Lesson 1 – Course Syllabus: Setting off on the Path of Engineering Complex Systems

ENGG 199: Model-Based Systems Engineering, Analysis & Simulation

Course Introduction

Prof. Amro M. Farid

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Syllabus Outline

Objective 1
To explain how we will learn to engineer complex systems . . .

- Course Logistics
- Instructional Team
- Course Rationale
- Course Components
- The Learning Environment
- Expectations
- Lecture Summary

Conclusion 1
Students will have a clear understanding how ENGG 199-MBSE will proceed this term.

Lecture Logistics

Course Title & Number: ENGG 199 Model-Based Systems Engineering

Term & Year: Winter 2019

Lecture Hall: Cummings Hall. Room 202.

Class Time: 2A-Block – TR 2:25 - 4:15

X-Hours: 2AX-Block – Wed 4:35-5:25. Note: Many X-Hours will be used this term.

Instructional Team

Lead Instructor

Lead Instructor: Prof. Amro M. Farid

Office Location: Maclean. Room 215.

Office Phone: (603) 646-1524

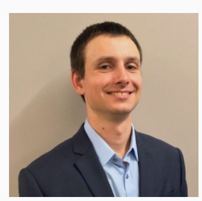
Email: amfarid@dartmouth.edu

Office Hours: Before Class. TR 1:25-2:25

Teaching Assistant

Teaching Assistant: Dakota Thompson

Email: dakota.j.thompson.th@dartmouth.edu



Course Rationale

Course Prerequisites

ENGG 199-MBSE, like other introductory graduate-level systems engineering courses at other universities, is meant to be taken after the student has well-established their undergraduate engineering program.

The prerequisites are:

- ENGS 20, 21, and 22
- At least 1 from ENGS 25 or 26 or 27 or 52
- Preferred 1 from ENGS 65 or 66 or 75 or 89.
- Equivalent courses allowed by permission.

Prerequisite Knowledge

1. **Scientific Computing**. Comfort in computer programs (in MATLAB or Python) that compute numerical values of several logically organized functions (ENGS 20)
2. **Introductory Design Skills**. Comfort in designing and implementing a small-scale engineered system in a small team environment *(ENGS 21)*
3. **Introductory Systems Analysis**. Comfort in analyzing analytically as well as numerically lumped parameter linear dynamic systems *(ENGS 22)*
4. **Intermediate Systems Analysis**. Comfort in analyzing analytically as well as numerically more complex systems (e.g. thermodynamic, controls-based, stochastic, or supply chains). *(ENGS 25, 26, 27, 52)*
5. **Intermediate Design Skills**. Comfort in designing and implementing a medium-scale engineering system in a medium-sized team environment. *(ENGS 65, 66, 75, or 89)*

Model-Based Systems Engineering sits upon a solid foundation of design-synthesis and mathematical analysis skills.

Without this foundation, MBSE is largely untenable in a 10-week term.

Course Description

This course is designed to introduce students to the world of model-based systems engineering. Systems Engineering is an interdisciplinary field of engineering and engineering management that enables the realization of successful complex systems over their life-cycles. Systems Engineering integrates multiple disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation to obsolescence. Systems Engineering considers the technical, social, and business needs of all stakeholders with the goal of realizing a successful system. At its core, systems engineering utilizes systems thinking principles to organize this body of knowledge.

This course will prepare students to engineer, analyze, and simulate complex systems. Such systems are characterized by a high level of heterogeneity and a large number of components. They will appreciate the physical, informatic, social and economic aspects of such systems. They will use systems thinking concepts and abstractions to manage complexity. They will learn to use model-based systems engineering techniques to model a system's form, function, and concept. They will analyze the structure of these systems using graph-theoretic approaches. Finally, they will learn to simulate social, technical, and economic systems with continuous-time and discrete-event dynamics. The systems engineering skills developed over the course are applicable to a broad range of disciplinary applications.

Course Components

Course Goal

To prepare students with the skills to engineer complex engineering systems through systematic steps of modeling, analysis and simulation.

Motivating Examples:

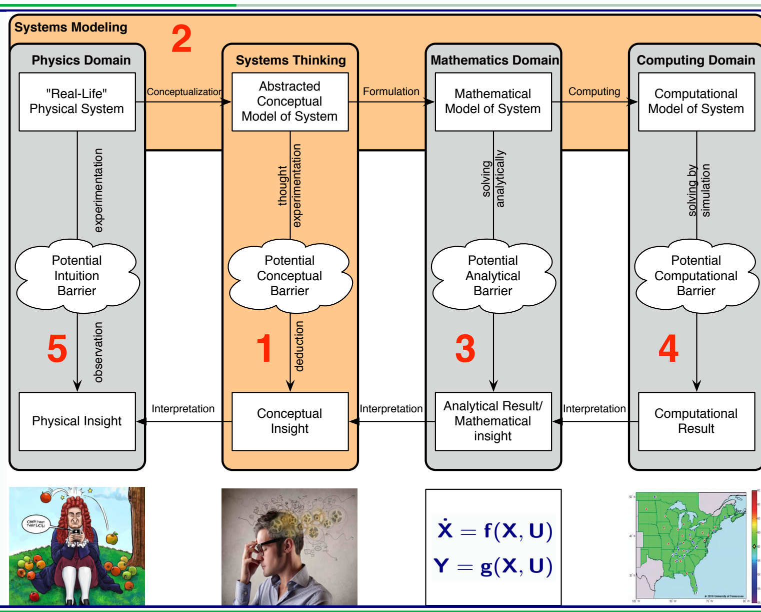
- Roving Mars 2006
- Curiosity Rover 2011
- 3 Epic Fails
- Why it is so hard?

Central Topics I

1. **Systems Thinking**: The ability to think about a question, circumstance, or problem explicitly as a system – a set of interrelated entities. *Whole Course.*
2. **Model Based Systems Engineereing**: The process of translating the structure, behavior, and concept of a "real-life" system into a graphical, analytical, or computational model or representation. *Weeks 1-5*
3. **Graph Theory**: The ability to analyze the structure of systems in terms of interconnected elements. *Weeks 6-7*
4. **Systems Simulation**: "Solving by Simulation". The ability to develop simulations of system models so as to conduct computational experiments that mimic the physical behavior of "real-life" system in the time domain. *Weeks 8-9*

But Why These Central Topics???

Why These Five Central Topics?



Learning Objectives

Upon completing this course, students will be able to:

1. Use "systems-thinking" concepts and abstractions to manage complexity in systems.
2. Use model-based systems engineering techniques to model system's form, function, and concept.
3. Analyze the structure of systems using graph-theoretic foundations.
4. Simulate systems with continuous-time and discrete-event dynamics.
5. Exercise these skills with an engineering team.
6. Present models, analyses, and simulations in written and oral form in a professional manner.

This course is about how to think not what to think about systems!

MBSE is both an art and a science. The course will require you to exercise and develop your engineering judgement.

Course Schedule Part I

Topic	Week	Date	Associated Reading	Homework Assigned	Homework/Lab Due
• ☑ 1 Course Introduction: Model-Based Systems Engineering, Analysis & Simulation	Week 1	Tuesday January 7		Progress Check 1: The System Scope & Boundary	
▾ ☑ 2 Introduction to Model Based Systems Engineering	Week 1	Wednesday January 8	CCS Chapters 1-3		CRQs
• ☑ 2.1 Q&A Session: Systems Thinking I					
▾ ☑ 3 Introduction to SysML & System Form	Week 1	ThursdayJanuary 9	FMS Chapter 4 & CCS Chapter 4		CRQs
• ☑ 3.1 Q&A Session: Systems Thinking					
• ☑ 3.2 Practical Session: Systems Thinking of a Complex Engineering System					
▾ ☑ 4 Practical Session: Block Diagram for the Formula Hybrid	Week 2	Tuesday, January 14	FMS Chapter 7 & MATLAB OOP Tutorial	Progress Check 2: The System Form	Progress Check 1: The System Scope & Boundary & CRQs
• ☑ 4.1 Q&A Session: Systems Form					
• ☑ 4.2 Practical Session: Modeling System Form in SysML & MATLAB					
▾ ☑ 5 Introduction to System Function I	Week 2	Wednesday, January 15	CCS Chapter 5		CRQs
• ☑ 5.1 Q&A Session: System Function					
▾ ☑ 6 Introduction System Function II	Week 2	Thursday, January 16	FMS Chapter 9		CRQs
• ☑ 6.1 Q&A Session: Modeling Flow Based Behavior w/ SysML					
• ☑ 6.2 Practical Session: Modeling System Function in SysML & MATLAB					
▾ ☐ 7 Activity, Sequence & State Machine SysML Diagrams	Week 3	Tuesday, January 21	FMS Chapter 10&11	Progress Check 3: The System Function	Progress Check 2: The System Form
• ☐ 7.1 Q&A Session: Modeling Message & Event Based Behavior w/ SysML					
• ☐ 7.2 Practical Session: Modeling System Function in SysML & MATLAB					
▾ ☐ 8 Introduction to System Concept	Week 3	Wednesday, January 22	CCS Chapter 6		CRQs
• ☐ 8.1 Q&A Session: System Concept					
▾ ☐ 9 Introduction to System Architecture	Week 3	Thursday, January 23	CCS Chapter 7&8		CRQs
• ☐ 9.1 Q&A Session: Introduction to System Concept & Architecture					
• ☐ 9.2 Practical Session: Modeling System Architecture in SysML & MATLAB					
• ☐ 10 **Class Cancelled**	Week 4	Tuesday January 28		**MBSE Report & Presentation**	Progress 3: The System Function
▾ ☐ 11 Introduction to the Allocated Architecture	Week 4	Wednesday, January 29	FMS Chapter 13		CRQs
• ☐ 11.1 Q&A Session: Modeling the Allocated Architecture w/ SysML					
▾ ☐ 12 The Mathematics of Networks	Week 4	Thursday, January 30	Newman Chapter 6		
• ☐ 12.1 Q&A Session: The Mathematics of Networks					CRQs
• ☐ 12.2 Practical Session: Modeling System Form as a Graph					

Course Schedule Part II

Topic	Week	Date	Associated Reading	Homework Assigned	Homework/Lab Due
▾ ☐ 13 Graph Measures & Metrics	Week 5	Tuesday February 4	Newman Chapter 7	Progress Check 4: Network Measures & Metrics	**MBSE Report & Presentation**
• ☐ 13.1 Q&A Session: Graph Measures & Metrics					
• ☐ 13.2 Student Presentations					
▾ ☐ 14 The Need for Hetero-functional Graph Theory	Week 5	Wednesday, February 5	SKF Chapters 1-3		CRQs
• ☐ 14.1 Q&A Session: Need for Hetero-functional Graph Theory					
▾ ☐ 15 HFGT: System Concept	Week 5	Thursday February 6	SKF Chapter 4-4.1, 5-5.3.		CRQs
• ☐ 15.1 Q&A Session: HFGT System Concept					
• ☐ 15.2 Practical Session: Modeling System Architecture as a Knowledge Base					
▾ ☐ 16 HFGT: Physical System	Week 6	Thursday, February 11	SKF Chapter 4.2, 5.4	Progress Check 5: Hetero-functional Adjacency Matrix	Progress Check 4: Network Measures & Metrics
• ☐ 16.1 Q&A Session: HFGT Hetero-functional Adjacency Matrix					
• ☐ 16.2 Practical Session: Modeling System Architecture as a Hetero-functional Graph					
▾ ☐ 17 HFGT Controllers & Decision-makers	Week 6	Tuesday, February 12	SKF Chapter 4.3-4.4, 5.5-5.6		CRQs
• ☐ 17.1 Q&A Session: HFGT Controllers & Decision-makers					
▾ ☐ 18 Introduction to Discrete-Event Dynamics	Week 6	Wednesday, February 13	Petri-Net Tutorial		CRQs
• ☐ 18.1 Q&A Session: Discrete-Event Dynamics					
• ☐ 18.2 Practical Session: Modeling Decision-Making Structure in HFGT					
▾ ☐ 19 HFGT Operands	Week 7	Tuesday, February 18	SKF Chapters 4.5-4.6, 5.7-5.8	Network Analysis Report & Presentation	Progress Check 5: Hetero-functional Adjacency Matrix
• ☐ 19.1 Q&A Session: HFGT Operands					
• ☐ 19.2 Practical Session: Modeling HFGT Operand Behavior					
▾ ☐ 20 HFGT System Adjacency Matrix	Week 7	Wednesday, February 19	SKF Chapters 4&5		CRQs
• ☐ 20.1 Q&A Session: HFGT System Adjacency Matrix					
▾ ☐ 21 Introduction to Continuous-Time Dynamics — Simscape	Week 7	Thursday, February 20	Simscape Tutorial		CRQs
• ☐ 21.1 Practical Session: Modeling HFGT System Structure					
• ☐ 21.2 Practical Session on Simscape					
• ☐ 22 Practical Session on Simulation Development	Week 8	Tuesday, February 26		Progress Check 7: Dynamic Simulation	
• ☐ **23 Student HFGT Presentations**	**Week 8**	**Wednesday, February 20**			**Network Analysis Report & Presentation**
• ☐ 24 Practical Session on Simulation Development	Week 8	Thursday, Febraury 28			
• ☐ 25 Practical Session on Simulation Development	Week 9	Tuesday March 3		Final MBSE Report	Progress Check 7: Dynamic Simulation
• ☐ 26 Course Conclusion	Week 9	Thursday March 5			
• ☐ **27 Final MBSE Report**	**Finals**	**Friday, March 13**			**Final MBSE Report**

Course Schedule Rationale: Why does this course exist at Thayer?

The motivation for this course comes from three immediate needs:

1. The MEM program is seeking to expand its "product development" track. This course specifically seeks to address product development of large complex systems where the tools of systems engineering are required to actively manage the complexity of the engineering development.
2. The Graduate Energy Program – as it is currently taught – exposes students to a wide variety of energy systems applications domains and then analyzes these energy systems with a wide variety of systems engineering tools. This is too much to do without prerequisite preparation. This ENGG 199 provides the underlying foundation for studying energy systems.
3. We currently do not have a graduate level systems engineering course for students in application domains other than energy.

Ultimately, 21st century engineers are facing a slew of engineering systems challenges, and MBSE sits at the heart of the solution.

The Learning Environment

Learning Environment: Overview of Learning Flow

- Independent Reading & Reflection
- In Class Q&A Sessions
- In Class Practical Sessions: Collaborative Modeling, Analysis & Simulation Time
- Independent Modeling, Analysis & Simulation Time

The practice of MBSE is ultimately conceptual & cognitive. Independent time for reflection is the key to developing these skills.

Nevertheless, the practice of MBSE is always implemented in collaborative teams. Class time will be used for interactive Q&A and collaborative modeling, analysis, and simulation exercises.

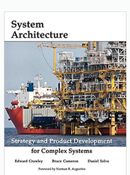
In order to ground our learning of MBSE, we will be using a complex engineering system throughout the course. (Groups of 2-3)

Independent Reading & Reflection

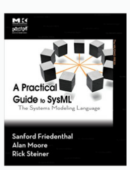
- The study of systems ultimately requires organizing the mind with **abstract** interconnected concepts.
- The books provide deeper explanations & examples of these concepts than a single in-class oral presentation.
- Reading abstract concepts requires the reader to engage more with the material than a lecture format.

In order to support Independent Reading, please prepare 5 Critical Reflection Questions on the reading for the start of every class.

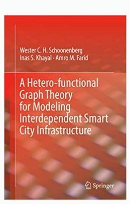
Independent Study: Required & Suggested Text Books



- **Required Text**: Crawley et. al. 2015.[1] *(purchase)*
- A new practical text focusing on learning the abstract principles of systems-thinking.
- Will be used extenstively in Weeks 1-5.



- **Required Text**: Friedenthal et. al. 2011 [2] *(handout)*.
- A new practical reference text on SysML and its syntax.
- Will be used extensively in Week 1-5 and then later as a reference.



- **Required Text**: Schoonenberg 2018[3]. *(purchase)*
- A comprehensive text on hetero-functional graph theory.
- Will be used extensively in Weeks 6-7.

In Class Q&A Sessions

- In addition to independent reflection, the systems thinking mind must be exercised in **engaged** collaborative discussion.
- This is a precursor to many discussions on complex engineering projects.
- We will have a structured Q&A discussion on the pre-assigned reading.
- There will be no use of lecture or powerpoint.
- Be ready to make these in-class discussions your own.

Engaged discussion requires engaged preparation prior to class.

In Class Practical Sessions

- In addition to engaged collaborative discussion, MBSE is best learned by **doing**.
- We will use class-time to initiate exercises in the MBSE of a complex engineering system of your choosing.
- Depending on class enrollment, we will break up into groups of 2-3.
- While this activity will be mostly independent, I'll be in class to steer you away from big modeling mistakes.
- These sessions will primarily focus on systems thinking skills rather than the syntax of MBSE.

Dive right in! Don't be afraid to make mistakes. Modeling is an iterative process.

Independent Modeling, Analysis & Simulation Time

- This is your chance to get it right.
- The rough draft modeling completed in class can be refined into computer-based modeling programs.
- While you will have to coordinate your efforts with others in class, ultimately much of the modeling, analysis and simulation time must be done independently.
- This will support accurate conclusions about architecture of the complex engineering system in your written reports and oral presentations.

This is where you see the large complex engineering system represented virtually.

Specific Student Needs

Religious Observances:

Some students may wish to take part in religious observances that occur during this academic term. If you have a religious observance that conflicts with your participation in the course, please meet with me before the end of the second week of the term to discuss appropriate accommodations.

Disabilities:

Students with disabilities enrolled in this course and who may need disability-related classroom accommodations are encouraged to make an appointment to see me before the end of the second week of the term. All discussions remain confidential, although the Student Accessibility Services office may be consulted to discuss appropriate implementation of any accommodation requested.

Expectations

Assessment

The course assessment is meant to support students in their learning of MBSE; breaking a very complex task of modeling a complex engineering system into manageable chunks.

- 22% Class Participation including submission of 5 critical reflection questions before class.
- 18% (6) Weekly Modeling Progress Checks
- 20% Model-Based Systems Engineering Report & Presentation
- 20% Network Analysis Report & Presentation
- 20% Final Simulation Report & Presentation

Dartmouth College Grade Descriptions

A Grade: Excellent mastery of course material. Student performance indicates a very high degree of originality, creativity, or both. Excellent performance in analysis, synthesis, and critical expression, oral or written. Student works independently with unusual effectiveness.

B Grade: Good mastery of course material. Student performance demonstrates a high degree of originality, creativity, or both. Good performance in analysis, synthesis, and critical expression, oral or written. Student works well independently.

C Grade: Acceptable mastery of course material Student demonstrates some degree of originality, creativity, or both Acceptable performance in analysis, synthesis, and critical expression, oral or written Student works independently at an acceptable level

D & E grades can be discussed on a case by case basis.

Conclusion 2

Every student will have the opportunity to **earn** an A grade.

Class Participation

The class discussion grade emphasizes the importance of independent reading, reflection and engaged in-class discussion.

- Complete the reading.
- Prepare at least 5 reflective questions noting the page(s) that inspired the question.
- Pose your questions in the class discussion
- Submit your questions to Canvas so that they can be collated into the MBSE Book of Questions.

Weekly Modeling Progress Checks

The weekly modeling progress checks are meant to give students milestones in completing the course's three reports and presentations.

- The Tortoise vs. the Hare. Steady consistent effort wins the race.
- The focus is on producing the figures, equations, and graphs that will anchor the reading of the report.
- Topic sentences and important conclusions can be bulleted.
- These checks will help you to flesh out the report and presentation straightforwardly in advance of the deadlines.

Model-Based Systems Engineering Report & Presentation

The report and presentation focuses on the MBSE of a complex engineering system using SysML as a modeling language. It must discuss:

- System boundary, context, and scope
- System Form
- System Function
- System Concept & Architecture
- The report need not be lengthy but it must comprehensively and clearly discuss the above points.
- The presentation emphasizes clarity of content and delivery.

Network Analysis Report & Presentation

The report and presentation focuses on the network analysis of a complex engineering system. It must discuss:

- Relevant Incidence Matrices
- Relevant Adjacency Matrices
- Decomposition to an "Appropriate" level.
- The report need not be lengthy but it must be comprehensively and clearly discuss the above points.
- The presentation emphasizes clarity of content and delivery.

Final Simulation Report Report & Presentation

The report and presentation focuses on the simulated behavior of the chosen engineering system. It's content will be approved in advance. It depends on the scope of your subsystem.

Academic Honor Principle Summary

The practice of MBSE is a collaborative endeavor. You are integrating a large amount of information from a wide variety of sources.

Some advice:

- Work with your peers.
- Cite early.
- Cite often.
- Give credit where credit is due.
- Ask me if you have doubts.

Syllabus Summary

Syllabus Outline

Objective 2

To explain how we will learn to engineer complex systems . . .

- Course Logistics
- Instructional Team
- Course Rationale
- Course Components
- The Learning Environment
- Expectations
- Lecture Summary

Conclusion 3

Students will have a clear understanding how ENGG 199-MBSE will proceed this term.

References I

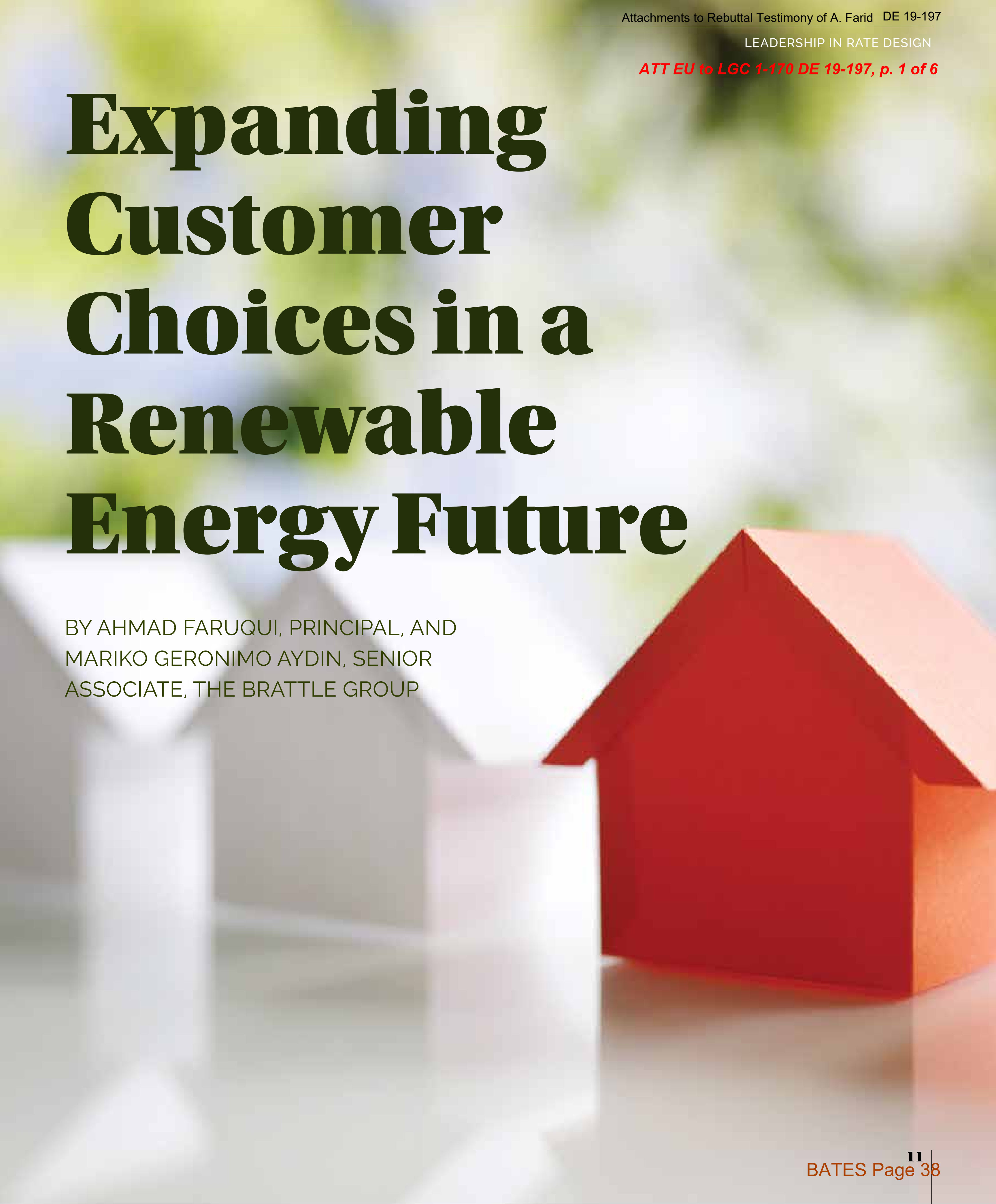
[1] E. Crawley, B. Cameron, and D. Selva, *System Architecture: Strategy and Product Development for Complex Systems*. Upper Saddle River, N.J.: Prentice Hall Press, 2015.

[2] S. Friedenthal, A. Moore, and R. Steiner, *A Practical Guide to SysML: The Systems Modeling Language*, 2nd ed. Burlington, MA: Morgan Kaufmann, 2011.

[3] W. C. Schoonenberg, I. S. Khayal, and A. M. Farid, *A Hetero-functional Graph Theory for Modeling Interdependent Smart City Infrastructure*. Berlin, Heidelberg: Springer, 2018. [Online]. Available: http://dx.doi.org/10.1007/978-3-319-99301-0

Expanding Customer Choices in a Renewable Energy Future

BY AHMAD FARUQUI, PRINCIPAL, AND MARIKO GERONIMO AYDIN, SENIOR ASSOCIATE, THE BRATTLE GROUP



For three years, Hawaii stood alone among other states in its commitment to reaching 100% renewable energy. In 2018 and early 2019, several large jurisdictions followed suit: California passed into law a policy of 100% clean energy by 2045; Washington, D.C.'s city council passed a standard for 100% renewables by 2032; New Mexico passed a 100% zero carbon requirement by 2045; and Puerto Rico adopted a policy for 100% renewable energy by 2050.[i] Many other states are considering and moving forward with similar policies and laws. Meanwhile, the number of cities and counties committed to 100% clean energy is growing dramatically.[ii] The 100% clean electricity supply that seemed impossible 10 years ago has now become a tangible and feasible future.

Figure 1 shows the end goal of state-level (plus Washington, D.C. and Puerto Rico) clean energy standards in terms of percent renewables or clean energy.[iii] Five more states are not far behind, with clean energy goals of 50% or more. With these policies, decarbonization of electricity is making great strides, with more to come as momentum builds.

The Value of Customer Flexibility in a High-Renewables World

In the first steps toward electricity decarbonization, going green is as straightforward as adding a solar or wind plant to the resource mix. In addition to forecasting peak demand as they have always done, resource planners and policymakers must determine when and where to build renewable resources and at what size these resources will be cost-effective.

With higher renewables penetration, planning for greener electricity becomes less about building individual resources and more about building a resource portfolio and system that — as a whole — is tuned to take advantage of clean power when it is available. One key challenge is what to do about the hour-to-hour and minute-to-minute mismatch between renewables output and electricity consumption. At times, electricity supply from renewables may be higher than consumption. At other times, supply may be lower than consumption. System operators must have the resources and tools they need to match supply and demand exactly.

In this context, customer flexibility becomes increasingly valuable. Any consumption that can be reasonably shifted to

Figure 1: End Goal of Clean Energy Standards by Jurisdiction

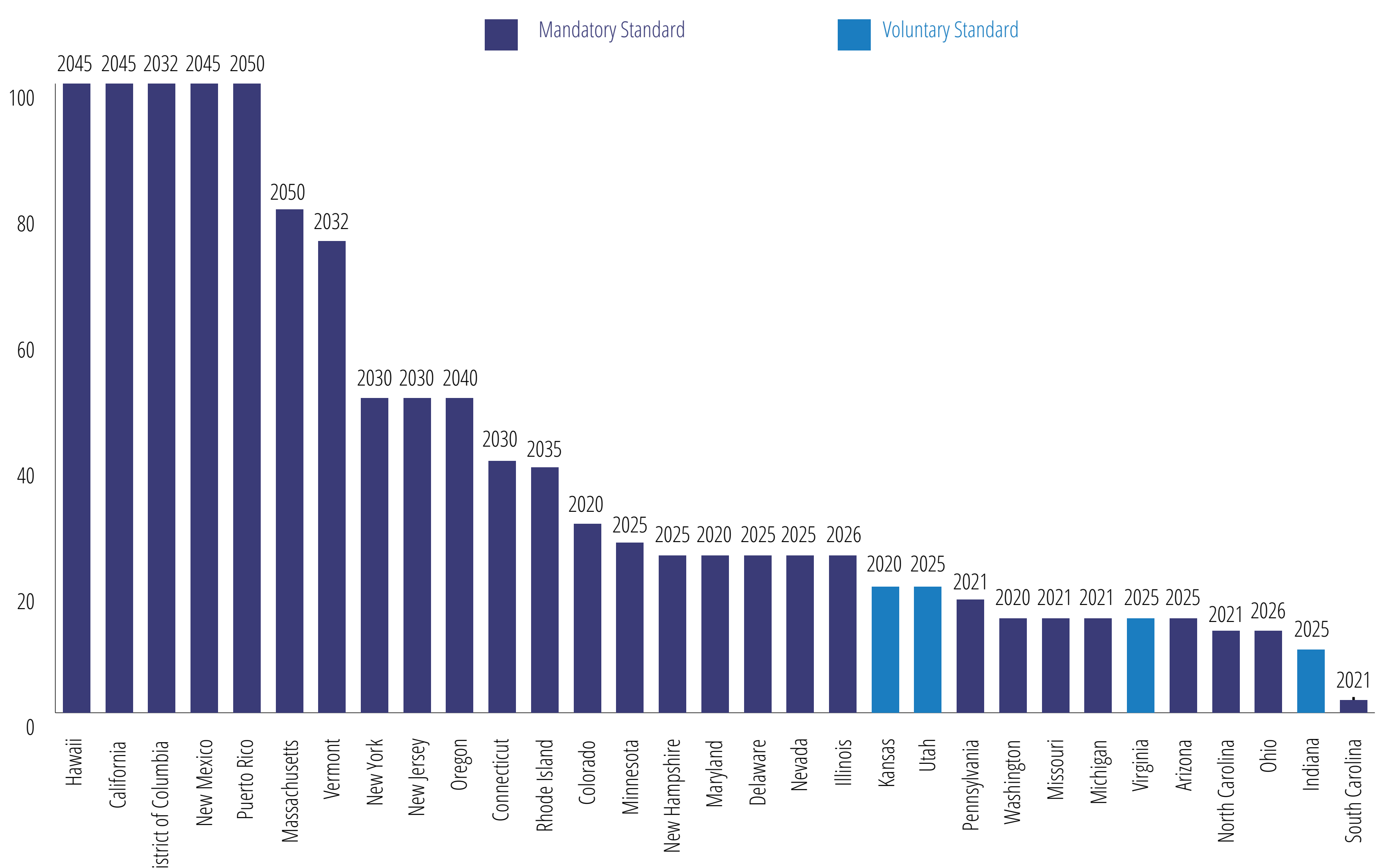


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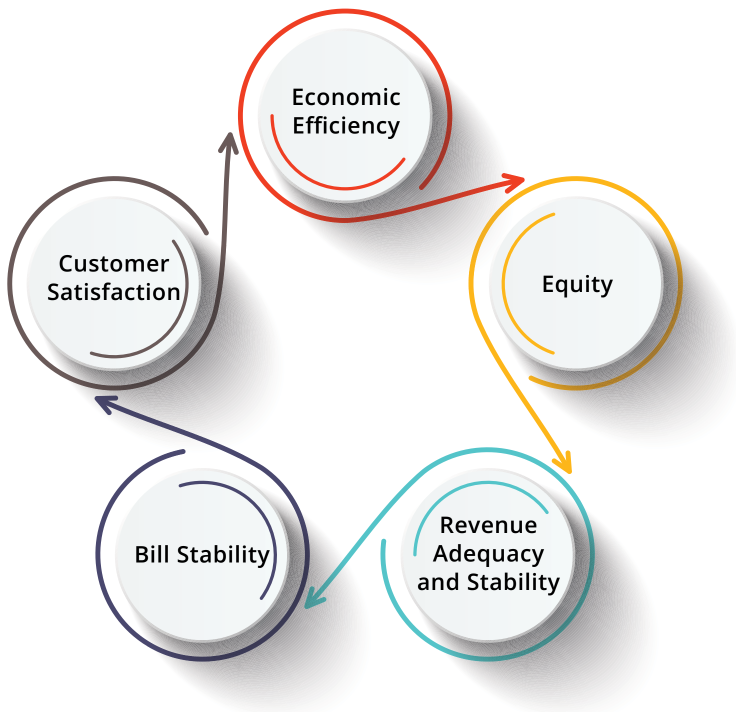
Figure 2: Objectives for Effective Retail Rates



Using customer flexibility as a resource in any and all hours is critical to getting the most out of a high-renewables system.

times when renewables-based supply is high will prevent loss or curtailment of renewables output when it is available. In doing so, customers also shift consumption away from times when renewables-based supply is lower, which can avoid the cost of power supplied by battery storage or even fossil fuel-based generation. This concept is expanding our traditional thinking about customer flexibility: from traditional "demand response" focused on moving consumption *away* from peak periods, to something more dynamic and including "load shift" *toward* low-cost periods.[iv]

Future studies and evaluations of demand response will need to broaden the definition of demand response and the scope of benefits it can provide.[v] Using customer flexibility as a resource in any and all hours is critical to getting the most out of a high-renewables system.

Principles for Meaningful Rate Options and Signals

Electricity is delivered (and sometimes produced) by a regulated natural monopoly, and customers pay for electricity through regulated retail rates. Given that framework, the principles of effective regulated rates hold true regardless of a high-renewables future. Effective rates should address and balance the regulator's high-level objectives for economic efficiency, equity, revenue adequacy and stability, bill stability, and customer satisfaction, as shown in Figure 2.[vi]

The objectives for retail rates are interrelated, and some can represent tangible tradeoffs for customers. One customer, for example, might want to see how power supply costs vary within a day, to moderate their air conditioner on the hottest days when costs are high and save money overall. Another customer might not have the same flexibility to cut air conditioning on the hottest days, might not want to feel penalized for that flexibility, and might prefer more bill stability and costs smoothed over time.

An in-between rate option with moderate cost variability over time — such as the traditional volumetric rates that dominate the industry today — might be meaningless to both customers. The first customer may feel that the cost variability they see is not a strong enough signal (or concentrated enough) to respond to. And the second customer may feel that the cost variability by month or season is not equitable nor helpful given that they can't respond to it. In either case, customers pay the total cost of service. How well rates are tailored to customers' preferences and their ability to respond can impact how effective the rates are in incentivizing customers to save money when they can reasonably do so, while increasing customers' satisfaction and sense of equity.

For customers of today and tomorrow, rate objectives need to be defined and addressed at a more granular level that is tailored to the diversity of customers and their preferences, possibly even at a customer-specific level. We now have better information technology and tools to understand customers' behaviors and preferences, and to help them receive and respond to signals so they can shape their consumption in a meaningful way.

An hourly real-time price signal... can help show customers exactly what hours contribute most (and least) to the cost to serve them.

The Diversity of Efficient Rate Options

How do customers weigh opportunities to reduce cost versus bill stability? Regulators and utilities have experimented with a wide range of rate options and signals, as demonstrated in Figure 3. Traditional volumetric rates (standard tariff) yield relatively low bill volatility. However, the potential for bill savings is limited — a customer is only empowered to reduce costs through bulk conservation (i.e., a customer reducing total kWh consumed over a month).

For even less bill volatility, utilities can offer a fixed monthly bill (e.g., budget billing plan), shown as the leftmost point in Figure 3. Under this approach, the utility estimates total seasonal or annual bills, then divides the total by the number of months, similar to a payment plan. For example, Ohio's regulated electric and natural gas distribution utilities offer annual budget billing.[vii] Customers may like this type of bill because it is easier to financially plan for. But they must accept the tradeoff of having no signal to consume power when it is economical to do so, which theoretically will yield higher costs to customers overall.

Customers might be willing to risk more bill volatility if they have the flexibility to move consumption away from high-priced periods. An hourly real-time price signal, shown as the rightmost point in Figure 3, can help show customers exactly what hours contribute most (and least) to the cost to serve them. To date, the U.S. has relatively little experience applying real-time prices to residential customers, but experience in other parts of the world may provide some insights.

For example, in early 2017, about 12 million small customers in Spain, or about half of those eligible, were enrolled in a real-time price-based electricity rate, as part of a regulatory redesign to incentivize more efficient customer behavior and lower costs.[viii,ix]

In a high renewables system in the U.S., a real-time price signal can also be simplified to indicate when fossil fuel is being burned to serve customers (relatively high cents per kilowatt-hour), versus when renewables output is plentiful (low or even negative ¢/kWh). Translating a real-time price signal into an emissions signal may be more meaningful for some customers.

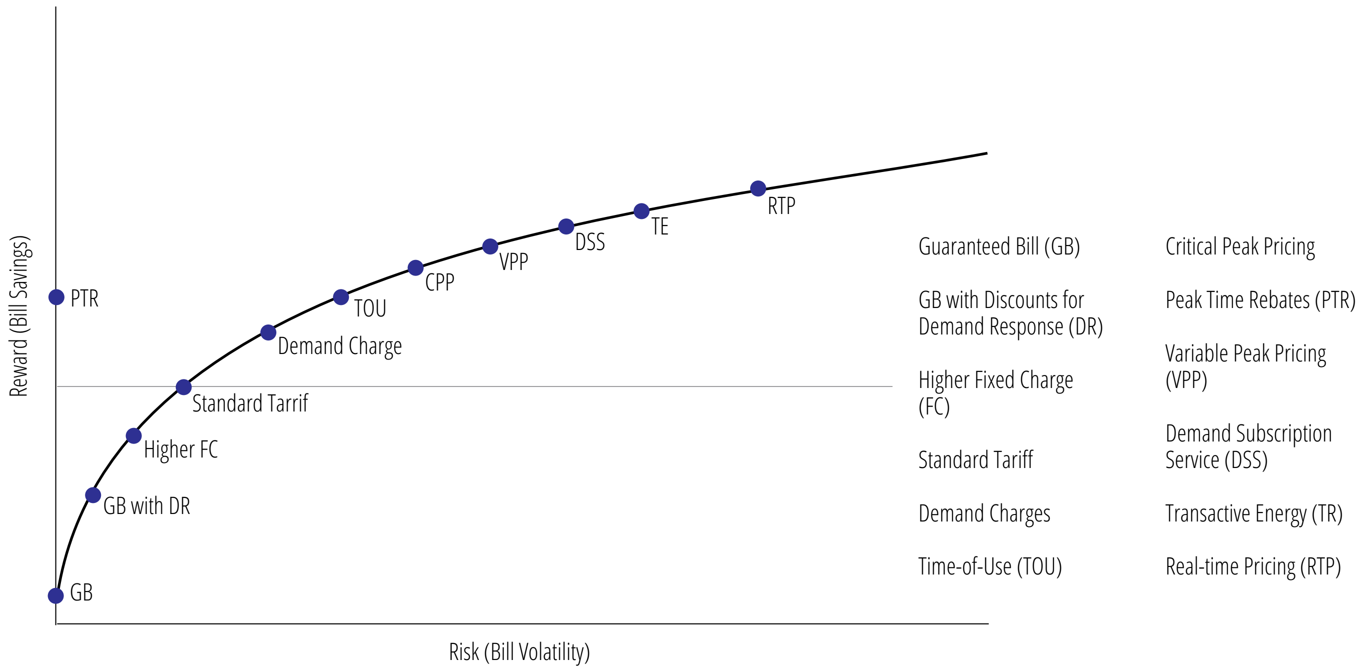
The tradeoff of higher bill volatility, however, can't completely be eliminated by the customer avoiding high-priced hours and consuming more in low-priced hours. There will always be the risk that prices are sometimes high when the customer can't or doesn't want to respond. More moderate time-varying price signals, like time-of-use rates and critical peak pricing, can also be quite effective if they are designed properly.[x]

Enabling Customer Flexibility through Tailored Retail Rates and Services

At its heart, traditional demand response is about giving better information to customers and letting them decide how to adjust (or not adjust) their consumption patterns. Studies on how electricity customers in the U.S. respond to cost signals — via retail rates and bills — have a history dating back to the late 1970s.[xi] Those studies affirm that customers care about cost and that they are willing and able to adjust their consumption away from high-cost periods.

Through subsequent decades of studies and experimentation, another thing is clear — customers have diverse preferences for types of cost signals they are willing to respond to. Preferences range from a flat guaranteed bill (low granularity cost signal) to retail rates that vary by hour in real time (high granularity cost signal), and many variations in between.

Figure 3: The Efficient Rate Frontier



Customers have shown that they will only respond to cost signals that are meaningful to them, and so customer options must be tailored carefully. To date, utilities and regulators have experimented with offering a handful of electricity rate options defined across broad customer classes. However, in other aspects of their lives, customers are getting used to having a world of options at their fingertips.

Today's customers have two important attributes that can affect their consumption patterns and must be considered along with retail rate design. First, customers have a heightened awareness of the electricity supply mix, and they may have stronger preferences for green attributes and where the power comes from (such as local or onsite power) than customers of yesterday. So, beyond cost signal options, customers might want options to choose a supply mix that better suits their preferences and values. There is growing evidence that customers want more control and options to tailor their power supply mix to their preferences.

Furthermore, customers are more comfortable with using technology and tools to make informed spending decisions. They use apps, search engines, web services and other tools on a daily basis to process and simplify an enormous amount of information to make even the simplest spending decisions. Advanced equipment like smart meters can improve the quality of cost, consumption, and supply mix data available to the customer. Tools and services including apps, price and consumption reports, and smart appliances can help the customer absorb that information quickly and adjust consumption patterns with more automation. Experiments with enabling technologies such as in-home displays and smart thermostats have already shown that customers can be more flexible if they are given better resources to do so.xii

The Path Forward

Electric utilities are well-poised to play a major role in providing tailored electricity services to customers in a new world where digital technologies and the internet of things are likely to be ubiquitous. To do so, utilities must continuously seek improved customer data to offer meaningful rate options and signals tailored to customer preferences. Utilities must also push forward with technology and tools that can help customers understand it all and respond with minimal effort.

The path to developing meaningful new rate structures and options for customers in a renewable energy future begins with better understanding how customer needs are changing. This can be done through focus groups and surveys that not only seek to understand preferences on cost versus bill stability, but also seek to understand preferences on power supply mix, environmental goals, and willingness to provide flexibility at different times of the day.

With customer preferences better understood, utilities can draw from the wealth of experience they already have in order to identify and test the effectiveness of different rate options. This includes field testing new rate designs, determining their acceptance and comprehension by customers, and evaluating the impact of the new rates on energy consumption and load shapes. Experience has shown that it would be best to carry out the tests using randomized control trials or similar methods to make sure the results are statistically valid and can be generalized to the population of interest. Tests should include considerations of technologies that enable customers to easily understand their rates and any price or environmental signals they are receiving, set preferences for responding to those signals, and respond automatically in a way that does not disturb customers' quality of life.

Utilities and regulators will then need to develop an implementation plan for new rates. They must determine if the new rates should be offered on an opt-in, opt-out, or mandatory basis and how that may change over time. There are many different approaches to this and each has its pros and cons. There may be useful lessons learned from other utilities that have already rolled out similar rates.

To quell fears of unexpected impacts, it will be useful to compute the bill changes that the new rates will bring about and find ways to mitigate any adverse impacts.

Finally, continuous customer education and outreach is crucial for customers to understand the array of rate options they have, and for them to make the best use of the rate they choose. In a sense, this effort both begins and ends with a conversation with customers. Through those conversations, electric utilities and regulators can help customers make great strides in realizing the benefits of their renewable energy future.

About the Authors

Ahmad Faruqui *is an internationally recognized energy economist. He has analyzed the efficacy of a variety of tariff structures and carried out a meta-analysis of experimental results. His areas of expertise include demand response, energy efficiency, distributed energy resources, advanced metering infrastructure, plug-in electric vehicles, energy storage, inter-fuel substitution, combined heat and power, microgrids, and demand forecasting. He has worked for nearly 150 clients on five continents and testified before commissions in several states and provinces.*

Mariko Geronimo Aydin *is an economist with almost fifteen years of experience in analyzing the policies and economics of electricity system planning, regulation and de-regulation of electricity supply, and wholesale electricity markets across the U.S. Mariko specializes in helping clients meet their potential in a changing industry, by evolving utility business models and by developing customer choice, resource planning, and wholesale market refinements that can make the best use of clean, distributed, and customer-driven power supply resources in synergy with more traditional resources.*

i These policies and laws refer to the following legislative bills: HB 623 (Hawaii), SB 100 (California), B22-0904 (Washington, D.C.), SB 489 (New Mexico), and PS 1121 (Puerto Rico).

ii Note that 130 cities and counties have also committed to 100% clean energy. Sierra Club, "100% Commitments in Cities, Counties, & States," https://www.sierraclub.org/ready-for-100/commitments, Accessed April 2019.

iii DSIRE, "Detailed Summary Maps: Renewable Portfolio Standards (October 2018)," http://www.dsireusa.org/resources/detailed-summary-maps/, Accessed April 2019. Supplemented with research by The Brattle Group. Texas also has a voluntary target of 10,000 MW by 2025 for retail entities.

Massachusetts' goal of 80% by 2050 is based on its Clean Energy Standard. Massachusetts also has a separate Renewable Portfolio Standard with an implied target of 35% by 2030, and the Class I requirement growing by 1% per year thereafter.

iv Note that although the idea of flexible load shapes is gaining attention in the industry today, it is a concept that has been around for some time. See, for example, Gellings, Clark W., Pradep C. Gupta, and Ahmad Faruqui, "Strategic Implications of Demand-Side Planning," Chapter 8 in Plummer, James L., Eugene N. Oatman, and Pradeep C. Gupta (eds), Strategic Management and Planning for Electric Utilities, Prentice-Hall, Englewood Cliffs, 1985, pp. 137–150. See also, Schweppe, Fred C., Richard D. Tabors, and James L. Kirtley, "Homeostatic Control: The Utility/Customer Marketplace for Electric Power," MIT Energy Laboratory Report MIT-EL 81-033, September 1981.

v Faruqui, Ahmad, and Ryan Hledik, "Reinventing Demand Response for the Age of Renewable Energy," December 14, 2018, http://files.brattle.com/files/15059_reinventing_demand_response_for_the_age_of_renewable_energy_12-12-2018.pdf. Accessed April 2019.

vi Bonbright, James C., Albert L. Danielsen, and David R. Kamerschen, "Principles of Public Utility Rates," Arlington, Va: Public Utility Reports, 1988.

vii See The Public Utilities Commission of Ohio, "Budget Billing for Natural Gas and Electric Service," https://www.puco.ohio.gov/be-informed/consumer-topics/budget-billing-for-natural-gas-and-electric-service/, Accessed April 2019.

viii The rate is called the Voluntary Price for Small Consumers, or VPSC.

ix EURELECTRIC, "Dynamic Pricing in Electricity Supply," position paper, page 6, http://www.eemg-mediators.eu/downloads/dynamic_pricing_in_electricity_supply-2017-2520-0003-01-e.pdf. Accessed April 2019.

x Faruqui, Ahmad, Sanem Sergici, and Cody Warner, "Arcturus 2.0: A Meta-Analysis of Time-Varying Rates for Electricity," The Electricity Journal, Volume 30, Issue 10, December 2017.

xi Faruqui, Ahmad, and Mariko Geronimo Aydin, "Moving Forward with Electricity Tariff Reform," Regulation, Fall 2017, pp. 42–48.

xii Faruqui, Ahmad, Sanem Sergici, and Cody Warner, "Arcturus 2.0: A Meta-Analysis of Time-Varying Rates for Electricity," The Electricity Journal, Volume 30, Issue 10, December 2017.