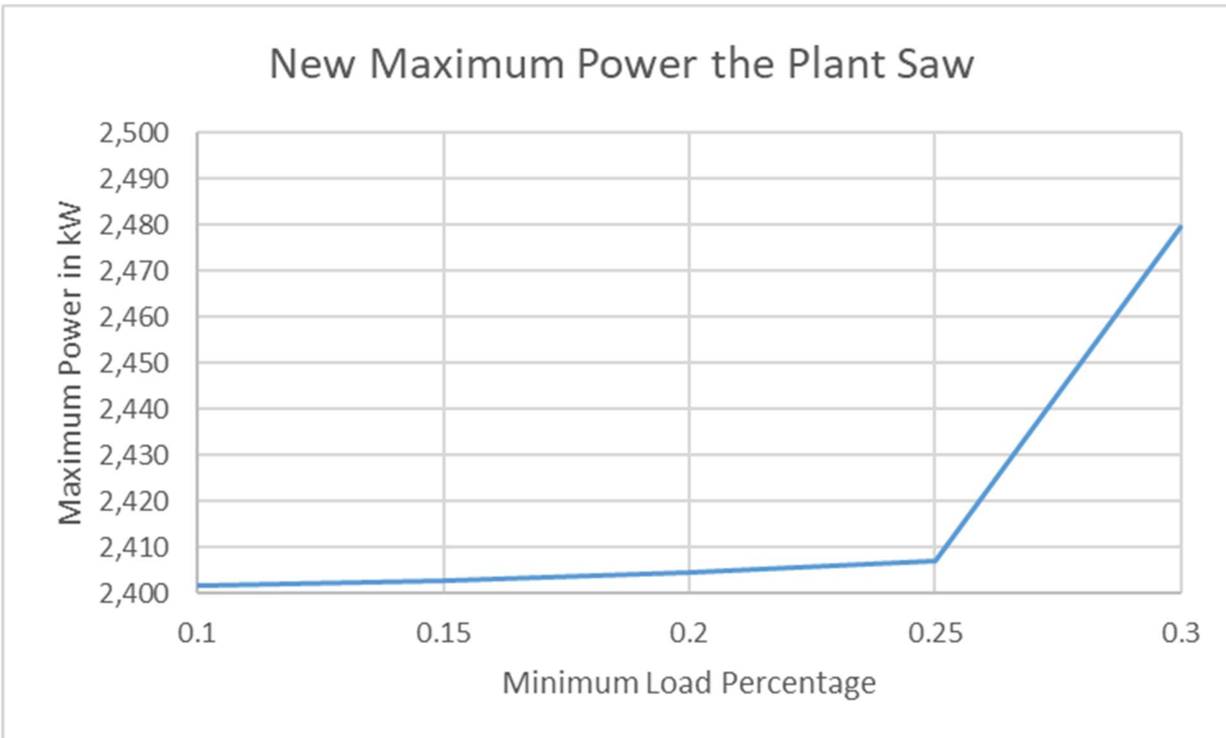


*Figure 90 Maximum power the plant experienced under the new grid conditions. As the solar comes in, it reduces the peak that the plant sees during operation and opens a new amount of delta for the additional load to fill.*

Finally, Figure 90 shows the new maximum power that the plant experienced from the subtractive impacts of the incoming solar power. At first glance, this may seem off, but again the system operates over several months with only one point defining the maximum. As the incoming solar influences that point, it then becomes more of the average days, and instead, the importance shifts to the minimum load capabilities. We still see some slight influence point to point but nothing like the initial difference between 30% and 25%. This new delta would allow for the additional load to be brought in or for the plant to operate more on the energy market but only in a small capacity.

Since there has been a loss of average power, it is more than likely that the plant would see a general negative economic competitive edge relative to this new solar hosting capability.

The solar introduced here also introduced our first ramp rate insufficiency. For all the data up until run 19, the ramp rate of the plant was 1%. At run 19, the solar induced a need for about 1.9%. Since that was the only failure and 2% was sufficient for the rest of this test, the rate was increased, and 1% was left out of future tests, much like the minimum load failures in Test 1.

### 6.1.3 Test 3

Test 3 can almost be split into two different tests since first the system goes through a calculation to find the look-ahead schedule for the CCS, and then the system is readjusted with the ramp rates specifically tested, and the load increased to take advantage of the new overhead. Table 7 The below table summarizes the major results from the first part of Test 3.Table 7 is only for the first half, with the CCS unit turning on and off.

*Table 7 The below table summarizes the major results from the first part of Test 3.*

| Minimum load percentage | Average solar over period in W | Maximum solar in W | Failure point | New average power in W | Old average power seen in W | Run number |
|---|---|---|---|---|---|---|
| 30 | 4,355 | 11,723 | 2,495,981 | 1,557,901 | 1,373,112 | 13 |
| 25 | 68,245 | 183,182 | 2,497,621 | 1,494,593 | 1,278,339 | 18 |
| 20 | 127,209 | 341,453 | 2,498,916 | 1,436,505 | 1,219,132 | 23 |
| 15 | 174,708 | 468,948 | 2,497,243 | 1,388,799 | 1,163,106 | 27 |
| 10 | 221,115 | 593,512 | 2,496,813 | 1,342,602 | 1,116,668 | 30 |

The results above mostly depend on the average power column as the solar is unchanged from Test 2's results. At this point it is assumed that the power plant can completely account for the 20%

ramp rate necessary for the CCS turning on and off. While the second part of the test shows why that is not quite true.

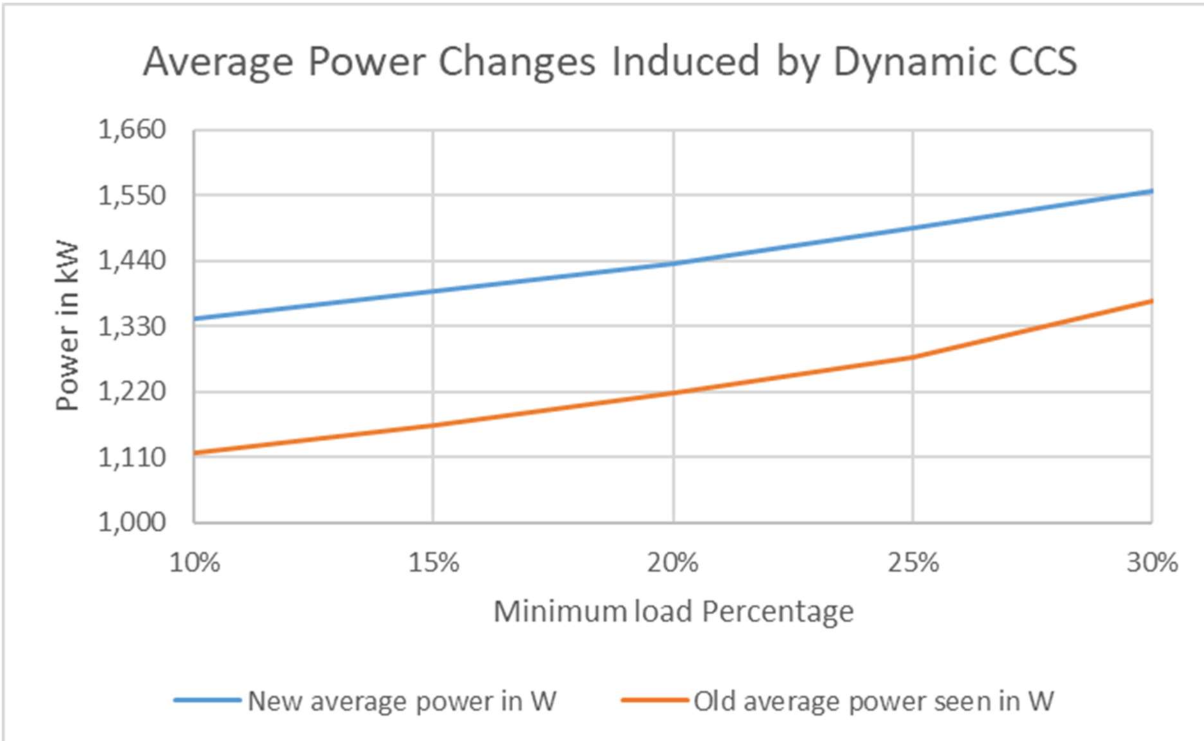


*Figure 91 The improvement in the average power induced from the dynamic CCS unit.*

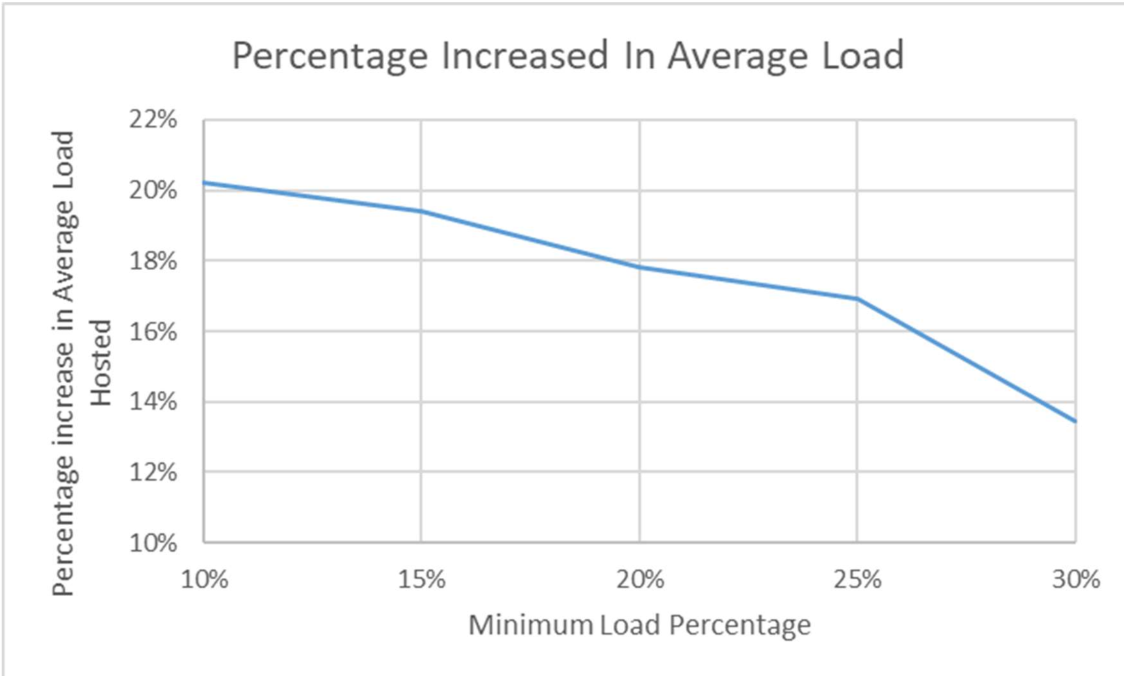


*Figure 92 The additional power hosted by the decreased minimum load percentage but displayed in percentage to see the differences more clearly.*

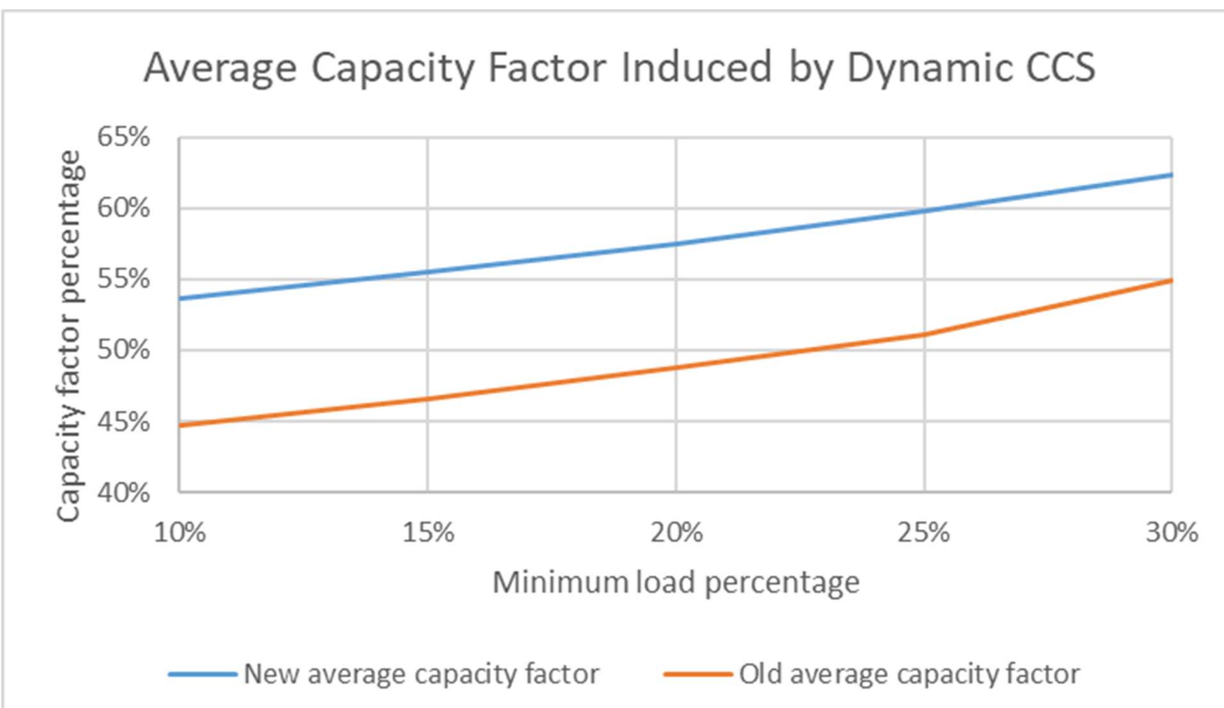


*Figure 93 Difference induced from the dynamic CCS unit shown by capacity factor.*

Figure 91, Figure 92, and Figure 93 show the changes in the plant from the CCS unit performing a look ahead dynamic schedule. The results are dramatic, with the lower end of 10% allowing more than 200 kW of additional average use and the 30% side just under 200 kW. This would make sense if we were to look at the CCS unit acting as a peak-shaving device or a load-shifting device.

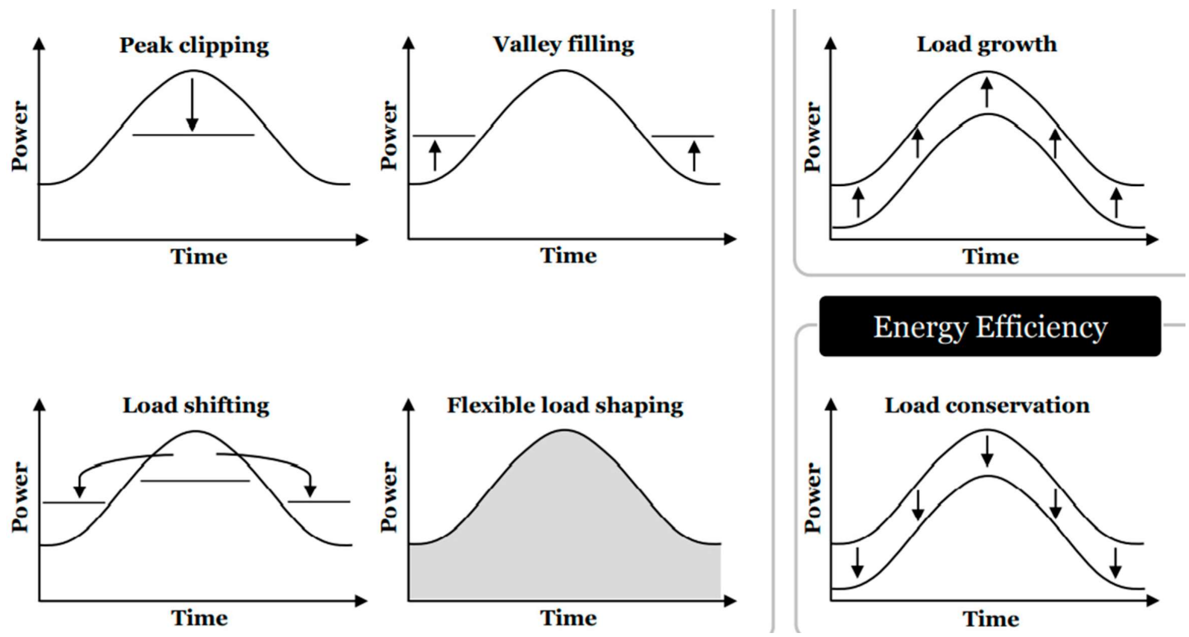


*Figure 94 There are various forms of load management strategies to help alleviate extreme demands on a system and increase efficiencies. (Lampropoulos, 2014)*

Figure 94 shows a variety of load management techniques that have been used in grid management. The peak shaving/load shifting is usually thought of in concurrence with BESS units with their release of energy into the grid or charging from it being controlled by economic or power needs. BESS units could be owned by customers or large-scale companies. The CCS unit represents something that is a little unusual in the sense that it is a significant power draw on grid resources but would likely be controlled by the plant operators themselves in a very close manner by the same people operating the power plant. While the plant would not “charge” like a BESS it could still operate in a similar way where it would only apply its demand in periods of calm. This also relates back to the explanation on TOU.

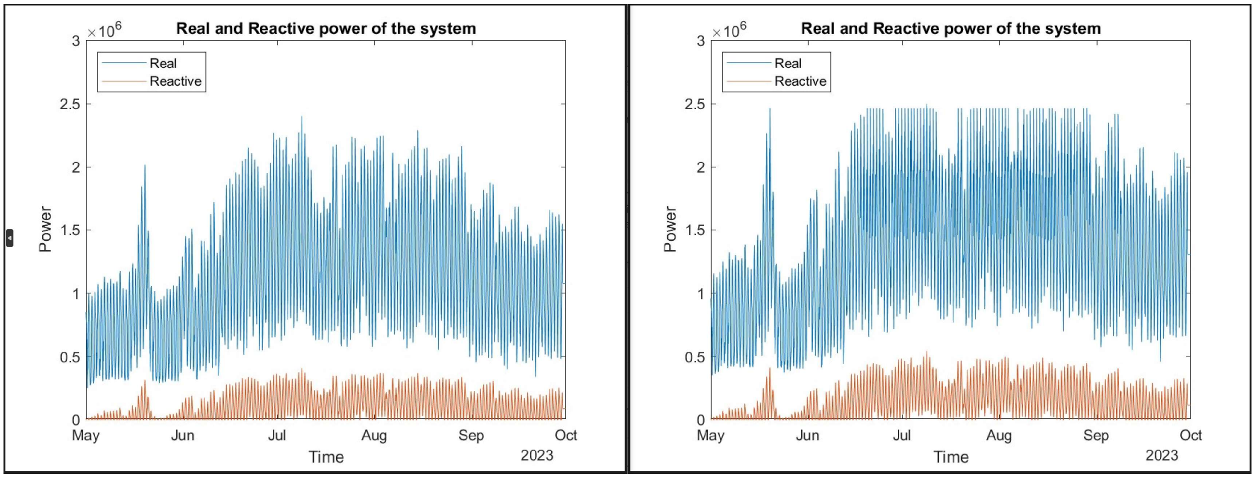


*Figure 95 A comparison of the best result from Test 2 compared to the early portion of Test 3 with 10% minimum load.*

The Figure 95 is a comparison of 10% minimum load in Test 2 and Test 3 with the dynamic CCS unit and increased load. The right-hand side clearly shows the peaks being shaved off by the CCS unit turning off when the trigger point of approximately 2.5 MW is expected by the look ahead scheduler. There is still a limitation on what the system can handle as while the CCS unit does take away its contribution as the load continues to grow it will still eventually peak above the capabilities of the plant itself. This is somewhat assisted by finding additional overhead from the solar power hosted in the last test.

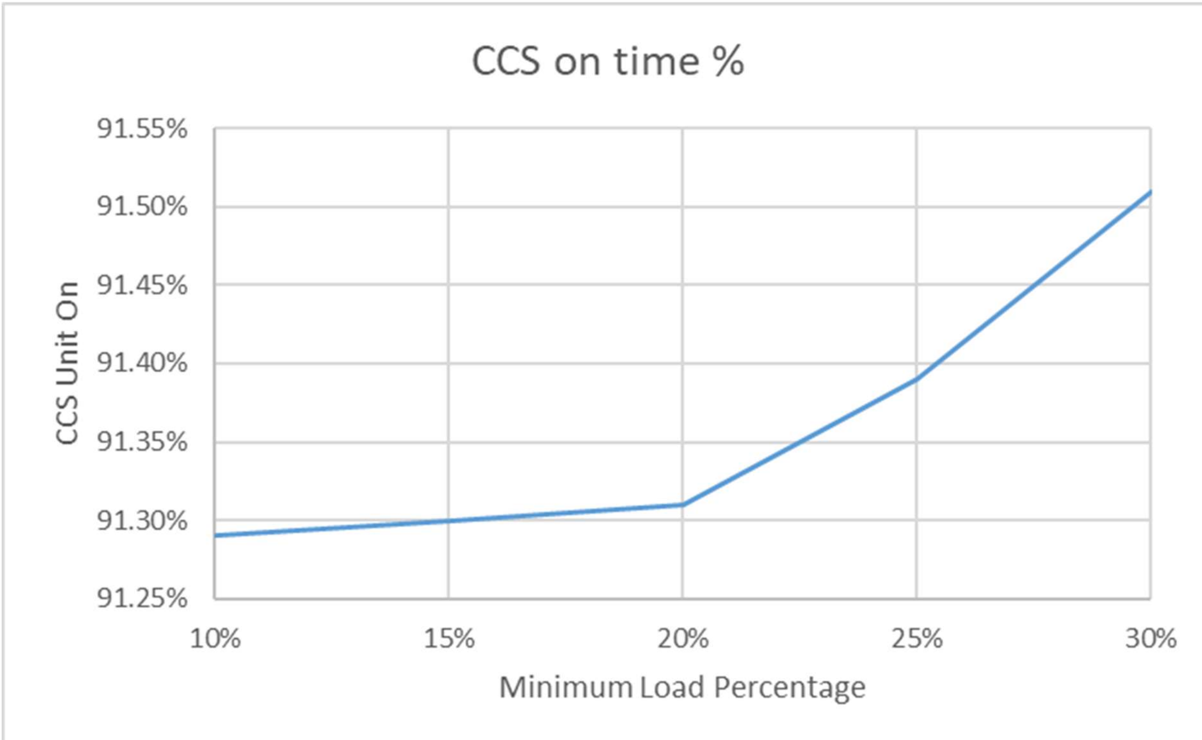


*Figure 96 Graph showing the variation of the minimum load percentage relative to CCS unit on time.*

In this first iteration, all test parameters returned with a CCS unit on time greater than 90% as shown in Figure 96. For these tests, the CCS unit on time was not significantly impacted by the flexibility parameters tested. There was a small decrease in on-time relative to the larger load handled by the lower percentages but not a significant one. Since CCS units are typically designed to target capture rates of 90% of all emissions (Moseman, 2021) there would be a major impact on emissions under these test parameters but would still garner the benefits of increased VRE hosting and peak loading parameters. This could be further enhanced by studying the system under energy market conditions to ensure economic viability.

In the next portion of the test, the minimum load percentage was kept at 10%, and the results from this early portion of the test were kept static for the remainder of the runs to highlight the ramp capabilities. Those parameters created the largest and most dynamic load profile, so it was the best testing ground for the different ramp rates. It is also assumed that the plants react immediately and in concert.

*Table 8 Summary of the results from the second part of Test 3*

| Ramp Percentage | Power Imported in W | Number of Minutes Power was Imported | Power Exported in W | Number of Minutes Power was Exported | Maximum amount of time |
|---|---|---|---|---|---|
| 2 | 133,753,385 | 562 | -129,562,155 | 555 | 10 |
| 4 | 60,759,693 | 253 | -59,761,712 | 249 | 5 |
| 6 | 36,421,458 | 186 | -35,852,928 | 186 | 3 |
| 8 | 24,408,856 | 124 | -24,123,788 | 124 | 2 |
| 10 | 15,390,710 | 67 | -15,273,131 | 63 | 2 |
| 12 | 12,268,138 | 62 | -12,172,847 | 62 | 1 |
| 14 | 9,168,138 | 62 | -9,072,847 | 62 | 1 |
| 15 | 7,618,138 | 62 | -7,522,847 | 62 | 1 |

Based on Table 8 above, there is an immediate clear indication of the capability of the ramp rate to handle changes within the system. The CCS unit is switched off immediately, and while there is some discussion about if that would be the appropriate response to its operation, there are documented cases where this immediate shut-off could be done to capture energy market prices advantageous to the power plant. As we have seen the significant change in the average power the plant would supply without any economic analysis, it is easy to see how the plant would want to capture these moments as quickly as possible.

Also keep in mind that while the CCS unit is controlled in this test case, there is no reason to not also look at it from the viewpoint that a sudden significant loss of load or influx of power demand could not happen. This could come in many forms but from the literature review we saw the sudden demand that could come from a storm like that of Uri, as well as the sudden loss of load that could occur from a substation coming under attack and being brought off the grid. The flexibility of the plant is paramount to its ability to stop a more dramatic grid failure from cascading.

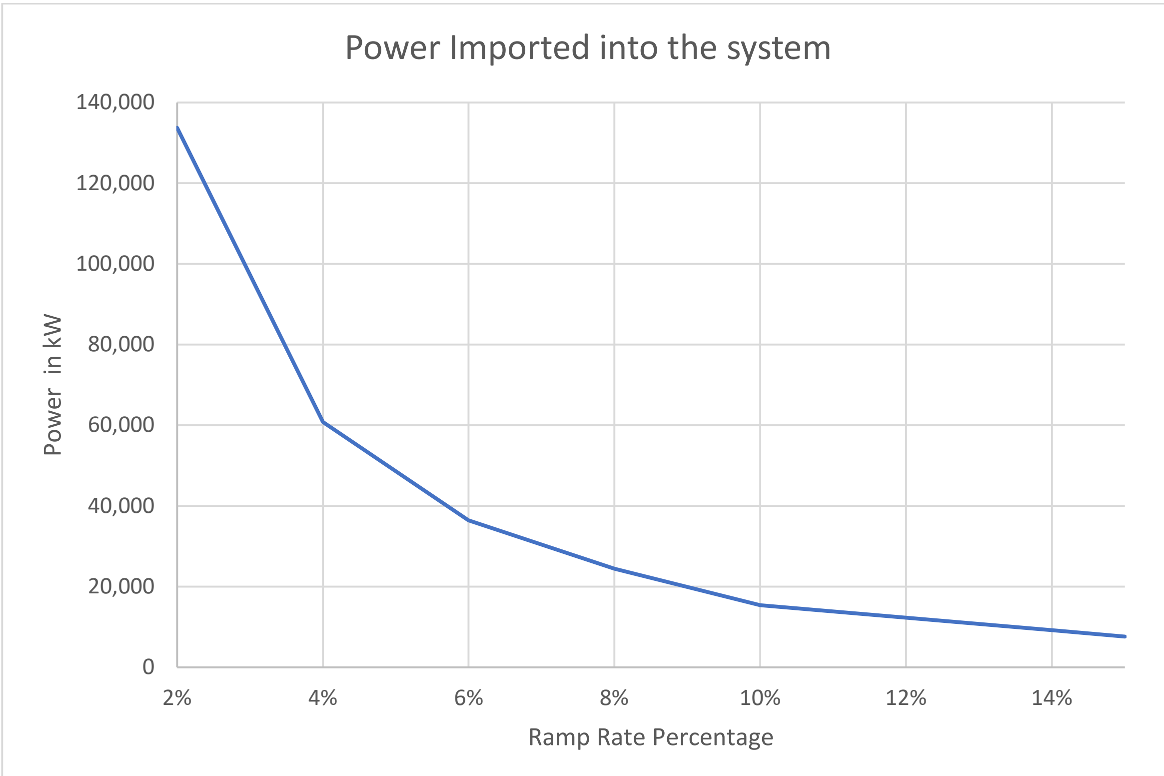


*Figure 97 The power that had to be brought in due to the inability of the plant to support the load demand.*

We can see that there is a significant drop off on power needed in the system as the ramp rate is brought up from 2% up to about 10% in Figure 97. That is not to say that there are not improvements being made as it continues to grow. Only the most significant increases are at the front end. This data is collated across the full-time frame of system operation and is, therefore, a total for the period. Even under the 15% marker, power still needs to be brought into the system, which makes sense since our CCS unit is a 20% parasitic load on the power plant so as the unit turns back on, there will be a significant sudden power draw.

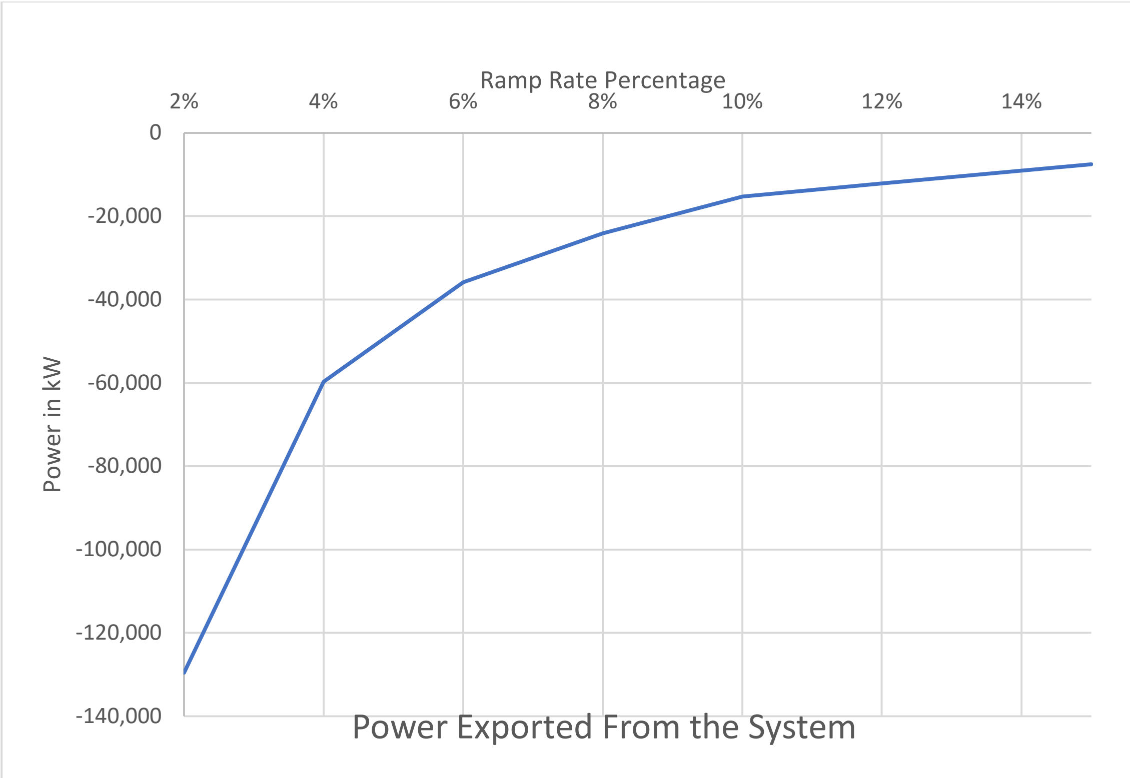


*Figure 98 Power exported from the system by the swing bus due to sudden loss of demand.*

At the same time, as the CCS unit turns off suddenly, the system produces far more power than necessary, which would also play havoc with the power grid connected. This could be solved in several ways internal to the plant or with some form of BESS, but here it is assumed that the excess power would be sent out to the external power grid and is, therefore, "exported" and is shown in Figure 98. This is still a problem, though, as sudden spikes in demand can damage pieces internal to the plant, throw voltage regulation out of specification, or cause frequency desynchronization, which would also cascade into other problems. Unfortunately, the limitations of Gridlab-D make simulating these impacts a whole other study in and of itself. Furthermore, there are no hard numbers or rules of thumb to say that these power spikes would be significant enough to cause a problem.

What can be said about these two pieces of data (the import and export) is that it is not good for grid operations. A plant with a higher ramp rate limits the need for imports or exports under this condition, with the most significant changes being between 2-10%, with those above still being good but not as significant.

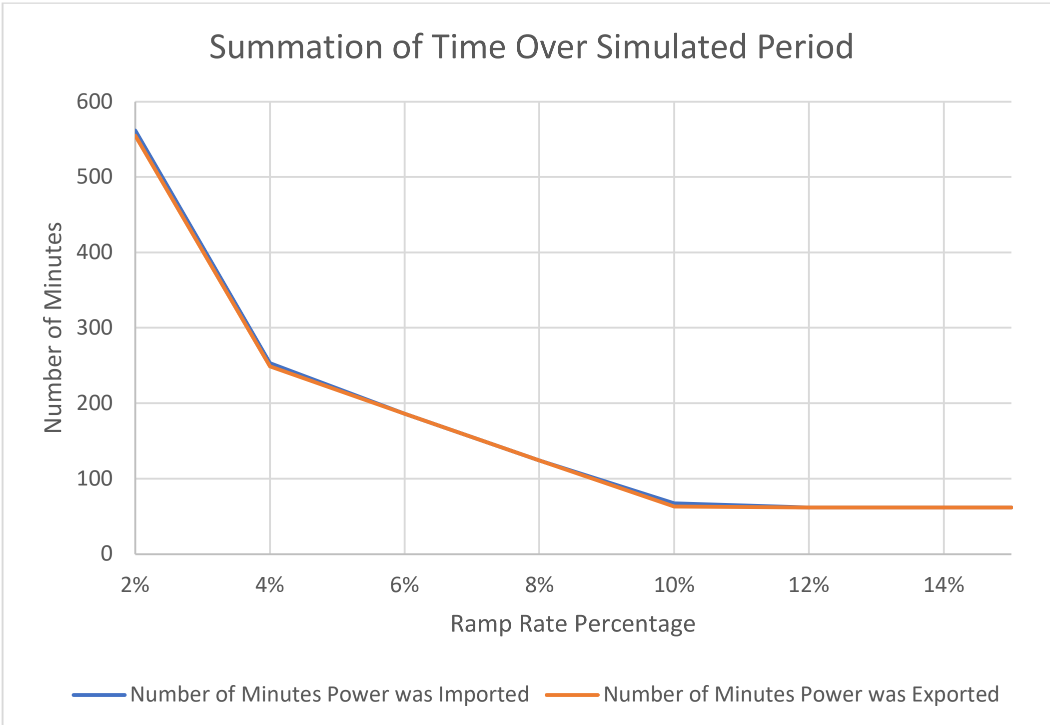


*Figure 99 This graph shows the summation of time over the period when the grid bus was required to bring in or send out power.*

While the amount of power is important, the amount of time this happens over the simulation period will help illustrate the differences between these ramp rates. A one-off situation might result in a problem, but a consistent situation will tax even the most robust systems. It turned out that the need to import or export was consistent and mostly driven by the CCS unit. As the unit is turned on or off, the dynamic nature of the system may have contributed to or alleviated the problem as the resident draw or solar installed contributed.

Again, we see the most significant contributions occurring between 2-10% and then it flatlining after that as seen in Figure 99. Doubling the ramp rate from 2% to 4% dropped the time needed for the system to call on outside help by half.

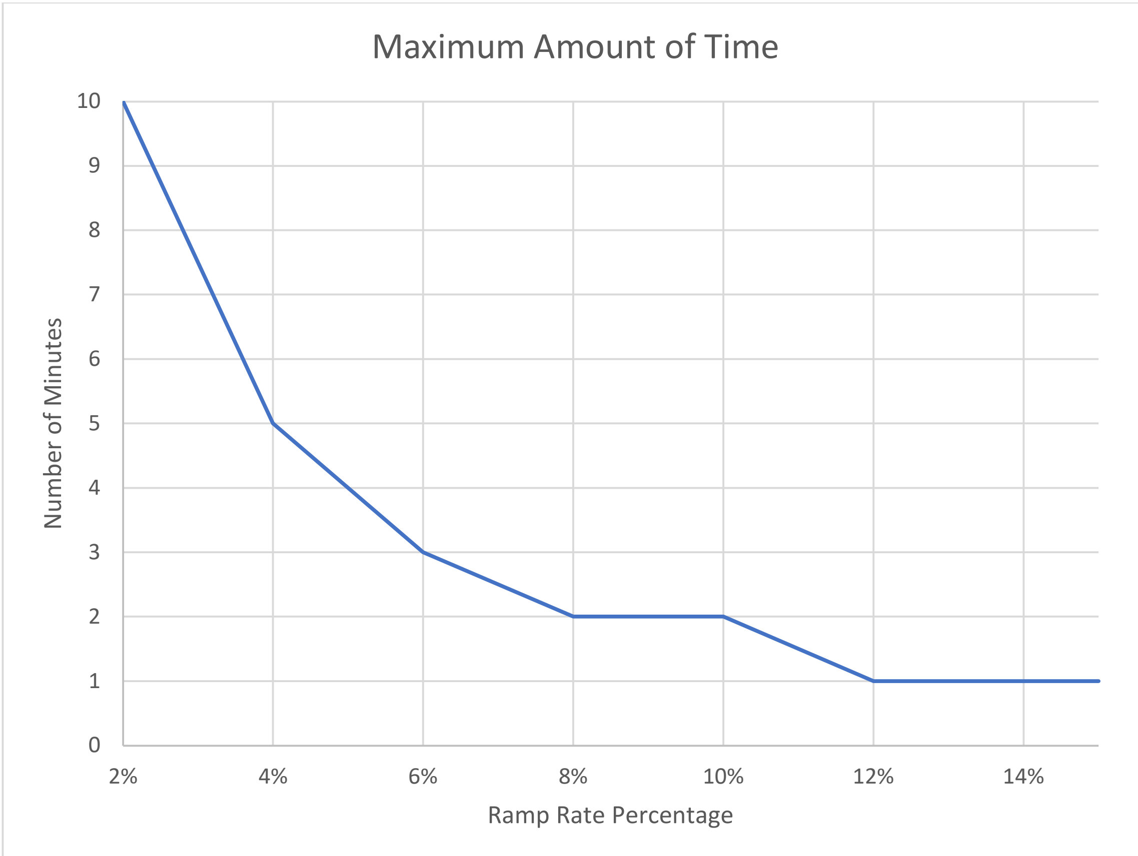


*Figure 100 Maximum number of concurrent minutes where import or export was needed for the simulated grid.*

Figure 100 is one of the most telling for this data set. It is hard to say what would qualify as a significant issue as it is so dependent on the load, the capability of the regulator, and even the location of the measured point, there is a significance to the length of time the problem occurs. In the case here the maximum amount of time that the grid is under insufficient out-of-balance status would be for 10 minutes which on a 60 HZ system is an eternity.

Going from 2-4%, cut this amount of time in half with significant improvements occurring up to about 8%. While we see another step increase of 10-12%, after that we see no major improvements. 15% is the maximum reported by the UK study in post flexibility plant improvement capabilities. Calling back to the fact that the CCS unit is a 20% parasitic load, it would make sense that we would stop seeing significant improvement after 10% in the minute-to-minute scale.

### 6.1.4 Test 4

Table 9 summarizes the results from this iteration of the test. We see that there was a significant difference in some portions of the work while others were immune to the prioritization change between parts 1 and 2. Both plants had the same maximum of 1.25MW. The more flexible plant had a minimum of 10% and a ramp rate of 15%, while the non-flexible variant had a minimum of 30% and a ramp rate of 2%. Plant "one" is designated as the unit under test. For the first part, that would make the less flexible plant number one, and then in the second part that switches, the more flexible plant was set as number one.

*Table 9 Summary of results from Test 4. The more flexible plants capacity factor and average power are highlighted in yellow.*

| Flexible plant highlighted in yellow | Exported Power in Watts | Imported Power in Watts | Number of times exporting was needed | Number of times importing was needed | Duration of longest shortage in minutes | Average total power of combined plants | Average cap factor of individual plant | Average Power in watts per plant |
|---|---|---|---|---|---|---|---|---|
| Less Flexible Plant Prioritized | -538,310,526 | 44,344,889 | 9059 | 296 | 580 | 1,3448,000 | 61.73% | 771,720 |
| | | | | | | | 45.85% | 573,130 |
| More Flexible Plant Prioritized | -538,310,526 | 111,273,995 | 9059 | 647 | 580 | 1,3445,000 | 49.69% | 621,230 |
| | | | | | | | 57.86% | 723,310 |

It is important to note that one of the major differences between the two parts is that the plants operate at different capacity factors during the test. Again, comparing it to standard thermal plants that act as base load suppliers of power, these are still within the realm of possibility. The EIA has tables that show thermal plants range from the low 40%-70% depending on time of year and type of system (EIA, n.d.).

Prioritizing the more flexible plant evened out the power supplied by each unit which could be important from an operations and maintenance perspective. Since the importance of being able to service the load is the paramount concern throughout this study, it is more important that part 1's ability not to import as much power is often the more desirable result of the two. Since the power being exported remains consistent between the two parts, it can seem a little confusing as to why the power imported doesn't and why that would be such a drastic difference. Below are a few graphs that help shows how this came about.

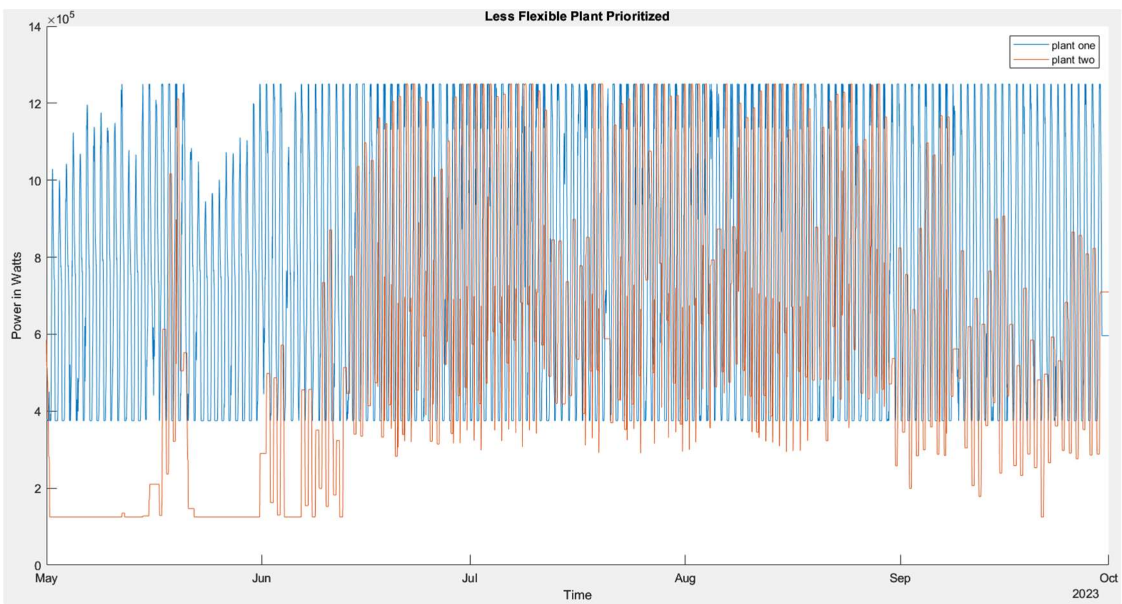


*Figure 101 The above graph shows the operational outputs of the 2 plants over time. The less flexible plant would be plant one.*

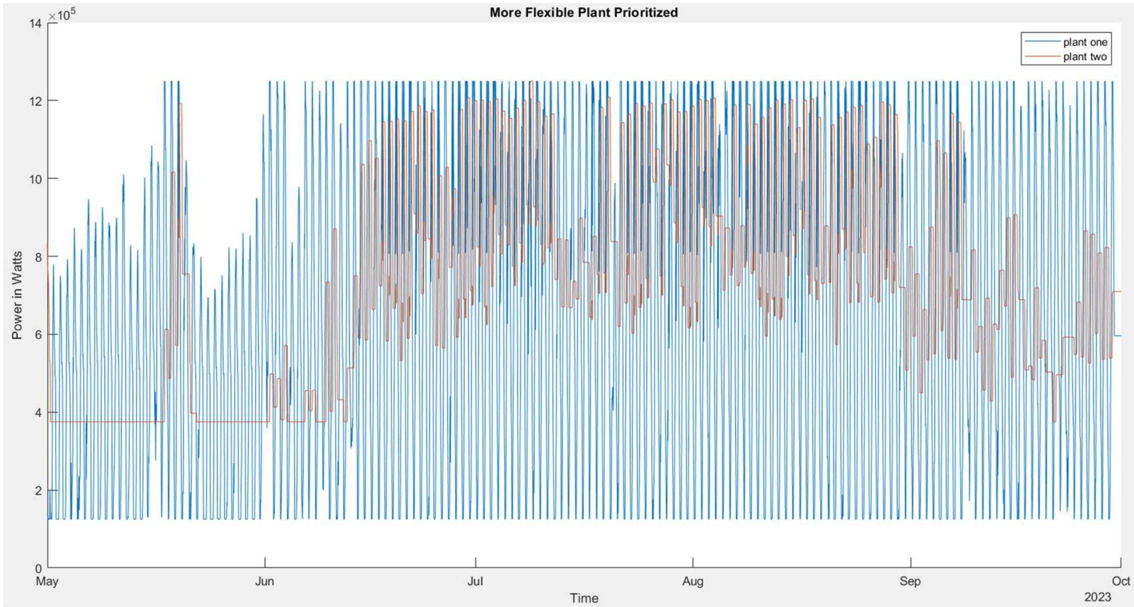


*Figure 102 In this graph the roles of the two plants are reversed. The more flexible plant was prioritized towards changes and dispatch first.*

Figure 101 & Figure 102 show the outputs of the two plants over the test time. In both, you can see the maximums and minimums are hit quite often. This is expected as the plants attempt to serve a load oversized for both their outputs combined. At the beginning of the test, there is a broad period where the less prioritized plant remains at its minimum for extended periods. The prioritized plant is the first to respond to changes in demand, and it does so to the extent of its abilities before the second plant comes into play. This can still be difficult to read, so below are also the graphs of the performance of the swing bus during these same times.

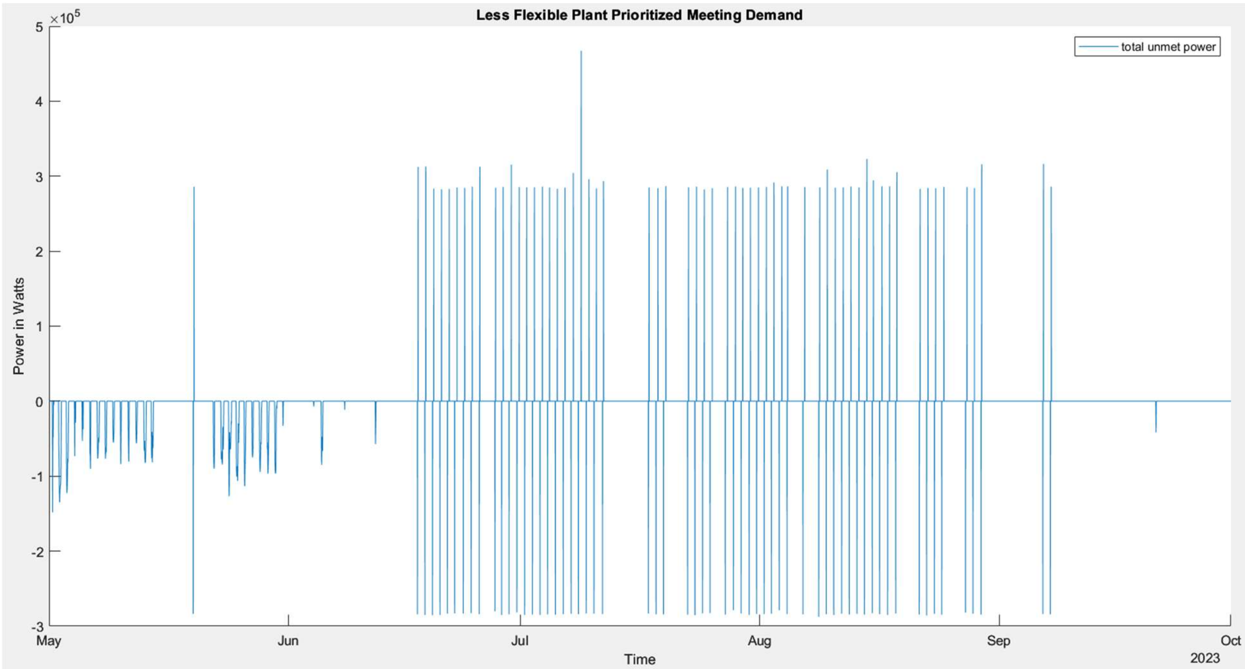


*Figure 103 The unmet power with the less flexible plant prioritized. These results are like test 3's in subtracting the power provided from the power needed.*

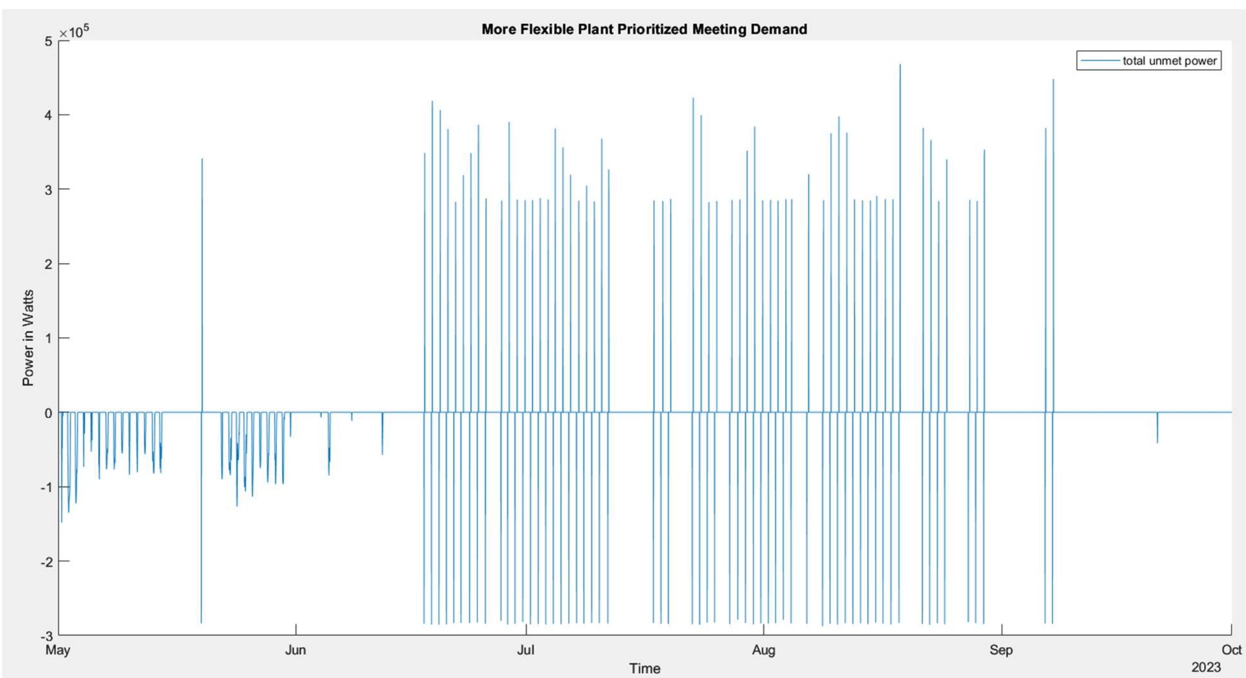


*Figure 104 Shown here is the opposite where the more flexible plant was prioritized.*

With Figure 103 & Figure 104, the picture becomes clearer. The main difference from operation comes during the height of the summer months when ramp rates and maximums are at their maximum. The less flexible plant prioritized allowed the more flexible version with the 15% ramp rate to be held in "reserve." So as the CCS was turned on and off, this overhead capability built into allowing that overhead to exist could be exercised naturally. This led to smaller spikes during those peak demand times and most of the difference between the two tests.

Presented below in Figure 105 &Figure 106 are the two plants directly held in comparison to one another. Whether flexible or not, the actual output of the plants was reminiscent of one another in their respective tests. This was expected since the overall simulation was designed to find the capabilities of the flexibility parameters. If we were to see major differences, there would have to have been another factor influencing its operations.

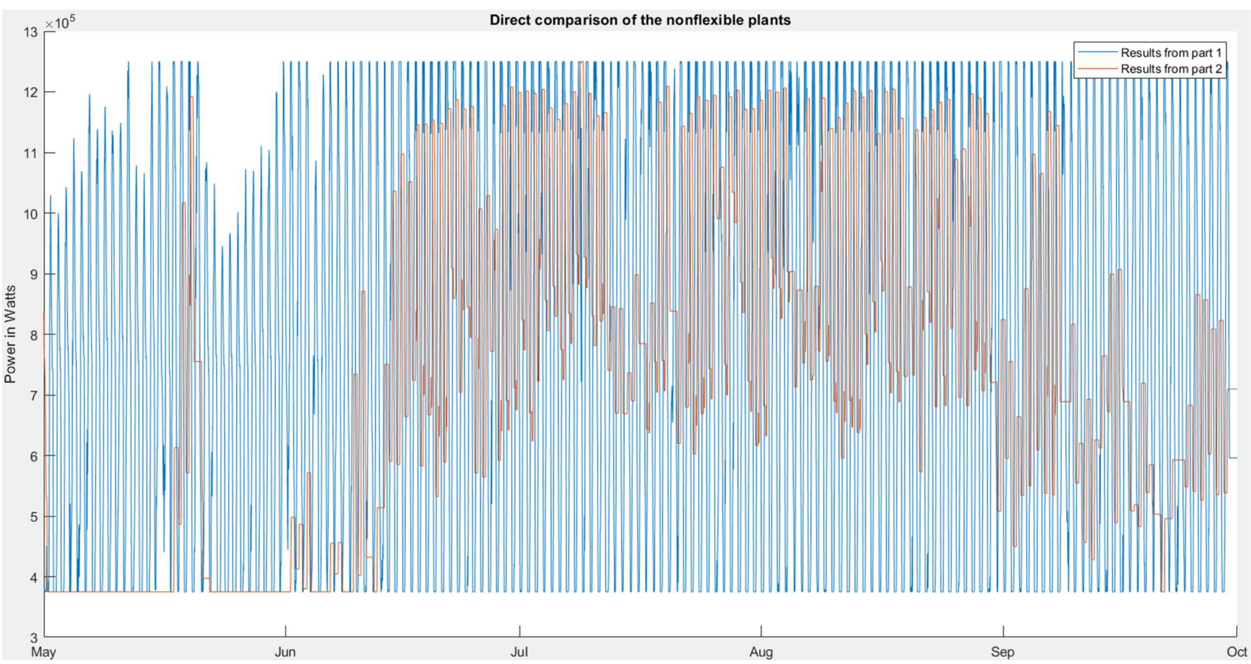


*Figure 105 The above traces show the very different dispatches of the plants despite the same capabilities.*

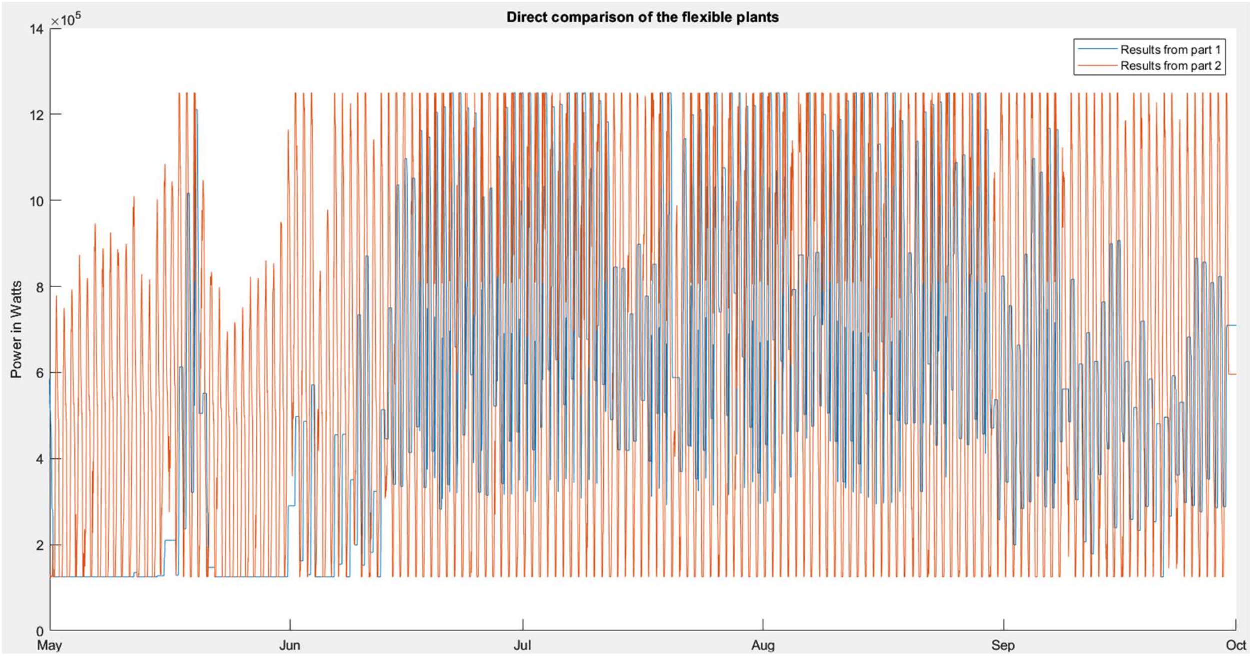


*Figure 106 The flexible plants also showed a very dynamic difference based on the prioritization.*

## 6.1.5 Test 5

Test 5 had limited direct results but still showed similar results to test 3's outcomes in that the more flexible plant is less dependent on the external swing bus system. The import of these results though was that they were reminiscent of their scaled counterparts. Table 10 shows the results that came from the simulations performed.

*Table 10 Summary of the results from Test 5*

| | Power imported | Import time | Power Exported | Export time | Maximum time of need |
|---|---|---|---|---|---|
| 2% ramp rate | 2,963,632,600 | 45 | -3,095,783,000 | 45 | 9 |
| 15% ramp rate | 170,984,400 | 5 | -173,669,000 | 5 | 1 |

With the 2% ramp rate, the maximum time period of need was 9 minutes. The load curve used here was significantly different, time period much shorter, and there are no renewables used in this test however at 9 minutes that is about the same as the 10 minute period that was found from the scaled test 3 results that also used the 2% ramp rate in the second half. This consistency bodes well for the results as the model performs similarly at scale. This exchange was dominated by the functionality of the CCS unit operating and is best portrayed by the graphs below.

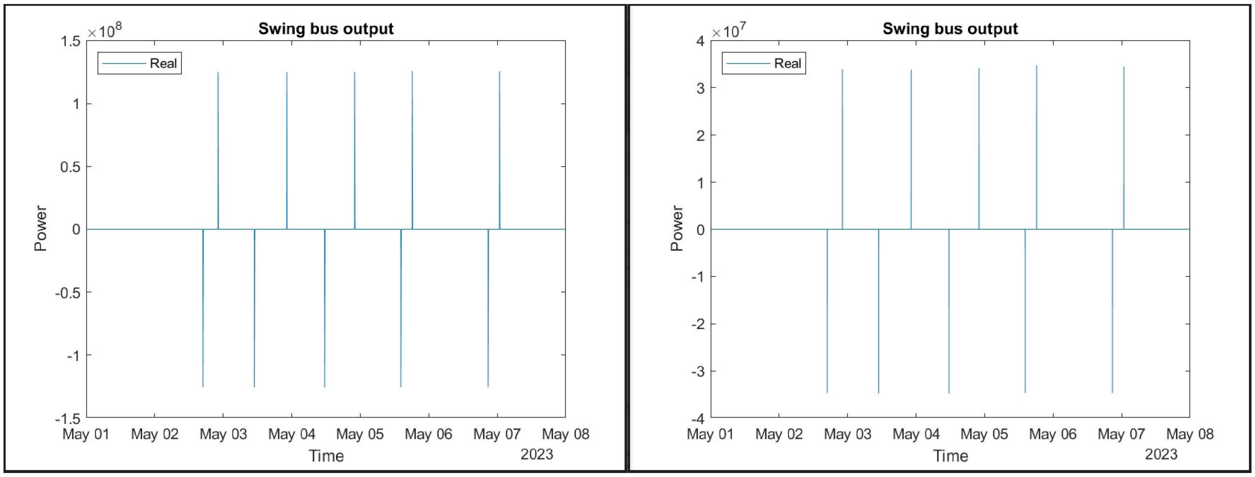


*Figure 107 Side-by-side comparison of the power demand for the swing bus system to account for the deficiencies of the 2% ramp rate on the left and 15% on the right. Note the axis of scale, as while the shapes are similar, the amounts are vastly different.*

Figure 107 shows the swing bus demand that worked to handle the power differential between what the plant could supply and what the demand needed. On the left, the spikes are slightly wider than on the right. The intensity of the peaks is also much higher on the left as the 2% ramp rate took longer to recover than the 15%.

These again correspond to when the CCS unit was used. In this final iteration of the study, the minimum on/off time was set to 4-hour periods to adjust to the unusual makeup of the load curve. Even with this extension, the CCS unit had an on-time of about 79%. While this initially looks significantly lower, the time under test was significantly shorter and the load curve's intensity was significantly enhanced. Since there was only the one-week period to look at maximums and minimums, the load was scaled to be the worst it could be within 7 days of operation.

If the test was repeated to have periods of time like the first few iterations with months studied at a time, the confidence is high that the CCS on time would have continued to perform similarly.

The import/export periods were also consistent with the ramp rates' differences, with the worst to best ratio being about 9 to 1. The results from Test 3 showed that the 2% ramp rate had 562 minutes of import and 15% 62 minutes. The export times were a slightly improved ratio, while in Test 5, they were the same.

Of more value was the establishment of a scaled test system. While the 10-node system isn't complicated, it shows that similar results under this model can be reproduced at scale. This allows confidence in the model not originally built from the scaled test. This can be then extended by modifying the baseload curve shape to include less industrial or commercial influence or by applying it to a different region's curve at different times.

# Chapter 7

## 7.1 Conclusion

The work here successfully demonstrates quantitative results for flexible power plants and the influencing factors related to them. The qualitative known of that of a flexible power plant could better support CCS and renewable energy is obvious, but with these quantitative results, others can better apply them to specific instances and adapt the work done here to investigate their unique circumstances better.

The minimum load capability of a plant showed that it was significantly tied to the VRE hosting capability regarding solar specifically. As the solar power incoming into the grid peaked at periods that typically were not the highest demand points of the day there was minimal impact on the peak's scene during testing but a great impact to the baseload curves. While the ability to host more solar power does meet the general greener direction of the grid's evolution, it negatively impacted the average power the thermal plant hosted and would therefore likely negatively impact the economics of that plant. More studies would need to be performed to ensure this though, as some sources say that VREs are beginning to crash the traditional energy market.

While this may be counterintuitive, the sheer expanse of the VREs low-cost energy input is relatively pricing themselves out of their market. "...as a result of basic supply-and-demand dynamics, solar capacity systematically reduces electricity prices during the very hours when solar generators produce the most electricity…..there is a system-dependent threshold of installed PV capacity beyond which adding further solar generators would no longer be profitable. (Amatya, et al., 2015)". In that study, they found that the market price of energy dipped down beneath the owner's "price" at about 10% penetration which was about where our best solar penetration values were found. There is an opportunity for a follow-on study to find out how the two may interrelate.

Also shown with this work was the capability of the CCS unit to allow the grid it hosts to operate far beyond the original capacity it was installed on, bringing down the peak demand required of the plant. This ranged from about a 13% increase in average power up to 20% for the more flexible power plant with the lower minimum load. While not tested iteratively, there would have been a corresponding increase in VRE hosting capability, as indicated by the results from Test 2. As our grid is becoming more and more taxed with plants being retired, VREs integrating, and malicious actors/severe storms beginning to come into play, the ability to shift power from ecological imperatives to preventing load shedding is critical.

The last large conclusion that was found was the benefit of the increased ramp rates on a flexible power plant and the extent that came to. As the CCS unit was operated in a worst-case scenario (much like a power outage of a significant load portion) it was shown that the larger ramp rates helped to reduce import/export dependency and therefore allowed the grid under test remain more independent. This did cap out though and showed diminishing returns much past the 10% rate as it was able to curtail the worst of the demand but was unable to fully engulf the change wrought by the CCS unit operating. This is important to note as the UK study the numbers were taken from was very clear that flexibility can come at a significant cost, and depending on the need, the resultant improvements may not be worth retrofitting an aging plant.

The above results have proven that qualitative analysis can be done with the model created for this work directly relating to my hypothesis set up in question #2. The results show that flexibility can be integral to a system when it comes to hosting more VREs and that the ability of the dynamic CCS unit positively influences the operational loading of the power plant with some caveats that the ramp rate must be able to handle the shifts in operation or outside factors will need to be brought in to maintain power demand.

The model itself was a novel portion of the work done here. Initial tests were done at scale, but with subsequent tests, it was shown to operate still. When situations arose, such as the unique wider demand curves that came up in test 5 and caused the CCS unit to come on during periods of continued high demand, the model was able to be modified to allow changes to operation solutions that were just as unique. This functionality is necessary for this work. It would be impossible to create an all-encompassing system of the evolving grid. It would be the same changes in the grid that made the work necessary in the first place.

With the IEEE 37-node system, a realistic residential load was applied to the residential system, showing the relationship between minimum load, ramp rates, VRE adoption rate, and CCS variability. With the 10-node system, the model was then tested at a scale and adapted to the unique features of a different load profile. That load profile also went through a process that allowed the user to influence the makeup of the load curve to be more representative of commercial, residential, and industrial sectors.

The MATLAB code provided several analysis methods to apply to the dataset that comes from the Gridlab-D files. That same code also allows the user to adapt the model to a user's needs and add in nodes or take advantage of MATLAB's ability to graphically display results with ease. With this question #1 is completed as well and the model is complete as needed here. These results can be influenced by the hosting system, but the model is fluid enough to be adapted to a user's need as shown by the at scale test as well as the adaptations necessary throughout this process.

As this work is closed out, below are Table 11 & Table 12 that highlight the major quantitative results found by this work.

*Table 11 The table below is a conglomeration from the first 3 various tests. It was found that the minimum load percentage directly influences the VRE hosting capability, which is also directly tied to the average power the plant outputs over the time period.*

| Minimum load percentage | Average solar over period in W | Maximum solar in W | New average power in W | Old average power seen in W | Average PV Penetration | Maximum PV Penetration |
|---|---|---|---|---|---|---|
| 30% | 4,355 | 11,723 | 1,557,901 | 1,373,112 | 0.31% | 0.47% |
| 25% | 68,245 | 183,182 | 1,494,593 | 1,278,339 | 4.87% | 7.33% |
| 20% | 127,209 | 341,453 | 1,436,505 | 1,219,132 | 9.09% | 13.66% |
| 15% | 174,708 | 468,948 | 1,388,799 | 1,163,106 | 12.48% | 18.76% |
| 10% | 221,115 | 593,512 | 1,342,602 | 1,116,668 | 15.79% | 23.74% |

*Table 12 The ramp rate directly influenced the amount of "help" the simulated grid needed during operation. While this was also tied to the operational aspects of the CCS system, this can be related to large outages by substations or other load servicing events.*

| Ramp Percentage | Number of Minutes Power Was Imported | Number of Minutes Power was Exported | Maximum Amount of Time |
|---|---|---|---|
| 2% | 562 | 555 | 10 |
| 4% | 253 | 249 | 5 |
| 6% | 186 | 186 | 3 |
| 8% | 124 | 124 | 2 |
| 10% | 67 | 63 | 2 |
| 12% | 62 | 62 | 1 |
| 14% | 62 | 62 | 1 |
| 15% | 62 | 62 | 1 |

# Chapter 8

## 8.1 Future Work

Due to the limitations of the study's depth and the initial highlighting elements about the lack of information in the field, significant portions of future work can be completed to expand upon these findings.

As has been repeatedly highlighted, the capabilities of CCS employed at this scale and upon these machines are still evolving rapidly. The assumed reduction in the power plant’s capacity of 20% is probably the first thing that came to mind, and it was attempted to make it easy for anyone who wishes to edit this work to do so quickly. In that sense, this work is still valid. Instead, the focus should be to call to the front that the CCS units' dispatch ability is still unknown. Can the units ramp along with the power plant? Can the units run less efficiently in a standby capacity to supplement short-term interruptions?

Can sub-hourly changes in operations significantly reduce the parasitic draw on the host plant? The answer to these questions is likely yes, but implementing those and modeling them becomes more difficult when topologies are evolving so quickly.

Larger level network studies can also be immediately added to the work list. This work focuses specifically on how the flexibility of the units are major contributors to grid dynamics. Flexibility is a known positive in this field and this work helps bring forth those strengths in greater detail. Then, taking this data and adding other parallel units or more diverse connected grids would add to an overall answer. With the algorithm developed here, this could also be adapted to other software systems and improved upon, subsequently propagating along. Our grid is exceedingly large and constantly evolving in both positive and negative ways. While there are a ton of examples in this text about past events, it is important to note that even today, there are problems in the grid that are emerging from the interconnection of the grid, as is highlighted by NV Energy recently attempting to separate itself from the California power grid (T & D World Staff, 2022).

NV Energy is putting forth a plan to add more energy infrastructure in its own backyard to become more self-reliant and, in the same move, pull away from the California grid and its history of increasingly severe heat wave-driven grid problems and policy changes. This includes adding a 200 MW battery system, another 140 MW of geothermal capability, and 440 gas-fired peaking turbines. The report highlights that NV Energy wants to meet its own independent energy goals while not competing in an energy market subject to severe California energy shortfalls in the last 3 summers. While we don't know how this will turn out, it is becoming an increasingly common worry on a power grid that once lauded interconnectivity as a strength.

CCS can play into this problem directly as both a solution and a problem, depending on its application. The 200 MW battery installation NV Energy hopes to bring online in the coming years is being placed on the site of a retiring coal plant in 2025. So, a state highlighting a competitive energy market is in the same plan as shutting down plants. As we have discussed multiple times, the problem is multi-faceted, and this case is no different as it was highlighted that green energy desires are forcing the closure to occur (Roth, 2022). CCS is a resource that can bridge this dichotomy of ideals but cannot without more information in its corner explaining its potential.

## 8.2 Work optimization

While the work presented here attempted to use good coding practices, a significant amount of optimization could be done. This isn't surprising, considering the GLM file came in at over 2500 lines, and the MATLAB script came in at over 500 lines in some iterations. Among those, there is also a significant amount of for, while, and other iterative loops, including test 3's significant double calls of the Gridlab-D solver. The optimization of the model would allow the user to focus less on the modification of parameters and more time to focus on getting the results that they need.

Furthermore, Gridlab-D allows the user to interact with the system under test directly but requires a significant amount of additional computer science capability to implement and more coding knowledge than operating this model originally required. Post-processing solutions are valid and have been proven as such here, but the limitations along with that fact are numerous. To expand this work to include other variables, such as additional generators, it becomes imperative that the system be allowed to impose limitations internally without outside software control.

### 8.2.1 Conversion of code to functions

A MATLAB script is not the most efficient way to operate this system as you have to constantly comment in and out unnecessary parts of the code. It leads to a cluttered view with hundreds of lines to troubleshoot at a given time. It was, however, the easiest way to develop and run the unit. One of the biggest improvements that could be completed would be to take the system apart and place it into functions that are easily called by the user and are only passed necessary variables.

The CCS load development system is a great example of something that could be modularized. Once the system was coded, it was immune to follow up changes. Another good example would be the Gridlab-D code. It was called by the main script in a single line and performed its function in the background allowing the main script to not be clogged up by the hundreds of additional lines that would have made troubleshooting more difficult.

Placing the system in calls should also help alleviate the long run times that were experienced. Some of the larger tests were extended passed 20 minutes in time. While that isn't an extreme period for most people, the system is very simple. As the complexity grows, so will the need for more efficient practices.

A copy of both the more complicated MATLAB script and Gridlab-D codes are included in the appendices for others to utilize should they desire to.

## 8.3 Multiple plants

Due to the time and scope limitations, this work didn't integrate other flexibility parameters that would likely have a major impact on the quantitative analysis of thermal plants. The capability of a flexible plant to perform a hot start or adapt and come out of cold operations quickly could be a major influencing factor in the interpretation of the results.

While a test with two plants was completed here the results were limited and only showed the bounding factors this work could encompass. The ability to better share loads between multiple players will continue to show the importance of flexibility parameters. The plants studied here also coexisted in the same location and could be better thought of as separate turbines more than another plant. As the system is built upon a radial feeder, the options were limited, but if the user was able to make something more independent this could be expanded upon.

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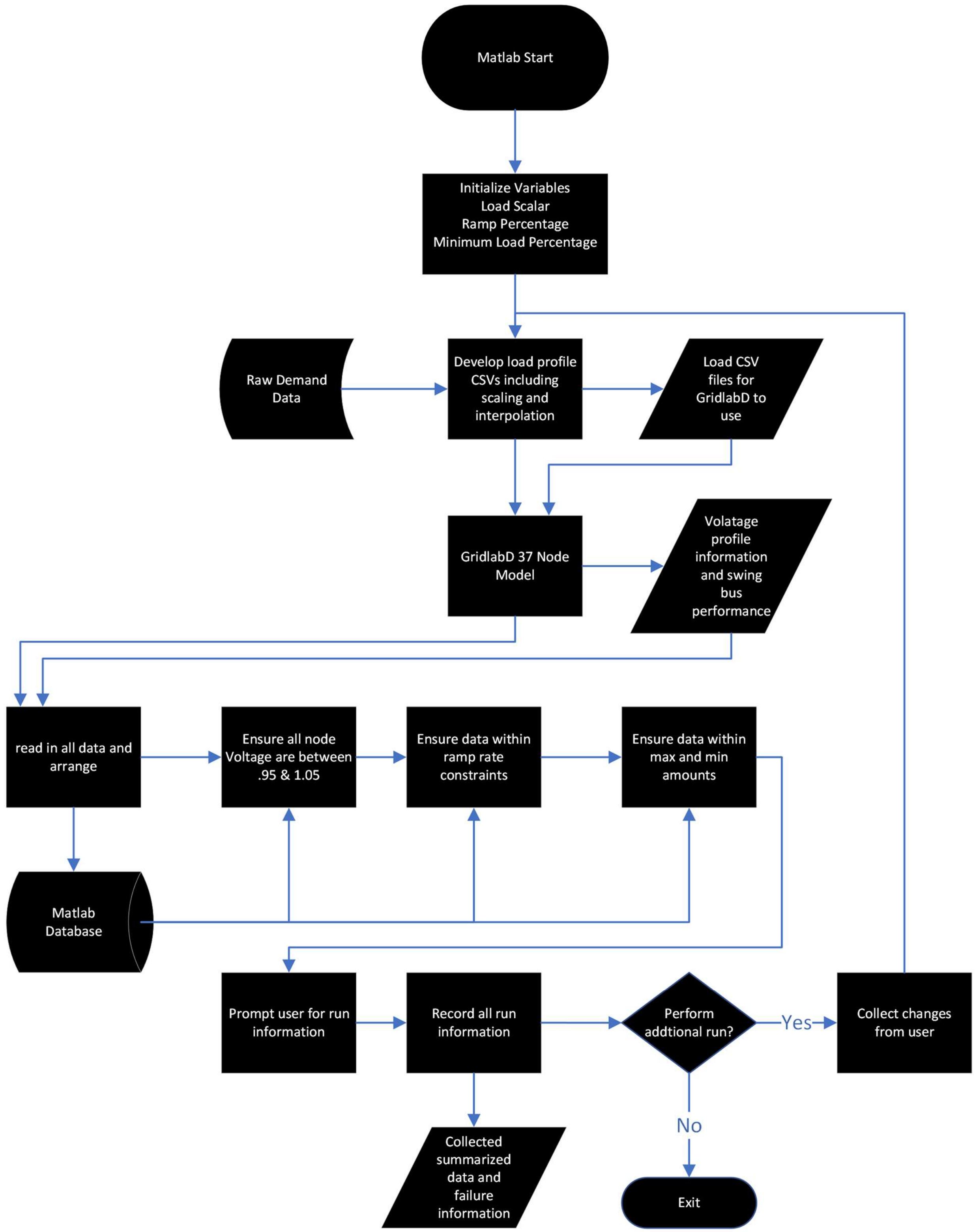
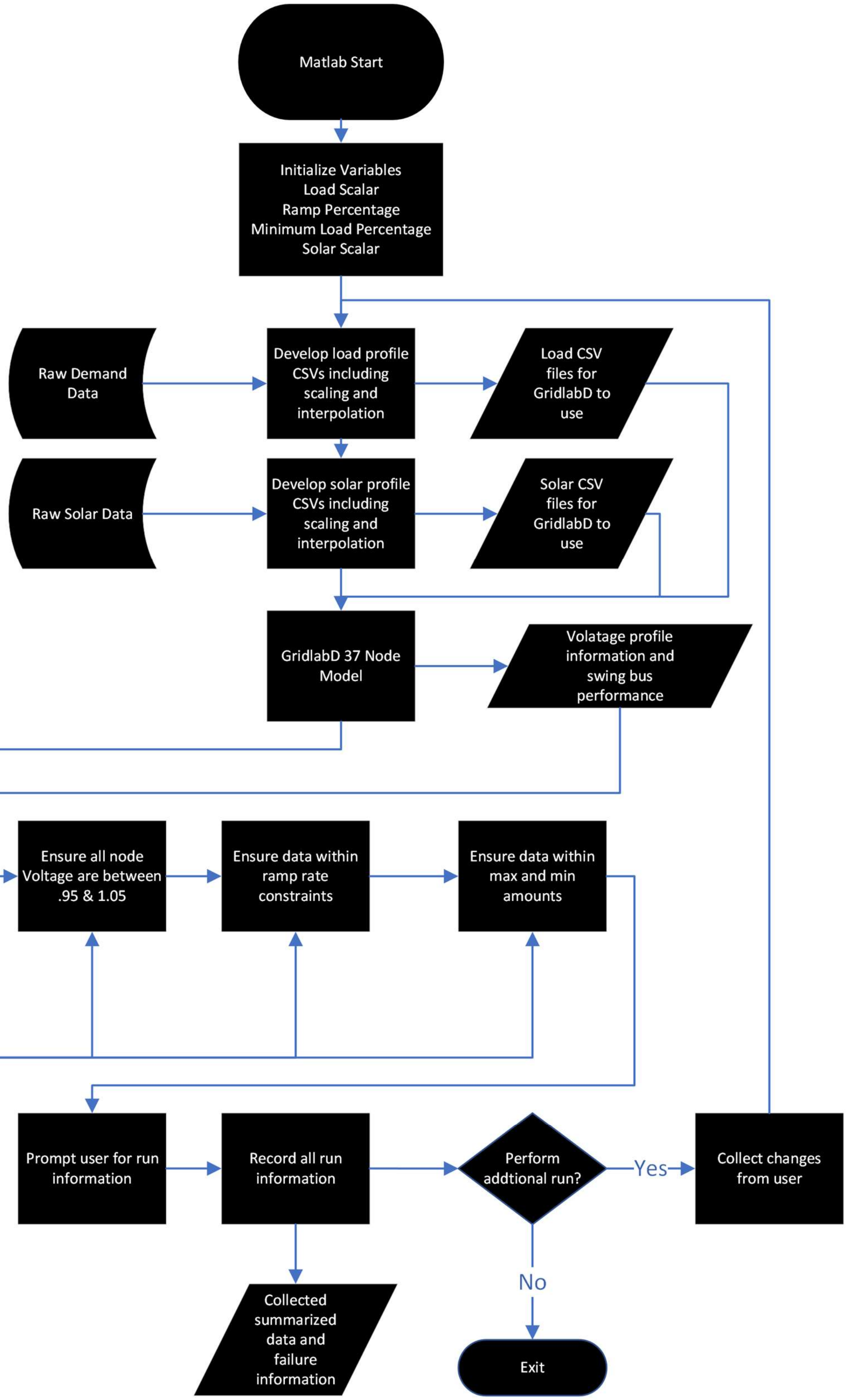
# Appendix

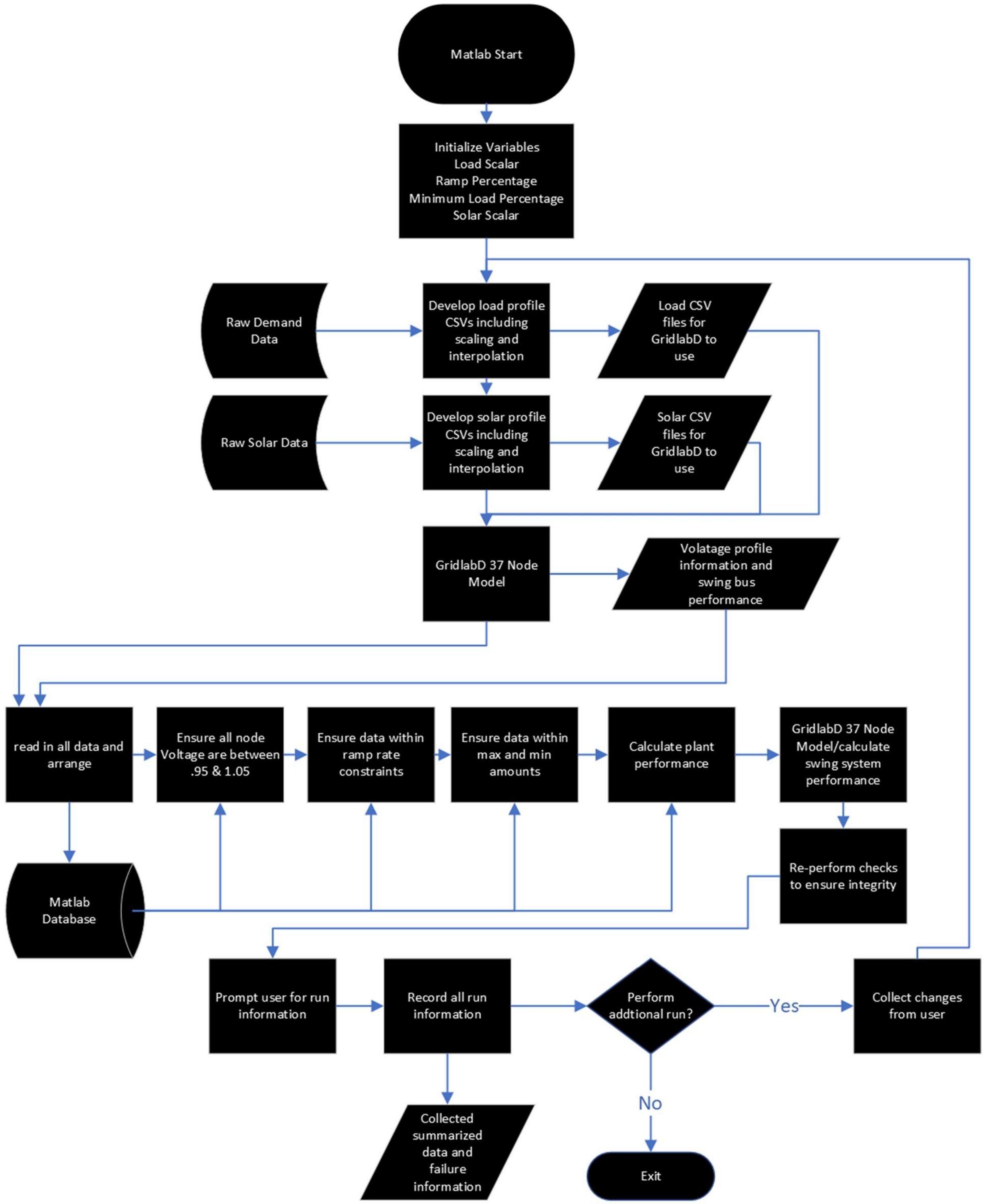
## Detailed flowchart for test 1



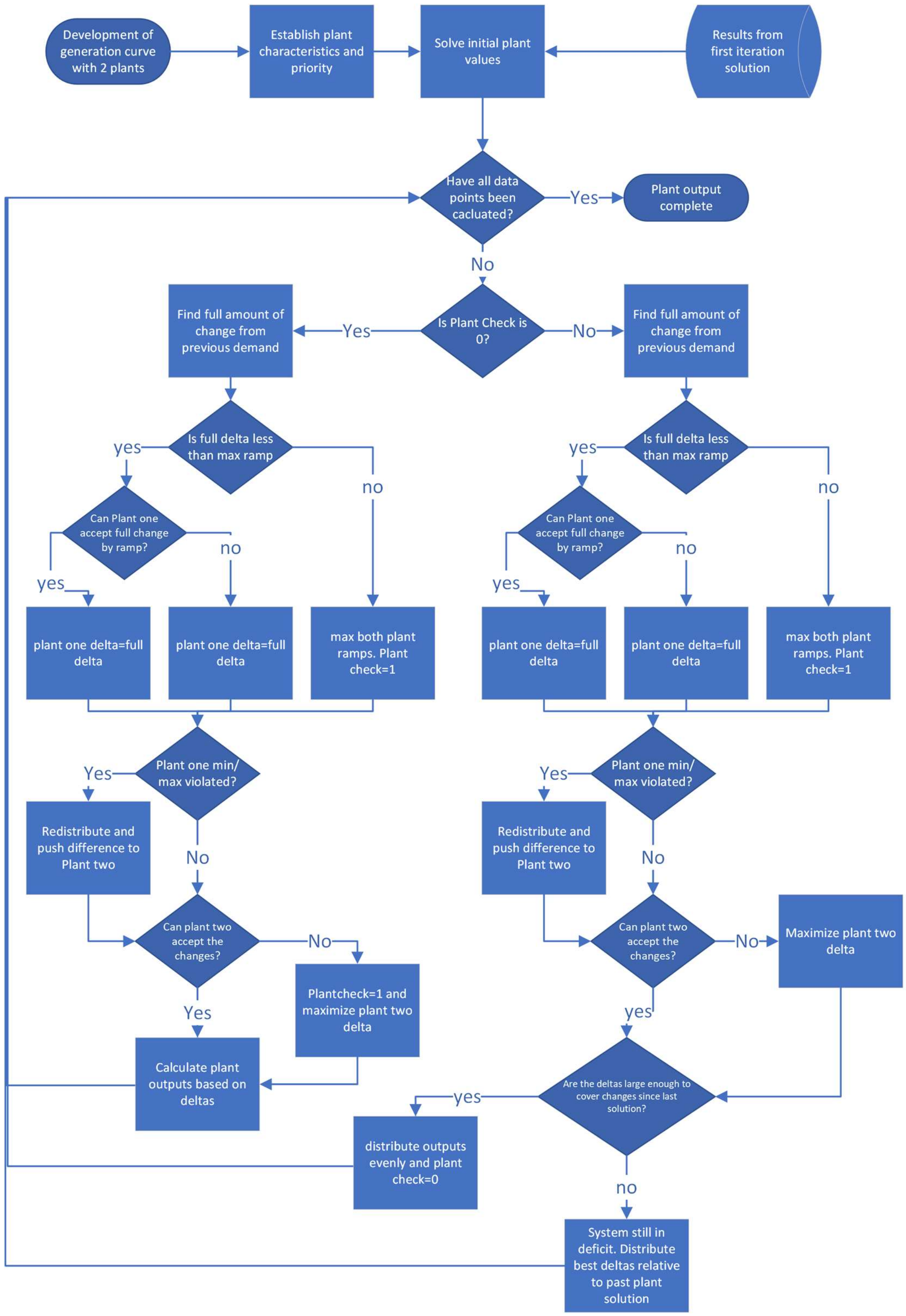
Detailed flowchart for test 2



Detailed flowchart for test 3



Detailed flowchart for test 4 dual plant operations



## Test 3 Full MATLAB Code

```
close all
clear workspace
format long g
scalar = 416000;%% begin setting initial variables. Set here in the beginning to allow easier updating
rampperc=.02;
minloadper=.1;
solarscalar=20.25;
for f=1:10 %% set up for loop in case the user wants to use the button prompts to reiterate the solution with updates

demandraw = readtable('demand.xlsx');%% first section focuses on reading in, scaling, and then distributing the load profile
deamadraw.date = datetime(demandraw.date,'Format','yyyy-MM-dd HH:mm:ss');
Headers =
{'date','MW','MVAR','N701AR','N701AI','N701BR','N701BI','N701CR','N701CI','N712CR','N712CI','N713CR','N713CI','N714AR','N714AI','N714BR','N714BI','N718AR','N718AI','N720CR','N720CI','N722BR','N722BI','N722CR','N722CI','N724BR','N724BI','N725BR','N725BI','N727CR','N727CI','N728AR','N728AI','N728BR','N728BI','N728CR','N728CI','N729AR','N729AI','N730CR','N730CI','N731BR','N731BI','N732CR','N732CI','N733AR','N733AI','N734CR','N734CI','N735CR','N735CI','N736BR','N736BI','N737AR','N737AI','N738AR','N738AI','N740CR','N740CI','N741CR','N741CI','N742AR','N742AI','N742BR','N742BI','N744AR','N744AI'};
demandcsv = cell2table(cell(218881,67),'VariableNames', Headers);
demandcsv.Properties.VariableNames;
t = table;
t1 = datetime(2008,5,1,0,0,0);
t2 = datetime(2008,9,30,0,0,0);
t = t1:minutes(1):t2;
t=t';
t = datetime(t,'InputFormat', 'yyyy-MM-dd HH:mm:ss');
real = interp1(demandraw.date, demandraw.MW, t,'cubic'); %% performing the interpolation step to get to minute time steps
imag = interp1(demandraw.date, demandraw.MVAR, t, 'cubic');
demandcsv.date = t;
demandcsv.date.Format = 'yyyy-MM-dd HH:mm:ss';
demandcsv.MW = real*scalar;
demandcsv.MVAR = imag*scalar;
demandcsv.N701AR=demandcsv.MW*.0383;%% values here come from the percentages in the 37 node load original
demandcsv.N701AI=demandcsv.MVAR*.0191;
demandcsv.N701BR=demandcsv.MW*.0383;
demandcsv.N701BI=demandcsv.MVAR*.0191;
demandcsv.N701CR=demandcsv.MW*.0957;
demandcsv.N701CI=demandcsv.MVAR*.0478;
demandcsv.N712CR=demandcsv.MW*.0232;
demandcsv.N712CI=demandcsv.MVAR*.0109;
demandcsv.N713CR=demandcsv.MW*.0232;
demandcsv.N713CI=demandcsv.MVAR*.0109;
demandcsv.N714AR=demandcsv.MW*.0046;
```

```
demandcsv.N714AI=demandcsv.MVAR*.0022;
demandcsv.N714BR=demandcsv.MW*.0057;
demandcsv.N714BI=demandcsv.MVAR*.0027;
demandcsv.N718AR=demandcsv.MW*.0232;
demandcsv.N718AI=demandcsv.MVAR*.0109;
demandcsv.N720CR=demandcsv.MW*.0232;
demandcsv.N720CI=demandcsv.MVAR*.0109;
demandcsv.N722BR=demandcsv.MW*.0383;
demandcsv.N722BI=demandcsv.MVAR*.0191;
demandcsv.N722CR=demandcsv.MW*.0057;
demandcsv.N722CI=demandcsv.MVAR*.0027;
demandcsv.N724BR=demandcsv.MW*.0115;
demandcsv.N724BI=demandcsv.MVAR*.0057;
demandcsv.N725BR=demandcsv.MW*.0115;
demandcsv.N725BI=demandcsv.MVAR*.0057;
demandcsv.N727CR=demandcsv.MW*.0115;
demandcsv.N727CI=demandcsv.MVAR*.0057;
demandcsv.N728AR=demandcsv.MW*.0115;
demandcsv.N728AI=demandcsv.MVAR*.0057;
demandcsv.N728BR=demandcsv.MW*.0115;
demandcsv.N728BI=demandcsv.MVAR*.0057;
demandcsv.N728CR=demandcsv.MW*.0115;
demandcsv.N728CI=demandcsv.MVAR*.0057;
demandcsv.N729AR=demandcsv.MW*.0115;
demandcsv.N729AI=demandcsv.MVAR*.0057;
demandcsv.N730CR=demandcsv.MW*.0232;
demandcsv.N730CI=demandcsv.MVAR*.0109;
demandcsv.N731BR=demandcsv.MW*.0232;
demandcsv.N731BI=demandcsv.MVAR*.0109;
demandcsv.N732CR=demandcsv.MW*.0115;
demandcsv.N732CI=demandcsv.MVAR*.0057;
demandcsv.N733AR=demandcsv.MW*.0232;
demandcsv.N733AI=demandcsv.MVAR*.0109;
demandcsv.N734CR=demandcsv.MW*.0115;
demandcsv.N734CI=demandcsv.MVAR*.0057;
demandcsv.N735CR=demandcsv.MW*.0232;
demandcsv.N735CI=demandcsv.MVAR*.0109;
demandcsv.N736BR=demandcsv.MW*.0115;
demandcsv.N736BI=demandcsv.MVAR*.0057;
demandcsv.N737AR=demandcsv.MW*.0383;
demandcsv.N737AI=demandcsv.MVAR*.0191;
demandcsv.N738AR=demandcsv.MW*.0344;
demandcsv.N738AI=demandcsv.MVAR*.0169;
demandcsv.N740CR=demandcsv.MW*.0232;
demandcsv.N740CI=demandcsv.MVAR*.0109;
demandcsv.N741CR=demandcsv.MW*.0115;
demandcsv.N741CI=demandcsv.MVAR*.0057;
demandcsv.N742AR=demandcsv.MW*.0022;
```

```
demandcsv.N742AI=demandcsv.MVAR*.0011;
demandcsv.N742BR=demandcsv.MW*.0232;
demandcsv.N742BI=demandcsv.MVAR*.0109;
demandcsv.N744AR=demandcsv.MW*.0115;
demandcsv.N744AI=demandcsv.MVAR*.0057;
plot (demandcsv.date,demandcsv.MW)
hold
plot (demandcsv.date,demandcsv.MVAR)
legend
hold off

d=4; %% this part here writes the files into csv files that gridlab-D uses
while d <= 67
a = "Nodeloaddata/";
b = demandcsv.Properties.VariableNames(d);
c = ".csv";
a = strcat(a,b,c);
writetable(demandcsv(:,[1 d]),a,"WriteVariableNames",false);
d=d+1;
end

solardemandraw = readtable('solardemand.xlsx');%% repeats the same process as above but now for
the solar demand
deamadraw.date = datetime(solardemandraw.date,'Format','yyyy-MM-dd HH:mm:ss');
Headers =
{'date','MW','MVAR','SN701AR','SN701AI','SN701BR','SN701BI','SN701CR','SN701CI','SN712CR','SN712CI'
,'SN713CR','SN713CI','SN714AR','SN714AI','SN714BR','SN714BI','SN718AR','SN718AI','SN720CR','SN720CI
','SN722BR','SN722BI','SN722CR','SN722CI','SN724BR','SN724BI','SN725BR','SN725BI','SN727CR','SN727CI
','SN728AR','SN728AI','SN728BR','SN728BI','SN728CR','SN728CI','SN729AR','SN729AI','SN730CR','SN730C
I','SN731BR','SN731BI','SN732CR','SN732CI','SN733AR','SN733AI','SN734CR','SN734CI','SN735CR','SN735
CI','SN736BR','SN736BI','SN737AR','SN737AI','SN738AR','SN738AI','SN740CR','SN740CI','SN741CR','SN74
1CI','SN742AR','SN742AI','SN742BR','SN742BI','SN744AR','SN744AI'};
solardemandcsv = cell2table(cell(218881,67),'VariableNames', Headers);
solardemandcsv.Properties.VariableNames;
st = table;
st1 = datetime(2008,5,1,0,0,0);
st2 = datetime(2008,9,30,0,0,0);
st = st1:minutes(1):st2;
st=st';
st = datetime(st,'InputFormat', 'yyyy-MM-dd HH:mm:ss');
sreal = interp1(solardemandraw.date, solardemandraw.MW, st,'cubic');
simag = interp1(solardemandraw.date, solardemandraw.MVAR, st, 'cubic');
solardemandcsv.date = st;
solardemandcsv.date.Format = 'yyyy-MM-dd HH:mm:ss';
solardemandcsv.MW = sreal*solarscalar;
solardemandcsv.MVAR = simag*solarscalar;
rowsToChange = solardemandcsv.MW > 0; %% does not allow the curve to go below 0. cannot draw
from the system
```

```
if ~isempty(rowsToChange)
        solardemandcsv.MW(rowsToChange) = 0;
end
rowsToChange = solardemandcsv.MVAR > 0;
if ~isempty(rowsToChange)
        solardemandcsv.MVAR(rowsToChange) = 0;
end
solardemandcsv.SN701AR=solardemandcsv.MW*.0383;
solardemandcsv.SN701AI=solardemandcsv.MVAR*.0191;
solardemandcsv.SN701BR=solardemandcsv.MW*.0383;
solardemandcsv.SN701BI=solardemandcsv.MVAR*.0191;
solardemandcsv.SN701CR=solardemandcsv.MW*.0957;
solardemandcsv.SN701CI=solardemandcsv.MVAR*.0478;
solardemandcsv.SN712CR=solardemandcsv.MW*.0232;
solardemandcsv.SN712CI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN713CR=solardemandcsv.MW*.0232;
solardemandcsv.SN713CI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN714AR=solardemandcsv.MW*.0046;
solardemandcsv.SN714AI=solardemandcsv.MVAR*.0022;
solardemandcsv.SN714BR=solardemandcsv.MW*.0057;
solardemandcsv.SN714BI=solardemandcsv.MVAR*.0027;
solardemandcsv.SN718AR=solardemandcsv.MW*.0232;
solardemandcsv.SN718AI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN720CR=solardemandcsv.MW*.0232;
solardemandcsv.SN720CI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN722BR=solardemandcsv.MW*.0383;
solardemandcsv.SN722BI=solardemandcsv.MVAR*.0191;
solardemandcsv.SN722CR=solardemandcsv.MW*.0057;
solardemandcsv.SN722CI=solardemandcsv.MVAR*.0027;
solardemandcsv.SN724BR=solardemandcsv.MW*.0115;
solardemandcsv.SN724BI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN725BR=solardemandcsv.MW*.0115;
solardemandcsv.SN725BI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN727CR=solardemandcsv.MW*.0115;
solardemandcsv.SN727CI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN728AR=solardemandcsv.MW*.0115;
solardemandcsv.SN728AI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN728BR=solardemandcsv.MW*.0115;
solardemandcsv.SN728BI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN728CR=solardemandcsv.MW*.0115;
solardemandcsv.SN728CI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN729AR=solardemandcsv.MW*.0115;
solardemandcsv.SN729AI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN730CR=solardemandcsv.MW*.0232;
solardemandcsv.SN730CI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN731BR=solardemandcsv.MW*.0232;
solardemandcsv.SN731BI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN732CR=solardemandcsv.MW*.0115;
```

```
solardemandcsv.SN732CI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN733AR=solardemandcsv.MW*.0232;
solardemandcsv.SN733AI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN734CR=solardemandcsv.MW*.0115;
solardemandcsv.SN734CI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN735CR=solardemandcsv.MW*.0232;
solardemandcsv.SN735CI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN736BR=solardemandcsv.MW*.0115;
solardemandcsv.SN736BI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN737AR=solardemandcsv.MW*.0383;
solardemandcsv.SN737AI=solardemandcsv.MVAR*.0191;
solardemandcsv.SN738AR=solardemandcsv.MW*.0344;
solardemandcsv.SN738AI=solardemandcsv.MVAR*.0169;
solardemandcsv.SN740CR=solardemandcsv.MW*.0232;
solardemandcsv.SN740CI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN741CR=solardemandcsv.MW*.0115;
solardemandcsv.SN741CI=solardemandcsv.MVAR*.0057;
solardemandcsv.SN742AR=solardemandcsv.MW*.0022;
solardemandcsv.SN742AI=solardemandcsv.MVAR*.0011;
solardemandcsv.SN742BR=solardemandcsv.MW*.0232;
solardemandcsv.SN742BI=solardemandcsv.MVAR*.0109;
solardemandcsv.SN744AR=solardemandcsv.MW*.0115;
solardemandcsv.SN744AI=solardemandcsv.MVAR*.0057;
plot (solardemandcsv.date,solardemandcsv.MW)
hold
plot (solardemandcsv.date,solardemandcsv.MVAR)
legend
hold off

d=4;
while d <= 67
a = "Nodeloaddata/";
b = solardemandcsv.Properties.VariableNames(d);
c = ".csv";
a = strcat(a,b,c);
writetable(solardemandcsv(:,[1 d]),a,"WriteVariableNames",false);
d=d+1;
end

CCS = table(demandcsv.date,demandcsv.MW,'VariableNames',["date","power"]); %% start of the CCS
curve development
CCS.CCSA=(CCS.power<4000000);
Ccheck = 0;
Cprev=2;
Cindex = 2;
while Cindex < 218882
   if Ccheck<120%% this is your 2 hour limit on toggling
      Cprev=Cindex-1;
```

```
        CCS{Cindex,"CCSA"}=CCS{Cprev,"CCSA"};
        Ccheck=Ccheck+1;
        Cindex=Cindex+1;
    else
        Cprev=Cindex-1;
        if (CCS{Cindex,"power"}) > 2880000 %% this is your check value to determine the trigger point. Will
be unique to user preferences
            if CCS{Cprev,"CCSA"}==0
              CCS{Cindex,"CCSA"}=0;
              Cindex=Cindex+1;
            else
              CCS{Cindex,"CCSA"}=0;
              Ccheck=0;
              Cindex=Cindex+1;
            end
        else
            if CCS{Cprev,"CCSA"}==1
            CCS{Cindex,"CCSA"}=1;
            Cindex=Cindex+1;
            else
            CCS{Cindex,"CCSA"}=1;
            Ccheck=0;
            Cindex=Cindex+1;
            end
        end
    end
end
plot(CCS.date,CCS.CCSA)
CCSuptime=(sum(CCS.CCSA)/218881)*100%% checking how much the system is on
CCS.CCSA=CCS.CCSA*166666;%% scaling the phases and values
CCS.CCSB=CCS.CCSA;
CCS.CCSC=CCS.CCSA;
% % % D = diff([0;CCS.CCSA;0]);
% % % S = find(D>0)
% % % E = find(D<0)-1
% % % F = E-S% % % %
d=3;
while d <= 5%% writing the csvs again
a = "Nodeloaddata/";
b = CCS.Properties.VariableNames(d);
c = ".csv";
a = strcat(a,b,c);
writetable(CCS(:,[1 d]),a,"WriteVariableNames",false);
d=d+1;
end

[status,result] = system('gridlabd CCScontrollerpart1.glm') % call first solution from gridlabd. When
rerunning some benefit can be found by not recreating the csvs if there were no changes
```

```
T1 = readtable('nodal sim outputs/baseoutput1.csv', 'Delimiter', ',',VariableNamingRule='preserve');%%
reading in the results from gridlabd
T2 = readtable('nodal sim outputs/baseoutput2.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T2 = removevars(T2,"# timestamp");
T3 = readtable('nodal sim outputs/baseoutput3.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T3 = removevars(T3,"# timestamp");
T4 = readtable('nodal sim outputs/baseoutput4.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T4 = removevars(T4,"# timestamp");
T5 = readtable('nodal sim outputs/baseoutput5.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T5 = removevars(T5,"# timestamp");
T6 = readtable('nodal sim outputs/baseoutput6.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T6 = removevars(T6,"# timestamp");
T7 = readtable('nodal sim outputs/baseoutput7.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T7 = removevars(T7,"# timestamp");
alloutputs = [T1 T2 T3 T4 T5 T6 T7];
analyzedoutputs = alloutputs(:,1);
x=2;
while x <= 162
y=x+1;
z = alloutputs.Properties.VariableNames{(x)};%% tailoring the table headers
z = erase(z,"measured_");
z = erase(z,".real");
analyzedoutputs.(z)= sqrt(alloutputs.(x).^2+alloutputs.(y).^2)/2771;%% putting the voltages into PU
values for analysis
x=x+2;
end
while x <=181
z = alloutputs.Properties.VariableNames{(x)};
z = erase(z,"measured_");
analyzedoutputs.(z)= alloutputs.(x);
x=x+1;
end
analyzedoutputs.("# timestamp") = erase(analyzedoutputs.("# timestamp"), ' PDT');
analyzedoutputs.("# timestamp") = erase(analyzedoutputs.("# timestamp"), '2008-');
analyzedoutputs.("# timestamp") = datetime(analyzedoutputs.("# timestamp"),'Format','MM-dd
HH:mm:ss');
analyzedoutputs.meter799A =
abs(alloutputs.("meter799:measured_voltage_A.real")+alloutputs.("meter799:measured_voltage_A.ima
g"))/1000;
x=82;
voutofrange = analyzedoutputs(:,1:82);
while x >= 2
z = voutofrange.Properties.VariableNames{(x)};
if (all(voutofrange.(z)<=1.05) && all(voutofrange.(z)>=.95))%% ensuring the voltage profiles are all
within range
```

```
voutofrange(:,x)=[];
end
x=x-1;
end
failcount=0
if width(voutofrange)>=2
   x=width(voutofrange);
   [min_val, min_idx] = min(min(voutofrange{:,2:end},[],2))%% helps to target where the voltage failure
occured if there was one
   [max_val, max_idx] = max(max(voutofrange{:,2:end},[],2))
   fprintf('date where minimum occurs');
   voutofrange(min_idx,:)
   fprintf('date where maximum occurs');
   voutofrange(max_idx,:)
   fprintf('Voltage went out of range');
   failcount=failcount+1
   return
end
plantsize = 2500000 %% resetting your plant size value
ramprate = plantsize*rampperc
minload = plantsize*minloadper
limitcheck = table;
limitcheck.date = analyzedoutputs.("# timestamp"); %% developing your data analysis table seperate
from the raw data
limitcheck.realpower =
analyzedoutputs.("p799:power_A.real")+analyzedoutputs.("p799:power_B.real")+analyzedoutputs.("p7
99:power_C.real");
limitcheck.reacpower =
analyzedoutputs.("p799:power_A.imag")+analyzedoutputs.("p799:power_B.imag")+analyzedoutputs.("p
799:power_C.imag");

plot(analyzedoutputs.("# timestamp"),analyzedoutputs.("p799:power_A.real"),analyzedoutputs.("#
timestamp"),analyzedoutputs.("p799:power_B.real"),analyzedoutputs.("#
timestamp"),analyzedoutputs.("p799:power_C.real"))
hold

plot(limitcheck.date,limitcheck.realpower)
hold;

plantsize = 2500000%% by this point in development there were several codes so reinitialization was
necessary at times
ramprate = plantsize*rampperc
minload = plantsize*minloadper
limitcheck = table;
limitcheck.date = analyzedoutputs.("# timestamp");
limitcheck.realpower =
analyzedoutputs.("p799:power_A.real")+analyzedoutputs.("p799:power_B.real")+analyzedoutputs.("p7
99:power_C.real");
```

```
limitcheck.reacpower =
analyzedoutputs.("p799:power_A.imag")+analyzedoutputs.("p799:power_B.imag")+analyzedoutputs.("p
799:power_C.imag");
limitcheck.pf= limitcheck.realpower ./ sqrt(limitcheck.realpower.^2 + limitcheck.reacpower.^2);%%
checking power factor
[~,maxidx] = max(limitcheck.realpower);
maximum=limitcheck(maxidx,:);%% checking maximum
maximum=table2array(limitcheck(maxidx,"realpower"));
[~,minidx] = min(limitcheck.realpower);
minimum=limitcheck(minidx,:);%% checking minimum
minimum=table2array(limitcheck(minidx,"realpower"));
averagepower=mean(limitcheck.realpower);%% recording average
averagepf=mean(limitcheck.pf);
dx = max(abs(diff(limitcheck.realpower)));
if ramprate < dx%% checking the ramp rate
   dx = (dx/plantsize)*100
   fprintf('ramp rate out of range %0.2f%%', dx)
else
   dx = (dx/plantsize)*100
   fprintf('ramp rate needed %0.2f%%', dx)
end


Plant = table;% % % begin follower system for the iterative power plant curves
Plant.date=analyzedoutputs.("# timestamp");
Plant.SimA=analyzedoutputs.("p799:power_A.real");
Plant.SimB=analyzedoutputs.("p799:power_B.real");
Plant.SimC=analyzedoutputs.("p799:power_C.real");
Plant.total =
analyzedoutputs.("p799:power_A.real")+analyzedoutputs.("p799:power_B.real")+analyzedoutputs.("p7
99:power_C.real");
plantcheck=0;
plantindex=2;
Plant.SimAI=analyzedoutputs.("p799:power_A.imag");
Plant.SimBI=analyzedoutputs.("p799:power_B.imag");
Plant.SimCI=analyzedoutputs.("p799:power_C.imag");
plantprev=plantindex-1;
Plant.phaseA=Plant.SimA;
Plant.phaseB=Plant.SimB;
Plant.phaseC=Plant.SimC;
Plant.phaseAI=Plant.SimAI;
Plant.phaseBI=Plant.SimBI;
Plant.phaseCI=Plant.SimCI;
while plantindex<(height(Plant)+1) %% see flowchart breakdown to better follow this process
   if abs(Plant{plantindex,"total"}-
(Plant{plantprev,"phaseA"}+Plant{plantprev,"phaseB"}+Plant{plantprev,"phaseC"}))<ramprate &&
plantcheck==0
   else
```

```
plantdiff=abs(Plant{plantindex,"total"}-
(Plant{plantprev,"phaseA"}+Plant{plantprev,"phaseB"}+Plant{plantprev,"phaseC"}));
phaseAdiff=(Plant{plantindex,"SimA"}-Plant{plantprev,"phaseA"})/plantdiff;
Plant{plantindex,"phaseA"}=(Plant{plantprev,"phaseA"})+(phaseAdiff*ramprate);
phaseBdiff=(Plant{plantindex,"SimB"}-Plant{plantprev,"phaseB"})/plantdiff;
Plant{plantindex,"phaseB"}=(Plant{plantprev,"phaseB"})+(phaseBdiff*ramprate);
phaseCdiff=(Plant{plantindex,"SimC"}-Plant{plantprev,"phaseC"})/plantdiff;
Plant{plantindex,"phaseC"}=(Plant{plantprev,"phaseC"})+(phaseCdiff*ramprate);
futureindex=plantindex+1;
futureindex(futureindex>116639)=116639;
  planttdiff=abs(Plant{futureindex,"total"}-
((Plant{plantindex,"phaseA"}+Plant{plantindex,"phaseB"}+Plant{plantindex,"phaseC"})));
  if planttdiff<ramprate
  plantcheck=0;
  else
  plantcheck=1;
  end
  end
  plantindex=plantindex+1;
  plantprev=plantindex-1;
end
Plant.phaseA=Plant.phaseA*-1;
Plant.phaseB=Plant.phaseB*-1;
Plant.phaseC=Plant.phaseC*-1;
Plant.phaseAI=Plant.phaseAI*-1;
Plant.phaseBI=Plant.phaseBI*-1;
Plant.phaseCI=Plant.phaseCI*-1;
Plant.limitcheck=(Plant.phaseA+Plant.phaseB+Plant.phaseC);
dx = max(abs(diff(Plant.limitcheck)));
plot(Plant.date,Plant.limitcheck)
hold
plot(Plant.date,Plant.total)
hold
Plant.check=Plant.limitcheck+Plant.total
d=9;
while d <= 14 %% writing power plant files out to csvs for second gridlabd operation
a = "Nodeloaddata/";
b = Plant.Properties.VariableNames(d);
c = ".csv";
a = strcat(a,b,c);
writetable(Plant(:,[1 d]),a,"WriteVariableNames",false);
d=d+1;
end
if ramprate < dx%% ensuring second ramp rate falls within allowable limit
  dx = (dx/plantsize)*100
  fprintf('ramp rate out of range %0.2f%%', dx)
else
  dx = (dx/plantsize)*100
```

```
    fprintf('ramp rate needed %0.2f%%', dx)
end

[status,result] = system('gridlabd CCScontrollerpart2.glm')% % %% call second solution. At this point in the radial feeder it was discovered that rerunning it was unnecessary. You could simply subtract the plant from the load to see the swing bus activity.


T1 = readtable('nodal sim outputs/baseoutput1.csv', 'Delimiter', ',',VariableNamingRule='preserve');%% reading in second iteration solution
T2 = readtable('nodal sim outputs/baseoutput2.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T2 = removevars(T2,"# timestamp");
T3 = readtable('nodal sim outputs/baseoutput3.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T3 = removevars(T3,"# timestamp");
T4 = readtable('nodal sim outputs/baseoutput4.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T4 = removevars(T4,"# timestamp");
T5 = readtable('nodal sim outputs/baseoutput5.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T5 = removevars(T5,"# timestamp");
T6 = readtable('nodal sim outputs/baseoutput6.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T6 = removevars(T6,"# timestamp");
T7 = readtable('nodal sim outputs/baseoutput7.csv', 'Delimiter', ',',VariableNamingRule='preserve');
T7 = removevars(T7,"# timestamp");
alloutputs = [T1 T2 T3 T4 T5 T6 T7];
analyzedoutputs = alloutputs(:,1);
x=2;
while x <= 162
y=x+1;
z = alloutputs.Properties.VariableNames{(x)};
z = erase(z,"measured_");
z = erase(z,".real");
analyzedoutputs.(z)= sqrt(alloutputs.(x).^2+alloutputs.(y).^2)/2771;
x=x+2;
end
while x <=181
z = alloutputs.Properties.VariableNames{(x)};
z = erase(z,"measured_");
analyzedoutputs.(z)= alloutputs.(x);
x=x+1;
end
analyzedoutputs.("# timestamp") = erase(analyzedoutputs.("# timestamp"), ' PDT');
analyzedoutputs.("# timestamp") = erase(analyzedoutputs.("# timestamp"), '2008-');
analyzedoutputs.("# timestamp") = datetime(analyzedoutputs.("# timestamp"),'Format','MM-dd HH:mm:ss');
analyzedoutputs.meter799A =
abs(alloutputs.("meter799:measured_voltage_A.real")+alloutputs.("meter799:measured_voltage_A.imag"))/1000;
x=82;
voutofrange = analyzedoutputs(:,1:82);
```

```
while x >= 2
z = voutofrange.Properties.VariableNames{(x)};
if (all(voutofrange.(z)<=1.05) && all(voutofrange.(z)>=.95))
voutofrange(:,x)=[];
end
x=x-1;
end
failcount=0
if width(voutofrange)>=2
   x=width(voutofrange);
   [min_val, min_idx] = min(min(voutofrange{:,2:end},[],2))
   [max_val, max_idx] = max(max(voutofrange{:,2:end},[],2))
   fprintf('date where minimum occurs');
   voutofrange(min_idx,:)
   fprintf('date where maximum occurs');
   voutofrange(max_idx,:)
   fprintf('Voltage went out of range');
   failcount=failcount+1
   return
end
plantsize = 2500000
ramprate = plantsize*rampperc
minload = plantsize*minloadper
limitcheck = table;
limitcheck.date = analyzedoutputs.("# timestamp");
limitcheck.realpower =
analyzedoutputs.("p799:power_A.real")+analyzedoutputs.("p799:power_B.real")+analyzedoutputs.("p7
99:power_C.real");
limitcheck.reacpower =
analyzedoutputs.("p799:power_A.imag")+analyzedoutputs.("p799:power_B.imag")+analyzedoutputs.("p
799:power_C.imag");
limitcheck.pf= limitcheck.realpower ./ sqrt(limitcheck.realpower.^2 + limitcheck.reacpower.^2);
[~,maxidx] = max(limitcheck.realpower);
maximum=limitcheck(maxidx,:);
maximum=table2array(limitcheck(maxidx,"realpower"));
[~,minidx] = min(limitcheck.realpower);
minimum=limitcheck(minidx,:);
minimum=table2array(limitcheck(minidx,"realpower"));
averagepower=mean(limitcheck.realpower);
averagepf=mean(limitcheck.pf);
dx = max(abs(diff(limitcheck.realpower)));
solarcheck.pf= -solardemandcsv.MW ./ sqrt(solardemandcsv.MW.^2 + solardemandcsv.MVAR.^2);%%
this portion is slightly different. Here solar is checked
solarcheck.pf=solarcheck.pf(~any(ismissing(solarcheck.pf),2),:);
averagesolarpf=mean(solarcheck.pf);
averagesolarpower=mean(solardemandcsv.MW);
maxsolar=min(solardemandcsv.MW);
if ramprate < dx
```

```
    dx = (dx/plantsize)*100;
    fprintf('ramp rate out of range %0.2f%%', dx);
    failcount=failcount+1
else
    dx = (dx/plantsize)*100;
    fprintf('ramp rate needed %0.2f%%', dx);
end
if plantsize < maximum
    fprintf('plant maximum insufficient %.1f', maximum);
    failcount=failcount+1
else
    fprintf('maximum power sufficient %.1f', maximum);
end
if minload > minimum
    fprintf('plant minimum insufficient.%.1f needed', minimum);
    failcount=failcount+1
else
    fprintf('minimum power sufficient. %.1f was experienced', minimum);
end
prompt = {'Enter Run number'}; %% get run number from user for automated record keeping
dlgtitle = 'Run Identifier';
dims = [1 50];
filename = inputdlg(prompt,dlgtitle,dims);
filenamegraphs1 = "C:\Users\17023\Desktop\Doctorate\37 node test folder\Final run information\" +
filename + "individualphases.jpeg";
filenamegraphs2 = "C:\Users\17023\Desktop\Doctorate\37 node test folder\Final run information\" +
filename + "overallpower.jpeg";
filenamegraphs3 = "C:\Users\17023\Desktop\Doctorate\37 node test folder\Final run information\" +
filename + "overallsolarpower.jpeg";
filename = "C:\Users\17023\Desktop\Doctorate\37 node test folder\Final run information\" + filename
+ ".txt";
lines = 'test information';
writelines(lines,filename,WriteMode="append");
lines = string(datetime);
writelines(lines,filename,WriteMode="append");
results =
table(scalar,plantsize,averagepf,averagepower,maximum,minimum,'VariableNames',{'scalar','plantsize','
averagepf','averagepower','maximum seen','minimum seen'});
writetable(results,filename,'WriteMode','append','WriteVariableNames',true);
results2 = table(ramprate,rampperc,minload,minloadper,'VariableNames',{'ramp rate setting','ramp
setting %','min load of plant','min load % setting'});
writetable(results2,filename,'WriteMode','append','WriteVariableNames',true);
results3 =
table(averagesolarpf,averagesolarpower,maxsolar,solarscalar,CCSuptime,'VariableNames',{'averagesolar
pf','averagesolarpower','maxsolar','solarscalar','CCSon'});
writetable(results3,filename,'WriteMode','append','WriteVariableNames',true);
```

```
limitcheck.swingreal =
analyzedoutputs.("p801:power_A.real")+analyzedoutputs.("p801:power_B.real")+analyzedoutputs.("p8
01:power_C.real");
limitcheck.swingreac =
analyzedoutputs.("p801:power_A.imag")+analyzedoutputs.("p801:power_B.imag")+analyzedoutputs.("p
801:power_C.imag");
figure(4)
plot(limitcheck.date,limitcheck.swingreal)
hold;
plot(limitcheck.date,limitcheck.swingreac)
title('Real and Reactive power of the swing bus')
xlabel('Time')
ylabel('Power')
legend ({'Real','Reactive'},'Location','northwest');
ylim([-1000000,3000000])
hold off;
if failcount>0
   lines='test failed check MATLAB';
   writelines(lines,filename,WriteMode="append");
else
   lines='test passed';
   writelines(lines,filename,WriteMode="append");
end

figure(1)%% various figures are captured for historical purposes
plot(analyzedoutputs.("# timestamp"),analyzedoutputs.("p799:power_A.real"),analyzedoutputs.("#
timestamp"),analyzedoutputs.("p799:power_B.real"),analyzedoutputs.("#
timestamp"),analyzedoutputs.("p799:power_C.real"))
hold
title('Real power of individual phases')
xlabel('Time')
ylabel('Power')
legend ({'Real A','Real B','Real C'},'location','northwest')
hold off
saveas(gca,filenamegraphs1)

figure(2)
plot(limitcheck.date,limitcheck.realpower)
hold;
plot(limitcheck.date,limitcheck.reacpower)
title('Real and Reactive power of the system')
xlabel('Time')
ylabel('Power')
legend ({'Real','Reactive'},'Location','northwest');
ylim([0,3000000])
hold off;
saveas(gca,filenamegraphs2)
figure(3)
```

```
plot(solardemandcsv.date,solardemandcsv.MW)
hold;
plot(solardemandcsv.date,solardemandcsv.MVAR)
title('Real and Reactive power injected by solar arrays')
xlabel('Time')
ylabel('Power')
legend ({'Real','Reactive'},'Location','northwest');
ylim([-1000000,0])
hold off;
saveas(gca,filenamegraphs3)

Finalcheck=limitcheck.realpower+Plant.limitcheck%% these were checking swing bus activity.
figure(5)
plot(limitcheck.date,Finalcheck)
hold;
title('check')
xlabel('Time')
ylabel('Power')
legend ({'Real','Reactive'},'Location','northwest');
ylim([-1000000,3000000])
hold off;

Finalcheck2=limitcheck.swingreal+Plant.limitcheck
figure(6)
plot(limitcheck.date,Finalcheck2)
hold;
title('check')
xlabel('Time')
ylabel('Power')
legend ({'Real','Reactive'},'Location','northwest');
ylim([-2000000,3000000])
hold off;


clear answer %% series of prompts to automate the process. Usefulness varied.
clear questdlg
answer = questdlg('Prepare for another run?', ...
        'Simulation and Data analysis complete', ...
        'Yes','No','No');
switch answer
  case 'Yes'
    disp([answer 'Praise the Omnissiah'])
    f=2
  case 'No'
    return
end

answer = questdlg('Change a parameter?', ...
```

```
                'Simulation and Data analysis complete', ...
                'Scalar','Ramp Rate %','Minimum Load %','Scalar');
switch answer

    case 'Scalar'
        answer2 = questdlg('Load or Solar?', ...
                'Simulation and Data analysis complete', ...
                'Load','Solar','Load');
        switch answer2
            case 'Load'
                prompt = {'Enter new scalar value'};
                dlgtitle = 'Scalar value';
                dims = [1 50];
                scalar = str2double(inputdlg(prompt,dlgtitle,dims));
            case 'Solar'
                prompt = {'Enter new scalar value'};
                dlgtitle = 'Scalar value';
                dims = [1 50];
                solarscalar = str2double(inputdlg(prompt,dlgtitle,dims));
        end
    case 'Ramp Rate %'
prompt = {'Enter new Ramp Rate % value'};
dlgtitle = 'Ramp Rate Value';
dims = [1 50];
rampperc = (str2double((inputdlg(prompt,dlgtitle,dims)))/100);
    case  'Minimum Load %'
 prompt = {'Enter new Minimum load % value'};
dlgtitle = 'Minimum Load Value';
dims = [1 50];
minloadper = (str2double((inputdlg(prompt,dlgtitle,dims)))/100);
end

end%% whole system loop ender
```

## Full Gridlab-D code for test 3 part 2

```
// IEEE 37 Node Feeder

#set profiler=1
#set pauseatexit=1
#set randomseed=1;
#set iteration_limit=100000;

clock {
	starttime '2008-05-01 0:00:00';
//	stoptime '2008-07-20 23:59:00';
	stoptime '2008-09-30 23:59:00';
}

module tape;
module generators;
module powerflow;
module powerflow{
	solver_method FBS;
	default_maximum_voltage_error 1e-9;
	line_limits FALSE;
};

class player{	//Initializes "value" property to allow player object to be created without parent object
  double value;
}

module climate;	//added in this module from the gridlabd wiki that activates the tmy2 data set also included in this folder. Data is older but it is the chosen file for gridlabd
class climate {
	double elevation[m];
	double tzoffset[h];
}
object climate {
	name "Las_vegas NV";
	tmyfile "NV-Las_vegas.tmy2";
	tzoffset -8;
	elevation 664;
}


// Phase Conductor for 721: 1,000,000 AA,CN
object underground_line_conductor:7210 {
	 outer_diameter 1.980000;
	 conductor_gmr 0.036800;
	 conductor_diameter 1.150000;
	 conductor_resistance 0.105000;
	 neutral_gmr 0.003310;
```

```
            neutral_resistance 5.903000;
            neutral_diameter 0.102000;
            neutral_strands 20.000000;
            shield_gmr 0.000000;
            shield_resistance 0.000000;
}

// Phase Conductor for 722: 500,000 AA,CN
object underground_line_conductor:7220 {
            outer_diameter 1.560000;
            conductor_gmr 0.026000;
            conductor_diameter 0.813000;
            conductor_resistance 0.206000;
            neutral_gmr 0.002620;
            neutral_resistance 9.375000;
            neutral_diameter 0.081000;
            neutral_strands 16.000000;
            shield_gmr 0.000000;
            shield_resistance 0.000000;
}

// Phase Conductor for 723: 2/0 AA,CN
object underground_line_conductor:7230 {
            outer_diameter 1.100000;
            conductor_gmr 0.012500;
            conductor_diameter 0.414000;
            conductor_resistance 0.769000;
            neutral_gmr 0.002080;
            neutral_resistance 14.872000;
            neutral_diameter 0.064000;
            neutral_strands 7.000000;
            shield_gmr 0.000000;
            shield_resistance 0.000000;
}

// Phase Conductor for 724: //2 AA,CN
object underground_line_conductor:7240 {
            outer_diameter 0.980000;
            conductor_gmr 0.008830;
            conductor_diameter 0.292000;
            conductor_resistance 1.540000;
            neutral_gmr 0.002080;
            neutral_resistance 14.872000;
            neutral_diameter 0.064000;
            neutral_strands 6.000000;
            shield_gmr 0.000000;
            shield_resistance 0.000000;
}
```

```
// underground line spacing: spacing id 515
object line_spacing:515 {
	distance_AB 0.500000;
	distance_BC 0.500000;
	distance_AC 1.000000;
	distance_AN 0.000000;
	distance_BN 0.000000;
	distance_CN 0.000000;
}

//line configurations:
object line_configuration:7211 {
	conductor_A underground_line_conductor:7210;
	conductor_B underground_line_conductor:7210;
	conductor_C underground_line_conductor:7210;
	spacing line_spacing:515;
}

object line_configuration:7221 {
	conductor_A underground_line_conductor:7220;
	conductor_B underground_line_conductor:7220;
	conductor_C underground_line_conductor:7220;
	spacing line_spacing:515;
}

object line_configuration:7231 {
	conductor_A underground_line_conductor:7230;
	conductor_B underground_line_conductor:7230;
	conductor_C underground_line_conductor:7230;
	spacing line_spacing:515;
}

object line_configuration:7241 {
	conductor_A underground_line_conductor:7240;
	conductor_B underground_line_conductor:7240;
	conductor_C underground_line_conductor:7240;
	spacing line_spacing:515;
}

//create lineobjects:

object underground_line { //:m701702 {
	phases "ABC";
	name linem701to702;
	from m701;
	to node:702;
	length 960;
```

```
            configuration line_configuration:7221;
}

object meter {
           name m701;
    phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}



object underground_line  {  //:701m701 {
            phases "ABC";
            name line701tom701;
            from load:701;
            to m701;
            length 0;
            configuration line_configuration:7221;
}

object underground_line:702705 {
            phases "ABC";
            name line702to705;
            from node:702;
            to node:705;
            length 400;
            configuration line_configuration:7241;
}

object underground_line   {   //:702ml713 {
            phases "ABC";
            name line702toml713;
            from node:702;
            to ml713;
            length 360;
            configuration line_configuration:7231;
}

object meter {
           name ml713;
            phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
```

```
}

object underground_line   {    //:ml713713 {
	phases "ABC";
	name lineml713to713;
	from ml713;
	to load:713;
	length 0;
	configuration line_configuration:7231;
}

object underground_line:702703 {
	phases "ABC";
	name line702to703;
	from node:702;
	to node:703;
	length 1320;
	configuration line_configuration:7221;
}

object underground_line:703727 {
	phases "ABC";
	name line703to727;
	from node:703;
	to load:727;
	length 240;
	configuration line_configuration:7241;
}

object underground_line:703730 {
	phases "ABC";
	name line703to730;
	from node:703;
	to load:730;
	length 600;
	configuration line_configuration:7231;
}

object underground_line:704714 {
	phases "ABC";
	name line704to714;
	from node:704;
	to load:714;
	length 80;
	configuration line_configuration:7241;
}

object underground_line:704720 {
```

```
		phases "ABC";
		name line704to720;
		from node:704;
		to load:720;
		length 800;
		configuration line_configuration:7231;
}

object underground_line:705742 {
		phases "ABC";
		name line705to742;
		from node:705;
		to load:742;
		length 320;
		configuration line_configuration:7241;
}

object underground_line:705712 {
		phases "ABC";
		name line705to712;
		from node:705;
		to load:712;
		length 240;
		configuration line_configuration:7241;
}

object underground_line:706725 {
		phases "ABC";
		name line706to725;
		from node:706;
		to load:725;
		length 280;
		configuration line_configuration:7241;
}

object underground_line:707724 {
		phases "ABC";
		name line707to724;
		from node:707;
		to load:724;
		length 760;
		configuration line_configuration:7241;
}

object underground_line:707722 {
		phases "ABC";
		name line707to722;
		from node:707;
```

```
	to load:722;
	length 120;
	configuration line_configuration:7241;
}

object underground_line:708733 {
	phases "ABC";
	name line708to733;
	from node:708;
	to load:733;
	length 320;
	configuration line_configuration:7231;
}

object underground_line:708732 {
	phases "ABC";
	name line708to732;
	from node:708;
	to load:732;
	length 320;
	configuration line_configuration:7241;
}

object underground_line:709731 {
	phases "ABC";
	name line709to731;
	from node:709;
	to load:731;
	length 600;
	configuration line_configuration:7231;
}

object underground_line:709708 {
	phases "ABC";
	name line709to708;
	from node:709;
	to node:708;
	length 320;
	configuration line_configuration:7231;
}

object underground_line:710735 {
	phases "ABC";
	name line710to735;
	from node:710;
	to load:735;
	length 200;
	configuration line_configuration:7241;
```

```
}

object underground_line:710736 {
	phases "ABC";
	name line710to736;
	from node:710;
	to load:736;
	length 1280;
	configuration line_configuration:7241;
}

object underground_line:711741 {
	phases "ABC";
	name line711to741;
	from node:711;
	to load:741;
	length 400;
	configuration line_configuration:7231;
}

object underground_line:711740 {
	phases "ABC";
	name line711to740;
	from node:711;
	to load:740;
	length 200;
	configuration line_configuration:7241;
}

object underground_line:713704 {
	phases "ABC";
	name line713to704;
	from load:713;
	to node:704;
	length 520;
	configuration line_configuration:7231;
}

object underground_line:714718 {
	phases "ABC";
	name line714to718;
	from load:714;
	to load:718;
	length 520;
	configuration line_configuration:7241;
}

object underground_line:720707 {
```

```
	phases "ABC";
	name line720to707;
	from load:720;
	to node:707;
	length 920;
	configuration line_configuration:7241;
}

object underground_line:720706 {
	phases "ABC";
	name line720to706;
	from load:720;
	to node:706;
	length 600;
	configuration line_configuration:7231;
}

object underground_line:727744 {
	phases "ABC";
	name line727to744;
	from load:727;
	to load:744;
	length 280;
	configuration line_configuration:7231;
}

object underground_line:730709 {
	phases "ABC";
	name line730to709;
	from load:730;
	to node:709;
	length 200;
	configuration line_configuration:7231;
}

object underground_line:733734 {
	phases "ABC";
	name line733to734;
	from load:733;
	to load:734;
	length 560;
	configuration line_configuration:7231;
}

object underground_line:734737 {
	phases "ABC";
	name line734to737;
	from load:734;
```

```
	to load:737;
	length 640;
	configuration line_configuration:7231;
}

object underground_line:734710 {
	phases "ABC";
	name line734to710;
	from load:734;
	to node:710;
	length 520;
	configuration line_configuration:7241;
}

object underground_line:737738 {
	phases "ABC";
	name line737to738;
	from load:737;
	to load:738;
	length 400;
	configuration line_configuration:7231;
}

object underground_line:738711 {
	phases "ABC";
	name line738to711;
	from load:738;
	to node:711;
	length 400;
	configuration line_configuration:7231;
}

object underground_line:744728 {
	phases "ABC";
	name line744to728;
	from load:744;
	to load:728;
	length 200;
	configuration line_configuration:7241;
}

object underground_line:744729 {
	phases "ABC";
	name line744to729;
	from load:744;
	to load:729;
	length 280;
	configuration line_configuration:7241;
```

```
}

object underground_line { //:781701
            phases "ABC";
            name line781top781;
            from node:781;
            to p781;
            length 0;
            configuration line_configuration:7211;
}

object underground_line {
            phases "ABC";
            name line799top799;
            from load799;
            to p799;
            length 0;
            configuration line_configuration:7211;
}

object underground_line {
            phases "ABC";
            name line801top801;
            from node:801;
            to p801;
            length 0;
            configuration line_configuration:7211;
}

object underground_line {
            phases "ABC";
            name p801toload799;
            from p801;
            to load799;
            length 0;
            configuration line_configuration:7211;
}

object meter {
           name p781;
   phases "ABC";
   voltage_A 2400.000000-1385.640646j;
           voltage_B -2400.000000-1385.640646j;
           voltage_C 0.000000+2771.281292j;
           nominal_voltage 4800;
}

object underground_line{ //:781701
```

```
            phases "ABC";
            name linep781toCCS;
            from p781;
            to CCS;
            length 0;
            configuration line_configuration:7211;
}

object underground_line{ //:781701
            phases "ABC";
            name CCSto701;
            from CCS;
            to load:701;
            length 1850;
            configuration line_configuration:7211;
}
//END of line

//create nodes and meters as pairs to nodes for troubleshooting ease

object node:801 {
           phases "ABC";
           name N801;
           bustype SWING;
           voltage_A 2400.000000-1385.640646j;
           voltage_B -2400.000000-1385.640646j;
           voltage_C 0.000000+2771.281292j;
           nominal_voltage 4800;
}

object meter {
           name meter801;
           parent N801;
   phases "ABC";
   voltage_A 2400.000000-1385.640646j;
           voltage_B -2400.000000-1385.640646j;
           voltage_C 0.000000+2771.281292j;
           nominal_voltage 4800;
}

object meter {
           name p801;
   phases "ABC";
   voltage_A 2400.000000-1385.640646j;
           voltage_B -2400.000000-1385.640646j;
           voltage_C 0.000000+2771.281292j;
           nominal_voltage 4800;
}
```

```
//object node:799 {
//	phases "ABC";
//	name N799;
//	voltage_A 2400.000000-1385.640646j;
//	voltage_B -2400.000000-1385.640646j;
//	voltage_C 0.000000+2771.281292j;
//	nominal_voltage 4800;
//}

object meter {
	name meter799;
	parent load799;
   phases "ABCD";
   voltage_A 2400.000000-1385.640646j;
	voltage_B -2400.000000-1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}

object meter {
	name p799;
   phases "ABCD";
   voltage_A 2400.000000-1385.640646j;
	voltage_B -2400.000000-1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}


//Create extra node for other side of regulator
object node:781 {
	 phases "ABC";
	 name N781;
	 //bustype SWING;
	 voltage_A 2400.0000-1385.640646j;
	 voltage_B -2400.0000-1385.640646j;
	 voltage_C 0.0000+2771.281292j;
	 nominal_voltage 4800;
}

//object node:800 {
//	phases "ABC";// had to establish node 800 as the regulator didnt like direct connections to the
power bus
//	name N800;
//	parent N781;
//	voltage_A 2400.000000-1385.640646j;
//	voltage_B -2400.000000-1385.640646j;
```

```
//	voltage_C 0.000000+2771.281292j;
//	nominal_voltage 4800;
//}

object load:800 {
	 phases "ABC"; // CCS built as 20% of 2.5MW so 500KW in total evenly divided among 3 phases
	 name CCS;
	 voltage_A 2400.000000 -1385.640646j;
	 voltage_B -2400.000000 -1385.640646j;
	 voltage_C 0.000000+2771.281292j;
//	constant_power_A 166666.6+0j;
//	constant_power_B 166666.6+0j;
//	constant_power_C 166666.6+0j;
	 nominal_voltage 4800;
	 object player {
			property constant_power_A_real;
			file Nodeloaddata/CCSA.csv;
			loop 1;
	 };
	 object player {
			property constant_power_B_real;
			file Nodeloaddata/CCSB.csv;
			loop 1;
	 };
	  object player {
			property constant_power_C_real;
			file Nodeloaddata/CCSC.csv;
			loop 1;
	 };
}

object meter {
	name v800;
	parent CCS;
	phases "ABCD";
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}

object load:799 {
	 phases "ABCD"; // Power plant
	 name load799;//CCSPlant;
	 voltage_A 2400.000000 -1385.640646j;
	 voltage_B -2400.000000 -1385.640646j;
	 voltage_C 0.000000+2771.281292j;
	 nominal_voltage 4800;
```

```
 object player {
                        property constant_power_A_real;
                        file Nodeloaddata/phaseA.csv;
                        loop 1;
            };
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/phaseAI.csv;
                        loop 1;
            };

            object player {
                        property constant_power_B_real;
                        file Nodeloaddata/phaseB.csv;
                        loop 1;
            };
            object player {
                        property constant_power_B_reac;
                        file Nodeloaddata/phaseBI.csv;
                        loop 1;
            };
             object player {
                        property constant_power_C_real;
                        file Nodeloaddata/phaseC.csv;
                        loop 1;
            };
                        object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/phaseCI.csv;
                        loop 1;
            };
}

object node:702 {
            phases "ABC";
            name N702;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object meter {
           name meter702;
           parent N702;
           phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
```

```
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object node:703 {
            phases "ABC";
            name N703;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object meter {
           name meter703;
           parent N703;
            phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object node:704 {
            phases "ABC";
            name N704;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object meter {
           name meter704;
           parent N704;
            phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object node:705 {
            phases "ABC";
            name N705;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
```

```
            nominal_voltage 4800;
}

object meter {
           name meter705;
           parent N705;
            phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object node:706 {
            phases "ABC";
            name N706;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object meter {
           name meter706;
           parent N706;
            phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object node:707 {
            phases "ABC";
            name N707;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object meter {
           name meter707;
           parent N707;
            phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
```

```
		nominal_voltage 4800;
}

object node:708 {
		phases "ABC";
		name N708;
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
}

object meter {
		name meter708;
		parent N708;
		phases "ABC";
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
}

object node:709 {
		phases "ABC";
		name N709;
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
}

object meter {
		name meter709;
		parent N709;
		phases "ABC";
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
}

object node:710 {
		phases "ABC";
		name N710;
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
```

```
}

object meter {
           name meter710;
           parent N710;
            phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object node:711 {
            phases "ABC";
            name N711;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object meter {
           name meter711;
           parent N711;
            phases "ABC";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

//Create loads
object load:701 {
            phases "ABCD";
            name load701;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
//          constant_power_A 140000.000000+70000.000000j;
//          constant_power_B 140000.000000+70000.000000j;
//          constant_power_C 350000.000000+175000.000000j;
            nominal_voltage 4800;

             object player {
                         property constant_power_A_real;
                         file Nodeloaddata/N701AR.csv;
                         loop 1;
            };
```

```
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/N701AI.csv;
                        loop 1;
            };

            object player {
                        property constant_power_B_real;
                        file Nodeloaddata/N701BR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_B_reac;
                        file Nodeloaddata/N701BI.csv;
                        loop 1;
            };
             object player {
                        property constant_power_C_real;
                        file Nodeloaddata/N701CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/N701CI.csv;
                        loop 1;
            };
}

object meter {
name solarmeter701;
parent load701;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
            phases "ABCD";
            name sload701;
            parent solarmeter701;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
            object player {
                        property constant_power_A_real;
```

```
                                file Nodeloaddata/SN701AR.csv;
                                loop 1;
        };
        object player {
                                property constant_power_A_reac;
                                file Nodeloaddata/SN701AI.csv;
                                loop 1;
        };
         object player {
                                property constant_power_B_real;
                                file Nodeloaddata/SN701BR.csv;
                                loop 1;
        };
        object player {
                                property constant_power_B_reac;
                                file Nodeloaddata/SN701BI.csv;
                                loop 1;
        };
        object player {
                                property constant_power_C_real;
                                file Nodeloaddata/SN701CR.csv;
                                loop 1;
        };
        object player {
                                property constant_power_C_reac;
                                file Nodeloaddata/SN701CI.csv;
                                loop 1;
        };
}

object meter {
        name v701;
        parent load701;
        phases "ABCD";
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
        nominal_voltage 4800;
}

object load:712 {
        phases "ABCD";
        name load712;
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
//      constant_power_C 85000.000000+40000.000000j;
        nominal_voltage 4800;
```

```
            object player {
                        property constant_power_C_real;
                        file Nodeloaddata/N712CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/N712CI.csv;
                        loop 1;
            };
}

object meter {
name solarmeter712;
parent load712;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
            phases "ABCD";
            name sload712;
            parent solarmeter712;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
            object player {
                        property constant_power_C_real;
                        file Nodeloaddata/SN712CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/SN712CI.csv;
                        loop 1;
            };
}

object meter {
           name v712;
           parent load712;
           phases "ABCD";
           voltage_A 2400.000000 -1385.640646j;
           voltage_B -2400.000000 -1385.640646j;
```

```
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object load:713 {
            phases "ABCD";
            name load713;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
//          constant_power_C 85000.000000+40000.000000j;
            nominal_voltage 4800;
             object player {
                        property constant_power_C_real;
                        file Nodeloaddata/N713CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/N713CI.csv;
                        loop 1;
            };
}

object meter {
name solarmeter713;
parent load713;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
            phases "ABCD";
            name sload713;
            parent solarmeter713;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
            object player {
                        property constant_power_C_real;
                        file Nodeloaddata/SN713CR.csv;
                        loop 1;
            };
            object player {
```

```
				property constant_power_C_reac;
				file Nodeloaddata/SN713CI.csv;
				loop 1;
		};
}

object meter {
		name v713;
		parent load713;
		phases "ABCD";
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
}

object load:714 {
		phases "ABCD";
		name load714;
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
//		constant_current_A 3.541667 -1.666667j;
//		constant_current_B -3.991720 -2.747194j;
		nominal_voltage 4800;
		object player {
				property constant_power_A_real;
				file Nodeloaddata/N714AR.csv;
				loop 1;
		};
		object player {
				property constant_power_A_reac;
				file Nodeloaddata/N714AI.csv;
				loop 1;
		};

		object player {
				property constant_power_B_real;
				file Nodeloaddata/N714BR.csv;
				loop 1;
		};
		object player {
				property constant_power_B_reac;
				file Nodeloaddata/N714BI.csv;
				loop 1;
		};
}
```

```
object meter {
name solarmeter714;
parent load714;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload714;
	parent solarmeter714;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_A_real;
			file Nodeloaddata/SN714AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/SN714AI.csv;
			loop 1;
	};
	object player {
			property constant_power_B_real;
			file Nodeloaddata/SN714BR.csv;
			loop 1;
	};
	object player {
			property constant_power_B_reac;
			file Nodeloaddata/SN714BI.csv;
			loop 1;
	};
}

object meter {
	name v714;
	parent load714;
	phases "ABCD";
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
```

```
}

object load:718 {
	phases "ABCD";
	name load718;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
//	constant_impedance_A 221.915014+104.430595j;
	nominal_voltage 4800;
	object player {
			property constant_power_A_real;
			file Nodeloaddata/N718AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/N718AI.csv;
			loop 1;
	};
}

object meter {
name solarmeter718;
parent load718;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload718;
	parent solarmeter718;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_A_real;
			file Nodeloaddata/SN718AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/SN718AI.csv;
```

```
                loop 1;
        };
}

object meter {
        name v718;
        parent load718;
        phases "ABCD";
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
        nominal_voltage 4800;
}

object load:720 {
        phases "ABCD";
        name load720;
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
//      constant_power_C 85000.000000+40000.000000j;
        nominal_voltage 4800;
         object player {
                property constant_power_C_real;
                file Nodeloaddata/N720CR.csv;
                loop 1;
        };
        object player {
                property constant_power_C_reac;
                file Nodeloaddata/N720CI.csv;
                loop 1;
        };
}

object meter {
name solarmeter720;
parent load720;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
        phases "ABCD";
        name sload720;
        parent solarmeter720;
```

```
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
            object player {
                        property constant_power_C_real;
                        file Nodeloaddata/SN720CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/SN720CI.csv;
                        loop 1;
            };
}

object meter {
            name v720;
            parent load720;
            phases "ABCD";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object load:722 {
            phases "ABCD";
            name load722;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
//          constant_current_B -27.212870 -17.967408j;
//          constant_current_C -0.383280+4.830528j;
            nominal_voltage 4800;
            object player {
                        property constant_power_B_real;
                        file Nodeloaddata/N722BR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_B_reac;
                        file Nodeloaddata/N722BI.csv;
                        loop 1;
            };
             object player {
                        property constant_power_C_real;
                        file Nodeloaddata/N722CR.csv;
```

```
				loop 1;
		};
		object player {
				property constant_power_C_reac;
				file Nodeloaddata/N722CI.csv;
				loop 1;
		};
}

object meter {
name solarmeter722;
parent load722;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
		phases "ABCD";
		name sload722;
		parent solarmeter722;
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
			object player {
				property constant_power_B_real;
				file Nodeloaddata/SN722BR.csv;
				loop 1;
		};
		object player {
				property constant_power_B_reac;
				file Nodeloaddata/SN722BI.csv;
				loop 1;
		};
		object player {
				property constant_power_C_real;
				file Nodeloaddata/SN722CR.csv;
				loop 1;
		};
		object player {
				property constant_power_C_reac;
				file Nodeloaddata/SN722CI.csv;
				loop 1;
		};
}
```

```
object meter {
        name v722;
        parent load722;
        phases "ABCD";
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
        nominal_voltage 4800;
}

object load:724 {
        phases "ABCD";
        name load724;
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
//      constant_impedance_B 438.857143+219.428571j;
        nominal_voltage 4800;

        object player {
                        property constant_power_B_real;
                        file Nodeloaddata/N724BR.csv;
                        loop 1;
        };
        object player {
                        property constant_power_B_reac;
                        file Nodeloaddata/N724BI.csv;
                        loop 1;
        };

}

object meter {
name solarmeter724;
parent load724;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
        phases "ABCD";
        name sload724;
        parent solarmeter724;
        voltage_A 2400.000000 -1385.640646j;
```

```
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
                        object player {
                                    property constant_power_B_real;
                                    file Nodeloaddata/SN724BR.csv;
                                    loop 1;
            };
            object player {
                                    property constant_power_B_reac;
                                    file Nodeloaddata/SN724BI.csv;
                                    loop 1;
            };
}

object meter {
            name v724;
            parent load724;
            phases "ABCD";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object load:725 {
            phases "ABCD";
            name load725;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
//          constant_power_B 42000.000000+21000.000000j;
            nominal_voltage 4800;
            object player {
                                    property constant_power_B_real;
                                    file Nodeloaddata/N725BR.csv;
                                    loop 1;
            };
            object player {
                                    property constant_power_B_reac;
                                    file Nodeloaddata/N725BI.csv;
                                    loop 1;
            };
}

object meter {
name solarmeter725;
parent load725;
```

```
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload725;
	parent solarmeter725;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
		object player {
			property constant_power_B_real;
			file Nodeloaddata/SN725BR.csv;
			loop 1;
	};
	object player {
			property constant_power_B_reac;
			file Nodeloaddata/SN725BI.csv;
			loop 1;
	};
}

object meter {
	name v725;
	parent load725;
	phases "ABCD";
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}

object load:727 {
	phases "ABCD";
	name load727;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
//	constant_power_C 42000.000000+21000.000000j;
	nominal_voltage 4800;

	 object player {
			property constant_power_C_real;
```

```
                                file Nodeloaddata/N727CR.csv;
                                loop 1;
            };
            object player {
                                property constant_power_C_reac;
                                file Nodeloaddata/N727CI.csv;
                                loop 1;
            };
}

object meter {
name solarmeter727;
parent load727;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
            phases "ABCD";
            name sload727;
            parent solarmeter727;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
                        object player {
                                property constant_power_C_real;
                                file Nodeloaddata/SN727CR.csv;
                                loop 1;
            };
            object player {
                                property constant_power_C_reac;
                                file Nodeloaddata/SN727CI.csv;
                                loop 1;
            };
}


object meter {
           name v727;
           parent load727;
           phases "ABCD";
           voltage_A 2400.000000 -1385.640646j;
           voltage_B -2400.000000 -1385.640646j;
           voltage_C 0.000000+2771.281292j;
```

```
            nominal_voltage 4800;
}

object load:728 {
            phases "ABCD";
            name load728;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
//          constant_power_A 42000.000000+21000.000000j;
//          constant_power_B 42000.000000+21000.000000j;
//          constant_power_C 42000.000000+21000.000000j;
            nominal_voltage 4800;

object player {
                        property constant_power_A_real;
                        file Nodeloaddata/N728AR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/N728AI.csv;
                        loop 1;
            };

            object player {
                        property constant_power_B_real;
                        file Nodeloaddata/N728BR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_B_reac;
                        file Nodeloaddata/N728BI.csv;
                        loop 1;
            };
             object player {
                        property constant_power_C_real;
                        file Nodeloaddata/N728CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/N728CI.csv;
                        loop 1;
            };
}

object meter {
```

```
name solarmeter728;
parent load728;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload728;
	parent solarmeter728;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_A_real;
			file Nodeloaddata/SN728AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/SN728AI.csv;
			loop 1;
	};
	object player {
			property constant_power_B_real;
			file Nodeloaddata/SN728BR.csv;
			loop 1;
	};
	object player {
			property constant_power_B_reac;
			file Nodeloaddata/SN728BI.csv;
			loop 1;
	};
		object player {
			property constant_power_C_real;
			file Nodeloaddata/SN728CR.csv;
			loop 1;
	};
	object player {
			property constant_power_C_reac;
			file Nodeloaddata/SN728CI.csv;
			loop 1;
	};
}
```

```
object meter {
	name v728;
	parent load728;
	phases "ABCD";
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}

object load:729 {
	 phases "ABCD";
	 name load729;
	 voltage_A 2400.000000 -1385.640646j;
	 voltage_B -2400.000000 -1385.640646j;
	 voltage_C 0.000000+2771.281292j;
//	 constant_current_A 8.750000 -4.375000j;
	 nominal_voltage 4800;

object player {
				property constant_power_A_real;
				file Nodeloaddata/N729AR.csv;
				loop 1;
	 };
	 object player {
				property constant_power_A_reac;
				file Nodeloaddata/N729AI.csv;
				loop 1;
	 };
}

object meter {
name solarmeter729;
parent load729;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	 phases "ABCD";
	 name sload729;
	 parent solarmeter729;
	 voltage_A 2400.000000 -1385.640646j;
	 voltage_B -2400.000000 -1385.640646j;
```

```
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
            object player {
                        property constant_power_A_real;
                        file Nodeloaddata/SN729AR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/SN729AI.csv;
                        loop 1;
            };
}

object meter {
            name v729;
            parent load729;
            phases "ABCD";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object load:730 {
            phases "ABCD";
            name load730;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
//          constant_impedance_C 221.915014+104.430595j;
            nominal_voltage 4800;
             object player {
                        property constant_power_C_real;
                        file Nodeloaddata/N730CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/N730CI.csv;
                        loop 1;
            };
}

object meter {
name solarmeter730;
parent load730;
phases "ABCD";
```

```
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload730;
	parent solarmeter730;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_C_real;
			file Nodeloaddata/SN730CR.csv;
			loop 1;
	};
	object player {
			property constant_power_C_reac;
			file Nodeloaddata/SN730CI.csv;
			loop 1;
	};
}

object meter {
	name v730;
	parent load730;
	phases "ABCD";
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}

object load:731 {
	phases "ABCD";
	name load731;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
//	constant_impedance_B 221.915014+104.430595j;
	nominal_voltage 4800;

	object player {
			property constant_power_B_real;
			file Nodeloaddata/N731BR.csv;
```

```
                    loop 1;
        };
        object player {
                    property constant_power_B_reac;
                    file Nodeloaddata/N731BI.csv;
                    loop 1;
        };

}

object meter {
name solarmeter731;
parent load731;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
        phases "ABCD";
        name sload731;
        parent solarmeter731;
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
        nominal_voltage 4800;
        object player {
                    property constant_power_B_real;
                    file Nodeloaddata/SN731BR.csv;
                    loop 1;
        };
        object player {
                    property constant_power_B_reac;
                    file Nodeloaddata/SN731BI.csv;
                    loop 1;
        };
}

object meter {
        name v731;
        parent load731;
        phases "ABCD";
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
        nominal_voltage 4800;
```

```
}

object load:732 {
	phases "ABCD";
	name load732;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
//	constant_power_C 42000.000000+21000.000000j;
	nominal_voltage 4800;
	 object player {
			property constant_power_C_real;
			file Nodeloaddata/N732CR.csv;
			loop 1;
	};
	object player {
			property constant_power_C_reac;
			file Nodeloaddata/N732CI.csv;
			loop 1;
	};
}

object meter {
name solarmeter732;
parent load732;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload732;
	parent solarmeter732;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_C_real;
			file Nodeloaddata/SN732CR.csv;
			loop 1;
	};
	object player {
			property constant_power_C_reac;
			file Nodeloaddata/SN732CI.csv;
```

```
                loop 1;
        };
}

object meter {
        name v732;
        parent load732;
        phases "ABCD";
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
        nominal_voltage 4800;
}

object load:733 {
        phases "ABCD";
        name load733;
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
//      constant_current_A 17.708333 -8.333333j;
        nominal_voltage 4800;
        object player {
                property constant_power_A_real;
                file Nodeloaddata/N733AR.csv;
                loop 1;
        };
        object player {
                property constant_power_A_reac;
                file Nodeloaddata/N733AI.csv;
                loop 1;
        };
}

object meter {
name solarmeter733;
parent load733;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
        phases "ABCD";
        name sload733;
        parent solarmeter733;
```

```
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
		object player {
				property constant_power_A_real;
				file Nodeloaddata/SN733AR.csv;
				loop 1;
		};
		object player {
				property constant_power_A_reac;
				file Nodeloaddata/SN733AI.csv;
				loop 1;
		};
}

object meter {
		name v733;
		parent load733;
		phases "ABCD";
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
}

object load:734 {
		phases "ABCD";
		name load734;
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
//		constant_power_C 42000.000000+21000.000000j;
		nominal_voltage 4800;
		 object player {
				property constant_power_C_real;
				file Nodeloaddata/N734CR.csv;
				loop 1;
		};
		object player {
				property constant_power_C_reac;
				file Nodeloaddata/N734CI.csv;
				loop 1;
		};
}
object meter {
name solarmeter734;
parent load734;
```

```
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload734;
	parent solarmeter734;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_C_real;
			file Nodeloaddata/SN734CR.csv;
			loop 1;
	};
	object player {
			property constant_power_C_reac;
			file Nodeloaddata/SN734CI.csv;
			loop 1;
	};
}

object meter {
	name v734;
	parent load734;
	phases "ABCD";
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}

object load:735 {
	phases "ABCD";
	name load735;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
//	constant_power_C 85000.000000+40000.000000j;
	nominal_voltage 4800;
	 object player {
			property constant_power_C_real;
			file Nodeloaddata/N735CR.csv;
```

```
				loop 1;
		};
		object player {
				property constant_power_C_reac;
				file Nodeloaddata/N735CI.csv;
				loop 1;
		};
}

object meter {
name solarmeter735;
parent load735;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
		phases "ABCD";
		name sload735;
		parent solarmeter735;
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
		object player {
				property constant_power_C_real;
				file Nodeloaddata/SN735CR.csv;
				loop 1;
		};
		object player {
				property constant_power_C_reac;
				file Nodeloaddata/SN735CI.csv;
				loop 1;
		};
}

object meter {
		name v735;
		parent load735;
		phases "ABCD";
		voltage_A 2400.000000 -1385.640646j;
		voltage_B -2400.000000 -1385.640646j;
		voltage_C 0.000000+2771.281292j;
		nominal_voltage 4800;
}
```

```
object load:736 {
	phases "ABCD";
	name load736;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
//	constant_impedance_B 438.857143+219.428571j;
	nominal_voltage 4800;
	object player {
			property constant_power_B_real;
			file Nodeloaddata/N736BR.csv;
			loop 1;
	};
	object player {
			property constant_power_B_reac;
			file Nodeloaddata/N736BI.csv;
			loop 1;
	};
}

object meter {
name solarmeter736;
parent load736;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload736;
	parent solarmeter736;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_B_real;
			file Nodeloaddata/SN736BR.csv;
			loop 1;
	};
	object player {
			property constant_power_B_reac;
			file Nodeloaddata/SN736BI.csv;
			loop 1;
```

```
            };
}

object meter {
           name v736;
           parent load736;
           phases "ABCD";
           voltage_A 2400.000000 -1385.640646j;
           voltage_B -2400.000000 -1385.640646j;
           voltage_C 0.000000+2771.281292j;
           nominal_voltage 4800;
}

object load:737 {
            phases "ABCD";
            name load737;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
//          constant_current_A 29.166667 -14.583333j;
            nominal_voltage 4800;
           object player {
                             property constant_power_A_real;
                             file Nodeloaddata/N737AR.csv;
                             loop 1;
            };
            object player {
                             property constant_power_A_reac;
                             file Nodeloaddata/N737AI.csv;
                             loop 1;
            };
}

object meter {
name solarmeter737;
parent load737;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
            phases "ABCD";
            name sload737;
            parent solarmeter737;
            voltage_A 2400.000000 -1385.640646j;
```

```
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
            object player {
                        property constant_power_A_real;
                        file Nodeloaddata/SN737AR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/SN737AI.csv;
                        loop 1;
            };
}

object meter {
            name v737;
            parent load737;
            phases "ABCD";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object load:738 {
            phases "ABCD";
            name load738;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
//          constant_power_A 126000.000000+62000.000000j;
            nominal_voltage 4800;
            object player {
                        property constant_power_A_real;
                        file Nodeloaddata/N738AR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/N738AI.csv;
                        loop 1;
            };
}

object meter {
name solarmeter738;
parent load738;
```

```
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload738;
	parent solarmeter738;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_A_real;
			file Nodeloaddata/SN738AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/SN738AI.csv;
			loop 1;
	};
}

object meter {
	name v738;
	parent load738;
	phases "ABCD";
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}

object load:740 {
	phases "ABCD";
	name load740;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
//	constant_power_C 85000.000000+40000.000000j;
	nominal_voltage 4800;
	 object player {
			property constant_power_C_real;
			file Nodeloaddata/N740CR.csv;
```

```
                loop 1;
        };
        object player {
                property constant_power_C_reac;
                file Nodeloaddata/N740CI.csv;
                loop 1;
        };
}

object meter {
name solarmeter740;
parent load740;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
        phases "ABCD";
        name sload740;
        parent solarmeter740;
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
        nominal_voltage 4800;
        object player {
                property constant_power_C_real;
                file Nodeloaddata/SN740CR.csv;
                loop 1;
        };
        object player {
                property constant_power_C_reac;
                file Nodeloaddata/SN740CI.csv;
                loop 1;
        };
}

object meter {
        name v740;
        parent load740;
        phases "ABCD";
        voltage_A 2400.000000 -1385.640646j;
        voltage_B -2400.000000 -1385.640646j;
        voltage_C 0.000000+2771.281292j;
        nominal_voltage 4800;
}
```

```
object load:741 {
	phases "ABCD";
	name load741;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
//	constant_current_C -0.586139+9.765222j;
	nominal_voltage 4800;
	 object player {
			property constant_power_C_real;
			file Nodeloaddata/N741CR.csv;
			loop 1;
	};
	object player {
			property constant_power_C_reac;
			file Nodeloaddata/N741CI.csv;
			loop 1;
	};
}

object meter {
name solarmeter741;
parent load741;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}

object load {
	phases "ABCD";
	name sload741;
	parent solarmeter741;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_C_real;
			file Nodeloaddata/SN741CR.csv;
			loop 1;
	};
	object player {
			property constant_power_C_reac;
			file Nodeloaddata/SN741CI.csv;
			loop 1;
```

```
	};
}

object meter {
	name v741;
	parent load741;
	phases "ABCD";
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}

object load:742 {
	phases "ABCD";
	name load742;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
//	constant_impedance_A 2304.000000+1152.000000j;
//	constant_impedance_B 221.915014+104.430595j;
	nominal_voltage 4800;
	object player {
			property constant_power_A_real;
			file Nodeloaddata/N742AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/N742AI.csv;
			loop 1;
	};

	object player {
			property constant_power_B_real;
			file Nodeloaddata/N742BR.csv;
			loop 1;
	};
	object player {
			property constant_power_B_reac;
			file Nodeloaddata/N742BI.csv;
			loop 1;
	};
}

//object underground_line: {
//	phases "ABC";
//	name lineS742to742;
```

```
//	from load:742;
//	to solarmeter742;
//	length 0;
//	configuration line_configuration:7241;
//}

 object meter {
 name solarmeter742;
 phases "ABCD";
 parent load742;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
 }


object load {
	phases "ABCD";
	name sload742;
	parent solarmeter742;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_A_real;
			file Nodeloaddata/SN742AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/SN742AI.csv;
			loop 1;
	};
		object player {
			property constant_power_B_real;
			file Nodeloaddata/SN742BR.csv;
			loop 1;
	};
	object player {
			property constant_power_B_reac;
			file Nodeloaddata/SN742BI.csv;
			loop 1;
	};
}

object meter {
```

```
            name v742;
            parent load742;
            phases "ABCD";
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
            nominal_voltage 4800;
}

object load:744 {
            phases "ABCD";
            name load744;
            voltage_A 2400.000000 -1385.640646j;
            voltage_B -2400.000000 -1385.640646j;
            voltage_C 0.000000+2771.281292j;
//          constant_power_A 42000.000000+21000.000000j;
            nominal_voltage 4800;
            object player {
                        property constant_power_A_real;
                        file Nodeloaddata/N744AR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/N744AI.csv;
                        loop 1;
            };
}

//object underground_line: {
//          phases "A";
//          name lineS744to744;
//          from load:744;
//          to solarmeter744;
//          length 0;
//          configuration line_configuration:7241;
//}

object meter {
name solarmeter744;
parent load744;
phases "ABCD";
 voltage_A 2400.000000 -1385.640646j;
 voltage_B -2400.000000 -1385.640646j;
 voltage_C 0.000000+2771.281292j;
nominal_voltage 4800;
}
```

```
object load {
	phases "ABCD";
	name sload744;
	parent solarmeter744;
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
	object player {
			property constant_power_A_real;
			file Nodeloaddata/SN744AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/SN744AI.csv;
			loop 1;
	};
}

object meter {
	name v744;
	parent load744;
	phases "ABCD";
	voltage_A 2400.000000 -1385.640646j;
	voltage_B -2400.000000 -1385.640646j;
	voltage_C 0.000000+2771.281292j;
	nominal_voltage 4800;
}

object transformer_configuration:400 {
	connect_type 2;
	install_type PADMOUNT;
	power_rating 500;
	primary_voltage 4800;
	secondary_voltage 480;
	resistance 0.09;
	reactance 1.81;
}

object transformer:23 {
	phases "ABC";
	from node:709;
	to node:775;
	configuration transformer_configuration:400;
}
object node:775 {
	phases "ABC";
```

```
            name N775;
            voltage_A 240.000000 -138.564065j;
            voltage_B -240.000000 -138.564065j;
            voltage_C -0.000000+277.128129j;
            nominal_voltage 480;
}

object regulator_configuration:79978101 {
            connect_type 2;
            band_center 122.000;
            band_width 2.0;
            time_delay 30.0;
            raise_taps 16;
            lower_taps 16;
            current_transducer_ratio 350;
            power_transducer_ratio 40;
            compensator_r_setting_A 1.5;
            compensator_x_setting_A 3.0;
            compensator_r_setting_B 1.5;
            compensator_x_setting_B 3.0;
            CT_phase "ABC";
            PT_phase "ABC";
            regulation 0.10;
            Control MANUAL;
            Type A;
            tap_pos_A 7;
            tap_pos_B 4;
}

object regulator:799781 {
            phases "ABC";
            from p799;
//          from node:799;
            to node:781;
            configuration regulator_configuration:79978101;
}


object multi_recorder {
    property
meter799:measured_voltage_A.real,meter799:measured_voltage_A.imag,meter799:measured_voltage
_B.real,meter799:measured_voltage_B.imag,meter799:measured_voltage_C.real,meter799:measured_
voltage_C.imag,m701:measured_voltage_A.real,m701:measured_voltage_A.imag,m701:measured_volt
age_B.real,m701:measured_voltage_B.imag,m701:measured_voltage_C.real,m701:measured_voltage_
C.imag,v712:measured_voltage_A.real,v712:measured_voltage_A.imag,v712:measured_voltage_B.real,
v712:measured_voltage_B.imag,v712:measured_voltage_C.real,v712:measured_voltage_C.imag,v713:m
easured_voltage_A.real,v713:measured_voltage_A.imag,v713:measured_voltage_B.real,v713:measured
_voltage_B.imag,v713:measured_voltage_C.real,v713:measured_voltage_C.imag,v714:measured_voltag
```

```
e_A.real,v714:measured_voltage_A.imag,v714:measured_voltage_B.real,v714:measured_voltage_B.ima
g,v714:measured_voltage_C.real,v714:measured_voltage_C.imag;
		file "nodal sim outputs/baseoutput1.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}

object multi_recorder {
	property
v718:measured_voltage_A.real,v718:measured_voltage_A.imag,v718:measured_voltage_B.real,v718:m
easured_voltage_B.imag,v718:measured_voltage_C.real,v718:measured_voltage_C.imag,v720:measure
d_voltage_A.real,v720:measured_voltage_A.imag,v720:measured_voltage_B.real,v720:measured_volta
ge_B.imag,v720:measured_voltage_C.real,v720:measured_voltage_C.imag,v722:measured_voltage_A.r
eal,v722:measured_voltage_A.imag,v722:measured_voltage_B.real,v722:measured_voltage_B.imag,v72
2:measured_voltage_C.real,v722:measured_voltage_C.imag,v724:measured_voltage_A.real,v724:meas
ured_voltage_A.imag,v724:measured_voltage_B.real,v724:measured_voltage_B.imag,v724:measured_v
oltage_C.real,v724:measured_voltage_C.imag,v725:measured_voltage_A.real,v725:measured_voltage_
A.imag,v725:measured_voltage_B.real,v725:measured_voltage_B.imag,v725:measured_voltage_C.real,
v725:measured_voltage_C.imag;
		file "nodal sim outputs/baseoutput2.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}

object multi_recorder {
	property
v727:measured_voltage_A.real,v727:measured_voltage_A.imag,v727:measured_voltage_B.real,v727:m
easured_voltage_B.imag,v727:measured_voltage_C.real,v727:measured_voltage_C.imag,v728:measure
d_voltage_A.real,v728:measured_voltage_A.imag,v728:measured_voltage_B.real,v728:measured_volta
ge_B.imag,v728:measured_voltage_C.real,v728:measured_voltage_C.imag,v729:measured_voltage_A.r
eal,v729:measured_voltage_A.imag,v729:measured_voltage_B.real,v729:measured_voltage_B.imag,v72
9:measured_voltage_C.real,v729:measured_voltage_C.imag,v730:measured_voltage_A.real,v730:meas
ured_voltage_A.imag,v730:measured_voltage_B.real,v730:measured_voltage_B.imag,v730:measured_v
oltage_C.real,v730:measured_voltage_C.imag,v731:measured_voltage_A.real,v731:measured_voltage_
A.imag,v731:measured_voltage_B.real,v731:measured_voltage_B.imag,v731:measured_voltage_C.real,
v731:measured_voltage_C.imag;
		file "nodal sim outputs/baseoutput3.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}

object multi_recorder {
	property
v732:measured_voltage_A.real,v732:measured_voltage_A.imag,v732:measured_voltage_B.real,v732:m
easured_voltage_B.imag,v732:measured_voltage_C.real,v732:measured_voltage_C.imag,v733:measure
```

```
d_voltage_A.real,v733:measured_voltage_A.imag,v733:measured_voltage_B.real,v733:measured_volta
ge_B.imag,v733:measured_voltage_C.real,v733:measured_voltage_C.imag,v734:measured_voltage_A.r
eal,v734:measured_voltage_A.imag,v734:measured_voltage_B.real,v734:measured_voltage_B.imag,v73
4:measured_voltage_C.real,v734:measured_voltage_C.imag,v735:measured_voltage_A.real,v735:meas
ured_voltage_A.imag,v735:measured_voltage_B.real,v735:measured_voltage_B.imag,v735:measured_v
oltage_C.real,v735:measured_voltage_C.imag,v736:measured_voltage_A.real,v736:measured_voltage_
A.imag,v736:measured_voltage_B.real,v736:measured_voltage_B.imag,v736:measured_voltage_C.real,
v736:measured_voltage_C.imag;
		file "nodal sim outputs/baseoutput4.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}

object multi_recorder {
	property
v737:measured_voltage_A.real,v737:measured_voltage_A.imag,v737:measured_voltage_B.real,v737:m
easured_voltage_B.imag,v737:measured_voltage_C.real,v737:measured_voltage_C.imag,v738:measure
d_voltage_A.real,v738:measured_voltage_A.imag,v738:measured_voltage_B.real,v738:measured_volta
ge_B.imag,v738:measured_voltage_C.real,v738:measured_voltage_C.imag,v740:measured_voltage_A.r
eal,v740:measured_voltage_A.imag,v740:measured_voltage_B.real,v740:measured_voltage_B.imag,v74
0:measured_voltage_C.real,v740:measured_voltage_C.imag,v741:measured_voltage_A.real,v741:meas
ured_voltage_A.imag,v741:measured_voltage_B.real,v741:measured_voltage_B.imag,v741:measured_v
oltage_C.real,v741:measured_voltage_C.imag,v742:measured_voltage_A.real,v742:measured_voltage_
A.imag,v742:measured_voltage_B.real,v742:measured_voltage_B.imag,v742:measured_voltage_C.real,
v742:measured_voltage_C.imag;
		file "nodal sim outputs/baseoutput5.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}

object multi_recorder {
	property
v744:measured_voltage_A.real,v744:measured_voltage_A.imag,v744:measured_voltage_B.real,v744:m
easured_voltage_B.imag,v744:measured_voltage_C.real,v744:measured_voltage_C.imag,v800:measure
d_voltage_A.real,v800:measured_voltage_A.imag,v800:measured_voltage_B.real,v800:measured_volta
ge_B.imag,v800:measured_voltage_C.real,v800:measured_voltage_C.imag;
		file "nodal sim outputs/baseoutput6.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}

object multi_recorder {
	property
p781:measured_power_A.real,p781:measured_power_A.imag,p781:measured_power_B.real,p781:mea
sured_power_B.imag,p781:measured_power_C.real,p781:measured_power_C.imag,p799:measured_po
```

```
wer_A.real,p799:measured_power_A.imag,p799:measured_power_B.real,p799:measured_power_B.im
ag,p799:measured_power_C.real,p799:measured_power_C.imag,p801:measured_power_A.real,p801:m
easured_power_A.imag,p801:measured_power_B.real,p801:measured_power_B.imag,p801:measured_
power_C.real,p801:measured_power_C.imag;
		file "nodal sim outputs/baseoutput7.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}


object multi_recorder {
	property
solarmeter742:measured_power_A.real,solarmeter742:measured_power_A.imag,solarmeter742:measu
red_power_B.real,solarmeter742:measured_power_B.imag,solarmeter742:measured_power_C.real,sol
armeter742:measured_power_C.imag;
		file "nodal sim outputs/solaroutput1.csv";
		interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}
```

## Full code for Test 5 scaled Gridlab-D system

```
// 10 Node Feeder

#set profiler=1
#set pauseatexit=1
#set randomseed=1;
#set iteration_limit=100000;

clock {
	starttime '2008-05-01 0:00:00';
	stoptime '2008-05-7 23:59:00';
}

module tape;
module generators;
module powerflow;
module powerflow{
	solver_method FBS;
	default_maximum_voltage_error 1e-9;
	line_limits FALSE;
};

class player{	//Initializes "value" property to allow player object to be created without parent object
  double value;
}

module climate;	//added in this module from the gridlabd wiki that activates the tmy2 data set also included in this folder. Data is older but it is the chosen file for gridlabd
class climate {
	double elevation[m];
	double tzoffset[h];
}
object climate {
	name "Las_vegas NV";
	tmyfile "NV-Las_vegas.tmy2";
	tzoffset -8;
	elevation 664;
}


// Phase Conductor for kiwi
object overhead_line_conductor:7211 {
	 //outer_diameter 1.735000;// in inches
	 name overhead_line_conductor_100;
	 geometric_mean_radius 0.0595; //GMR in ft
	 diameter .347000;// in inches
	 resistance 0.105000;//given in ohm/mile
}
```

```
// overhead line spacing: spacing id 515
object line_spacing:515 {
	distance_AB 43.3;//line spacing is based upon general 500kV line spacing
	distance_BC 43.3;
	distance_AC 86.6;
}

//line configurations:
object line_configuration:600 {
	conductor_A overhead_line_conductor:7211;
	conductor_B overhead_line_conductor:7211;
	conductor_C overhead_line_conductor:7211;
	spacing line_spacing:515;
}

//create lineobjects:

object overhead_line { //:781701
	phases "ABC";
	name line781top781;
	from node:781;
	to p781;
	length 0;
	configuration line_configuration:600;
}

object overhead_line {
	phases "ABC";
	name line799top799;
	from load799;
	to p799;
	length 0;
	configuration line_configuration:600;
}

object overhead_line {
	phases "ABC";
	name line801top801;
	from node:801;
	to p801;
	length 0;
	configuration line_configuration:600;
}

object overhead_line {
	phases "ABC";
```

```
            name p801toload799;
            from p801;
            to load799;
            length 0;
            configuration line_configuration:600;
}

object meter {
           name p781;
   phases "ABC";
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
            nominal_voltage 250000;
}

object overhead_line{ //:781701
            phases "ABC";
            name linep781toCCS;
            from p781;
            to CCS;
            length 0;
            configuration line_configuration:600;
}

object overhead_line{ //:781701
            phases "ABC";
            name lineCCSto701;
            from CCS;
            to load:701;
            length 528000;// number of feet in 100 miles
            configuration line_configuration:600;
}

object overhead_line{ //:781701
            phases "ABC";
            name line701to702;
            from load:701;
            to load:702;
            length 528000;// number of feet in 100 miles
            configuration line_configuration:600;
}

object overhead_line{ //:781701
            phases "ABC";
            name line702to703;
            from load:702;
            to load:703;
```

```
	length 528000;// number of feet in 100 miles
	configuration line_configuration:600;
}

object overhead_line{ //:781701
	phases "ABC";
	name lineCCSto704;
	from CCS;
	to load:704;
	length 528000;// number of feet in 100 miles
	configuration line_configuration:600;
}

object overhead_line{ //:781701
	phases "ABC";
	name line704to705;
	from load:704;
	to load:705;
	length 528000;// number of feet in 100 miles
	configuration line_configuration:600;
}

object overhead_line{ //:781701
	phases "ABC";
	name line705to706;
	from load:705;
	to load:706;
	length 528000;// number of feet in 100 miles
	configuration line_configuration:600;
}

object overhead_line{ //:781701
	phases "ABC";
	name line706to707;
	from load:706;
	to load:707;
	length 528000;// number of feet in 100 miles
	configuration line_configuration:600;
}

object overhead_line{ //:781701
	phases "ABC";
	name lineCCSto708;
	from CCS;
	to load:708;
	length 528000;// number of feet in 100 miles
	configuration line_configuration:600;
}
```

```
object overhead_line{ //:781701
            phases "ABC";
            name line708to709;
            from load:708;
            to load:709;
            length 528000;// number of feet in 100 miles
            configuration line_configuration:600;
}

object overhead_line{ //:781701
            phases "ABC";
            name line709to710;
            from load:709;
            to load:710;
            length 528000;// number of feet in 100 miles
            configuration line_configuration:600;
}
//END of line

//create nodes and meters as pairs to nodes for troubleshooting ease

object node:801 {
           phases "ABC";
           name N801;
           bustype SWING;
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
            nominal_voltage 250000;
}

object meter {
           name meter801;
           parent N801;
   phases "ABC";
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
            nominal_voltage 250000;
}

object meter {
           name p801;
   phases "ABC";
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
```

```
            nominal_voltage 250000;
}

object meter {
           name meter799;
           parent load799;
   phases "ABCD";
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
            nominal_voltage 250000;
}

object meter {
           name p799;
   phases "ABCD";
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
            nominal_voltage 250000;
}


//Create extra node for other side of regulator
object node:781 {
            phases "ABC";
            name N781;
            //bustype SWING;
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
            nominal_voltage 250000;
}


object load:800 {
            phases "ABC"; // CCS built as 20% of 500MW so 100MW in total evenly divided among 3 phases
            name CCS;
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
//         constant_power_A 33333333+0j;
//         constant_power_B 33333333+0j;
//         constant_power_C 33333334+0j;
            nominal_voltage 250000;
            object player {
                          property constant_power_A_real;
                          file Nodeloaddata/CCSA.csv;
```

```
                loop 1;
        };
        object player {
                property constant_power_B_real;
                file Nodeloaddata/CCSB.csv;
                loop 1;
        };
         object player {
                property constant_power_C_real;
                file Nodeloaddata/CCSC.csv;
                loop 1;
        };
}

object meter {
        name v800;
        parent CCS;
        phases "ABCD";
         voltage_A 250000.000 -144337.567j;
         voltage_B -250000.000 -144337.567j;
         voltage_C 0+288675.135j;
         nominal_voltage 250000;
}

object load:799 {
         phases "ABCD"; // Power plant
         name load799;//CCSPlant;
         voltage_A 250000.000 -144337.567j;
         voltage_B -250000.000 -144337.567j;
         voltage_C 0+288675.135j;
         nominal_voltage 250000;
        //  object player {
        //          property constant_power_A_real;
        //          file Nodeloaddata/phaseA.csv;
        //          loop 1;
        // };
        // object player {
        //          property constant_power_A_reac;
        //          file Nodeloaddata/phaseAI.csv;
        //          loop 1;
        // };

        // object player {
        //          property constant_power_B_real;
        //          file Nodeloaddata/phaseB.csv;
        //          loop 1;
        // };
        // object player {
```

```
	//			property constant_power_B_reac;
	//			file Nodeloaddata/phaseBI.csv;
	//			loop 1;
	// };
	//  object player {
	//			property constant_power_C_real;
	//			file Nodeloaddata/phaseC.csv;
	//			loop 1;
	// };
	//			object player {
	//			property constant_power_C_reac;
	//			file Nodeloaddata/phaseCI.csv;
	//			loop 1;
	// };
}

//Create loads
object load:701 {
	phases "ABCD";
	name load701;
	voltage_A 250000.000 -144337.567j;
	voltage_B -250000.000 -144337.567j;
	voltage_C 0+288675.135j;
//	constant_power_A 140000.000000+70000.000000j;
//	constant_power_B 140000.000000+70000.000000j;
//	constant_power_C 350000.000000+175000.000000j;
	nominal_voltage 250000;

	 object player {
			property constant_power_A_real;
			file Nodeloaddata/N701AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/N701AI.csv;
			loop 1;
	};

	object player {
			property constant_power_B_real;
			file Nodeloaddata/N701BR.csv;
			loop 1;
	};
	object player {
			property constant_power_B_reac;
			file Nodeloaddata/N701BI.csv;
			loop 1;
```

```
	};
	 object player {
			property constant_power_C_real;
			file Nodeloaddata/N701CR.csv;
			loop 1;
	};
	object player {
			property constant_power_C_reac;
			file Nodeloaddata/N701CI.csv;
			loop 1;
	};
}

object meter {
	name v701;
	parent load701;
	phases "ABCD";
	voltage_A 250000.000 -144337.567j;
	 voltage_B -250000.000 -144337.567j;
	 voltage_C 0+288675.135j;
	nominal_voltage 250000;
}

object load:702 {
	 phases "ABCD";
	 name load702;
	voltage_A 250000.000 -144337.567j;
	 voltage_B -250000.000 -144337.567j;
	 voltage_C 0+288675.135j;
//	 constant_power_C 85000.000000+40000.000000j;
	nominal_voltage 250000;
	 object player {
			property constant_power_A_real;
			file Nodeloaddata/N702AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/N702AI.csv;
			loop 1;
	};

	object player {
			property constant_power_B_real;
			file Nodeloaddata/N702BR.csv;
			loop 1;
	};
	object player {
```

```
                        property constant_power_B_reac;
                        file Nodeloaddata/N702BI.csv;
                        loop 1;
            };
             object player {
                        property constant_power_C_real;
                        file Nodeloaddata/N702CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/N702CI.csv;
                        loop 1;
            };
}

object meter {
            name v702;
            parent load702;
            phases "ABCD";
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
            nominal_voltage 250000;
}

object load:703 {
            phases "ABCD";
            name load703;
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
//          constant_power_C 85000.000000+40000.000000j;// Stopped here 5/8
            nominal_voltage 250000;
             object player {
                        property constant_power_A_real;
                        file Nodeloaddata/N703AR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/N703AI.csv;
                        loop 1;
            };

            object player {
                        property constant_power_B_real;
                        file Nodeloaddata/N703BR.csv;
```

```
                loop 1;
        };
        object player {
                property constant_power_B_reac;
                file Nodeloaddata/N703BI.csv;
                loop 1;
        };
         object player {
                property constant_power_C_real;
                file Nodeloaddata/N703CR.csv;
                loop 1;
        };
        object player {
                property constant_power_C_reac;
                file Nodeloaddata/N703CI.csv;
                loop 1;
        };
}

object meter {
        name v703;
        parent load703;
        phases "ABCD";
         voltage_A 250000.000 -144337.567j;
         voltage_B -250000.000 -144337.567j;
         voltage_C 0+288675.135j;
         nominal_voltage 250000;
}

object load:704 {
        phases "ABCD";
        name load704;
        voltage_A 250000.000 -144337.567j;
        voltage_B -250000.000 -144337.567j;
        voltage_C 0+288675.135j;
//      constant_current_A 3.541667 -1.666667j;
//      constant_current_B -3.991720 -2.747194j;
        nominal_voltage 250000;
         object player {
                property constant_power_A_real;
                file Nodeloaddata/N704AR.csv;
                loop 1;
        };
        object player {
                property constant_power_A_reac;
                file Nodeloaddata/N704AI.csv;
                loop 1;
        };
```

```
		object player {
				property constant_power_B_real;
				file Nodeloaddata/N704BR.csv;
				loop 1;
		};
		object player {
				property constant_power_B_reac;
				file Nodeloaddata/N704BI.csv;
				loop 1;
		};
		 object player {
				property constant_power_C_real;
				file Nodeloaddata/N704CR.csv;
				loop 1;
		};
		object player {
				property constant_power_C_reac;
				file Nodeloaddata/N704CI.csv;
				loop 1;
		};
}

object meter {
		name v704;
		parent load704;
		phases "ABCD";
		 voltage_A 250000.000 -144337.567j;
		 voltage_B -250000.000 -144337.567j;
		 voltage_C 0+288675.135j;
		 nominal_voltage 250000;
}

object load:705 {
		phases "ABCD";
		name load705;
		voltage_A 250000.000 -144337.567j;
		voltage_B -250000.000 -144337.567j;
		voltage_C 0+288675.135j;
//		constant_power_C 85000.000000+40000.000000j;
		nominal_voltage 250000;
		 object player {
				property constant_power_A_real;
				file Nodeloaddata/N705AR.csv;
				loop 1;
		};
		object player {
				property constant_power_A_reac;
```

```
                file Nodeloaddata/N705AI.csv;
                loop 1;
        };

        object player {
                property constant_power_B_real;
                file Nodeloaddata/N705BR.csv;
                loop 1;
        };
        object player {
                property constant_power_B_reac;
                file Nodeloaddata/N705BI.csv;
                loop 1;
        };
         object player {
                property constant_power_C_real;
                file Nodeloaddata/N705CR.csv;
                loop 1;
        };
        object player {
                property constant_power_C_reac;
                file Nodeloaddata/N705CI.csv;
                loop 1;
        };
}

object meter {
        name v705;
        parent load705;
        phases "ABCD";
        voltage_A 250000.000 -144337.567j;
        voltage_B -250000.000 -144337.567j;
        voltage_C 0+288675.135j;
        nominal_voltage 250000;
}

object load:706 {
        phases "ABCD";
        name load706;
        voltage_A 250000.000 -144337.567j;
        voltage_B -250000.000 -144337.567j;
        voltage_C 0+288675.135j;
//      constant_current_B -27.212870 -17.967408j;
//      constant_current_C -0.383280+4.830528j;
        nominal_voltage 250000;
         object player {
                property constant_power_A_real;
                file Nodeloaddata/N706AR.csv;
```

```
				loop 1;
		};
		object player {
				property constant_power_A_reac;
				file Nodeloaddata/N706AI.csv;
				loop 1;
		};

		object player {
				property constant_power_B_real;
				file Nodeloaddata/N706BR.csv;
				loop 1;
		};
		object player {
				property constant_power_B_reac;
				file Nodeloaddata/N706BI.csv;
				loop 1;
		};
		 object player {
				property constant_power_C_real;
				file Nodeloaddata/N706CR.csv;
				loop 1;
		};
		object player {
				property constant_power_C_reac;
				file Nodeloaddata/N706CI.csv;
				loop 1;
		};
}

object meter {
		name v706;
		parent load706;
		phases "ABCD";
		 voltage_A 250000.000 -144337.567j;
		 voltage_B -250000.000 -144337.567j;
		 voltage_C 0+288675.135j;
		 nominal_voltage 250000;
}

object load:707 {
		phases "ABCD";
		name load707;
		voltage_A 250000.000 -144337.567j;
		voltage_B -250000.000 -144337.567j;
		voltage_C 0+288675.135j;
//		constant_impedance_B 438.857143+219.428571j;
		nominal_voltage 250000;
```

```
 object player {
                    property constant_power_A_real;
                    file Nodeloaddata/N707AR.csv;
                    loop 1;
        };
        object player {
                    property constant_power_A_reac;
                    file Nodeloaddata/N707AI.csv;
                    loop 1;
        };

        object player {
                    property constant_power_B_real;
                    file Nodeloaddata/N707BR.csv;
                    loop 1;
        };
        object player {
                    property constant_power_B_reac;
                    file Nodeloaddata/N707BI.csv;
                    loop 1;
        };
         object player {
                    property constant_power_C_real;
                    file Nodeloaddata/N707CR.csv;
                    loop 1;
        };
        object player {
                    property constant_power_C_reac;
                    file Nodeloaddata/N707CI.csv;
                    loop 1;
        };
}

object meter {
        name v707;
        parent load707;
        phases "ABCD";
         voltage_A 250000.000 -144337.567j;
         voltage_B -250000.000 -144337.567j;
         voltage_C 0+288675.135j;
         nominal_voltage 250000;
}

object load:708 {
         phases "ABCD";
         name load708;
         voltage_A 250000.000 -144337.567j;
         voltage_B -250000.000 -144337.567j;
```

```
	voltage_C 0+288675.135j;
//	constant_impedance_A 221.915014+104.430595j;
	nominal_voltage 250000;
	 object player {
			property constant_power_A_real;
			file Nodeloaddata/N708AR.csv;
			loop 1;
	};
	object player {
			property constant_power_A_reac;
			file Nodeloaddata/N708AI.csv;
			loop 1;
	};

	object player {
			property constant_power_B_real;
			file Nodeloaddata/N708BR.csv;
			loop 1;
	};
	object player {
			property constant_power_B_reac;
			file Nodeloaddata/N708BI.csv;
			loop 1;
	};
	 object player {
			property constant_power_C_real;
			file Nodeloaddata/N708CR.csv;
			loop 1;
	};
	object player {
			property constant_power_C_reac;
			file Nodeloaddata/N708CI.csv;
			loop 1;
	};
}

object meter {
	name v708;
	parent load708;
	phases "ABCD";
	 voltage_A 250000.000 -144337.567j;
	 voltage_B -250000.000 -144337.567j;
	 voltage_C 0+288675.135j;
	 nominal_voltage 250000;
}

object load:709 {
	phases "ABCD";
```

```
            name load709;
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
//          constant_power_B 42000.000000+21000.000000j;
            nominal_voltage 250000;
             object player {
                        property constant_power_A_real;
                        file Nodeloaddata/N709AR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/N709AI.csv;
                        loop 1;
            };

            object player {
                        property constant_power_B_real;
                        file Nodeloaddata/N709BR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_B_reac;
                        file Nodeloaddata/N709BI.csv;
                        loop 1;
            };
             object player {
                        property constant_power_C_real;
                        file Nodeloaddata/N709CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/N709CI.csv;
                        loop 1;
            };
}

object meter {
           name v709;
           parent load709;
           phases "ABCD";
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
            nominal_voltage 250000;
}
```

```
object load:710 {
            phases "ABCD";
            name load710;
            voltage_A 250000.000 -144337.567j;
            voltage_B -250000.000 -144337.567j;
            voltage_C 0+288675.135j;
//          constant_power_A 42000.000000+21000.000000j;
//          constant_power_B 42000.000000+21000.000000j;
//          constant_power_C 42000.000000+21000.000000j;
            nominal_voltage 250000;

object player {
                        property constant_power_A_real;
                        file Nodeloaddata/N710AR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_A_reac;
                        file Nodeloaddata/N710AI.csv;
                        loop 1;
            };

            object player {
                        property constant_power_B_real;
                        file Nodeloaddata/N710BR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_B_reac;
                        file Nodeloaddata/N710BI.csv;
                        loop 1;
            };
             object player {
                        property constant_power_C_real;
                        file Nodeloaddata/N710CR.csv;
                        loop 1;
            };
            object player {
                        property constant_power_C_reac;
                        file Nodeloaddata/N710CI.csv;
                        loop 1;
            };
}

object meter {
           name v710;
           parent load710;
```

```
            phases "ABCD";
             voltage_A 250000.000 -144337.567j;
             voltage_B -250000.000 -144337.567j;
             voltage_C 0+288675.135j;
             nominal_voltage 250000;
}

object regulator_configuration:79978101 {
            connect_type 2;
            band_center 122.000;
            band_width 2.0;
            time_delay 30.0;
            raise_taps 16;
            lower_taps 16;
            current_transducer_ratio 350;
            power_transducer_ratio 40;
            compensator_r_setting_A 1.5;
            compensator_x_setting_A 3.0;
            compensator_r_setting_B 1.5;
            compensator_x_setting_B 3.0;
            CT_phase "ABC";
            PT_phase "ABC";
            regulation 0.10;
            Control MANUAL;
//          Control OUTPUT_VOLTAGE;
            Type A;
            tap_pos_A 7;
            tap_pos_B 4;
}

object regulator:799781 {
             phases "ABC";
             from p799;
//           from node:799;
             to node:781;
             configuration regulator_configuration:79978101;
}


object multi_recorder {
    property
meter799:measured_voltage_A.real,meter799:measured_voltage_A.imag,meter799:measured_voltage
_B.real,meter799:measured_voltage_B.imag,meter799:measured_voltage_C.real,meter799:measured_
voltage_C.imag,v701:measured_voltage_A.real,v701:measured_voltage_A.imag,v701:measured_voltag
e_B.real,v701:measured_voltage_B.imag,v701:measured_voltage_C.real,v701:measured_voltage_C.ima
g,v702:measured_voltage_A.real,v702:measured_voltage_A.imag,v702:measured_voltage_B.real,v702:
measured_voltage_B.imag,v702:measured_voltage_C.real,v702:measured_voltage_C.imag,v703:measur
ed_voltage_A.real,v703:measured_voltage_A.imag,v703:measured_voltage_B.real,v703:measured_volt
```

```
age_B.imag,v703:measured_voltage_C.real,v703:measured_voltage_C.imag,v704:measured_voltage_A.real,v704:measured_voltage_A.imag,v704:measured_voltage_B.real,v704:measured_voltage_B.imag,v704:measured_voltage_C.real,v704:measured_voltage_C.imag;
		file "nodal sim outputs/baseoutput1.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}

object multi_recorder {
	property
v705:measured_voltage_A.real,v705:measured_voltage_A.imag,v705:measured_voltage_B.real,v705:measured_voltage_B.imag,v705:measured_voltage_C.real,v705:measured_voltage_C.imag,v706:measured_voltage_A.real,v706:measured_voltage_A.imag,v706:measured_voltage_B.real,v706:measured_voltage_B.imag,v706:measured_voltage_C.real,v706:measured_voltage_C.imag,v707:measured_voltage_A.real,v707:measured_voltage_A.imag,v707:measured_voltage_B.real,v707:measured_voltage_B.imag,v707:measured_voltage_C.real,v707:measured_voltage_C.imag,v708:measured_voltage_A.real,v708:measured_voltage_A.imag,v708:measured_voltage_B.real,v708:measured_voltage_B.imag,v708:measured_voltage_C.real,v708:measured_voltage_C.imag,v709:measured_voltage_A.real,v709:measured_voltage_A.imag,v709:measured_voltage_B.real,v709:measured_voltage_B.imag,v709:measured_voltage_C.real,v709:measured_voltage_C.imag;
		file "nodal sim outputs/baseoutput2.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}

object multi_recorder {
	property
v710:measured_voltage_A.real,v710:measured_voltage_A.imag,v710:measured_voltage_B.real,v710:measured_voltage_B.imag,v710:measured_voltage_C.real,v710:measured_voltage_C.imag,v800:measured_voltage_A.real,v800:measured_voltage_A.imag,v800:measured_voltage_B.real,v800:measured_voltage_B.imag,v800:measured_voltage_C.real,v800:measured_voltage_C.imag;
		file "nodal sim outputs/baseoutput3.csv";
	interval 60;	//defines sampling interval in seconds: 240sec = 4 minutes
	limit 1000000;		//defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
		//mode polar;
}

object multi_recorder {
	property
p781:measured_power_A.real,p781:measured_power_A.imag,p781:measured_power_B.real,p781:measured_power_B.imag,p781:measured_power_C.real,p781:measured_power_C.imag,p799:measured_power_A.real,p799:measured_power_A.imag,p799:measured_power_B.real,p799:measured_power_B.imag,p799:measured_power_C.real,p799:measured_power_C.imag,p801:measured_power_A.real,p801:measured_power_A.imag,p801:measured_power_B.real,p801:measured_power_B.imag,p801:measured_power_C.real,p801:measured_power_C.imag;
		file "nodal sim outputs/baseoutput4.csv";
```

```
interval 60;    //defines sampling interval in seconds: 240sec = 4 minutes
limit 1000000;            //defines number of samples, in this case 360*4 minutes = 1440 minutes = 1 day
        //mode polar;
}
```

## Unedited Measured Load Curve Data

| date | MW | MVAR |
|---|---|---|
| 5/1/2008 0:00 | 1.642246604 | 0.109890111 |
| 5/1/2008 1:00 | 1.398046374 | 0.109890111 |
| 5/1/2008 2:00 | 1.398046374 | 0.021978023 |
| 5/1/2008 3:00 | 1.275946259 | 0.021978023 |
| 5/1/2008 4:00 | 1.275946259 | 0.021978023 |
| 5/1/2008 5:00 | 1.275946259 | 0.021978023 |
| 5/1/2008 6:00 | 1.312576294 | 0.021978023 |
| 5/1/2008 7:00 | 1.44688642 | 0.021978023 |
| 5/1/2008 8:00 | 1.44688642 | 0.074725278 |
| 5/1/2008 9:00 | 1.44688642 | 0.074725278 |
| 5/1/2008 10:00 | 1.593406558 | 0.074725278 |
| 5/1/2008 11:00 | 1.593406558 | 0.162637368 |
| 5/1/2008 12:00 | 1.593406558 | 0.145297259 |
| 5/1/2008 13:00 | 1.618409276 | 0.157727733 |
| 5/1/2008 14:00 | 1.574866056 | 0.13811098 |
| 5/1/2008 15:00 | 1.560098886 | 0.129421711 |
| 5/1/2008 16:00 | 1.550287247 | 0.130182445 |
| 5/1/2008 17:00 | 1.666666627 | 0.133834869 |
| 5/1/2008 18:00 | 1.666666627 | 0.137487307 |
| 5/1/2008 19:00 | 1.788766742 | 0.141139746 |
| 5/1/2008 20:00 | 2.191697121 | 0.144792184 |
| 5/1/2008 21:00 | 2.326007366 | 0.151426196 |
| 5/1/2008 22:00 | 2.057387114 | 0.15384616 |
| 5/1/2008 23:00 | 1.778046131 | 0.15384616 |
| 5/2/2008 0:00 | 1.617826581 | 0.15384616 |
| 5/2/2008 1:00 | 1.483516455 | 0.128511757 |
| 5/2/2008 2:00 | 1.324659944 | 0.097072996 |
| 5/2/2008 3:00 | 1.31004107 | 0.039560441 |
| 5/2/2008 4:00 | 1.3043046 | 0.039560441 |
| 5/2/2008 5:00 | 1.29856801 | 0.039560441 |
| 5/2/2008 6:00 | 1.29283154 | 0.039560441 |
| 5/2/2008 7:00 | 1.422466397 | 0.044198789 |
| 5/2/2008 8:00 | 1.422466397 | 0.052071512 |
| 5/2/2008 9:00 | 1.463357449 | 0.063886292 |
| 5/2/2008 10:00 | 1.55608952 | 0.082837403 |
| 5/2/2008 11:00 | 1.606309175 | 0.180219784 |
| 5/2/2008 12:00 | 1.613030314 | 0.180219784 |
| 5/2/2008 13:00 | 1.61947751 | 0.180219784 |
| 5/2/2008 14:00 | 1.625242233 | 0.167008653 |
| 5/2/2008 15:00 | 1.631006956 | 0.174274817 |
| 5/2/2008 16:00 | 1.636771679 | 0.154658079 |
| 5/2/2008 17:00 | 1.764346719 | 0.206593409 |
| 5/2/2008 18:00 | 1.764346719 | 0.206593409 |
| 5/2/2008 19:00 | 1.764346719 | 0.232967034 |
| 5/2/2008 20:00 | 2.191697121 | 0.232967034 |
| 5/2/2008 21:00 | 2.191697121 | 0.145054951 |
| 5/2/2008 22:00 | 2.069597006 | 0.15384616 |
| 5/2/2008 23:00 | 1.813186765 | 0.15384616 |
| 5/3/2008 0:00 | 1.678876638 | 0.15384616 |
| 5/3/2008 1:00 | 1.434676409 | 0.065934069 |
| 5/3/2008 2:00 | 1.434676409 | 0.065934069 |
| 5/3/2008 3:00 | 1.312576294 | 0.065934069 |
| 5/3/2008 4:00 | 1.312576294 | 0.065934069 |
| 5/3/2008 5:00 | 1.312576294 | 0.065934069 |
| 5/3/2008 6:00 | 1.324786305 | 0.074725278 |
| 5/3/2008 7:00 | 1.324786305 | 0.074725278 |
| 5/3/2008 8:00 | 1.44688642 | 0.072982043 |
| 5/3/2008 9:00 | 1.568986535 | 0.049824715 |
| 5/3/2008 10:00 | 1.728500009 | 0.164249539 |
| 5/3/2008 11:00 | 1.734752655 | 0.178722873 |
| 5/3/2008 12:00 | 1.862026811 | 0.27692309 |
| 5/3/2008 13:00 | 1.849816799 | 0.294109136 |
| 5/3/2008 14:00 | 1.849816799 | 0.290277302 |
| 5/3/2008 15:00 | 1.971916914 | 0.312087923 |
| 5/3/2008 16:00 | 1.971916914 | 0.312087923 |
| 5/3/2008 17:00 | 1.971916914 | 0.312087923 |
| 5/3/2008 18:00 | 2.059022903 | 0.268131882 |
| 5/3/2008 19:00 | 2.045176983 | 0.32967034 |
| 5/3/2008 20:00 | 2.338217258 | 0.241758242 |
| 5/3/2008 21:00 | 2.362637281 | 0.285714298 |
| 5/3/2008 22:00 | 2.203907251 | 0.285714298 |
| 5/3/2008 23:00 | 1.947496891 | 0.251958996 |
| 5/4/2008 0:00 | 1.703296661 | 0.118681319 |
| 5/4/2008 1:00 | 1.581196547 | 0.118681319 |
| 5/4/2008 2:00 | 1.434676409 | 0.118681319 |
| 5/4/2008 3:00 | 1.434676409 | 0.092307694 |
| 5/4/2008 4:00 | 1.300366282 | 0.092307694 |
| 5/4/2008 5:00 | 1.300366282 | 0.092307694 |
| 5/4/2008 6:00 | 1.300366282 | 0.004395605 |
| 5/4/2008 7:00 | 1.300366282 | 0.004395605 |
| 5/4/2008 8:00 | 1.434676409 | 0.092307694 |
| 5/4/2008 9:00 | 1.69108665 | 0.15384616 |
| 5/4/2008 10:00 | 1.837606788 | 0.294505507 |
| 5/4/2008 11:00 | 1.959706903 | 0.289064229 |
| 5/4/2008 12:00 | 2.081807137 | 0.373626381 |
| 5/4/2008 13:00 | 2.203907251 | 0.461538464 |
| 5/4/2008 14:00 | 2.313797235 | 0.54155767 |
| 5/4/2008 15:00 | 2.326007366 | 0.549450576 |
| 5/4/2008 16:00 | 2.313797235 | 0.540659368 |
| 5/4/2008 17:00 | 2.416710138 | 0.540659368 |
| 5/4/2008 18:00 | 2.289377213 | 0.540659368 |
| 5/4/2008 19:00 | 2.289377213 | 0.452747256 |
| 5/4/2008 20:00 | 2.655677557 | 0.364835173 |
| 5/4/2008 21:00 | 2.533577442 | 0.364835173 |
| 5/4/2008 22:00 | 2.411477327 | 0.364835173 |
| 5/4/2008 23:00 | 2.118437052 | 0.268131882 |
| 5/5/2008 0:00 | 1.727716684 | 0.180219784 |
| 5/5/2008 1:00 | 1.60561657 | 0.180219784 |
| 5/5/2008 2:00 | 1.483516455 | 0.092307694 |
| 5/5/2008 3:00 | 1.36141634 | 0.092307694 |
| 5/5/2008 4:00 | 1.36141634 | 0.092307694 |
| 5/5/2008 5:00 | 1.36141634 | 0.092307694 |
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| 5/18/2008 10:00 | 3.461538553 | 1.024175882 |
| 5/18/2008 11:00 | 3.92551899 | 1.323076963 |
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| 9/26/2008 20:00 | 4.843711853 | 1.639560461 |
| 9/26/2008 21:00 | 4.536019325 | 1.54285717 |
| 9/26/2008 22:00 | 4.133089066 | 1.331868172 |
| 9/26/2008 23:00 | 3.59584856 | 1.243956089 |
| 9/27/2008 0:00 | 3.168498278 | 0.98901099 |
| 9/27/2008 1:00 | 2.826617718 | 0.865934074 |
| 9/27/2008 2:00 | 2.603890419 | 0.76973027 |
| 9/27/2008 3:00 | 2.570207596 | 0.720601737 |
| 9/27/2008 4:00 | 2.289377213 | 0.610989034 |
| 9/27/2008 5:00 | 2.252747297 | 0.523076952 |
| 9/27/2008 6:00 | 2.236052036 | 0.53186816 |
| 9/27/2008 7:00 | 2.366125822 | 0.613919437 |
| 9/27/2008 8:00 | 2.920618057 | 0.804395616 |
| 9/27/2008 9:00 | 3.057455063 | 0.939780235 |
| 9/27/2008 10:00 | 3.845748663 | 1.331868172 |
| 9/27/2008 11:00 | 4.522627831 | 1.610263586 |
| 9/27/2008 12:00 | 5.005052567 | 1.930969 |
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| 9/27/2008 16:00 | 5.805827618 | 2.316483498 |
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| 9/29/2008 4:00 | 2.041072607 | 0.47912088 |
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| 9/29/2008 13:00 | 4.304029465 | 1.604395628 |
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| 9/29/2008 15:00 | 4.997808456 | 1.978191137 |
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| 9/29/2008 23:00 | 3.313705921 | 0.970269501 |
| 9/30/2008 0:00 | 2.865680218 | 0.839560449 |

## Contact Email

For questions on help and implementation you can contact me at Michael.k.misch@gmail.com