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Qualitative Description of Electric Power System Future States

February 2018

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CD Corbin

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Summary

This work proposes a common basis for the simulation and evaluation of transactive systems. Using existing literature, a qualitative survey of the future states of the electric power system was conducted. Forces exerting influence on the state of the power system, called "drivers," were identified. Specific future states in the literature were identified and classified into five general groups, and the effects of twelve previously identified drivers were assessed for each individual future state in the literature. Relationships between the five general future states were defined through a Venn diagram and system evolutions were demonstrated through notional narratives and corresponding paths through the diagram. A relational measure of the complexity and extent of the change implied by each future state was also created.

Acronyms and Abbreviations

AC	alternating current
CCS	carbon capture and sequestration
DER	distributed energy resource
DSO	distribution system operator
EU	European Union
PMU	phasor measurement unit
PV	photovoltaic
UML	Unified Modeling Language

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1.0 Introduction

The simulation and evaluation of transactive systems depends to a large extent on the context in which those efforts are performed. Assumptions regarding the composition of the electric power system, the regulatory and policy environment, the distribution of renewable and other distributed energy resources (DERs), technological advances, and consumer engagement all contribute to, and affect, the evaluation of any given transactive system, regardless of its design. It is our position that the assumptions made about the state of the future power grid will determine, to some extent, the systems ultimately deployed, and that the transactive system itself may play an important role in the evolution of the power system.

Defining the potential future states of the power grid is a daunting task. Numerous assumptions regarding a great variety of potential drivers of the future power system must be researched, justified, and documented. New socio-techno-economic models may need to be developed to capture the pervasive impacts of transactive systems, which have been largely investigated at small scale. Even with new models, a great deal of uncertainty about each potential driver remains.

It is our belief that defining every detail of the future power system is unnecessary, and that ranges of values explored in the context of a set of notional future states ultimately yields more useful information, and is less prone to the "garbage in, garbage out" problem that plagues many models. It is with this justification that we have developed a select set of future states that may be realized over the next several decades, with which we may evaluate transactive systems and their performance given the uncertainties that exist.

Our work is built upon many similar efforts by others and is intended to be a summary of the themes we have found in the literature that are driving the evolution of the power system. In the document that follows, we present the results of our survey of the existing literature, starting first with the drivers, and then following with the future states they induce. We then evaluate these states in terms of their drivers to determine where the overlap in the perspectives of individual authors exists and categorize the composite findings into a relatively small number of general future states. Lastly, we evaluate these general future states to determine their general relationship to one another and the complexity and extent of the change to the power system they imply.

To be clear, this document is not intended to define specific values regarding the characteristics of the future power system; rather, it is intended to define a range of possible futures in which the future power system may exist, and a context in which transactive systems may be simulated and evaluated.

2.0 Taxonomy

This document makes use of several terms that are used throughout the literature, but that are used somewhat inconsistently in the documents we have reviewed. To provide clarity and consistency, we present a set of definitions that most accurately captures the meaning of concepts represented in similar studies, and that are central to the simulation and evaluation of the future power system.

The two primary concepts discussed in this document are: "driver" and "future state." These concepts lie at the top of the conceptual model shown in Figure 1. This model provides a simple framework, which defines the context in which a transactive system may be simulated.[1]

- ***Driver*** – Drivers are political, economic, societal, and technological forces that shape the conditions at some future point in time, e.g., the rapidly declining prices of photovoltaic systems. A collection of drivers (given time) will define a future state but exist independent of it. Drivers are discussed in Section 3.0.
- ***Future State*** – A future state provides a high-level description of the world at some point in time. It is the broad context in which a simulation or evaluation is performed, e.g., a highly decentralized fleet of small generation assets. Future states are discussed in Section 4.0.

Although not explored in this document, "use case" and "scenario" are related technical terms and must also be defined for any given transactive system simulation:

- ***Use Case*** – A use case is a problem to be solved or an action to be performed, e.g., the integration of electric vehicles into the power system at large scale. A use case may refer to multiple future states, and may only exist in the context of those future states. Use case(s) may be formed with respect to another use case(s).
- ***Scenario*** – A scenario is a proposed sequence of actions by actors that address a use case. Multiple scenarios may be proposed to address a use case. Scenarios exist only in the context of a use case. The sequence of steps taken by a transactive system would be an example of a scenario.

Those familiar with the definition of use cases and scenarios in the context of Unified Modeling Language (UML) will observe a similarity to our model (see Figure 1). This is intentional. A parallel effort related to this work focuses on the creation of templates that assist in the development of a common set of use cases and scenarios against which transactive systems may be tested. As Figure 1 also shows, drivers and future states are integrally related to the definitions of use cases and their corresponding scenarios. Drivers form future states, which create specific problems to be solved (use cases) and hence scenarios that propose methods to solve those problems. UML provides a useful set of tools with which many in the software design and development disciplines are familiar; the use case and scenario templates created in the parallel effort mirror those used in practice.

Finally, we note that the model presented here formalizes, and is consistent with, terms appearing in *Pacific Northwest National Laboratory's Transactions-Based Building Controls Framework, Volume 1: Reference Guide)*. (Somasundaram et al. 2014)

[1] The conceptual model shown here is not comprehensive. Ongoing work will define the additional components necessary to fully specify a Transactive System simulation.

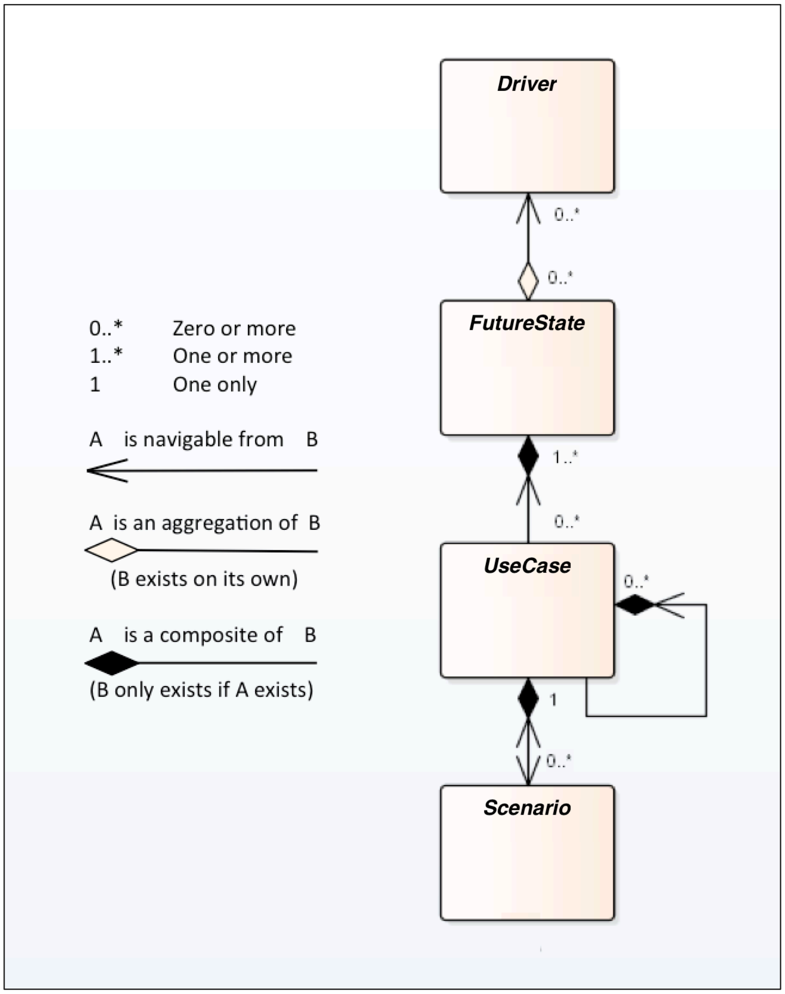

Figure 1. Proposed High-level UML Model of Conceptual Components in a Transactive System Simulation Platform

3.0 Drivers

The foundations for considering potential future states of the power system are the forces, pressures, sentiments, and motivations that exhibit influence on the researchers, architects, regulators, builders, and operators of the power system as it evolves. These are what we term drivers. These drivers exert influence on the system (sometimes directly) and its underpinning philosophies, forcing all interested parties to adjust and potentially take action in their spheres of influence. Drivers can often be philosophical in nature and do not exert uniform influence throughout the system; the response to a driver is not generally coordinated and may result in related parties taking contradictory actions.

These drivers are expressed, become apparent, or are realized in many ways, such as

- federal, state, and local regulations
- availability and prices of generator fuels
- retail electrical prices and tariff structures
- public sentiment regarding various energy sources (coal, nuclear, hydro, solar, etc.)
- topics and fields on which researchers focus.

The drivers themselves are not static either, growing and diminishing in influence as the system evolves and the influence of other drivers becomes more dominant. Because of this dynamic nature, predicting the longevity and overall influence of an individual driver is practically impossible and will not be attempted here.

3.1 Drivers in Literature

To help identify and understand the drivers in the electrical power system, the current relevant literature was reviewed. These drivers can be considered existing or soon to exist factors that are promoting change in the current operation of the power system and/or factors that are being considered by those planning for the future operation of the power system. They are not intended to be considered predictions in and of themselves but rather technical, regulator, political or behavioral realities that are currently manifest or likely enough to manifest that those who are planning for the future of the power system are considering the effects they are having (or might reasonably be expected to have). Here are the common drivers we found.

- **Increasing renewable energy production enabled by decreasing renewable energy costs** – Prices for renewable generation have been falling for over a decade, with costs of solar seeing the most dramatic reductions lately. Prices are now low enough that these technologies are being adopted on a broad scale, both by energy customers and by utility-scale installations. These renewable energy sources have already introduced new dynamics and uncertainty into the operation of the power system, and will continue to do so. For customer-owned solar photovoltaic (PV) installations (residential or commercial rooftop), regulation, legislation, and tariff structures will have a significant effect on the business case of solar PV and may dramatically affect their appeal. (Appelrath et al. 2012; Bronski et al. 2015a; Taft and Becker-Dippmann 2015; Zinaman et al. 2015)
- **Increasing interest in widespread energy storage deployment that is just beginning to be realized** – Similar to what is being seen with renewable generation, energy storage offers great potential to both mitigate some of the complexities introduced by renewable generation as well as enable a completely new philosophy of operation of the power system, one where load and generation are much more loosely coupled. Such decoupling will allow for more efficient operation of the power

system at the cost of greater complexity. Though the costs of energy storage still remain high enough to prevent immediate broad-scale adoption, interest is high and prices are continuing to fall. (Appelrath 2012; CSRIO 2013; Taft and Becker-Dippmann 2015)

- **Slowing average load growth with a trend toward increasing peakiness** – Average load growth across the U.S. has declined to nearly zero, while simultaneously beginning to become increasingly peaky. This presents a challenge to power system companies as they feel the squeeze of limited sales growth while increased demand is being placed on their systems. (Appelrath et al. 2012; Bronski et al. 2015a; Propper 2015; US Energy Information Administration 2015)
- **Flat rate volume-based tariffs ($/kWh) becoming outdated and leading to increased electricity rates** – Closely related to the slowing load growth, traditional volume-based tariffs may be outdated and may be placing a financial stranglehold on utilities. These tariffs are beginning to appear out of step with the current trends in energy consumption. There is growing interest in and implementation of more dynamic energy prices that more closely match the changing cost of energy distribution that utilities pay and that also incorporate compensation for customer energy production (net metering). (CSIRO 2013; Propper 2015; U.S Energy Information Administration 2015)
- **Widespread aging infrastructure whose replacement and/or refurbishment allows for an opportunity to implement some degree of system redesign** – Much of the core of the power system is well over a half-century old and is due for significant refurbishment and/or upgrade. Given the need for significant investment, a unique opportunity is presented to those planning and designing these replacements: will they be new and improved versions of the old, decommissioned infrastructure or will the new infrastructure be a strong departure from the past? That is, in what ways will there be evolution within the system and in what ways does this clean slate support revolutionary new approaches?

  In some cases, such as with nuclear power plants, it is unclear whether it is even possible to replace a decommissioned nuclear power plant with a newer design or whether, for the time being, alternative sources of energy must be used. In other cases, such as with distribution systems, analog meters are being replaced with digital smart meters and serious consideration is being given to moving overhead distribution lines underground, improving reliability. (CSIRO 2013; Propper 2015)
- **Increasing concern toward and implemented legislation regarding climate change and the de-carbonization of the energy system** – Global concern over climate change has led to the federal government and many individual states implementing legislation that moves their energy systems toward being less carbon intensive. Often this takes the form of renewable portfolio standards, and in the case of California, energy storage deployment goals. Increased possibilities of a carbon tax or cap-and-trade system have many fossil-fuel based generators exploring the possibility of switching to a lower-carbon fuel (primarily natural gas). In some places, individual electricity customers have the option of opting in to programs where they pay higher prices to support renewable energy production. (CSIRO 2013; Bronski et al. 2015a; Zinaman et al. 2015)
- **Dramatically increasing technical capability enabled by low-cost information technology** – The increasing performance and decreasing costs of information technology that enabled the rapid growth of the internet has continued and is enabling distribution system operators a degree of system awareness and (possibly) control that was not previously available. Traditionally, the power system information network largely stopped at the substation but the deployment of smart meters is beginning to provide near-real-time information at a highly granular level and enables a tighter integration between supply and demand. (Neumann et al. 2016)
- **Changing fuel price landscape** – The natural gas boom in the U.S. has driven changes at all levels of the power system and continues to do so. Electricity customers are switching from using electric water heaters, electric ranges, and heat pumps to natural gas-powered versions of those same

appliances. This change in consumption has been a significant contributor in the change of most utilities' peak load from cold winters to hot summers. Electricity suppliers are finding improved economics for combined cycle gas turbines as mid-tier generation as well as simple-cycle peaking units. Due to environmental concerns and increased emissions regulation, demand for coal is dwindling though domestic supplies remain stable. (U.S Energy Information Administration 2015)

- **Electrification of transportation** – Electric vehicles and plug-in hybrid vehicles are still only a slight fraction of the total U.S. transportation fleet. Their growth, though, has been significant over the past decade with many major automobile manufacturers developing or producing at least one electric vehicle model. The viability of electric vehicles in the marketplace is strongly tied to improvements in cost, weight, and energy density for energy storage devices. Assuming these improvements continue at their current rate, electric vehicles will become increasingly common and present an entirely new load class to the electrical system with its own load pattern. Electric vehicle charging loads will drive the household average and peak loads up, potentially straining distribution systems not designed for such extreme electrical loads. (U.S Energy Information Administration 2015)

- **Increasing diversity in power market participation** – Enabled by rooftop solar, sophisticated controllers, and energy management software using commoditized algorithms and supporting communication infrastructure with system operators, it is now conceivable (and in some cases realized) for commercial and residential customers to participate in the daily operation of the power system. These traditional customers are interested in reducing their energy costs by selling excess energy from their generation assets (rooftop solar) and modifying their load profile (demand response). Traditionally, participation in this way was limited to very large commercial and industrial customers that could individually significantly affect the system as a whole. Smaller customers feel they should be able to participate on equal footing and system operators are beginning to see that, in aggregate, the potential to affect the system is equally significant.

  In some cases, this participation by small customers is nothing more complex than net metering arrangements that can effectively reduce their monthly energy costs to zero, or time-of-use energy rates that encourage customers to move load out of peak periods. In other cases, more sophisticated market structures and participation are being explored such as those proposed by transactive energy structures. (Cisco 2011; De Martini 2013; Propper 2015; Taft and Becker-Dippmann 2015)

- **Increasing in capability of power electronics** – The same growth in the semiconductor industry that has enabled rapid growth in communication systems has also resulted in higher performance transistors for power electronics applications. Combined with control algorithm development, these devices have allowed the creation of power converters that have higher performance and lower costs than those made a decade or two ago. These power converters are an essential component of solar PV and energy storage systems, which are direct current (DC) devices but typically need to interact with the alternating current (AC) power system. These modern devices also operate at higher voltages and have provided a foundation for serious discussion of expanding the role of high-voltage DC in the bulk power system, moving it from its existing niche role in enabling specific point-to-point energy transfer to the consideration of a continental-scale energy backbone that can move energy farther with lower losses. The higher voltage has also enabled power converters in the AC system (flexible AC transmission systems, or FACTS devices) to control power flows in ways not previously possible. (Li et al. 2010)

- **Widespread deployment of phasor measurement units (PMUs)** – Through the same enabling growth in computing technology and the reduction in cost to access a GPS's (Global Positioning System's) high precision clock, the PMU is changing both the types and accuracies of measurements being made in the power system. PMU deployment has seen a steady increase over the last decade and deployments will continue over the coming years; and with this comes data on a scale not

> previously seen by power system operators. Managing and utilizing these data well is a challenge for the operators, but as these issues are addressed and best practices formed, PMU data will be an enabling factor in how the power system is operated. The change it is enabling is similar in nature to that which brought supervisory control and data acquisition (SCADA) several decades earlier. Not only will PMUs allow operators to perform their existing functions at a higher level of performance, PMUs will allow new operating techniques that will increase the efficiency and reliability of the system. (Martin and Carroll 2008)

Examining this somewhat extensive list quickly reveals that these drivers are not each independent from each other. As was stated earlier, drivers influence, enable, and compete with each other. For example, the growth in computation and communication technology is foundational to several of the listed drivers, enabling methods of operating the power system and new devices on the power systems. Though effort could be made to distill the above list down to its roots and try to determine the orthogonal base drivers, we have not chosen to do so. Instead, we have enumerated drivers in commonly understood or conventional forms, listing the common manifestations and more easily understood and identifiable forces that have changed the nature of the power system and continue to do so.

4.0 Future States

Given a particular combination of drivers, the power system as a whole will change over time, reaching a new collection of equipment, policies, and interactions between participating parties. We call these "future states." It should be noted that though the states do not interact in the same way drivers do, there can be relationships between them and they are not necessarily independent of each other. Some are intermediate states of others, some are the results of very similar drivers but differ in a key way that produces a significantly different state, and some are heavily influenced by drivers not listed above.

4.1 Future States in Literature

The following future states were identified in a review of literature relating to the power system of the future. The list includes contributions from a wide cross section of industry, from government funded laboratories and nonprofit organizations, to investor-owned utilities. These reports are also international in scope and thus their applicability to the United States would need to be considered. As a given source may define several future states and there are no common classification criteria for the states, the following list does not provide a mutually exclusive list of alternatives. In fact, although different names are used, a large degree of commonality exists in the diversity of the contributions. The list that follows is in no particular order and a reference designator has been included in each listing to simplify identification in later analysis.

- **Nuclear alternative [A]** (Mathias and Newcomb 2012) – Given the consequences of nuclear generator failure, unplanned outages for safety concerns can last months or years as they often prompt the reexamination of the desirability of the generator. During the outage, the power system must find a way to handle the shortfall left by the nuclear generator. Filling this resource gap can be accomplished through distributed generation, storage, demand response programs, and energy efficiency efforts. Assuming the success of these efforts, the need and/or desire for nuclear generation in general may wane and efforts to restart the plant and/or plans for any nuclear expansion may be suspended.
- **Customer-owned distributed energy resources (DER)s integrated with traditional grid [B]** (Bronskil et al. 2015b) – As DERs (with solar PV and energy storage in particular) become very common and reach high penetration levels, power system operators find effective ways of integrating them into the grid as a whole, effectively utilizing their unique characteristics to provide value to the system.
- **Political capital funds going green [C]** (National Grid 2016) – Society as a whole has embraced a low-carbon future and this is broadly expressed through regulations, policies, and individual consumer choices. Widespread increase in gross domestic product enables societal changes (including changes to low-carbon electricity generation) to come at relatively low cost.
- **Customer DERs enable load and grid defection [G]** (Bronskil et al. 2015b) – In the absence of policies, regulations, and incentives that encourage customers with DERs to stay integrated with the larger power system, individuals begin shifting load to match their DER generation output and eventually, with the help of storage, discontinue traditional electrical service entirely. This starts a death spiral in some parts of the power system where assumptions of guaranteed revenue lead to large capital expenditures (generators, transmission expansion, etc.) that must be covered by an ever-shrinking customer base. Fewer customers lead to higher prices, which only encourages more grid defection.
- **Slow transition to green energy [U]** (National Grid 2016) – Though there is broad interest in transitioning to a green energy system, economic conditions limit the speed at which this transition

can take place. Necessary regulatory and technological changes to the system are slow in coming and consumers are doing what they can, given the limited options available to them.

- **No transition to green energy [V]** (National Grid 2016) – Interest in meeting carbon reduction goals is limited at best with most consumers focused on low-cost, known technologies for managing their energy footprint. Traditional central generation technologies (such as natural gas and nuclear) along with wind dominate the generation mix. There is limited government intervention in the energy sector.

- **Consumer-driven energy system [J]** (National Grid 2016) – Government mandate and regulatory requirement plays a very limited role in managing the energy system with consumers and markets playing a central role. Carbon reduction is not a priority though it does occur as a side effect of the rapid technological development and adoption of consumer-oriented generator technology (solar PV and energy storage in particular).

- **Performance-motivated power system operators [E**] (Zinaman et al. 2015)– Rather than compensation based on costs, public utility commissions shift to compensation based on performance and value delivered. This shift motivates utilities to find ways of enabling their customers to achieve their specific energy goals. Utilities offer (either directly or through partnerships) services to install and manage rooftop solar PV, home energy management, demand response, and neighborhood or community microgrid design, construction, and operation. Customers who might have previously been motivated to defect from the grid see benefit in staying and having the security of supply from centralized generation and worry-free management of their rooftop solar PV while enjoying reduced energy costs.

- **Prioritization of green energy [I]** (Zinaman et al. 2015) – Using the experience and expertise of the existing actors, policy changes are made that prioritize green energy sources. These existing actors respond to these policy changes and are able to retain their roles in the system but realign, shift, and adjust its components and mechanisms to meet these new requirements. The result is a system that is structurally traditional and recognizable but has been altered in its composition and focus.

- **Rise of the distribution system operator (DSO)** [L] (Zinaman et al. 2015) – With increasing DERs and consumer sophistication, distribution system operators have a strong incentive to attempt tighter integration with the bulk transmission system and its markets. Supporting regulatory changes is necessary, but if correctly implemented, the potential of all the assets in the distribution system can be realized and the value available unlocked, via even simple changes in the load profile through retail real-time prices.

- **Set and forget [Z]** (CSIRO 2013; Graham et al. 2013)– "Sustained high retail prices, heightened awareness about the issue of peak demand, and new business opportunities lead residential, commercial, and industrial customers to adopt peak demand management. But, recognizing the busy lives of many customers, the demand management systems are designed to be on a 'set and forget' basis after customers have decided which level of demand management suits them. Measures include building large-appliance control (air-conditioning, pumps), on-site storage, specialized industrial demand reduction markets, and electric vehicle charge management, as well as advanced metering and communication to enable these services." (CSIRO 2013)

- **Rise of the prosumer [P]** (CSIRO 2013; Graham et al. 2013) – "Continued falling costs of solar photovoltaic panels and other on-site generation technologies, sustained high retail prices, and increasingly innovative financing and product packaging from energy services companies leads to the widespread adoption of on-site generation. Residential consumers in particular are empowered by their choice to become more actively engaged in their electricity supply and call themselves 'prosumers.' Electric vehicle adoption is also popular. The use of on-site generation is also strong in commercial and industrial customer sectors, but with a stronger preference for cogeneration or trigeneration technologies. By 2050, on-site generation supplies almost half of all consumption." (CSIRO 2013)

- **Leaving the Grid [Y]** (CSIRO 2013; Graham et al. 2013) – "The continued dominance of volume-based pricing among residential and small commercial consumers encourages energy efficiency without accompanying reductions in peak demand growth. The subsequent declining network utilization feeds increases in retail prices. New energy service companies sensing a market opportunity invite consumers to leave the grid, offering an initially higher-cost solution but one that appeals to a sense of independence from the grid. Consumers have already become comfortable using small amounts of storage on site and in their vehicles and a trickle of consumers takes up the offer. By the late 2030s, with reduced storage costs, disconnection becomes a mainstream option and the rate of disconnection accelerates. Customers remaining on the system are those with poor access to capital and industrial customers whose loads cannot be easily accommodated by on-site generation." (CSIRO 2013)
- **Renewables thrive [F]** (CSIRO 2013; Graham et al. 2013) – "Confidence in the improving costs of renewable technologies, achieved by combined efforts from government and industry around the world, results in the introduction of a linearly phased 100 percent renewable target by 2050 for centralized electricity generation. To shift demand and meet renewable supply gaps, storage technology is enabled to achieve the target at utility, network, and consumer sites. Some customers maintain on-site backup power (for example, diesel) for remote and uninterruptible power applications, offsetting their emissions by purchasing credits from other sectors, such as carbon forestry. Overall, the renewable share, taken as a share of both centralized and on-site generation, is 86 percent by 2050." (CSIRO 2013)
- **Large-scale renewables [H]** (Sanchias and Anderski 2015) – "The focus is on the deployment of large-scale RES [renewable energy source] technologies. A high priority is given to centralized storage solutions accompanying large-scale RES deployment."
- **Market-based energy policies [Q]** (Sanchias and Anderski 2015) – "The main elements are an internal EU [European Union] market, EU-wide security of supply, and coordinated use of interconnectors for cross-border flows and exchanges within the EU. CCS [carbon capture and sequestration] technology is assumed to be mature."
- **Large fossil-fuel with carbon capture and sequestration (CCS) and nuclear [R]** (Sanchias and Anderski 2015)– "The electrification of transport, heating, and industry is considered to occur mainly at the centralized (large-scale) level. No flexibility is needed since variable generation from PV and wind is low."
- **100% renewables [B′]** (Sanchias and Anderski 2015)– "Generation is based 100% on renewable energy, with both large- and small-scale installations and links with North Africa. Both large- and small-scale storage technologies are needed to balance the variability in renewable generation."
- **Small and local [O]** (Sanchias and Anderski 2015) – "The focus here is on local solutions involving decentralized generation and storage and smart grid solutions, mainly at the distribution level."
- **Adaptable, flexible DSOs [K]** (Ochoa et al. 2016) – Retail customer solar PV, electric vehicles, energy storage, and demand response are driving distribution system operators to adopt a more flexible stance toward their management of the power system. Traditional set-and-forget and overly conservative design principles are no longer sufficient due to the dynamic nature of the consumer load and generation patterns.
- **20th century [S]** (Appelrath et al. 2012)– No significant effort has been made to increase the penetration of renewable generation. To meet climate goals, centralized generation dominates and is all low carbon and/or uses CCS technologies. The transmission system has experienced significant

expansion to continue to support large centralized generation. Both renewables and any distributed generation are not readily supported by the power system. Energy costs are stable but high.

- **Complexity trap [T]** (Appelrath et al. 2012)– The energy revolution that seemed possible with the widespread use of renewable energy (at both the transmission and distribution levels) has been stalled out due to differing priorities among those who legislate and regulate. Traditional centralized generation continues to dominate because existing regulations and tariff structures give it an incumbent's advantage. The communication infrastructure to enable a broad-scale smart grid has not been deployed on a sufficient level and programs such as demand response play a minor role.
- **Sustainable and economic [W]** (Appelrath et al. 2012)– The dream of the low-carbon smart grid has been realized. Renewable energy provides 60% of the load, and market forces are working as designed, with consumers playing a significant role. The supporting communication infrastructure has been broadly deployed.
- **Customer DERs enable grid defection [G]** (Bronski et al. 2015a) – Due to the continued decline of the cost of solar PV plus battery storage and demand-side improvement, including investments in energy efficiency and user controlled load flexibility, more customers will choose to power themselves and leave the grid. To make up for the lost revenue (which is necessary to cover repayment costs on large assets such as generation and transmission lines), tariff structures are altered and/or rates are raised, making the economics of leaving the grid even more favorable for their existing customers.
- **Widespread use of flexible loads [A′]** (Bronksi et al. 2016c)– Though average load has ceased growing and has trended down, the peak demand has continued to rise. Rather than increasing their portfolio of traditional assets, which would be operated sparingly but would need to be paid for through rate increases, utilities revise rate structures and implement control devices and programs that shift their customers' loads with negligible effect on the customer experience. This mitigates the increasing peakiness of the load and allows the existing generation assets to be well utilized.

4.2 Proposed Future State

Using these future states identified in the literature, each state was subjectively rated in terms of the influence of the previously identified drivers (see Section 3.0); the table in Figure 2 is a summary of this work. Based on these ratings and the description of each future state, the future states were grouped based on similarities, resulting in five general future states. (Two future states, Nuclear Alternative [A] and Complexity Trap [T], did not neatly fit into the defined groups and were placed in an "Uncategorized" group, not shown or discussed.)

- **Business as Usual** – The architecture and operation of the power system as we know it at the close of the 20th century remains more or less unchanged through the 21st century. This does not preclude modest amounts of renewable integration (particularly utility-scale projects), distributed resources, or demand response; however, none of these energy sources or technologies comes to dominate the system. Any concern over climate change is accommodated through CCS and/or nuclear, and the bulk of the energy in the system is provided by large centralized generation using a variety of fuel sources. There is no revolution in the power system and incumbent players continue to exert controlling influence. As shown in the graphs, virtually none of the drivers identified have a significant influence in these future states.
- **Automated Customer Participation** – Though load growth has slowed, growth in peak load has not and continues to be a problem for power system operators. To manage this peak-load growth and other emerging problems in the system, power system architects implement widespread load controllers connected to a centralized control system through a distribution-level communication

system. Through the use of well-designed algorithms and with minimal necessary input from customers, distribution system operators are able to shape the aggregate load to better match the efficiencies and strengths of the centralized generation fleet. The effect on customers due to the load shaping is generally minimal, though peak-load events do generate some inconvenience. Changes in rate structures result in appropriate compensation for customers that provides sufficient value to offset these inconveniences.

- **High Renewable Penetration** – High value renewables, electric vehicles, and energy storage create very compelling business cases across all levels of the power system, prompting ubiquitous adoption. Centralized generation projects are primarily renewable generation, and some amount of rooftop solar with sufficient energy storage is common on most residences and commercial buildings. The use of renewable energy has resulted in accelerated decommissioning of traditional fossil-fuel plants, reaching CO_2 goals early or on schedule.
- **Distribution System Dominance** – Power system architects adopt a philosophy that the problems and solutions of the power system are found in the distribution system. Rooftop solar and energy storage in the distribution system are common and building energy management software has become equally ubiquitous. This software coupled with a distribution system communication network allows distribution system operators to more effectively manage the devices and power flows. Enabled by the communication system, demand response programs on all scales and with a variety of devices (including electric vehicle charge management and electrical energy storage) are common. Tariff structures have been well adjusted to provide meaningful value to customers, with the distribution system acting as the hub of market activity. Using these same distributed energy sources, microgrids may form both to provide full or limited energy operation during power system service disruptions and to help manage local power flows during normal operations.
- **Grid Defection** – Renewable generation and energy storage provide increasing value but tariff structures have not been adjusted accordingly. Prices on these devices and their controllers have fallen to the point where some customers can meet virtually all of their load with self-generated energy. Enough of these customers choose to end their traditional electricity service that retail electricity rates are increased to compensate for the lost revenue, making the economics of self-generation even more attractive. This "death spiral" leaves a limited number of customers who cannot or choose not to disconnect paying very high energy rates to cover the fixed costs of the power system; this system largely under-utilized and many generation assets are prematurely retired.

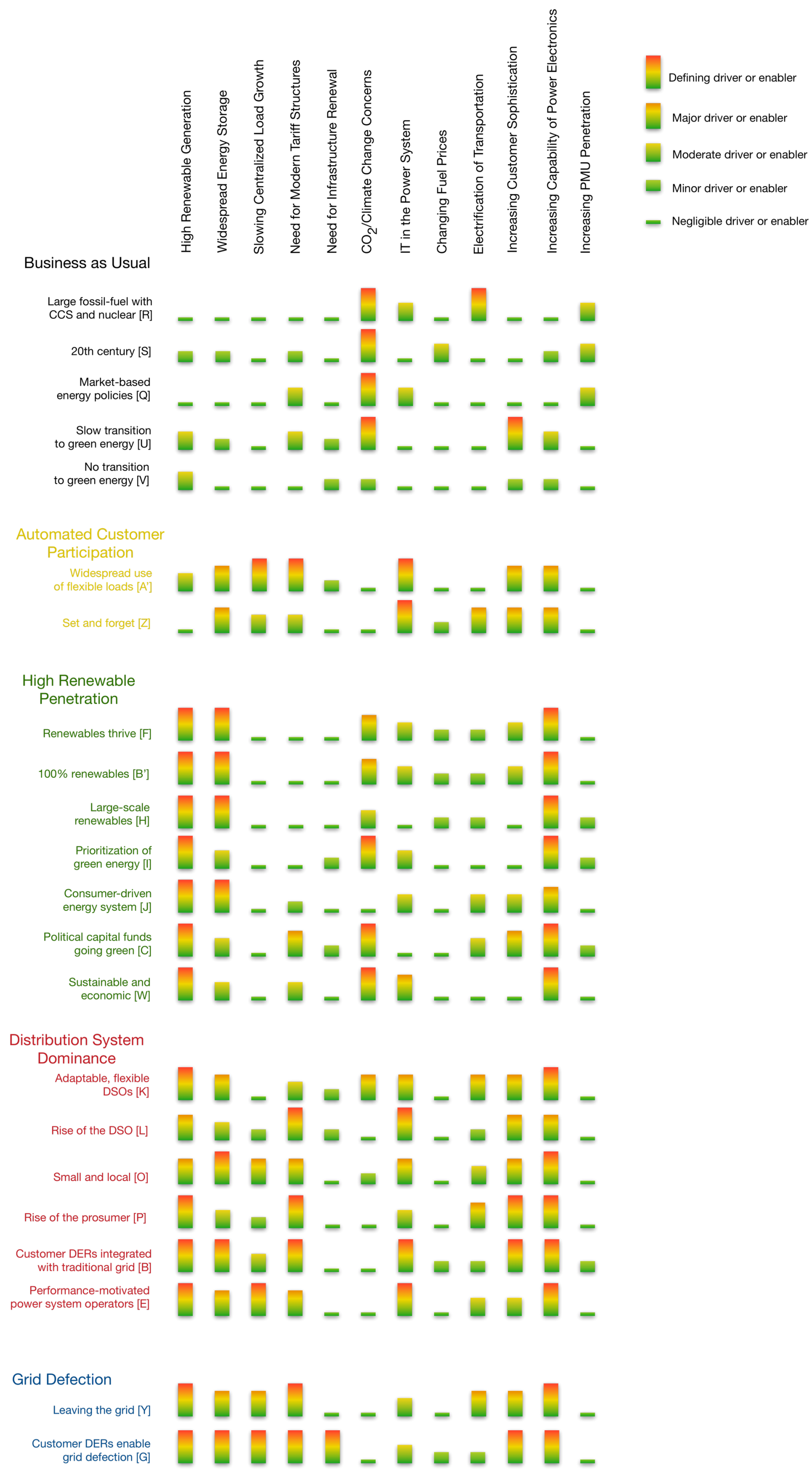

Figure 2. The Relationship between Drivers and Future States Observed in the Literature

As in the case of the drivers and the individual future states (and as shown in Figure 2), these summarized future states are not independent or orthogonal. Though there are key differences between them, there are also many elements in common, the most frequent being the increased role of distributed generation and energy storage.

4.3 Relationship between Future States

Figure 3 below provides an illustrative example of how the summarized future states relate to each other; the sizes of the circles have no specific meaning . In this diagram, all of the future grid states share some commonality with the Business as Usual state with the exception of grid defection because this is not a common state in our current power system. As a notional straight-line derivative of the existing power system, it is reasonable to expect such a level of commonality. The role of renewables is also shown, as the High Renewables Penetration state overlaps with all other states; the centrality of the distribution system is also shown by similar overlaps in the Distribution System Dominance state. Notably, the grid defection state and Automated Customer Participation state do not overlap, indicating the mutually exclusive visions of the future: one where the distribution utility is of central importance and one where it is not.

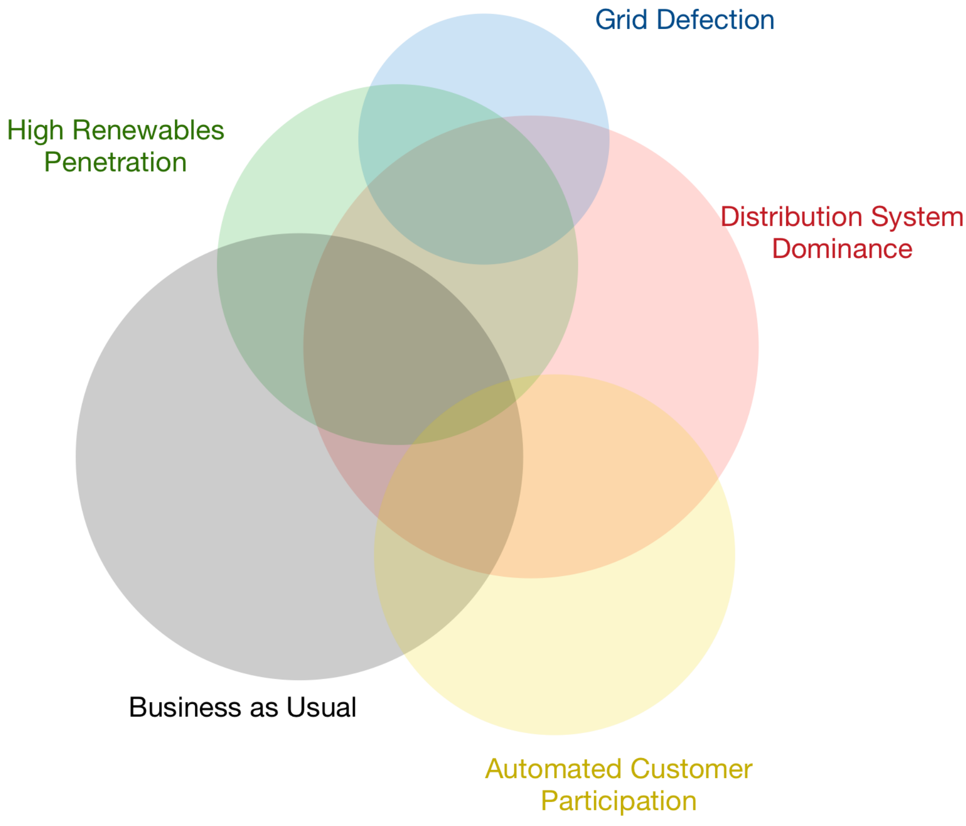

Figure 3. Venn Diagram Showing Overlap in Proposed Future States

It is also possible to notionally show paths or scenarios in this diagram through which the power system as a whole may evolve over time (see Figure 4).

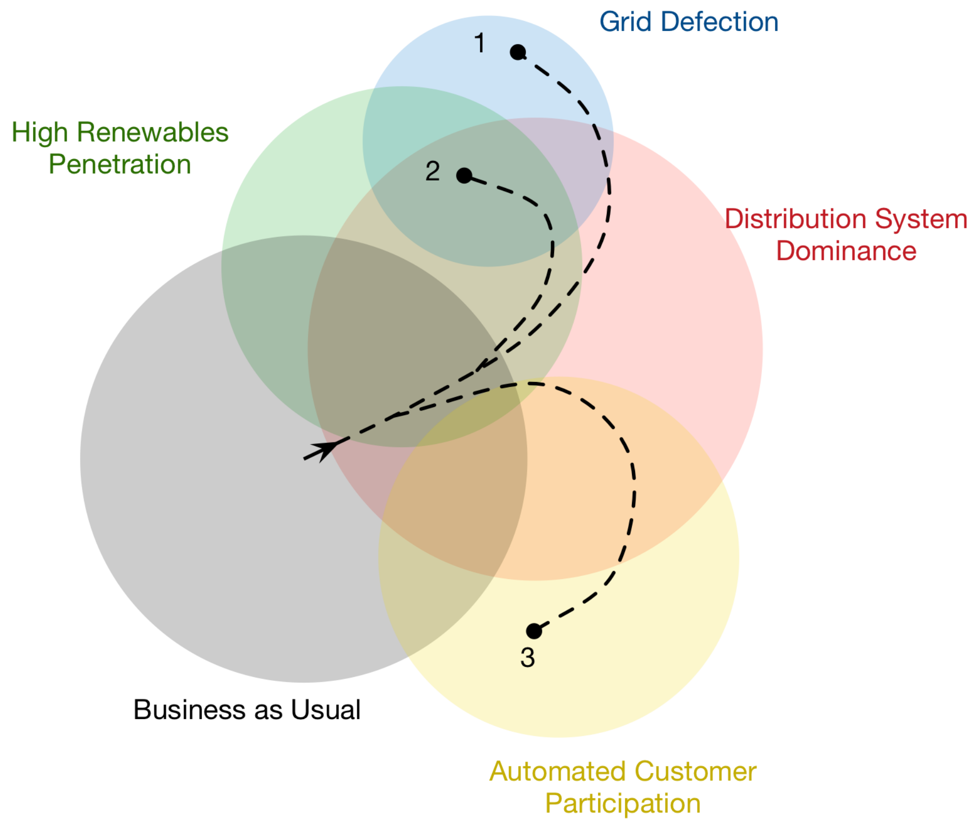

Figure 4. Evolutionary Paths Taken by the Power System

For example, the power system may take a path to the end state labeled "1." Renewables initially start out priced low enough that retail customers begin to adopt them, leading to the development of high-performance, low-cost home energy management systems and communication systems (both for the utility and for the individual customers). Perhaps, though, the declining cost of renewables stagnates and the cost of natural gas falls low enough to enable widespread combined heat and power and/or on-site natural gas generation. At the same time, carbon regulations have forced traditional centralized utilities to prematurely retire many coal assets while simultaneously constructing and commissioning nuclear and natural gas generators, driving wholesale and retail prices up. Faced with rising costs, many customers find it less expensive to power themselves, utilizing the advanced load controls and energy storage they already own to efficiently match their self-generation with their demand.

Alternatively, renewable prices may continue to fall for some time and the power system reaches an end state like "2." Prices of renewable generation in combination with creative financing and aggregation business models lead to widespread adoption of renewables in the distribution system. Advanced communication and controls also proliferate and system operators find decreasing need for central generation plants, choosing not to replace existing generation as it reaches end of life. Instead, they have found it very cost effective to manage their customers' distributed generation and controllable loads for them and many customers find the benefit of reduced complication worth the extra cost. Other customers find higher value in using their own home energy manager to produce similar operations, and inexpensive energy storage has allowed them to disconnect from the distribution system entirely.

The path to end state "3," though, would be very different. Again, an initial interest in renewables results in some degree of adoption for both large- and small-scale installations. To manage these and other assets well, utilities invest in communication and control infrastructure for the distribution system. As in end state "2," the widespread installation of renewables is never realized but the supporting infrastructure is allowing more precise and specific management of some types of customers' loads. Customers experience little to no inconvenience from such activities and are compensated well enough that soon the practice is widespread. Utilities continue to rely primarily on central generation but the need for new, large-scale generation is muted as dispatchable load has come to be seen as a valuable resource and thus is now readily available to system operators as an energy balancing resource.

These three end states and their corresponding fictitious (though plausible) supporting narratives show that though these future states of the power system have been generally grouped, there is still a great deal of diversity within each one and they are far from mutually exclusive. To think of these labels as indicating distinct futures has some merit, but such considerations must be made with the recognition that the evolution of the power system will likely pass through the regimes of multiple future states.

4.4 Complexity and Change

The power system is likely to undergo significant changes in the coming decades as the effects of drivers are experienced. It may closely resemble the one we have today or may be very different depending on the path taken. The changes it undergoes may, in some cases, manifest in regulatory structures, where in others it may manifest in changes to power system topology or in control methods. Each future state represents a different extent of change and a different level of complexity.

While it is difficult to arrive at a universal definition of change in the power system, we may broadly categorize the changes we expect in terms of Extent of Change and Complexity of Change. Admittedly, these terms, too, are fairly vague and subject to interpretation. Nevertheless, each future state may be evaluated along these dimensions and plotted (Figure 5) in the appropriate location. The location of a future state along each dimension is notional at best, but the relative position of one state to another reveals additional insights into the potential paths that may be realized.

Viewing the future states in this way yields several interesting insights:

- As expected, states classified as Business as Usual (black circles) deviate little from today's power system. The variation between them is likely due to differences in assumptions.
- In states classified as High Renewable Penetration (green circles), both extent and complexity of change are higher if renewables are distributed, compared to deployments of utility-scale renewables.
- Distribution Dominance states (pink circles) are represented at a variety of extents and complexities. This implies that this future state may be realized in a variety of ways, some quite a bit different from today's power system.
- Automated Customer Participation states (yellow circles) tend to require fairly complex changes but not necessarily widespread change.
- Some examples of states classified as High Renewables Penetration (green circles) and Distribution Dominance (pink circles) are very similar, e.g., B′, C, J, P, and K.
- Grid Defection states (blue circles) represent a significant departure from today's power system, but at very little increase in complexity.

- That there are no definite patterns (aside from Business as Usual) in the colors, i.e., no clumps of similar colors, helps to illustrate that the states are on a continuum, and not mutually exclusive.

As we noted previously, future states may share many common attributes, but one critical difference in a single driver may be responsible for vastly different outcomes between the states. Consider, for example, the states *Customer DERs integrated with traditional grid* (B) and *Customer DERs enable load and grid defection* (G). These states are virtually identical aside from an economic driver that results in large-scale residential disconnection from the power system. Indeed, the transition from state B to G could be quick and relatively easy, with an effect that far outweighs the transition effort. This suggests that "phase change" transitions like this could play a significant role in shaping the power system. The implication is that a given transactive system must be fully examined in a variety of future states in order to anticipate such transitions and avoid unintended consequences.

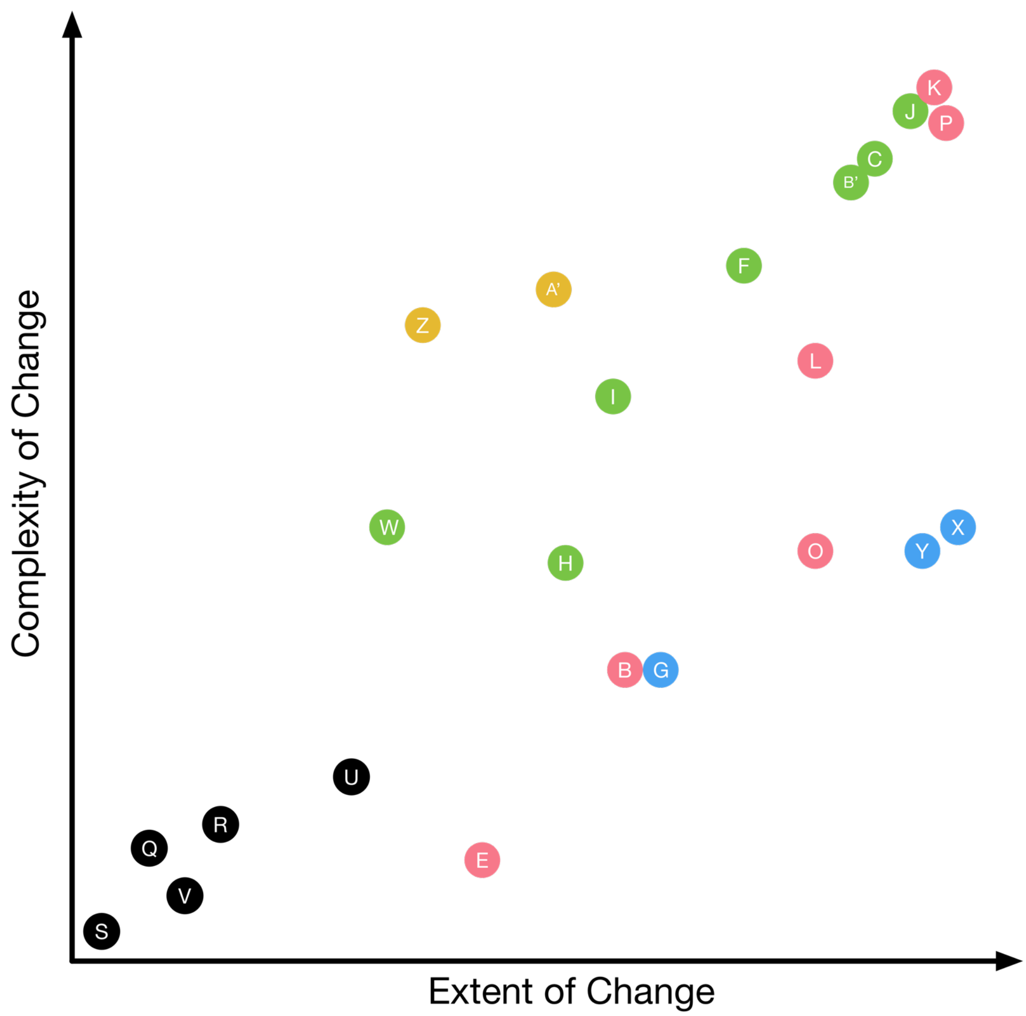

Figure 5. A Notional Representation of the Complexity of Change and Extent of Change Characteristic of the Future States Proposed in the Literature

5.0 Conclusion

The simulation and evaluation of transactive systems depends heavily on assumptions regarding the future state of the electric power system. To define every simulation detail is a challenging task. It is made more difficult, and is of questionable value, given the uncertainty inherent in the many factors that will influence the evolution of the power system.

Instead, we have surveyed the literature for common themes and distilled our findings into a select set of future states and the drivers that produce them. These future states are

- **Business as Usual** – The architecture and operation of the power system as we know it at the close of the 20th century remains more or less unchanged through the 21st century.
- **Automated Customer Participation** – Through the use of well-designed algorithms and with minimal necessary input from customers, distribution system operators are able to shape the aggregate load to better match the efficiencies and strengths of the centralized generation fleet.
- **High Renewable Penetration** – High value renewables and energy storage create very compelling business cases across all levels of the power system. prompting ubiquitous adoption.
- **Distribution System Dominance** – Power system architects adopt a philosophy that the problems and solutions of the power system are found in the distribution system, and are aided by rooftop solar, energy storage, and building energy management.
- **Grid Defection** – Renewable generation and energy storage provide increasing value but tariff structures have not been adjusted accordingly, resulting in defection of load and customers from the power system.

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