Dysfunctional Modeling: A Combined Method to Improve Sociotechnical Energy System Analysis

A Research Paper Submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

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Spring, 2021

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

As the demand for energy in the US increases each year, so does the necessity to meet that need while minimizing toxic emissions. The Earth's climate has been rapidly changing for the worse, and large-scale power generation stands as one of the greatest perpetrators by releasing substantial quantities of carbon dioxide (CO_2) each day (Mason-Delmotte, 2018; Pilorgé et al., 2020). CO_2 emissions have been dropping from their levels in the early 2000s; however, by 2035 they are projected to rise again, which must be prevented in order to halt anthropogenic CO_2 emissions (U.S. Energy Information Administration, 2021). In the technical portion of this project, a 600 MW natural gas power facility is designed based on the Allam Cycle that will emit zero atmospheric carbon. A question that arises while designing and his facility is will it actually be accepted into a community and used to its full potential? Despite the years of study that have gone into carefully crafting frameworks to describe energy technology systems that should answer this question, we still have no definite answer.

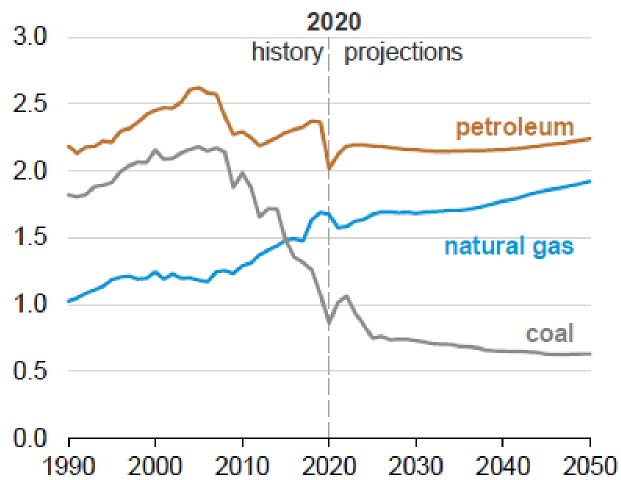

Figure 1 - U.S. energy-related carbon dioxide emissions by fuel AEO 2021 Reference Case in billion metric tons (AEO, 2021)

The social implications of renewable energy technologies (RET), and associated alternative technologies, have been studied since the first major wind farm constructions of the 1980s (Batel, 2020). Despite almost 40 years of study, there is still an incomplete understanding of the ways in which RET positively and negatively interacts with actors in associated networks. The prime evidence to support this is that RET is not currently adopted into the power generation system as mainstream technology, and it is not positioned to for a very long time. Discussions of resistance to RET have historically created frameworks that are flawed by placing too much weight on financial or resource obstacles, or fail to encapsulate a variety of perspectives on social and institutional factors (Batel, 2020), which means that they are inadequate for identifying and mapping resistance to RET, and a more sophisticated way of using models is required for forward progress in understanding obstacles to the adoption of RET technology. I propose my own approach, called the combined method, to compensate for the inadequacies of current stand-alone frameworks and provide more useful analysis of these crucial systems.

Where's the RET?

A Lack of Response to Dangerous Climate Changes

Glaciers are melting at faster rates, biomes are changing, and species are going extinct as their previously stable environments are changing at an alarming pace as seen in Figure 2 (IPCC, 2018; NASA, 2021). With the rise of the middle class around the world, industrialism, and advanced technology, humanity has continued to manipulate the natural resources of the earth with little to no regard to the consequences (Brosius et al., 2005). Countless studies have been performed that all point to environmental and subsequently human destruction via continued neglect of the Earth (IPCC, 2018). Despite all of these findings and evidence that change needs to be made in order to preserve the planet, the power industry continues to resist mainstream adoption of RET and other alternative energy technologies (Batel, 2020; Geels, 2019; Sawyer et al., 2019; Tidwell et al., 2018). As a responsible engineer, the only acceptable question is to search for the reason why this resistance is occurring to the end of understanding the problem as the first step of finding a solution.

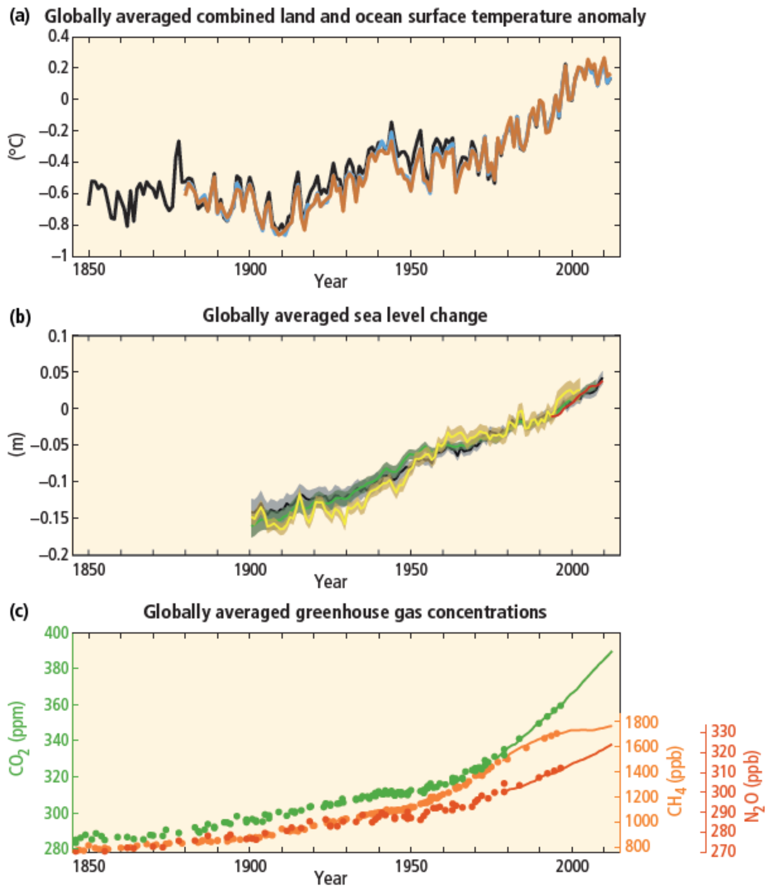

Figure 2 - Statistics of temperature rise, sea level change, and greenhouse gas concentrations associated with rising CO_2 emissions and atmospheric pollution (IPCC, 2018)

Financial and Social Dilemmas

Time and time again, regardless of the field or specific artifact in question, we see a systematic struggle to change systems so that they incorporate technical innovations. Change, especially when challenging the "standard operating procedures" of life, is difficult (Mahoney, 1990; Palmer, 2004). This pattern of resistance to change also transcends the individual, and it finds itself as a unique facet of the societal level as well (Dudovskiy, 2012). Human's distaste for change is no secret, and it is something so studied and accounted for that there are whole management strategies built around coaxing people through necessary change (Desai, 2010; Tuominen, 2016). Historically the power generation industry, in line with the normal human response to change, is very slow to adopt new technologies that impact incumbent ones—this has been particularly true for RET (Grübler & Wilson, 2014). In pondering the question of, "Why is the power industry so slow at changing?", there are many answers. Large capital cost associated with the implementation of new units or advancements in the field is a very real problem for this industry. On the scale power generation facilities are developed, multiple millions of dollars can be dropped into singular pieces of equipment, clearly demonstrating the financial risk associated with new technology (Gevorkian, 2017). Concepts such as sunken investments and economies of scale are massive when it comes to this financial argument. In the context of green energy adoption, oil corporations that have spent years investing in drilling sites for future profit will be left with large amounts of land, with far less value than before. Additionally, all existing infrastructure in place is already designed around incumbent technologies to a large degree, requiring a change of course to go through multiple pay walls to achieve integration (Geels, 2019).

When new or experimental technological advancements are tested in the field, there is also a large safety concern. With any new product in development that is unlike what has been made/used before, there is a lack of standards for safety and regulation (Sheldon, 2021). Developing these guidelines for use and integration is something that takes time, also making it more difficult to change from proven practice. A change of this magnitude implies a larger governing body alteration that can accommodate procedures deviating from preestablished guidelines (Elzen et al., 2004). Groups like the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and health (NIOSH) are dynamic and responsive entities that are structured to adapt to the specific setups of different industries, but even still those changes cannot happen overnight, particularly when the new changes in question are of the magnitude of RET (Sheldon, 2021).

In addition to the known quantitative costs associated with new technology in the power industry, a much more difficult to quantify social force that plays a part in dictating change is also present. This social response is one that has been studied and recognized as significant for some time, and as suggested by Batel can be broken into three waves of study illustrated in Figure 3 (Batel, 2020). In the first wave, initial models to determine the social/societal response to RET worked on the basis of defining supporting and opposing actors in industry, public office, and communities, and how said actors arrived at their points of view (Sovacool, 2014). This wave of study operated on the uninformed belief that understanding the social side of RET was unnecessary in finding ways to reduce opposition. The second, more

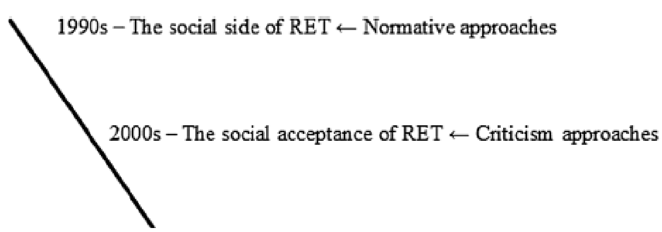

Figure 3 **-** *Figure from Batel illustrating the flow of research on social acceptance of RET. She emphasizes in here research that these are not completely independent or fully consecutive waves (Batel, 2020)*

robust wave, operated in opposition to the first which was characterized by oversimplified viewpoints of the public stance on RET. In this era of research of the public response to RET, an attempt was made at understanding why communities might want to reject RET being deployed nearby by acknowledging what values communities hold, and how higher-level systems such as planning, financial support, or other institutional entities can influence communities' perceptions (Haggett, 2008). The third and most recent wave of study on this topic, attempts to organize into three axes: ideological, theoretical, and methodological. This era of study provides major changes in how community response to RET is viewed and interpreted. It changes the stance that resistance to RET is deviant and something to be overcome, it provides increased theory to be considered on how, when, and where RET implementation is possible. Furthermore, this last wave emphasizes that methods of data collection for public response to RET must be improved as to better represent the actual view the public wishes to convey (Batel, 2020; Labussière & Nadaï, 2018).

As time has passed and study on the intersection of RET and society has continued, our understanding of how the public and institutions respond has improved. Even though the understanding of the failure to take advantage of RET has improved, there remains a large-scale resistance to adoption. This continued resistance allows for an inference to be drawn that previous studies on RET and society have been inadequate. There are many ways to observe this; for example, in the US popular media and politics, there is much controversy over the necessity of RET. Multiple groups oppose RET on the basis of the economic argument earlier presented, or on the grounds that climate science is in fact fake or full of fallacies (Walker, 1995). In US politics, climate science driven developments are often overshadowed by political disputes setting conversations about life-saving sustainable technology to the side. A good example of this is the political response to the early 2021 Texas power outages where certain lawmakers pointed fingers at the unreliability of RET, whereas the actual overarching problem was inaction after recommendations from the Federal Energy Regulatory Commission (FERC) for increased system winterization following the 2011 southwest cold weather event (Magness, n.d.). Another common reason listed as to why RET is not more widely supported is the concept of Not-In-My-Backyard, better known as NIMBY (Thomsett, 2004). This is a catch-all term for community resistance to power infrastructure being developed in close proximity to their residential area. It originated under the first wave of study on RET and is commonly referred to as a poor answer to the question of why new RET are not used because it takes for granted the forces influencing a community's view on a new technology (Batel, 2020). Even though the weakness of NIMBYism has long since been known in the community studying the social implications of RET, it is still used as a mainstream response. These resistances as described are emblematic of the overall problem of non-negligible resistance to RET that has slowed down its adoption.

While the financial and social risks associated with RET are real and valid, there is an urgency that should incite a desire in individuals and institutions alike to overcome these holdups. From the conception of RET, there have been large amounts of progress associated with making the technology less cost prohibitive and more efficient. There is still room for improvement and optimization for RET, but this optimization is at a small enough scale that the financial argument has grown weak. The most costly aspect of this transition that still exists is the predominantly fossil fuel build infrastructure present in the US that will need to be replaced. This being said, the price required for developing and implementing RET itself has drastically reduced over time, thus eliminating the ability to argue that the technology's price point alone is the issue. The social argument associated with RET is not fully understood due to lackluster solutions previously arrived at in the past, does have merit, and is likely the primary reason that we are unable to mobilize RET on the largescale arena. Moving forward, the method for grappling with the social aspects of RET should be to approach it from a systemic network perspective. What this means is to understand that each individual technology has a network associated with who it impacts and is impacted by, and that is a part of a larger system influenced and influencing smaller scale innovation below, and the greater landscape above specific RET.

Untangling the Web

This section of my research seeks to lay out the foundational frameworks used to analyze RET systems. Here I introduce Geel's Multi Level Perspective and Grübler & Wilson's Energy Technology Innovation System and explain how they each use different methods to describe how new RET does or does not become a part of the incumbent energy system. After this, I acknowledge their shortcomings and propose an improved way to deploy these frameworks and others like it that provide more accurate representations of energy systems and their relationship to RET.

Geels' Multi Level Perspective

An initial understanding that needs to be grasped in the attempt to influence the actions of the power generation industry, and other industries as large and established for that matter, is that for something as large scale as different modes of power production to be adopted, a series of "socio-technical transitions" have to occur (Geels, 2019). These transitions are systemic in nature, and require non-menial changes in preexisting systems of infrastructure, products transportation, consumer habits, cultural trends, and scientific knowledge (Geels, 2011). In an initial attempt to explain this, and model the sociotechnical system that is power generation, I utilized Geels' Multi Level Perspective (MLP). Geels' MLP ties together concepts from evolutionary economics, science and technology studies, structuration theory,

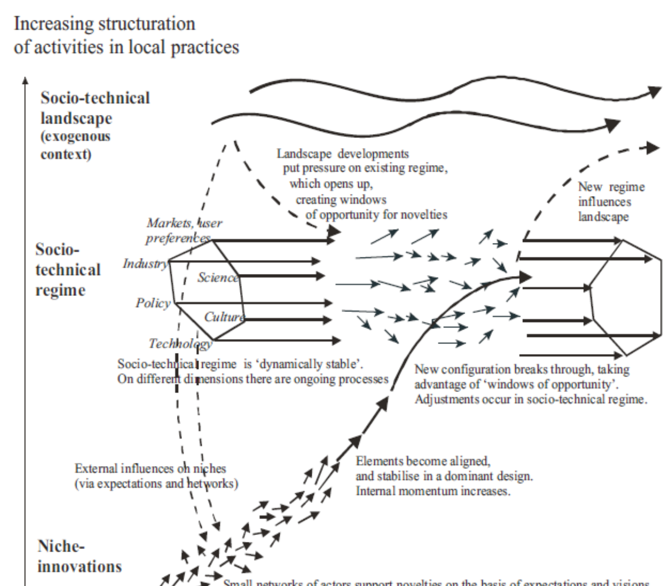

Figure 4 - Geels Multi Level Perspective (Geels, 2011)

and neo-institutional theory in order to "[conceptualize] overall dynamic patterns in socio-technical transitions." (Geels, 2011) In this sociotechnical theory, Geels states that the flow of innovation through various sizes of institutions can be modeled in three levels: the niche, regime, and landscape levels, as seen in Figure 4. To summarize the implications of this perspective, the sociotechnical regime, which is a deeply rooted structure with unofficial rules coordinating the actions of various connected parties to a particular system, dictates the stability and structure of the system as a whole. Technological innovation often begins in what is called the niche level – lower stakes environments such as laboratories and startups, and these innovations are often radical to the current regime. Once large enough and brought to the regime level, these innovations in questions either fail and do not become a part of the regime, or alter the regime altogether dictating the aforementioned "socio-technical transition." Upon a transition occurring, the regime then changes and begins to influence the landscape, the level at which general views/ideologies of politics, culture, and society in general reside, in new ways.

This model of sociotechnical transition structure and organization is applicable to understanding the response to RET for a few reasons, some of which are laid out well in Geels' 2011 paper on the MLP in relation to sustainability focused technologies. One of these reasons, also noted by Sen and von Schickfus, is the existence and influence that large incumbent firms hold in the industry (Sen & von Schickfus, 2020). These firms have massive amounts of money, deep political ties, and are culturally solidified by decades of existence in communities (Batel, 2020; Brosius et al., 2005; Labussière & Nadaï, 2018). These firms alone could not lead the charge to total regime change however with their support, assuming they could move past sunken investments, scale economies, and other "lock-in" clauses keeping them in line, they have large contributable assets through capital and influence that could increase the speed the of sustainable technology innovation (Geels, 2019). Another indicator that MLP is an appropriate way of viewing this phenomenon, is the altruistic nature of sustainable technology in its adaptation. In the selfish sense, sustainable technology does not offer immediate payout to the user that incumbent technology doesn't. Both technological stances generate power, but moving to sustainability focused ones from the current regime will be costly, and offer seemingly the same things. The nature of the technology is to provide long term benefit for the common good, and not immediate payout on behalf of the owner or investor. Due to this reality, it requires economic frame condition alterations, as put by Geels, in order to support environmental innovations taking over (Geels, 2019). Alterations as referenced in this context come in the form of tax subsidies for carbon sequestration, and regulatory organizations pushing industry in the necessary directions (Elzen et al., 2004).

Grübler & Wilson's Energy Technology Innovation System

In order to fully grasp the process of how to adopt new technology into the power generation system, Geels' MLP helps on the large scale, but when drilled down something else is occurring at the intersection of the regime and niche levels where innovation is clashing with incumbent technology. Geels' explanation of this point of interaction does not go into enough detail about how the niche innovation would go about overcoming the regime (Geels, 2019). At said intersection, I believe that Wilson and Gruber have a much more specific way of modeling the sociotechnical aspect of new technology's lifespan called the Energy Technology Innovation System (ETIS) (Grübler & Wilson, 2014). The purpose of this model is to describe how and why new technology gets adopted throughout its lifespan. As seen in Figure 5, it operates by basing all interaction between the interconnected four pillars of knowledge, resources, actors and institutions, and adoption and use. The knowledge pillar deals with the exchange and gathering

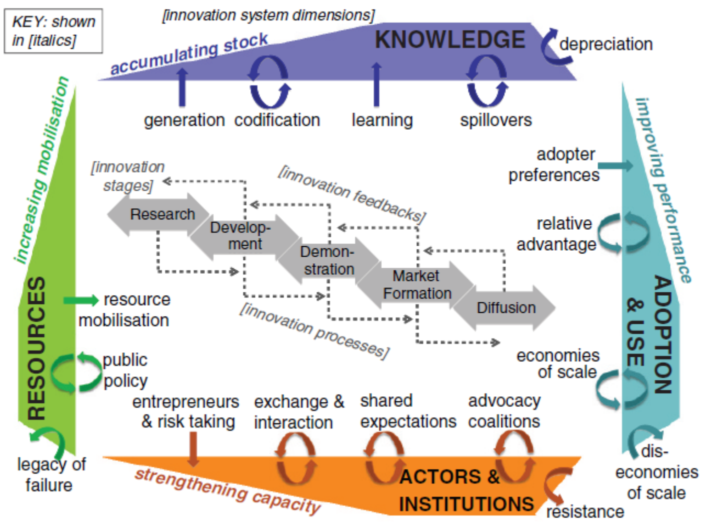

Figure 5 - The Energy Technology Innovation System (Grübler & Wilson, 2014)

of scientific knowledge, and the actors and institutions pillar coordinates the interactions between end users, firms, and public entities and their associated networks. Moving to the side pillars, adoption and use as a pillar regards exactly how, when, and if innovative technology is adopted and used, and the resources pillar describes the key input to the innovation system of financial, human, intellectual property, and effort needed to even begin trying to implement innovative technology. Based on this way of viewing the innovation system, all four of these pillars are necessary, and one cannot be enlarged to compensate for a lack in another. This way of viewing new technology is particularly valuable when evaluating the status of sustainable methods in the power industry. Clearly, the widespread adoption and use—stated as the benchmark for successful innovation by Wilson and Gruber—is not evident for sustainable modes of power generation, so it brings into question which of the four pillars presented are truly lacking, in the case of RET.

By combining Geels' MLP and Wilson and Grubers ETIS, a much better view of the power generation system's response to innovative sustainable technology can be garnered. The ETIS helps to evaluate on the "micro" scale that is the intersection of the niche-regime levels, and the MLP puts that impact into the perspective of the greater landscape. The combined method emerges from this overlap of MLP and ETIS. This method operates on the principle that the two frameworks presented operate better together than they do alone, and by combining them a more accurate view of the RET system is gained. To use these frameworks in tandem, the four pillars must of ETIS must be reviewed to find weak points in the energy adoption. Each time one of these points are found, they must be related to the greater system flow as described by Geels to determine the greater source of the weakness informing the network connections to a greater degree.

Limitations of the Frameworks

I approached this research with the intention of understanding how well ETIS and MLP work when describing RET systems, and how the use of frameworks overall can be improved. I explored these things by first employing ETIS and MLP to determine the issues associated with RET adoption to determine what the frameworks do well and identify as the problem. After this, I sought to understand where these frameworks failed to accurately describe the whole system, and for a way to alter their deployment to improve findings.

Failures of the power generation system as seen through ETIS and MLP

The power generation system when split into its four pillars as described is achieving two of the four fundamental requirements—resources and knowledge. The science and engineering of how to make sustainable energy modes reliable, efficient, and profitable exists, and is proven with resources required to achieve this is already in existence (United States Congress Senate Committee on Energy and Natural Resources Subcommittee on Water and Power & United States Congress Senate, 2014). The same materials needed to produce incumbent technology are required for the more sustainable counterparts on all fronts. The raw materials are available, and actors and institutions have the investment required in the energy field as we see incumbent technology continuing to prosper and dominate the market (Sawyer et al., 2019). The pillars in which the system is lacking is adaptation and use, which is where this research paper originated from, and actors and institutions. It is clear that over time, gradual optimization has occurred to innovate sustainable power generation technology to a place of usability, but it continues to be left out as a primary portion of large firms' portfolios. I assert that based on the various cases referenced in this paper, as well as from the perspective of sociotechnical frames used, the largest failure in this technological innovation occurs in the actor and institutions pillar.

Diving a little deeper into what the actor and institution's pillar of ETIS entails, entrepreneurs and risk taking, exchange and interaction, shared expectations, advocacy coalitions, and resistance are the routes by which actors and institutions have and are impacted by technological innovation (Grübler & Wilson, 2014). What we are seeing here is the resistance factor being far larger than the other four factors forcing a halt on this groups ability to interact with the innovation. Through the presented studies it is seen that while there is support and advocacy for sustainable energy systems from some public groups on the national and international scale, there are just as many or more apathetic or opposed groups nationally. To explain, Geels' put it best when they indicated that the end product user will ultimately influence the industry, and as it stands, the end product user base for this particular technology is deeply divided. The public within the US does not have one unified, or even majority leaning stance when it comes to sustainable energy. Because of this, there is no political pressure—as democracy is intended to be an extension of the beliefs and desires of the masses—not enough social pressure from individuals, and the market has little incentive to change on its own. It should be acknowledged that there is some action that has been taken to the end of inciting change. This action has come in the form of political action groups, subsidies and tax breaks for carbon sequestration, and international efforts for accountability. Despite this, the same results are still obtained. This is because these actions are still at what Geels would call the niche level overall.

Further findings of this study would indicate that pressure from the landscape level of the system either is not strong enough or does not exist as a force for change in the regime. The regime making up the power industry has remained largely static since 2000, with an exception of increased diversification towards natural gas and away from coal (EIA, 2019). This lacking force coming from the landscape level provides innovative technology form the niche level no assistance in making it into the regime structure. Despite incredibly innovative technology developed in the niche level such as CCS based systems, they alone are unable to change the rigid structure that the power industry has rooted itself in. There is still public and political belief that green energy is unnecessary, financial fear of investment is pervasive, policies have not been changed to any noticeable degree, and the end user market continues to indiscriminately consume power regardless of its source.

Failures of the frameworks

Perhaps the most interesting and valuable part of this study is the finding that both Geels' MLP and Wilson and Gruber's ETIS don't fully account for some technological innovation that is occurring—like their predecessor frameworks. Both of these frameworks operate on the assumption that in order for any technological innovation to have success or get implemented that all factors and levels must work in tandem. With this in mind, there are still instances of sustainable tech popping up and gaining great momentum without greater institutional consent or support—something that is unaccounted for in the popular frameworks. A prime indicator of this is the movement of GA from 22^{nd} to 9^{th} in most solar usage in US states (Tidwell et al., 2018). One could make the argument that these models could be contorted to a smaller scale to explain this, but I believe what has occurred here and in other instances is the tireless efforts of very dedicated actors. This surge in GA solar usage was not a result of the entire power generation industry's regime (the subject of this study) getting altered, and nor is it an instance of actors, resources, knowledge, and adaptation at a large level all finding synchroneity. This was a direct result of dedicated actors on the niche level forcing innovation past the regime which intentionally or not was holding it down.

These findings indicate a larger more pervasive issue than either the failure of the actors and institutions, or MLP and ETIS on their own: "tunnel vision" often occurs in frameworks that are developed in an attempt to model social response to RET. The frameworks designed, as robust or researched as they may be, are still reductionist in nature when it comes to the sophisticated situation of adapting RET into mainstream power generation systems. If the aim of studying the intersection of society and RET is to be able to describe each party's response to the other in order to inform future decision about technology, a single framework will likely always be inadequate. Yes, over time sociotechnical studies towards RET have improved for the better, but they still lack in the ability to describe something that is new and rapidly changing in the same way that RET does. One likely answer to explain this is the relative age of both this sort of sociotechnical way of thinking, and the relative age of RET. The sociotechnical field of study is not all that old and still developing. Likewise, RET is certainly an emerging technology, and has not had the opportunity to develop a strongly rooted institutional backing to be studied by the sociotechnical field. The older that the sociotechnical field and the technologies in question become, the more data will exist to inform sociotechnical frameworks. Additionally, the concept of using a single sociotechnical framework to describe the interactions between technology is outdated, and always ineffectual. It is counterintuitive to use frameworks intended to have basis in actor network theory in singularity without using multiple other frameworks in tandem because it is in effect cutting off part of the network via limited perspective. Moving forward with studies on RET, the use of multiple frameworks—as attempted in this study with MLP and ETIS—will provide a more full and correct understanding of the subject at hand as illustrated in Figure 6. Harnessing this method of combining frameworks rather than basing decisions around RET moving forward on one framework or understanding alone will likely have much higher success rates. Still however, the dynamic and complex nature of RET systems remain true, and while the combined method better approaches mapping these networks, there remains unknown information as indicated by the grey in Figure 6.

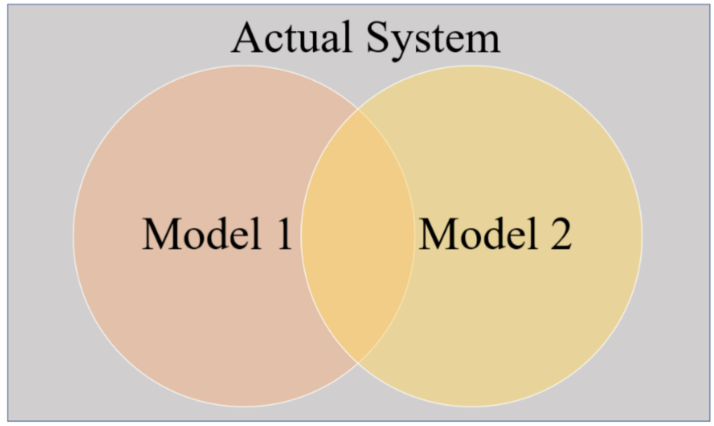

Figure 6 - *Illustration of multiple sociotechnical framework model utilization providing greater yet still incomplete mapping of a real system*

Conclusion

The analysis presented in this paper yields an image of RET as a newly borne, complex, and regularly changing system that continues to be difficult to read and make educated decisions about. Attempts to utilize frameworks designed from established sociotechnical understandings about new technology emergence to date have been unable to articulate RETs in such a way that the findings can be utilized to implement RET on a larger scale. This inability to come up with a model describing RET well enough is alarming as it perpetuates the current status of the US power generation which continually damages the ecosystem pushing climate change further and further along. This study demonstrates that the reasons for the lack of RET in mainstream power generation are beyond simple financial hurdles, and are in fact part of a greater sociotechnical system that is too little understood to accurately directed toward a specific end. A proposed solution practiced in this study is the combination of multiple sociotechnical frameworks to cover multiple perspectives, and allow for a greater field of vision of the network.

A limitation of this study lies in the claim made that previous studies have not already implemented multiple sociotechnical frameworks in order go obtain a greater understanding of a system. What I can say here is that I only came across studies in which individual frameworks were used to understand systemic behavior. Additionally, there is the future hypothetical framework that could encapsulate every facet of the power generation system. If such a framework were to exist, it would render these findings unnecessary and superfluous.

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