System Dynamics Modeling

AN APPROACH TO PLANNING AND DEVELOPING STRATEGY IN THE CHANGING ELECTRICITY INDUSTRY

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April 2019

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The electric utility business is changing in complex ways. Supply-driven hierarchical structures are being challenged by new technologies that are largely distributed and characterized by decentralized decision-making. Customer adoption is partly based on the economics of energy but also on cultural and other factors less familiar to utility industry planners. Understanding the feedbacks and interdependencies caused by these changes is becoming more important than ever.

Such feedbacks and interdependencies may be on a macro scale, such as how utility decisions affect the job market and overall economy, or on a more local scale, such as how the adoption of new technologies can affect the planning and operational paradigms of utilities and the associated impacts they may lead to. This paper introduces the structure and insights of a modeling approach, known as System Dynamics, that is well-suited to helping understand these feedbacks and interdependencies, and to developing effective strategies against these ongoing changes. The paper also discusses how this modeling approach could be utilized for various systems being developed around the world.

I. The Changing Industry

A wide variety of new energy supply and energy use management technologies have been developing and permeating rapidly into the electric power industry. Many of these technologies are at the "grid-edge" space that lies between the distribution and retail business sectors of the electric utilities and directly face customers. Grid-edge technologies are best recognized by (but not limited to) the various types of distributed energy resources (DERs) that largely take the form of distributed generation (DG) and energy-use optimization technologies, including advanced energy efficiency (EE) and demand response programs. The most prominent DER technologies include solar photovoltaics (PVs), electric vehicles (EVs), and energy storage (ES), often in the form of batteries. A common feature among these DER technologies is that their adoption is generally driven by policy-induced customer decisions, which are not necessarily based on engineering economics but rather by the assessments of electricity system planners.[1] As a result, they may sometimes be added in places and in quantities that are not well correlated with system needs, and may even create new remedial needs when concentrated in areas with limited "hosting capacity" for such DERs. On the other hand, they may provide system benefits if well located.

[1] Around the world, regulatory incentives combined with the falling costs of DERs (PVs may be a good representative example) are driving end customers to adopt and invest in these DER technologies. Policies such as net metering, grid resiliency initiatives, and global movements to transition to cleaner energy have further accelerated this movement.

DERs usually involve some degree of self-supply or conservation and therefore can contribute to reducing system load growth and may help defer system upgrade needs to accommodate load growth for a target area. Oftentimes, DERs are added for reasons that have more to do with the needs and developments in other industries than the power sector, but they could have profound effects on the latter, thus highlighting the interdependencies and coupling between different industry sectors. In addition, due to several factors, including the shifting economy, energy efficiency, and increase DERs, electric utilities (especially in OECD countries) are facing an era of little, and sometimes negative, load growth. DERs reducing net load to the utility can have several consequences. For example, due to the use of volumetric pricing of electricity, the fixed costs of the utility for existing and new infrastructure need to be assigned to a smaller base of sales, raising average electricity rates; however, this could change as EVs and other electrification technologies play a bigger role in the energy mix. In short, as DERs potentially transform electric power systems, the approaches to planning and operations will have to evolve.

Examples from around the world show that feedbacks caused by the interdependencies of different variables related to increased penetration of DERs are real and important to understand, especially if more sustainable solutions that encourage efficient DER adoption are found. DER penetration has differential and correlated impacts across the different sectors of the electric utility industry. It is important to note the value power grids provide even in an environment of more DERs. Importantly, while some customers will base such decisions on avoidable rates, in an increasing hybrid grid of centralized and decentralized solutions, the value of the grid and systems will have to be reflected in the decisions to invest in DERs. In many OECD countries, the traditional regulatory frameworks and rate structures are being modified to account for higher penetration of DERs. However, to meet policy objectives such as reliability, resilience, fairness, affordability, and other broader societal benefits, more and more emphasis is being placed on the value of grid services to customers as new regulatory frameworks are designed.

Such dynamics make planning and pricing for modern distribution systems and services more difficult. For example, it becomes harder to anticipate where future net load growth will occur or how much variance in loading might be experienced by a given piece of equipment and, in general, what the benefits will be to the entire system. With a higher penetration of DERs, there will be a need for greater visibility and coordination both during planning and operations.

Developing strategies for power systems with higher penetrations of DERs is even more complex, because external factors add to the decision criteria and customer behavior. Some of these external factors are the aforementioned regulatory and policy incentives; for example, tax incentives (such as the U.S. Investment Tax Credits and Production Tax Credits), "green energy bank" loan assistance policies, or Feed-in-Tariffs implemented in a number of countries all encourage installing renewable resources at various levels. As such, electric utility personnel, their regulators, and policymakers may not see the overall intertwined picture using conventional planning approaches. Finally, planning in this ever-changing environment involves a lot of uncertainty—for stakeholders associated with new technologies, new customer behaviors, and policy and regulation—leading to many differing opinions about the pace, extent, risks, and benefits of potential changes. This leads to difficulty in gaining consensus among the different departments and individuals even within one entity, or amongst stakeholders in the sector.

Many utilities around the world have tried to address the impact of DER growth through traditional scenario-based analyses. For example, assessing the impact to the distribution equipment with deep DER penetrations using various hypothetical renewable penetration scenarios; e.g., "what if" analyses of 2%, 5%, 10%, or 20% levels of rooftop PV penetration. These scenario-based analyses can be informative as snapshots of possible futures, but they are often simply a range of conditions that seem to span the likely outcomes, with little consideration of what could cause those results to occur. The associated feedback and interactions are limited to what the analyses are set up for, or in other words, what the utilities understand. In more mature electricity markets, such as in OECD countries, utilities, generally, are largely aware of the interactions between politics and markets even though they may still use scenario-based analyses. However, in less developed markets, utilities may overlook feedback and interactions in the system.

In addition, scenario-based analysis is typically more linear and often can be monotonic (projecting changes in one direction, either up or down) in how it builds in anticipated future conditions with discrete changes and inputs that depend on exogenous drivers. By design, it typically addresses the impacts among variables on the assumption that they are relatively independent of each other. Implicitly, they tend to involve the belief that the potential range of the variable being tested and the way it will affect other behaviors on the system is relatively well understood. For problems that have been recurring for years or longer, this is a perfectly reasonable set of assumptions. For instance, it is quite plausible to model the U.S. wholesale power prices of today as being largely sensitive to the price of natural gas, which has a historical range of price variability that can be used to span many scenarios.

However, unlike the case for well-known technologies, projecting the extent of the adoption and consequences of DER penetration is very different; it often lacks enough history or statistical evidence to be indicative of where it will go or what it will affect. For example, in many utility territories in OECD and some emerging economies, rooftop PVs have only been adopted by less than 1% of the customers, and many of those may not be typical of future adopters, instead leaning towards a very small percentage of the population (such as group of technology enthusiasts) that may not well represent the public. It is extremely difficult to extrapolate their history of adoption into the future using conventional scenario-based analysis techniques. In today's evolving environment, where fewer variables are predictable and new players (e.g., DER manufacturers and installers, customers, and policymakers) make decisions based on their own objectives that are not necessarily in line with system-wide objectives, scenario-based analysis may be insufficient, especially because the potential range of variability is constantly increasing. Furthermore, non-linear interdependencies and feedbacks are becoming more and more important and the intertwined sensitivities among the variables cannot be adequately captured in scenario-based analyses. Moreover, as a foible of our intellectual skills, most people are not very good at foreseeing how non-linear and probabilistic processes can behave. It is too hard to envision (or build conventional scenario-based models for) how several variables changing somewhat independently yet interactively will evolve. The interaction between DER penetration—in particular DG implementation and their technical performance, the implications for rate structures, and other exogenous factors—can no longer be easily and adequately addressed by planning based on scenario analysis.

II. The System Dynamics Approach

Planning power systems or developing policies and regulations in today's challenging environment with vexing complexity requires holistic approaches. A dynamic model that ties together the various segments along the various electricity value chains and emerging value networks together and addresses non-linear interactions among them is needed. An ideal dynamic model will be explicit about drivers of the decisions facing the various actors in the market and how the decisions will interact. Of course, because there is uncertainty about the drivers, responses, and strengths of interactions in such a model, it must also be easy to test the sensitivities of various drivers and assumptions to see what types of conditions and resulting behaviors are plausible and internally consistent. Ease of testing capability allows the user to compare a number of alternative assumptions and strategies in real time. Finally, the model needs to be simple and easy to understand, while not trivializing the underlying assumptions and interdependent processes.

Towards this end, this paper proposes a new approach to planning the utilization of System Dynamics methods to simulate the complex and interdependent aspects and impacts of new technology adoption improvements, regulatory policies, rate structure, and resulting financial performance and business sustainability.

System Dynamics[2] is a modeling approach that has been used for analyzing many complex processes where multiple participants are involved and there are known feedbacks among their behaviors. For instance, it is used extensively in the planning of very large engineering projects that have a dynamic critical path. It is designed to aid in understanding non-linear complex systems and to provide the ability to visualize the business process impacts. Essentially, it involves converting an influence diagram of how numerous factors in a complex process relate to each other into a framework that utilizes stocks, flows, and feedback loops to keep track of how those influences could play out under various stimuli. This allows changes to unfold from the interaction

[2] System Dynamics modeling was developed at the Massachusetts Institute of Technology (MIT) as an extension of the mathematics of control theory and numerical solutions to complex differential equations. It is known for the ability to visualize business organizations in terms of the structures and policies that create dynamics and regulate performance. System Dynamics courses taught at MIT use simulation models and case studies, among other materials, to develop principles of policy design for successful management of complex strategies, and to improve understanding of the ways in which an organization's performance is related to its internal structure and operating policies, as well as those of customers, competitors, suppliers, and other stakeholders.

of internal structures and outside stimuli, rather than requiring those changes to be predicted statistically or assumed as structural scenarios. There are still projections of the future in such a model, but "scenarios" in System Dynamics are projections of how assumed change factors will interact and play out, without presuming any specific outcome state, by modeling the dynamic effects associated with endogenous variables and rates of change. This will reveal what can cause accelerations or reversals of change, or could induce "tipping points", as well as what the culprits are for any such tipping points. For instance, a System Dynamics model can reveal when and why you might have a 20% penetration of a DER as a function of rate design, the pace of technology change, and financial incentives, rather than just having to assume such a scenario might occur and then testing its consequences conventionally.

System Dynamics utilizes stocks, flows, and mathematical relationships to create feedback loops. The variables that are "stocks" are metrics that accumulate, such as cumulative number of customers that have adopted a type of DER. The variables that are "flows" are the transfers between stocks, often represented by simple algebra. However, the relationships between variables can also contain non-traditional functions, such as a time delay component, or non-linear growth rates and correlations, to model adequately the interdependencies. Such relationships are shown using arrows, which create a model that visually resembles an influence diagram. Behind each of the arrows are fairly simple and intuitive mathematical formulas representing the operative relationships between the different variables and stocks (oftentimes business elements). The mathematical formulas can be simple because each variable that affects, or is affected by, another often has a simple marginal relation over short-time intervals and modest changes in the exogenous inputs, which is how the model simulates and solves.

Figure 1 illustrates a simple System Dynamics model of customers adopting a product (e.g., PVs or EVs).

Figure 1: System Dynamics Modeling Approach

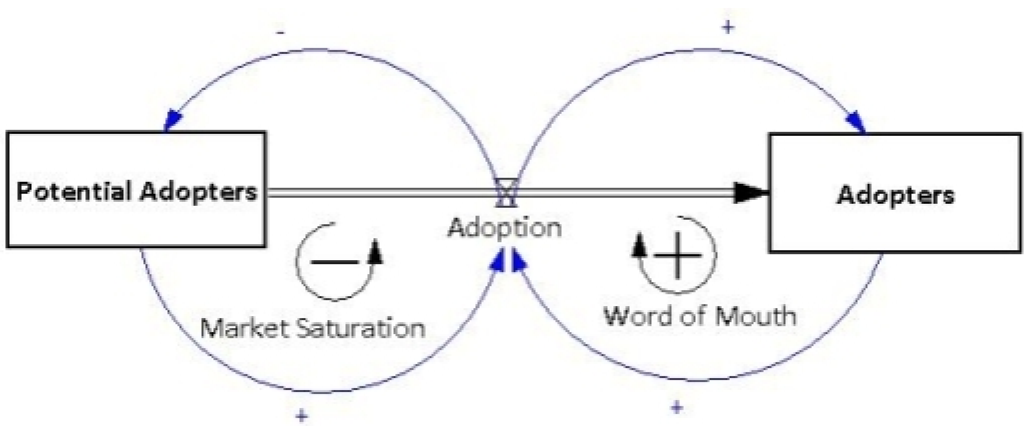


Figure 1 shows two stocks, "Potential Adopters" and "Adopters", and a flow "Adoption." In scenario analysis, the flow would be given a set rate (for example, 100 customers adopt PV or EVs every month). However, System Dynamics models the inherent feedback that affects the rate of adoption. The circular blue arrows on the left-hand side of Figure 1 represent a "balancing" loop.

As more customers adopt, the market becomes more saturated and there are fewer customers (potential adopters) left who are interested in adopting, which puts downward pressure on the adoption rate. Therefore, the overall Market Saturation impact is shown as "negative," indicating higher market penetration rates will reduce the rate of adoption. The circular blue arrows on the right-hand side represent a "reinforcing" loop. As more customers adopt a technology, word-of-mouth and social contagion leads to greater levels of adoption. Therefore, the overall Word of Mouth impact is shown as "positive," indicating increased Word of Mouth raises the rate of adoption. The balancing and reinforcing loops are both at play, pushing and pulling on total adoption. Therefore, at different times or based on different assumptions, technology adoption could lead either to a higher or lower rate of future adoption. Such feedback cannot be readily modeled using traditional scenario-based analysis.

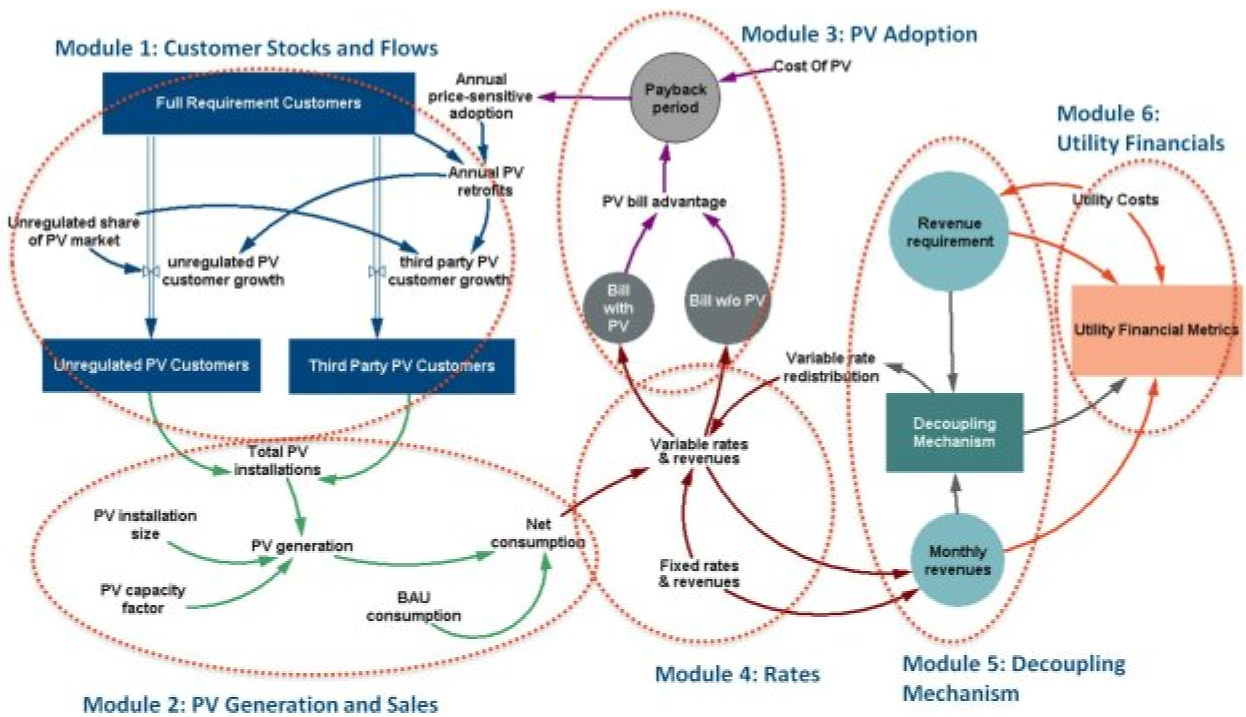
These abilities allow users to explore alternative strategies for mitigating risks or for capturing opportunities from suitably phased provision of the infrastructure—for example, how is timing of need for more efficient pricing related to timing of technology improvements in DERs, or, how much can distribution costs increase to support DERs while the total net customer bill is falling? Finally, visualizing the business process will show the interdependency of the various influences changing the industry. While, in general, utilities in OECD countries are constantly improving their stakeholder engagement processes, the use of the holistic System Dynamics approach can further facilitate conversation and dialogue, especially for executive management committees or regulatory proceedings and policymaking that involve participation of multiple actors with diverse backgrounds and interests.

In addition to being well-suited to the emergence of DERs, the System Dynamics approach is helpful for any other industry developments that involve third-party decisions, rapid changes in technology, and strong feedbacks reflecting the interdependencies between sectors, such as transportation and electricity, that have their own distinct economics and decision makers. For instance, there may be a long-run tension between whether renewables will be more substantially developed at the high voltage, wholesale end of the supply chain or at the low voltage, distribution, and customer end. Each dampens the need for the other, and whichever prevails has huge implications for load levels and where the new grid infrastructure and services will be needed. As another example, if there is a very strong long-term drive towards renewable electricity, the use of energy sources could potentially decline, with resulting changes in fuel costs and the viability of gas generation and even gas use for non-electric purposes. These are distant concerns, but they affect the value of resources that could be developed today, such as new power plants or fuel pipelines, which all have long lives. Increasingly, a system perspective is needed to understand what the future could look like and what can improve the prospects for attractive, stable outcomes. Other considerations may include how different drivers, such as customer behavior and needs, urbanization, and population growth, can affect changes in other aspects of the systems in the short and long term. For example, long-term population increase concentrated in urban areas with limited space, such as in mega cities, (and therefore leading to multi-dwelling high-rise buildings) may not allow deployment of DERs, and favor resources that come from large centralized power stations in remote locations. In the same vein, providing access to electricity to hundreds of millions around the globe who live in rural and peri-urban communities would favor more DER.

III. Illustrative Example of the System Dynamics Model

Figure 2 below shows an example System Dynamics model configuration that focuses on the DER adoption dynamics discussed earlier. This model analyzes the impact of PV adoption for a hypothetical utility—a well-recognized representative example of DER technology affecting the utility business world-wide. The influence diagram shown here illustrates the major connected elements of the model, which also reflects how it was developed and its value for simplifying and providing an easier understanding of the intertwined issues.

Figure 2: System Dynamics Model Architecture



One unique feature of the System Dynamics model is its ability to visualize the business processes. The System Dynamics model shown in Figure 2 contains six different utility business segments, with each segment being a module. In this simplified architecture, customer adoption of PV is tracked using **Module 1: Customer Stocks and Flows.** As customers adopt PV, they move out from the "Full Requirement Customers" stock and into a stock of customers who have adopted PV. The number of customers who adopt PV naturally affects **Module 2: PV Generation and Sales**. PV generation impacts net consumption, which will change how much electricity the utility sells in **Module 4: Rates.** Modifying rates and rate structures in **Module 4: Rates** and **Module 5: Decoupling Mechanism** will affect the next-period economics of PV adoption in **Module 3: PV Adoption**, and thus feed back into **Module 1: Customer Stocks and Flows.** The revenues collected from rates also feed into **Module 6: Utility Financials** where key financial metrics are tracked.

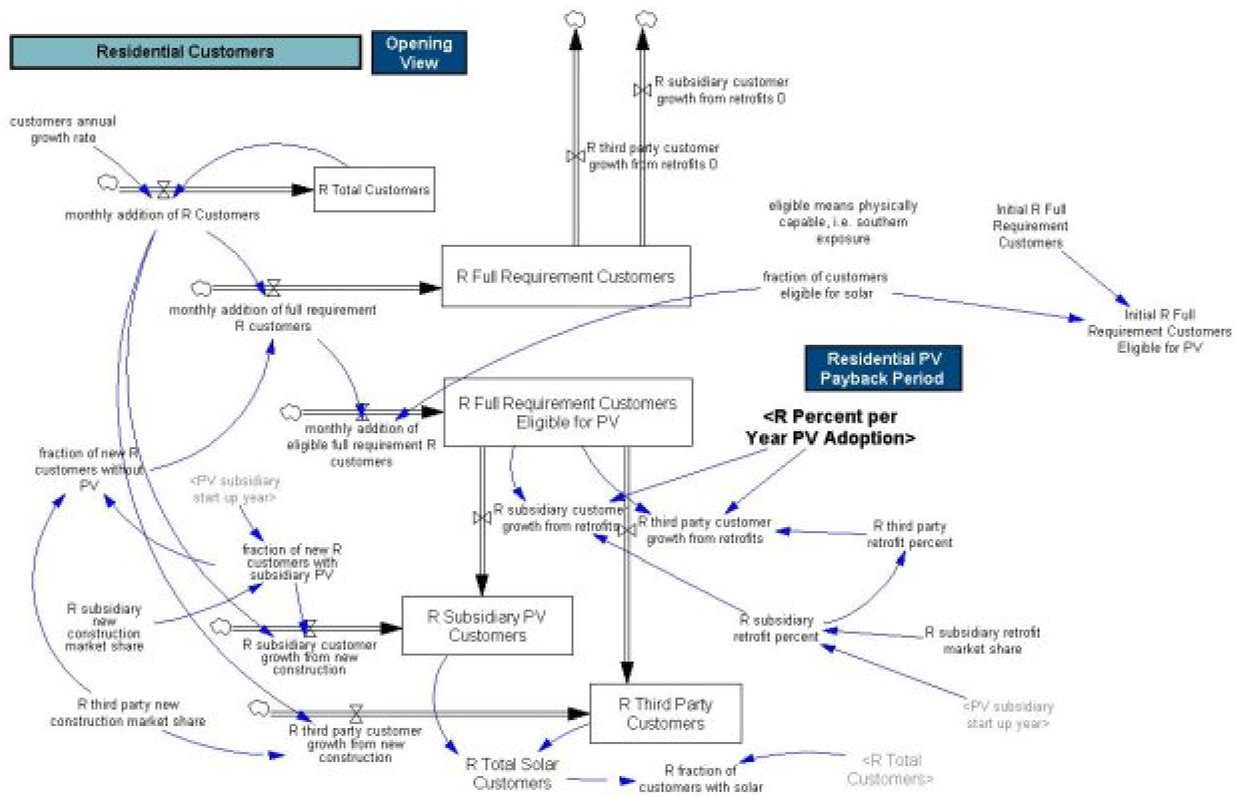
The model architecture schematic appears simple, and indeed each of the stocks and flows individually usually are quite intuitive and easy to design. However, building this collection of basic relationships up to a System Dynamics model as a whole provides insight into the underlying complexity of the issue. For example, in Figure 2, **Module 1: Customer Stocks and Flows** tracks customers as they move from being full-requirement customers to adopting PV (the two downward facing arrows). To create a robust model of customer stocks and flows, one would need to consider a number of different items, some listed here:

- Customer population
  - What is the load forecast?
  - What are the customer segments?
  - Do customers make cross-product choices (e.g., adopting EE instead of PV)?
- Avoidable utility costs
  - Is there a locational value to PV, requiring more insight into customers?
  - What is the outlook for energy and capacity prices? At what point do they start to be affected by DERs?
- DER (i.e., PV in this example) development
  - How long does it take to develop a PV system?
  - What are the offer terms? Is it a leasing or sale program?
  - How do solar developers market to customers?
- Switching load
  - For economic factors in choosing PV, is total cost, Levelized Cost of Entry (LCOE), or payback more important?
  - How much difference does it make if PV systems are purchased vs. leased?
  - What are the non-economic motivations of PV adoption (such as social contagion)?

The need for such considerations often becomes more apparent from having built even a fairly simple integrated model, because it will reveal previously untested underlying complexities. Highlighting this complexity in the forefront helps utilities understand their customers and their systems, as well as map their customers' journey, which can then help them to be more proactive in their corporate planning.

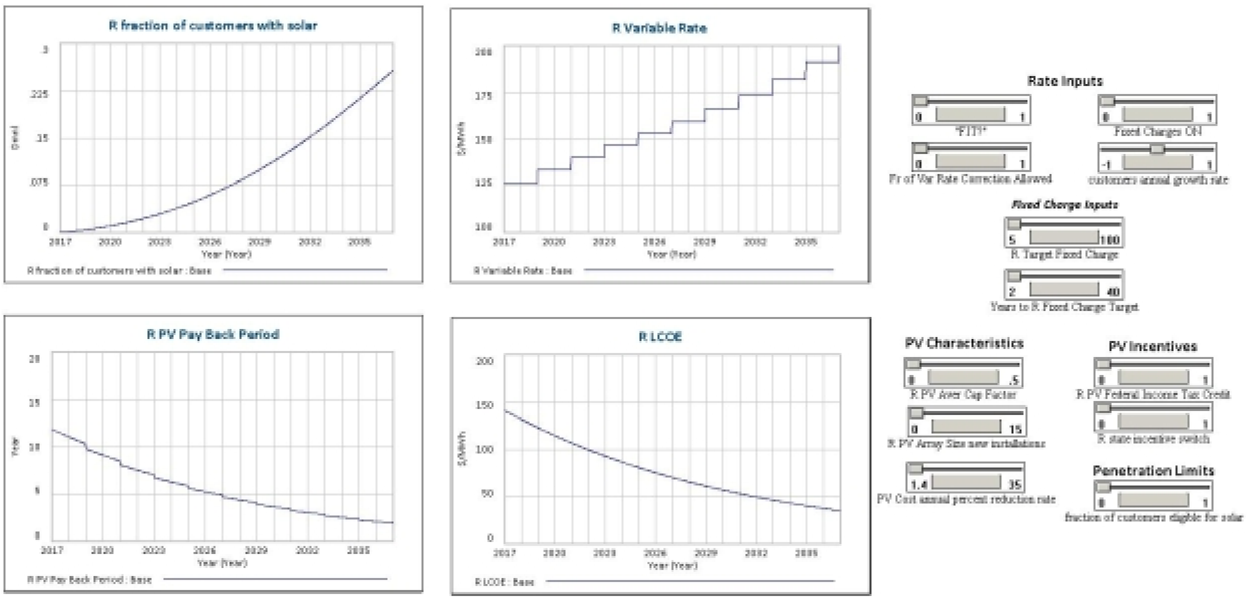
As the needs for more sophistication or nuance of behavior in the model become apparent, it can readily be split into additional sub-processes that make the results more realistic. Figure 3 below shows how details within **Module 1: Customer Stocks and Flows** from Figure 2 can be expanded to better represent the choices customers may make. The model allows the user to see the underlying formulas associated with each individual arrow.

Figure 3: Expansion of Module 1) Customer Stocks and Flows in System Dynamics Model Architecture



Similar to the process flows, the model results are presented visually in real time. This ability becomes especially important when dealing with multiple stakeholders with different objectives. Even within a single organization, individuals representing different departments may not necessarily agree on what is important and on what the focus should be. Figure 4 below is a sample output from the model shown in Figures 2 and 3. By using the “sliders” shown on the right-hand side, the user can test the sensitivities of inputs and immediately observe changes through the figures on the left-hand side.

Figure 4: System Dynamics Model Output



An associated advantage of the System Dynamics model is that, once the relationships between variables, stocks, and flows are defined, disparate assumptions can drive the model, and the starting point does not need to be from Module 1. It is a set of closed loops, amenable to focusing anywhere and manipulating any starting condition or flow rate, while dynamically monitoring whatever stocks of outcomes are of interest. For example, acceleration in the decline of installation costs for PV would make the payback period shorter in the near-term future, resulting in more customers adopting PV quicker. As more customers adopt PV they could use less electricity from the power grid, which ultimately affects how rates are structured. *The feedback of such non-linearity is not captured in or accounted for in typical linear models,* unless the models were constructed specifically to address the issue of the impact of declining PV costs.

IV. Application of the System Dynamics Approach

The System Dynamics model lends itself to being used by system planners, strategy managers, and policymakers to test alternative business and regulatory decisions. It is useful in examining the potential impacts and interactions of adopting centralized and/or decentralized solutions. Importantly, it should be noted that this approach to modeling does not make the problem—such as how customers will behave or how fast technology will evolve—go away. Some aspects of behavioral economics will have to be carefully considered. What the System Dynamics model reveals is how sensitive a future situation is to the various assumptions, for example, how new technology acceptance by consumers can impact the grid planning and operations, as well as rate structure.

The System Dynamics approach of analytical rigor coupled with relative simplicity can be expanded beyond system planning by electric utilities. Because of its ability to address and visualize the interdependencies of various actions of multiple parties and the sensitivities of these actions to each other, the System Dynamics approach is well-suited to designing business models from the bottom up, where doing so would be dependent on what is happening in the rest of the economy. Such situations arise especially in countries and jurisdictions that are currently in the midst of an ongoing energy transition and perhaps developing their own macro-economy and commercial infrastructure at the same time as building up the electric utility industry. In such countries, there may be other external forces that are not typically considered in traditional utility planning—including the electric utility's role of creating jobs, leading the country's research and development activities, and functioning as a budget collection and allocation vehicle. [3] There are many additional feedbacks that become important, for which System Dynamics modeling is well-suited. For example, enhanced electrification may stimulate new growth by providing power for various applications that would otherwise be constrained, including developing industries and building smarter infrastructures.

In particular, developing public policy initiatives that set targets and goals, possibly including incentives associated with those goals, requires a robust economic and feasibility analysis that covers a wide spectrum of stakeholders with varying agendas to ensure (or at least reduce the odds) that no unintended consequences occur. System Dynamics would also provide a holistic approach to understanding the different approaches to grid modernization and designing customer experience taking place around the world.

Figure 5 provides an example sketch of how System Dynamics could model the utility on an island with a tourism-based economy—often struggling with high fuel costs and a not well-diversified energy base, and accounting for the inherent interdependencies in the system, something at which traditional scenario-based modeling would struggle. Observing the cross-sectoral interactions in such a model would allow different stakeholders to realize the interrelationships among various business segments and allow for a more robust policy discussion based on results that can identify the comparative sensitivities of the various assumptions, rather than an individual stakeholder's intuition and feel.

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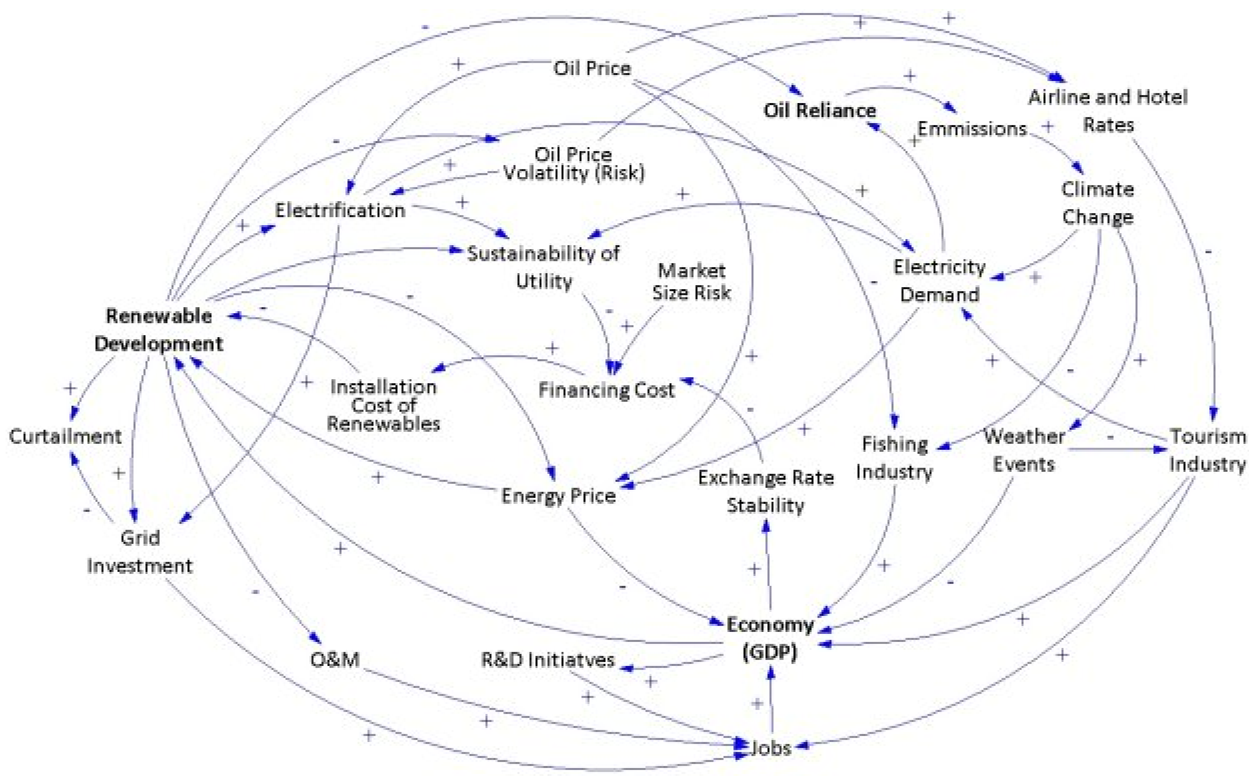
3 For example, some jurisdictions outside the U.S. include a "trash collection fee" in their electricity bills, rather than collect it through taxes. This is because people will try to avoid taxes but will still pay electricity bills to avoid being cut off from service.

Figure 5: Illustrative System Dynamics Sketch of Island Utility



For non-OECD and emerging economy countries that are modernizing their energy sectors today, the System Dynamics approach, by visualizing the rather complex and intertwining process flows and sensitivities, can help plan and design from the ground up the future utility system and the associated regulatory framework, rather than relying on mimicking selected aspects of the existing systems and models in OECD countries, which are also undergoing transformations due to new market conditions and industry trends. This may be critical because the feedbacks of the various impacts are more direct and acute in smaller economies. In the long run, if the future utility planning in less industrialized countries proves to be successful, industrialized nations may consider re-importing such models. The System Dynamics model could help implement the new model by identifying the least painful transformation path. In general, while it is not a panacea for modeling the changing global utility industry, it is a powerful way of confronting the complexity and increasing interdependency between what utilities choose to do in response to or anticipation of customer and stakeholder expectations, and how the future could unfold for mutual benefits for all.

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