Sustainable Global Real Assets
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Power Dynamics: A Comparative Study of the US and Swedish Electrical Grids

Abstract:
Climate change and current energy demand has necessitated a shift towards renewable electrification, making the generation, transmission, regulation, and consumption of electricity more critical than ever before.

- **Electricity Generation:** Sweden generates 70% of its electricity from renewable sources, with capabilities in solar, wind, hydroelectric, and nuclear generation techniques. While the US utilizes similar techniques, only 21% of its power comes from renewable sources.
- **Electricity Transmission:** Transmission, or the bulk movement of electricity from the site of generation to a localized substation, varies between the US and Sweden due to geographical differences and the centralization of regulating authorities.
- **Interconnection Process:** Both Sweden and the United States struggle with years-long interconnection queues, hampering their ability to ramp up electricity supply. Grid Enhancing Technologies offer a near-term solution to lessen their queues without revamping their interconnection processes.
- **Political Directives and Regulations:** Sweden has a unified goal to utilize renewable energy with support from citizens, leaders, and corporations. The US faces challenges due to governmental fragmentation, constituent support, and incumbent corporations.
- **Consumption of Power:** Per capita use of energy differs drastically between the countries, with the US using 18,000kWh more annually than Sweden. This consumption difference is based on regional climates, personal preferences, residential and commercial space utilization, and consumer demands.
- **Future and Historical Planning:** Both the US and Sweden have set significant targets to utilize renewable energy in the coming years and build a resilient power system. Sweden has been setting and meeting targets for more than 30 years, where the US has a shorter history of demanding the use of renewable energy.

Introduction:

Now more than ever, a robust and resilient electrical grid is a necessity for countries as climate change forces a shift away from oil and gas in favor of electrification. Nations across the world all face this identical challenge, though each country's unique circumstances allow it to approach the problem differently. Studying each country's approach to its electrical grid allows us to take best practices from one region and apply them elsewhere, leveraging the most innovative ideas and processes worldwide in the pursuit of carbon neutrality. This paper explores the past, present, and future of the United States' and Sweden's electrical grids and what lessons each country can learn from the other.

Electricity Generation

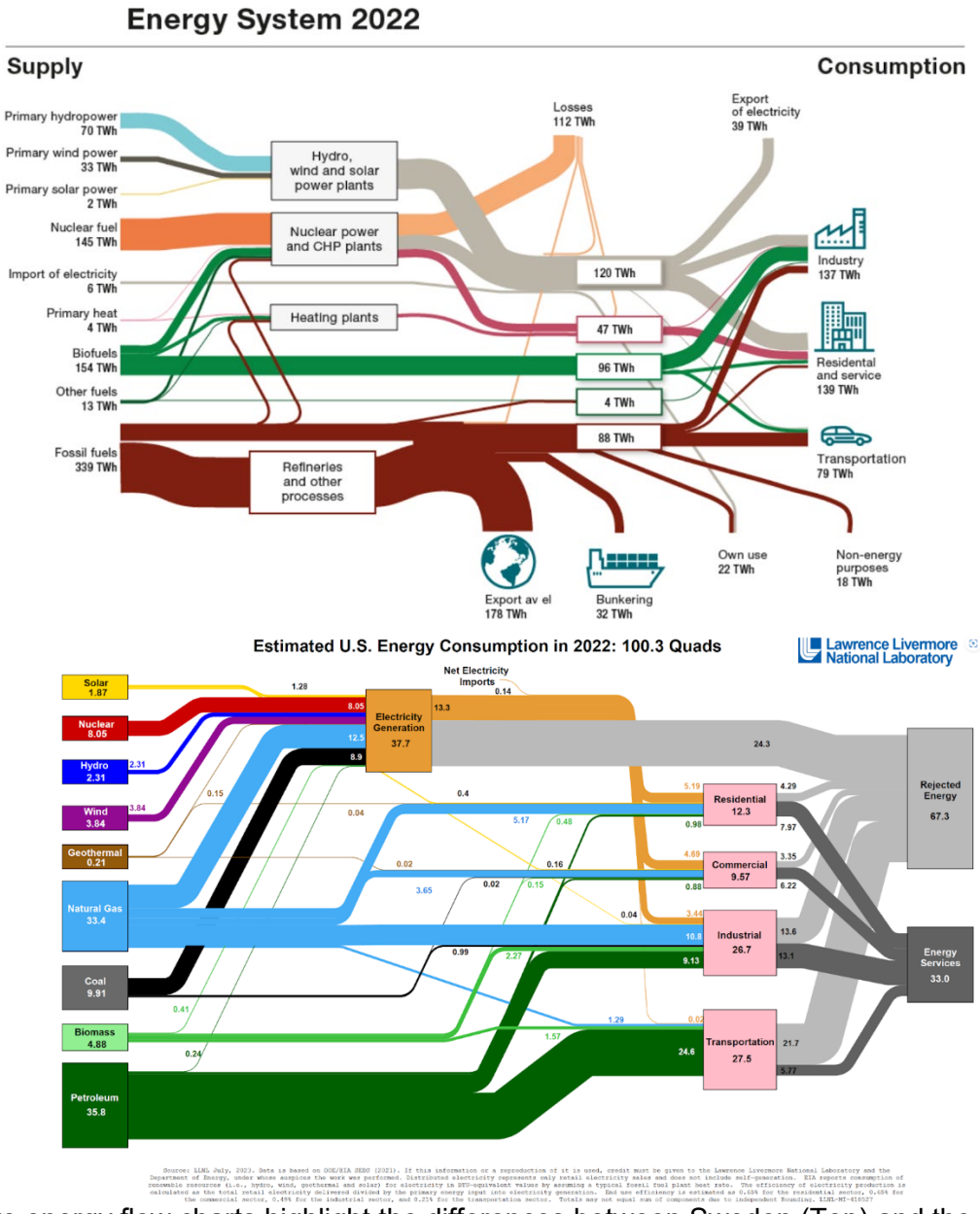
For much of its history, the United States has been on the forefront of innovation in how it generates electricity. Thomas Edison opened the first power station in the US in 1882, kicking off a centuries-long race to generate increasingly more energy that has lasted until today. Coal was used to run the first power stations, but hydropower joined the mix soon after and quickly rivaled coal in supplying electricity around the country. In the 1950s, the first nuclear power stations came online, and the United States shifted to increasing its nuclear fleet in place of hydropower for the next few decades. By the 1980s, coal and natural gas dominated the market with over 60% of market share. This was the status quo until the 2010s, at which point renewables such as wind and solar became popular and economically feasible. Most recently,

coal's share of the market has decreased considerably to ~20%, with natural gas, solar, and wind capturing the difference.[1]

There is significant disagreement on what the future of electricity generation in the United States looks like, but what is absolutely clear is that that future will be driven by clean sources due to regulatory and economic reasons. From a regulatory perspective, the federal government has issued a net-zero greenhouse gas emissions by 2050 goal, which will require a massive amount of clean energy to be built. From a purely economic point of view, demand for electricity in the US is set to rise dramatically over the coming decades, and the cheapest form of new energy to build right now is renewable energy. These two tailwinds have driven enormous investment into wind and solar development across the country, as well as into more innovative technologies such as geothermal, batteries, and small-scale nuclear reactors. As a point of reference, in 2023 fossil fuel electricity generation only grew 0.8% while solar and wind generation grew 23% and 10%, respectively.[2] While these growth rates are impressive, consensus within the energy community is that solar and wind will have to grow even faster, as they will ultimately need to be the largest suppliers of energy for the US by 2050 and therefore represent the majority of grid expansion going forward.

Given the natural resources unique to Sweden, the nation was able to approach electricity generation from a very different perspective compared to the United States. As previously stated, hydroelectric power quickly followed coal powered plants in the late 19th century, so Sweden's snowy mountains and plentiful rivers provided the perfect opportunity to generate substantial energy for the country. For the first half of the 20th century, Sweden relied almost entirely on hydroelectric power, with some additional help from coal plants. Much like the United States, Sweden experienced a boom of nuclear production in the 1970s and by 1990 was running on roughly half hydroelectric and half nuclear power. Since then, the only noteworthy update to Sweden's electricity mix has been the popularization of wind and biomass throughout the 2010s, which now jointly generate roughly 25% of Sweden's electricity.[3] Going forward, Sweden will likely address its need for additional energy by increasing its nuclear and wind fleet.

Despite the United States and Sweden concluding to wholly different energy mixes, both countries developed their grid by focusing on their strengths and the natural resources around them. Sweden, to its advantage, has natural resources that lend themselves to renewable energy, whereas the United States has far more oil and gas resources. The largest divergence between the two countries–the effects of which are still seen today–is the difference in each country's appetite for nuclear energy. Both countries ramped up their nuclear fleet around the same time, but Sweden's commitment to nuclear has lasted until today and is projected to grow in the future. This is in stark contrast to the United States where nuclear fell out of favor in the 1990s and has still not fully recovered. As a result of building very few new nuclear plants for the past three decades, the United States has lost much of its ability to do so effectively, limiting the potential to ramp production back up to levels required to meet its 2050 carbon neutral goals.



The above energy flow charts highlight the differences between Sweden (Top) and the US (Bottom) sources and uses of energy.[29, 30] Most notably, Sweden has a robust export network for their unused power, where in contrast, the US "rejects" the energy. Roughly 67% of power generated in the US is rejected, demonstrating significant underutilization. Sweden's lack of rejected energy is also attributed to their leading transmission & distribution methods, as discussed further below.

Transmission & Distribution

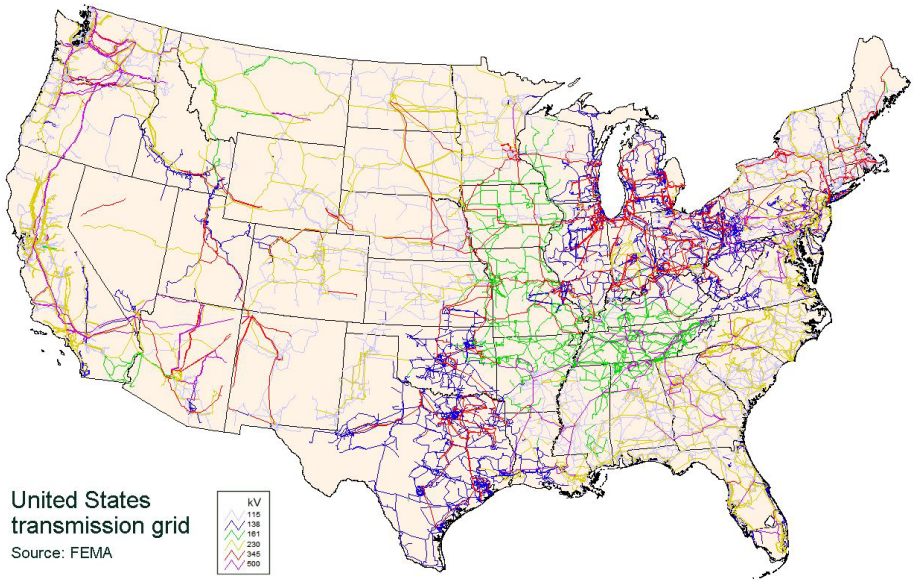
As electricity needs across the globe rise rapidly–a result of electrification and artificial intelligence–countries are beginning to realize that their ability to move sufficient energy from power plants to end users is an even larger problem than generating additional electricity. Most developed countries have a similar transmission & distribution ("T&D") system: energy is generated at a source like a solar farm, then transmitted using high-voltage lines over long

distances to substations, at which point the voltage is lowered and then distributed to users such as homes and businesses. This system has worked for the past century but faces serious risks for the coming century.

The United States has recently come to terms with the fact that building massive amounts of new solar and wind farms will be pointless if the infrastructure to transport that new energy is not in place first. Unfortunately for the US, this infrastructure is far behind where it needs to be, and there are very few affordable or quick fixes for this problem. The first roadblock the US faces is that the power lines will almost always span across different cities, counties, and even states, and authority to build new lines must be granted by all parties involved. As each governing authority has its own energy goals and budgetary constraints, gaining universal approval is almost impossible in today's polarized political environment. Negotiations can take years, even a full decade, all before a single hard cost is incurred. From a budgetary standpoint, these new lines are also prohibitively expensive, costing between $1M-$9M per mile, not including the land or substation costs.[4] One estimate from the Department of Energy projects that by 2035 the US will need 47,000 new T&D miles, which implies nearly $235B of capital costs.[5] All in, a new set of T&D lines in the US can take 10-15 years to build and cost billions of dollars, much of which is passed on to consumers to pay for. The US will face significant challenges in meeting its future clean energy goals as it stands, spurring recent conversations at the federal level on how to alleviate this issue.

Sweden's process for developing new T&D lines is more streamlined than the United States', though it still takes into account and appeases all parties involved. The biggest difference is that Sweden has a centralized transmission authority, Svenska kraftnät, that is responsible for updating and maintaining the country's T&D, whereas the United States delegates this responsibility to dozens of organizations across the country. By centralizing this power within one organization, Sweden is better able to plan holistically and with scale, driving down costs and time required. When Svenska kraftnät determines an area needs additional line capacity, it consults with any locality that line will run through, writes and submits a proposal to the Swedish government, pays any person or business affected by the new lines, and then begins construction. Compared to the United States' 10–15-year timeline for new T&D, Sweden is able to average 5-10 years, allowing for faster responses to increases in electricity demand.[6]

The United States' T&D expansion worked well for decades when electricity demand rose slowly and steadily each year, but the recent rapid rise in demand and the urgency of the problem threatens the continued success of the process. Sweden's more centralized approach, which mirrors much of its political economy, is better suited for the problems at hand. In order to meet its 2050 carbon goals, the United States will need to take a page from Sweden's book and empower agencies, such as the Federal Energy Regulatory Commission (FERC), to expedite procedures that slow down the current processes. The electrical grid is a complicated and sprawling network with many regional nuances, so the more red tape the US can eliminate, the better chance it stands at facing the many problems coming down the pike.



The Swedish grid consists of approximately 10,870 miles of cables, compared to 600,000 miles in the US.[27, 28]

Interconnection Process

Part and parcel of the T&D issues the United States faces is the process through which new energy supply is connected into the larger grid. This process, referred to as interconnection, was as underprepared for the surge in energy demand in the US as T&D expansion. Each

region's interconnection procedures vary slightly, but in general, when a developer wants to build new generation, they must submit a detailed application to the regional grid operator who then undertakes a multi-step study that can take a few years to complete. Throughout this study, the grid operator continuously makes the developer confirm they are still interested in moving forward because at the end of the study, the developer must pay for all updates to the grid that would result from their additional energy supply. Often, when developers reach the end of the study and are presented with the exorbitant cost to update the grid, they decide to terminate the project, meaning the years of work done by both parties goes to waste. To illustrate how serious this problem has become, in December 2023 the number of gigawatts waiting for approval to connect to the grid was twice that of the entire current US electrical grid.[7] Furthermore, projects built in the early 2000s waited less than two years on average to gain interconnection approval, but in 2023 that time has more than doubled to five years.[8]

Sweden's interconnection process is fairly similar to the United States' and does not seem to benefit from having one centralized grid operator when it comes to interconnection queues. Logistically, a developer first submits a connection application to Svenska kraftnät, who then provides preliminary findings within a month. If the developer decides to move forward, Svenska kraftnät undertakes a twelve-month investigation to determine feasibility and cost to the developer. Upon completion of the investigation, the developer must sign a letter of intent, which kicks off a technical feasibility study. Finally, when the technical feasibility study is complete, the developer signs a connection agreement with Svenska kraftnät, who then needs at least three years to undertake the necessary work to upgrade the grid. It is difficult to find estimates on how long this entire process can take from start to finish, but if the investigation and grid upgrades together take four years on average, one can assume the addition of the technical feasibility study will bring total interconnection time in line with, if not longer, than the United States' five-year average.

Clearly, both the United States and Sweden could stand to rework their interconnection queue process in order to bolster their electrical grids faster, though this is easier said than done. Some scholars have proposed that grid operators should group applications across multiple developers together, but this presents problems of its own by relying on the cooperation of all parties involved. To the extent that one exists, a potential silver bullet to solve both countries' interconnection problem is what is known as Grid Enhancing Technologies ("GETs"). GETs include a group of technologies that allow grids to increase their carrying capacity without having to build entirely new T&D lines. For example, countries can replace the wires currently used throughout T&D systems with recently invented ones that can hold more electricity, requiring only the labor and materials costs of these new wires to expand capacity significantly. Similarly, software that uses artificial intelligence to actively manage grid capacity to avoid overloads has come a long way recently and could further alleviate interconnection queues.

Political Directives and Regulations

Sweden has been at the forefront of clean energy production for over 30 years, with credit given to the Swedish Energy Agency (Energimyndigheten) for the policy directives. The agency has created and implemented transformative energy policy with the goal of securing a sustainable energy system for the future. The 1997 passage of the Electricity Act, and subsequent amendments, have set the stage for a progressive and significant increase in renewable energy generation.

Outside of governmental mandates, Sweden citizens and corporations face social pressure to generate in a renewable fashion. The environment has long been of interest to citizens, and

interestingly it is Swedish law that people can pass over private land in efforts to enjoy and spend time in the countryside. The Right to Roam, aka “everyman’s right”, is in the Swedish Constitution, and is utilized by people throughout the country as well as part of the Visit Sweden marketing campaign.[9] This fundamental right speaks to the Swedish mindset on the importance of exploring in nature and interacting with the environment.

Grassroots climate focused movements are common in Sweden, notably with Greta Thunberg’s Fridays for Future campaign and high public opinion of sustainable practices. Naturvard, the Swedish Environmental Protection Agency, states that 81% of Sweden believes that they personally have the ability to slow down climate change.[10] 95% of Swedish people believe that climate change will affect their country. These numbers are quite different from America, where, according to Pew Research Center surveys, only 61% of US adults think that “global climate change is affecting their local community.[11] The data shows that Swedish people intrinsically care about climate and climate change more than people in the US.

Sweden’s energy policies are aligned with the broader EU objectives, which set ambitious targets for renewable energy and carbon emissions reduction.[12] This directive aims that at least 42.5% of energy generated is renewable by 2030. Sweden is above the threshold with 68% of their energy coming from renewable sources.[13] Sweden has set its own national goals aiming for 100% renewable energy generation by 2040, relying on the prideful Swedish ideal of leading region in forward progress.

The EU’s Green Deal sets objectives to reduce net GHG emissions by 55% (1990 baseline). Sweden complies with directives and has access to financing through development banks (EIB) and more to ensure compliance and forward progress within the regulatory framework.

The regulatory landscape in the US is different than in the EU due to the division of responsibilities between federal and state governments. At the federal level, agencies like the Federal Energy Regulatory Commission, (FERC) oversee interstate transmission and wholesale electricity markets, setting a baseline for nationwide energy policies. However, states have considerable autonomy in regulating their retail electricity markets and implementing renewable energy programs. This system results in a disparity of energy policies, with states like California aggressively pursuing renewable energy targets, while others lag behind. The fragmented regulatory and decision-making approach leads to disparities in renewable energy adoption and policy efficacy in the US, unlike the more cohesive and trend-setting regulatory framework seen in Sweden.

Consumption
Sweden is markedly different from the United States in terms of geography, population, and sentiment regarding power uses. Located north of the US in terms of longitudinal positioning, Sweden’s highest recorded temperature in history was 100F compared to the US record of 134F.[14] 134F[14]. These environmental and population density differences lead to different use patterns of electricity and overall consumption of power.

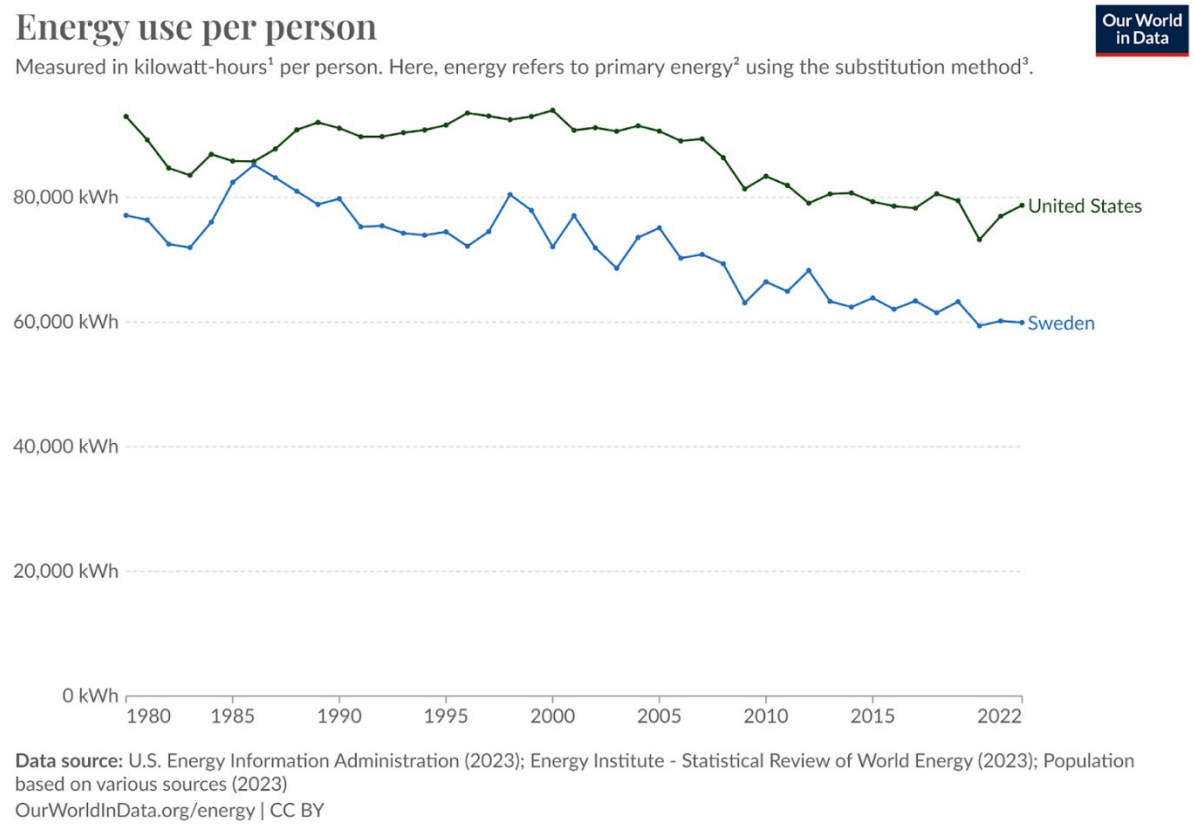
<u>Population</u>
The population differences between Sweden and the United States significantly influence energy consumption patterns in each country. Sweden, with a population of 10.6m people[15], is much smaller than the US where population exceeds 330m people. Sweden, with a population of 10.6m people, is much smaller than the US where population exceeds 330m people.[17] Sweden’s population is generally concentrated in urban areas such as Stockholm, Gothenburg,

and Malmo, allowing for efficient energy distribution and consumption. Barely 2% of the Swedish population lives in sparsely populated areas, with more than 77% residing in urban areas.[16] In contrast, the US has a larger population living in rural areas, roughly 20%, leading to higher energy consumption due to the need for extensive transmission infrastructure and higher per capita usage in less densely populated regions.[17]

Uses of Power - Sweden vs US

The uses of power in Sweden and the US differ markedly, driven by cultural, climate, and technological factors. In Sweden, the residential sector primarily uses electricity for heating purposes given the country's cold climate. Almost all homes rely on electric heat pumps or district heating.[18] In the US, air conditioning is a major consumer of electricity. Each home typically has their own heating and cooling system. The reliance on air conditioning significantly drives up residential energy consumption during the summer months. Per capita energy consumption between Sweden and the US, as measured in Gigajoules per capita per year, is 215 GJ/cap vs. 283 GJ/cap, respectively.[19]

Energy per Capita/Sqft in Different Asset Types



Measured in kWh, the US consumes significantly more energy per capita than Sweden. Annually, each person consumes 78,754 vs 59,927kWh (US/Sweden).[20] This 18,827kWh difference is partially attributable to the average home square footage of the countries, which is 2,164sqft vs 893sqft in the US vs Sweden, respectively.[26] When evaluating the energy consumption of Sweden, it is important to consider the smaller property footprint as well as energy demands. The lesser demands effectively lessen the burden to adopt renewable energy technologies and increase the ease of technological adaptation.

Future and Historical Planning (Goals and Targets)

History of Swedish Energy Target Setting

Sweden has a long history of setting ambitious energy and environmental targets. They have been proactive in establishing goals aimed at reducing GHG emissions and increasing the use of renewable energy. The Swedish government first adopted significant climate targets in the 1990s, following the adoption of the Kyoto Protocol. Over the years, Sweden has continually updated its targets to align with the latest scientific findings and technological advancements, as well as amended their targets to exceed those of the greater European Union. In 2017, Sweden redacted a Climate Act that requires the government to create an annual climate report and four-year reviews of climate policies.[21] Sweden aims for zero net GHG emissions by 2045.

US Federal Energy Regulatory Commission (FERC)

The US Government, in conjunction with the FERC, has also taken significant steps towards renewable energy planning. Most recently, FERC introduced new policies aimed at modernizing the grid and facilitating the integration of renewable energy sources. All decisions must be analyzed with a 20-year time horizon in mind, ensuring that the US moves towards a more renewable future. The Landmark Transmission Rule, adopted in 2022, focuses on improving long-term transmission planning to further accommodate future renewable energy projects.[22] This rule mandates utility companies consider future demand and the 2044+ energy landscape, serving the increased needs of the US population. This change to the energy landscape, as well as movement towards the revitalization of energy efficiency, positions the US for a more renewable energy future.

Lessons Each Region Could Take from the Other

It is empirically unfair to compare the two countries, Sweden and US, in terms of energy consumption and planning. The US is 3200% larger than Sweden in terms of population, and significantly larger in terms of industrialization and urbanization. This aside, Sweden has a long history of aggressive target setting and renewable energy compliance, which could be taken to the US market.[23] Sweden's focus on sustainability and public perception of such endeavors can serve as a model for the US where energy policy changes are often fragmented and subject to political challenges. The US has made progress with the recent innovative FERC policies, but it is yet to be seen how these are tangibly and fully implemented throughout the country, especially in polarized states.

Future Goals and Targets

Looking ahead, Sweden and the United States have set ambitious goals to transform the electricity landscape. This includes how power is generated, transmitted, and new projects are connected to the grid infrastructure. Sweden aims to achieve 100% renewable energy production by 2040, and the US has set a goal to achieve "carbon pollution-free power sector by 2035."[24] This US goal was set by the current president, President Biden, but is up to future administrations to support and maintain. The US political parties have polarizing views on climate change, where the Swedish political parties and constituents align on the importance of climate change and renewable energy production.[25] It is unlikely that policy in Sweden will change with the next election, helping the country keep a steady course of renewable energy progress and policy for future years to come.

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