A Simulation Based Design and Evaluation Framework for Energy Product-Service System in Liberalized Electricity Markets

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Abstract

Environmental considerations, as well as economic sustainability, encourage the rise of the Product-Service Systems (PSS) concept. Its ultimate goals are to reduce resource consumption while at the same time achieving customer satisfaction. This study is intended to tackle the problem of designing and evaluating Energy-Product-Service Systems (EPSS) as a specific subset of PSS, in which consumers are released from electrical appliance ownership and provided with energy service performance in liberalized electricity markets. However, knowledge and understanding about EPSS is very limited due to no previous experience. For this reason, this study proposes a simulation-based design methodology for EPSS design and evaluation. The method is demonstrated to evaluate the effect of altering managerial processes of three elements of the system to enhance expected system performance, including tangible products (i.e. household electrical appliance), information, and energy.

This thesis is made-up of five chapters. ***Chapter 1*** introduces Energy Product-Service-Systems, followed by ***Chapter 2*** where a novel approach to design EPSS, namely Simulation-Based Design (SBD) for EPSS is developed. The point of the method is to construct the system causality that depicts the behaviour and interaction between various stakeholders, based on knowledge of existing systems. The information about actors' interests, behaviour, decisional processes and attributes are selected according to evidence from the current energy market or knowledge on other existing systems with similar characteristics to EPSS. In addition, information regarding the exogenous factors that influence actors' behavior and decisional processes in existing systems are explored. The system causality is then used as the basis to simulate and evaluate the system performance. The method also incorporates Agent-Based Simulation to depict the interaction between multiple actors on certain socio-technical environments. The method is then used to identify the conditions for EPSS to achieve minimum cost and emissions generation from households' electricity consumption without sacrificing consumer satisfaction. Conditions derived from a combination of market variables are simulated and analysed. The selected variables include EPSS service level, Recycling Law enactment, reprocessing rate, and appliance replacement policy. The chapter clarifies the conditions for EPSS to achieve the design goal.

Chapter 3 improves the method in chapter 2 by incorporating the "Worst Scenario" method to address the issue of uncertain correlation between input design and system performance in EPSS. The method is used to investigate enablers for EPSS design to achieve win-win solutions for all stakeholders. EPSS with service provision allows the modification of information-

sharing mechanisms that differ from current systems. The modified information-sharing mechanism is expected to deliver win-win solutions for all the involved actors. SBD for EPSS is implemented to evaluate EPSS design under different market environments. Three scenarios of information-sharing mechanisms are evaluated with several market conditions which are characterized by the share of alternative seeker consumers, share of dominant consumer preferences and policy measures. The study clarifies the conditions that lead to unexpected results from EPSS information-sharing mechanisms.

In ***Chapter 4***, SBD for EPSS is implemented for designing EPSS in the context of a renewable energy market. It was suggested that future energy markets must be designed to achieve an efficient balance of supply-demand by sending signals through revenue gain for more investment in renewable energy production and supporting facilities. EPSS providing services allows a company to control and manage appliance usage and operation and demonstrates greater flexibility from the demand side to respond to supply uncertainties. Three conditions that lead to the worst performance for renewable energy markets in the short-run and long-run have been identified in this study. In addition, this chapter reviews the performance of techniques incorporated to the method in addressing EPSS design problems, as well as improvements required for the method.

Finally, ***Chapter 5*** concludes the research by clarifying the development of the novel method and incorporated techniques to design EPSS. This chapter also verifies the performance of the method in addressing design problems for the designated goals.

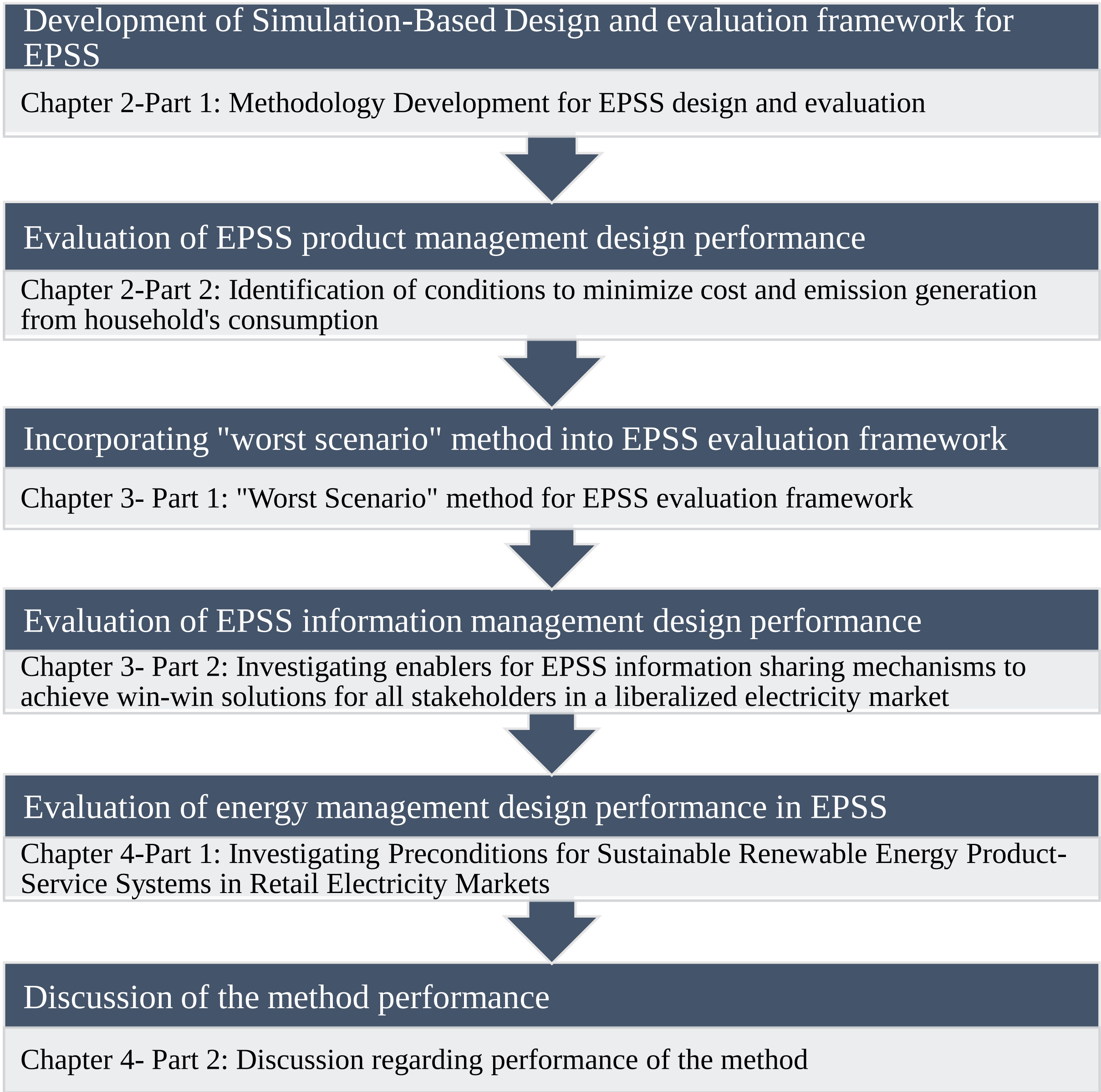


Figure 0. Thesis flow diagram.

Acknowledgments

Praise be to Allah, The Most Beneficent and Merciful, for granting me strength, health and wisdom to undertake the PhD research work and enabling me to its completion. I would also like to express my sincerest and deepest gratitude to all the people and institutions who have contributed towards the completion of this thesis

First of all, I would like to extend my deepest gratitude to Prof. Tetsuo Tezuka, my supervisor and mentor, for his excellence guidance in a number of ways by challenging me to go beyond my knowledge into the unknown. For his invaluable support, encouragement, and never-ending patience throughout my study. He is a wonderful PhD mentor, for which I am forever grateful.

I am also very much indebted to Associate Professor Benjamin McLellan, my co-supervisor for the encouragement, advice, and continuous support during my study, as well as for the valuable feedback on my research work and paper writing.

I would like to acknowledge the Ministry of Education, Culture, Sports and Science and Technology (MEXT) Japan for providing scholarship for pursuing Doctoral degree in Kyoto University.

I am also especially thankful to Ms Tomoko Tomomatsu, the laboratory secretary, as well as Ms. Shiho Nakamura, and Ms. Nozomi Kamura, her predecessor for taking care of my matters at the University, and during my stay in Japan.

My deep appreciation to all the people on Energy Economics Laboratory for their kindness and hospitality during my study. And also, thank you for Ranran, Niken, Senyo, Pawpaw, Rioz, Lina, Salma, Ed and Kiky, for sharing the laughter, joy, and delicious home cooking. It means a lot, especially during those difficult times.

And finally, I am forever indebted to my parents and my siblings, who always showering me with prayers and support to pursue my interest throughout my life.

Table of Contents

CHAPTER 1 1

INTRODUCTION 1

1.1 CONCEPTUAL FRAMEWORK OF ENERGY PRODUCT-SERVICE SYSTEMS 1
1.1.1 UNDERLYING THEORY OF THE RESEARCH 1
1.1.2 MOTIVATION, OBJECTIVE AND DEFINITION OF ENERGY PRODUCT SERVICE SYSTEMS 13
1.1.3 THE DIFFERENCE BETWEEN EPSS AND OVERLAPPING SYSTEMS 15
1.1.4 EPSS DESIGN PROBLEM 17
1.2 RESEARCH QUESTIONS AND OBJECTIVES 18
1.3 RESEARCH STEPS 19
1.4 OBJECT OF THE STUDY 20
1.4.1 ACTORS' ATTRIBUTES AND BEHAVIOUR 22
1.5 STRUCTURE OF THE THESIS 27

CHAPTER 2 30

METHODOLOGY: SIMULATION-BASED DESIGN FOR ENERGY PRODUCT-SERVICE-SYSTEMS 30

2.1 RELATED STUDIES 30
2.1.1 SIMULATION-BASED DESIGN 30
2.1.2 AGENT-BASED MODEL 32
2.2 DEVELOPMENT OF SIMULATION-BASED DESIGN FRAMEWORK FOR EPSS 33
2.3 THE METHOD IMPLEMENTATION TO IDENTIFY CONDITIONS FOR EPSS DESIGN TO REDUCE EMISSIONS AND TOTAL COST OF CONSUMPTION WITHOUT SACRIFICING CONSUMER SATISFACTION 36
2.3.1 OBJECT OF THE STUDY 36
2.3.2 SYSTEM PERFORMANCE MEASUREMENT 38
2.3.3 ACTORS' BEHAVIOR AND THE DECISIONAL PROCESS 40
2.3.3.1 CONSUMER BEHAVIOR AND THE DECISIONAL PROCESS 40
2.3.3.2 APPLIANCE PRODUCER BEHAVIOR RULE 42
2.3.3.3 ELECTRICITY RETAILER BEHAVIOR RULE 46
2.3.4 DEVELOPMENT OF SYSTEM CAUSALITIES 48
2.3.5 SIMULATION DEVELOPMENT AND DESIGN EXPERIMENT 48
2.3.6 SIMULATION RESULTS AND ANALYSIS 51
2.3.6.1 EPSS DESIGN FOR EPSS MARKET 51
2.3.6.2 EPSS INTRODUCTION TO EPOS MARKET 54
2.3.7 MANAGERIAL IMPLICATIONS 56
2.4 CLOSING REMARKS 58

CHAPTER 3 59

INVESTIGATING ENABLERS FOR EPSS INFORMATION SHARING MECHANISMS TO ACHIEVE WIN-WIN SOLUTIONS FOR ALL STAKEHOLDERS IN A LIBERALIZED ELECTRICITY MARKET 59

3.1 INTRODUCTION 59
3.2 WORST SCENARIO METHOD TO DESIGN EPSS INFORMATION SHARING MECHANISM 60
3.3 RELATED STUDIES 61
3.3.1 POLICY FOR ADDRESSING EPOS MARKET FAILURES 62
3.3.2 SYSTEM LOCK-IN AND PATH DEPENDENCIES FOR EPSS 64
3.4 OBJECT OF THE STUDY 64
4.4.1 "WIN" SITUATION FOR EACH ACTOR 65
4.4.2 CAUSALITY DIAGRAM 67
4.4.3 AGENTS' DECISION-MAKING PROCESSES TO ACHIEVE THEIR WIN SITUATION 67
4.4.4 EPSS PROVISION 72
4.4.5 INFORMATION-SHARING MECHANISM IN COMPETING MARKET 73
4.4.6 POLICY MEASURES FOR EPSS INTRODUCTION 76
4.4.7 SIMULATION AND DESIGN EXPERIMENT 76
3.5 SIMULATION RESULTS AND ANALYSIS 78
3.5.1 EPSS MARKET PENETRATION 78
3.5.2 WIN-WIN RESULTS OF MARKET ACTORS 82
3.6 MANAGERIAL IMPLICATIONS 85
3.7 CLOSING REMARKS 86

CHAPTER 4 88

INVESTIGATING PRECONDITIONS FOR SUSTAINABLE RENEWABLE ENERGY PRODUCT-SERVICE SYSTEMS IN RETAIL ELECTRICITY MARKETS 88

4.1 RESEARCH BACKGROUND 88
4.2 RELATED LITERATURE 89
4.2.1 ESCAPING CARBON LOCKED-IN 89
4.2.2 FUTURE RENEWABLE ENERGY MARKET 91
4.2.3 PROMOTING ENERGY PRODUCT-SERVICE SYSTEMS FOR SUSTAINABLE ENERGY MARKET DESIGN 92
4.3 OBJECT OF THE STUDY 93
4.3.1 MARKET PLAYERS' BEHAVIOR AND DECISION-MAKING PROCESS 94
4.3.1.1 ELECTRICITY RETAILER BEHAVIOUR AND DECISION-MAKING PROCESS 95
4.3.1.2 OTHER MARKET PLAYERS 98
4.3.2 EPSS PROVISION 99
4.3.3 MARKET PERFORMANCE MEASUREMENTS 100
4.3.4 SIMULATION AND SCENARIO DESIGN 102
4.4 SIMULATION RESULTS AND ANALYSIS 103
4.4.1 THE IMPACT OF HETEROGENEOUS CONSUMER BIAS AND MARKET COMPETITION TOWARD RENEWABLE ENERGY MARKET 103
4.4.2 MANAGERIAL IMPLICATIONS 107
4.5 THE PERFORMANCE OF SBD FOR EPSS DESIGN 108

4.6 THE FUTURE WITH EPSS 109
4.7 CLOSING REMARKS 110

CHAPTER 5 111

RESEARCH CONCLUSIONS 111

REFERENCES 113

APPENDIX I. MODEL CAUSALITIES, PARAMETER, AND VARIABLES 132

APPENDIX II. MODEL SENSITIVITY ANALYSIS 140

PUBLICATION LIST 159

List of Figures

Figure 1. The physical product life-cycle (Sundin, 2009) 12
Figure 2. Flow of the thesis 20
Figure 3. The boundary of the study object 21
Figure 4. Consumer decision flow 26
Figure 5. Simulation-Based Design for EPSS design 35
Figure 6. Description of actors` attributes and behaviour in the model 37
Figure 7. Consumer behavior and decision flow 41
Figure 8. Appliance producer behavior and decision flow 43
Figure 9.Electricity retailer producer behavior and decision flow 47
Figure 10. Example of parameter causalities of total emission generation 48
Figure 11. Comparison of total cost to deliver electricity service performance for consumers 52
Figure 12. Comparison of the total emission generation from service consumption 53
Figure 13. Comparison of EPSS market share from various market conditions 55
Figure 14. Comparison of time required for EPSS dominates market share 56
Figure 15. Simulation-Based Design with the “Worst Scenario” method for EPSS design 62
Figure 16. Description of actors` attributes and behaviour in the model 65
Figure 17. Example of causality depicting interactions that influence win-win solution........67
Figure 18. Information-sharing mechanism in EPOS 74
Figure 19. Agents’ information acquisition and processing for decision-making process in EPOS 75
Figure 20. Example of information-sharing mechanism design for EPSS 75
Figure 21. Evaluated variable impact on EPSS market share 79
Figure 22. Gap years until EPSS market share stabilized 81
Figure 23. Worst conditions for EPSS market penetration 81
Figure 24. Percentage incentive for highly efficient appliances 82
Figure 25. Highly electricity purchase cost of retailer 83
Figure 26. Worst situation for consumer satisfaction 83
Figure 27. Worst conditions for policy maker 84
Figure 28. Market players' interaction in the observed market 94
Figure 29.EPOS retailer behaviour and decision flow 96
Figure 30.EPSS retailer behaviour and decision flow 97
Figure 31. Market conditions affect PV installed capacity 104
Figure 32. Market conditions affect the storage capacity 104
Figure 33. Market conditions affect aggregate consumer satisfaction 105
Figure 34. Market conditions affect retailer revenue 106

List of Tables

Table 1. Definition of PSS according to literatures 5
Table 2. PSS Typology in literature....8
Table 3. The division of PSS based on value proposition dependency toward product....10
Table 4. Summary of PSS benefits 12
Table 5. Summary of PSS barriers to implementation 13
Table 6. Approaches, Technique and Tools integrated to Simulation-Based Design....32
Table 7. EPSS design service for evaluation....37
Table 8. Investigated variables and values for EPSS design 50
Table 9. Description of simulation variables and value....51
Table 10. The “win” situation for each market player....66
Table 11. Description of EPSS provision 72
Table 12. Influential factors in consumer’s decision-making behaviour....77
Table 13. Selected variables to tested in simulation....78
Table 14.EPSS type and description....100
Table 15. The influential factor of consumer’s decisional behavior 100
Table 16. Selected variables for scenario design....103
Table 17. Worst conditions result in lowest consumer satisfaction....105

Chapter 1

Introduction

Energy systems have been the focus of many efforts to mitigate global greenhouse emissions due to their central role in consuming fossil fuels. At the same time, they are significant consumers of materials across the supply chain and the need to have greater recycling rates to maintain resource security and improve lifecycle environmental impacts is apparent (Watari et al., 2019). Liberalised markets are expected to open up opportunities for increasing renewable energy in the supply mix, increase efficiency and reduce costs for consumers. Among the strategies for enhancing the reduction of emissions in conjunction with liberalisation, is the servitisation of energy – moving from the sales of energy and energy utilisation devices to the sales of the services provided by energy (e.g. temperature control). In contrast with the current system, which we refer to as Energy, and Product-Oriented Systems (EPOS), Energy Product-Service Systems (EPSS) would provide the consumer with the electrical appliance service performance they require through a contract involving potential combinations of devices (e.g. air conditioner) and energy (e.g. electricity to run the air conditioner) charged at a rate for providing the service (e.g. temperature at given setting) (Kusumaningdyah, McLellan, & Tezuka, 2019a). As the provision of appliances is centralised with the EPSS provider, there is a potential for more efficient recovery of end-of-life products, and therefore retention of materials in the economy.

This chapter clarifies the basic concept of EPSS, including the underlying theory of EPSS development, identification of the research problem, and then presents the objective of the research. The structure of the thesis, depicting the layout of the study is presented at the end of this chapter.

1.1 Conceptual Framework of Energy Product-Service Systems

1.1.1 Underlying Theory of the Research

1.1.1.1 Product-Service Systems

Research agrees that the manufacturing industry creates considerable environmental impacts while at the same time having a significant role in society and economic development. Energy consumption in the industrial sector varies between countries, range from 30% - 70% of total energy use (Abdelaziz, Saidur, & Mekhilef, 2011), not to mention the emissions resulting from energy use during the production stage (Hendriks et al., 1999). Despite the environmental impact, the important role of industry in economic development is undeniable. In response to these issues, a survey reported that since 2007 CEOs have started to incorporate sustainability concepts into their business activity (UN Global Compact, 2013). Various approaches and methods have been investigated and developed to address these issues. However, it appears that the proposed methods provide only parts of the ultimate solution. Each solution has its strengths and limitations with regards to minimizing environmental impact. However, when those methods are integrated into a system, suboptimal performance might occur and this may reduce the method's efficiency in addressing environmental issues (Mont, 2002). It was argued that previous approaches are not sufficient to solve environmental problems (O. Mont, n.d.; O. K. Mont, 2002; Roy, 2000). Moreover, existing industries are challenged with more sophisticated demand related to energy efficiency and material flows (O. K. Mont, 2002). Under these circumstances, Product-Service Systems (PSS) were introduced, offering solutions for multi-dimensional challenges faced by industry (e.g. Cavalieri & Pezzotta, 2012; Williams, 2006).

In reality, however, a range of business models are considered as PSS despite its environmental performance. Consider the following illustrative examples of business approaches emphasizing service-domain logic.

- Local Motors is a vehicle manufacturer that combines co-creation and micro-manufacturing, offering personalized vehicles in a reduced time compared to others. To achieve their purpose, it established a co-creation platform as a means to connect and collaborate on ideas between the company, customer, and contributors while maintaining alliances with several major manufacturing companies (e.g. Airbus). The manufacturing process utilized their own resources and technology and is used to offer experience to build cars for their customers, together with after sales service including maintenance and modification. The experience of building a vehicle is done with the support of Local Motor Engineer ("Company Overview of Local Motors, Inc.," 2016). Not only do they sell the vehicle, but Local Motors also provide valuable experience for customers to make their own car. Using their co-creation platform, Local Motors also collects designs and ideas to build cars for targeted customers. In this sense, the service is provided before and after the product sales, in addition customization of products and experience will potentially increase customer satisfaction. However, resource productivity as one of the goals of PSS is hard to achieve.

- Volkswagen Mietermobil program, a collaboration between Volkswagen and some apartment complexes in Germany, offered mobility for building tenants. The offers constitute various types of vehicle maintained by Volkswagen dealers, washed by local filling stations, and used exclusively by residents of the buildings (UNEP, 2002). In terms of the production line, it has similar level of criteria with Toyota Manufacturing. In terms of service however, the company builds partnerships with different sectors, including apartment owners, filling stations and VW local dealers. The service does not necessarily need sophisticated networks and technology, due to the offer being predetermined by the company. Regarding customer satisfaction, the customer survey revealed that most of them prefer to use their own vehicle for personal mobility and flexibility. Despite that this scheme benefits to reduce the need for vehicle production and increases productivity, the competitiveness remains low.
- Rolls-Royce is a company engaged in the field of aero-propulsion and industrial gas turbines. It offers Power-by-the-Hour service packages for aircraft engines, where maintenance, repair, and overhaul services are charged per hour of flight (Gaiardelli, Resta, Martinez, Pinto, & Albores, 2014; Garetti, Rosa, & Terzi, 2012). Rolls-Royce maintains close relationships and intensive communication with their customers to satisfy current needs and capture future demand. The company uses a collaborative approach on innovation with many knowledge institutions in designated topics and technologies. This indicates that the business includes a high diversity of actors. In terms of technology, Rolls-Royce depends on extensive in-house technology capability (Rolls Royce, 2014).

  Analyzing the PSS performance, under this scheme, Rolls-Royce increases the material productivity by prolonging product lifetime through proper usage and maintenance. In terms of system capability, the company performs better in terms of providing different values and solving various problems related with customized needs of their customer.

In view of these diverse examples, we address the description of Product-Service Systems in more detail in the next section.

1.1.1.1.1. PSS Typology

The idea of PSS is to transform the conventional manufacturing industry's business model, which focuses on product sales, into a more service-provision oriented model. Environmental considerations, as well as economic sustainability, encourage the rise of the PSS concept. Its ultimate goals are to reduce resource consumption while at the same time achieving customer satisfaction (Goedkoop, Van Halen, Te Riele, & Rommens, 1999; O. K. Mont, 2002). Studies in PSS stated that instead of selling goods, a business that adopts PSS will provide services and utilities for consumers through the use of product-service combined to achieve results expected by customers (Baines et al., 2007; O. K. Mont, 2002; Roy, 2000).

Literature provides various definitions of PSS (presented in Table 1). Those definitions share similar components consisting of the entities of the system (i.e. product, service, infrastructure, network), and the purpose of the system (summarized as to satisfy the customer and lower environmental impact). Despite the definition involving products and services within a system, it is necessary to understand that PSS has beeen largely addressed for manufacturing and production systems. PSS focuses on increasing resource productivity through alternative scenarios for product use, and therefore, reducing resource consumption. To close the material cycle from shifting ownership since consumers do not necessarily own or buy goods to fulfil their needs is also the main purpose of PSS practice (e.g. O. K. Mont, 2002; Roy, 2000). Accordingly, looking at the PSS definition as a guide for PSS framework development, it is critical to highlight that the objectives of PSS differ to the conventional industrial system (both production system and service system). Focusing on the entity of PSS (combined product-service) may result in misleading directions in PSS development.

The ambiguity of PSS definition implies a PSS typology. The widely used PSS categories within literature were introduced by Tukker (2004), classifying PSS into three types: 1) Product-oriented; 2) Service-oriented; 3) Result-oriented. The classification is based on value created, delivered and captured by a company for consumers. Ostaeyen et al. (2013) argued that the PSS categories of Tukker fail to capture the complexity of PSS examples found in practice. Hence his study refined the PSS typology based on revenue mechanisms, distinguishing PSS into four types including: 1) Input-Based revenue mechanism; 2) Availability-Based revenue mechanism; 3) Usage-Based revenue mechanism; 4) Performance-Based revenue mechanism. Another study in PSS typology classifies PSS based on the business model (Adrodegaria, Alghisia, Ardolinoa, & Saccania, 2015). This distinguished PSS into two major categories, ownership-oriented, and service-oriented, and divided each category into subcategories associated with the revenue mechanism and value proposition. To include the product-oriented category in PSS types without further concern to PSS objectives potentially leads to bias when designing PSS business models. However, the typologies are beneficial as a guide for PSS transition from existing practice into expected implementation which aims for the specific goals of PSS. The description of each PSS typology is presented in Table 2.

Table 1. Definition of PSS according to literatures

Author(s)	**PSS Definition**
(Goedkoop et al., 1999)	'A marketable set of products and services capable of jointly fulfilling a user's need. PSS is provided by either a single company or by an alliance of companies. It can enclose products (or just one) plus additional services. It can enclose a service plus an additional product. And product and service can be equally important for the function fulfilment'
(O. Mont, 2001)	'A system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact then traditional business models
(Manzini & Vezzoli, 2003)	'An innovation strategy, shifting the business focus from designing (and selling) physical products only, to designing (and selling) a system of products and services which are jointly capable of fulfilling specific client demands'
(Tukker & Tischner, 2006)	'A mix of tangible products and intangible services designed and combined so that they are jointly capable of fulfilling final customer needs'
(Annarelli, Battistella, & Nonino, 2016)	'A business model focused toward the provision of a marketable set of products and services, designed to be economically, socially and environmentally sustainable, with the final aim of fulfilling customer's needs'

Each PSS typology is compared to another, and similar character of each type has been identified. Enabling the comparison, a matrix is developed to describe the division of PSS typology, as well as to describe the transition of the business model. This study found that even though the basic categorizations are distinct for each PSS typology, the final description of PSS types share similar traits, including property rights, value proposition, and revenue mechanism, as shown in Table 3**.**

The discussion of property rights emphasized the ownership of tangible assets. PSS promotes ownerless consumption and assumes that without product ownership resource consumption can be reduced, ultimately resulting in lower environmental impact. Conversely, traditional consumption that focuses on product selling, albeit with better technology efficiency, may lead to a rebound effect. The type of value proposition of each system is found to be similar as well. Regarding this trait, the matrix is divided into three levels to describe the value proposition and dependency toward a particular product. For traditional consumption, value proposition lies in the product. Hence, the revenue mechanism strongly depends on the product. Service is offered and sold separately from the product itself. Some offer service to support and increase sales.

In addition to the previous types of PSS, another model exists, in which not only after sales service are offered, but also pre-sale service. Combining more services into product sales may lessen the value dependency toward the product while maintaining revenue. The level of sophistication of business processes and activities to deliver customer satisfaction is increased. The lower the value dependence on the product, the higher requirement of system capability to create intangible value that satisfies the customer.

As in ownerless consumption, the matrix reveals that the lesser the dependency of the value proposition on a particular product, the more value options for the customer. In contrast, when the value proposition is strongly associated with a particular product, it is more likely to limit the possibility of value creation for the consumer, and therefore, impact on their satisfaction. For service types with high dependency on particular products, consumer is allowed to access the product designated by the company. In this sense, the consumer is charged based on a period of access to a product/service. The medium level of service value depends on product focus on providing service through the usage of the available product. It is similar to the product-oriented business model, without transfer of ownership to the customer, where the company provides facilities for the customer to create their value through service. In this case, pricing should consider risk during customer usage. The lowest level value dependency to the product in ownerless consumption is to deliver a particular result or performance disregarding the product itself, in which the company should be able to produce the expected result for the consumer through the combination of products and services within the system.

In summary, it appears that ownership status has been projected to link directly to environmental impact. On the other hand, the dependency level of the value proposition to the particular product is associated with the amount of value that can be created, as well as to the level of sophistication of business processes and activities. Better process capability to deliver various value components to respond to customer demand leads to higher customer satisfaction. Apparently, PSS with the lowest dependency of value proposition toward a particular product, results in the most desirable outcome, including lower environmental impacts and higher customer satisfaction.

1.1.1.1.2. Networks and Infrastructure

Networks and infrastructure are frequently mentioned in the PSS literature. Morelli (2006) emphasises technological knowledge embedded in equipment and cultural aspects of participant actors that influence system development in PSS design activity. Other studies suggest infrastructure, partnership and information are considered to have a strong influence for operational excellence of PSS (Cherubini, Iasevoli, & Michelini, 2015; Schuh, Gudergan, Feige, Buschmeyer, & Krechting, 2015; G. V. A. Vasantha et al., 2013). Authors believe that internal process capability strongly depends on resources and knowledge, while the network is useful to extend the process capability to the desired level.

Table 2. PSS Typology in literature

Categorization Based	PSS Category	Description
Type 1: Based on value created, delivered and captured by a company for consumers (Tukker, 2004)	Product-oriented (PO) model	- Provider delivers a service in addition to selling a product - Product remains with customer
	Use-oriented (UO) model	- Provider does not sell a physical product - Product available under rental or leasing agreements - Ownership remains with the provider
	Result-oriented (RO) model	- Provider delivers result or outcome - No specific product is involved - Provider is paid based on the result they deliver to customer
Type 2: Based on Functional Hierarchy Modelling (FHM), focus on the level of integration and the performance orientation of the dominant revenue mechanism (Ostaeyen et al., 2013)	An input-based (IB) revenue mechanism	- Product property is transferred to the customer - Revenue is generated together with the ownership transfer
	An availability-based (AB) revenue mechanism	- Revenue transfer occurs based on the period during which the product or service is available for the consumers
	A usage-based (UB) revenue mechanism	- Revenue is generated only during the actual usage of product or service - Usage can be expressed in time units or other units that associate to the usage dimensions
	A performance-based (PB) revenue mechanism	- Revenue is generated from the functional performance of product or service
	A solution-oriented performance based (PB-SO) revenue mechanism	- Revenue is generated based on particular solution-specific functional performance indicator.
	An effect-oriented performance based (PB-EO) revenue mechanism	- Revenue is generated according to objective environment –specific functional performance indicator.
	A demand fulfilment-oriented performance based (PB-DO) revenue mechanism	- Revenue is generated according to a subjective functional performance indicator that expresses how well a customer demand is fulfilled.

Table 2. PSS Typology in literature (continued)

Categorization Based	PSS Category	Description
<u>Type 3:</u> Based on the building block of the business model framework (Adrodegaria et al., 2015)	Product-focused PSS type (GROUP A – Ownership oriented)	- Provider sells the product separately from the customer service needs during the usage phase.
	Product and processes focused PSS type (GROUP A – Ownership oriented)	- Similar to product-focused PSS - The difference is the service is provided both in the pre- and after-sale phases.
	Access-focused PSS type (GROUP B – Service oriented)	- Customer pays a fixed regular price to have access to the product or service - Service comprises preventive maintenance, product upgrade, retrofit, and revamping - Relational interaction that covers long period of time
	Use-focused PSS type (GROUP B – Service oriented)	- Customer pays a variable price that depends on the usage of the product - The company is responsible for the whole product cost during lifecycle - Pricing mechanism should consider risk aspect.
	Outcome-focused business PSS type (GROUP B – Service oriented)	- Customer pays the price based on the outcome according to a contract agreement in terms of product/service performance or the result of its usage.

Table 3. The division of PSS based on value proposition dependency toward product

<table>
<tr><th rowspan="2">Property Rights</th><th rowspan="2">PSS Typology</th><th colspan="6">DEPENDENCY LEVEL OF VALUE-PROPOSITION TOWARD PRODUCT</th></tr>
<tr><th colspan="2">High</th><th colspan="2">Medium</th><th colspan="2">Low</th></tr>
<tr><td rowspan="3">Customer ownership</td><td>Type1</td><td>Product oriented</td><td rowspan="3"><u>Revenue mechanism:</u>
From product selling and service that provided separately during usage phase

Price is charged based on [Product Cost/unit product]</td><td colspan="2">-</td><td colspan="2">-</td></tr>
<tr><td>Type2</td><td>Input-Based</td><td colspan="2">-</td><td colspan="2">-</td></tr>
<tr><td>Type3</td><td>Product-Focused</td><td>Product & Processes focused</td><td><u>Revenue mechanism:</u>
From product selling, and service provided before and after sales.

Price is charged based on [Product Cost/unit product]</td><td colspan="2">-</td></tr>
<tr><td rowspan="3">Service Provider Ownership</td><td>Type1</td><td>Service-Oriented</td><td rowspan="3"><u>Revenue mechanism:</u>
From providing access to an available function of product/service during the period of time.

Price is fixed based on access cost/period</td><td colspan="2">-</td><td>Result-Oriented</td><td rowspan="3"><u>Revenue mechanism:</u>
From the outcome resulted from product/service performance, or the result of its usage.

Price is charged based on unit performance according to contract</td></tr>
<tr><td>Type2</td><td>Availability-Based</td><td>Usage-Based</td><td rowspan="2"><u>Revenue mechanism:</u>
From the actual usage of product/service.

Price is variable based on the unit usage (e.g. dimension, time)</td><td>Performance-Based</td></tr>
<tr><td>Type3</td><td>Access-Focused</td><td>Use-Focused</td><td>Outcome-Focused</td></tr>
</table>

1.1.1.1.3. PSS features

Throughout the literature, several features have been identified as PSS characteristics as described below.

a. Shifting of role and ownership

In contrast to the current paradigm, despite selling goods, PSS focus on providing services rather than ownership by renting or leasing products (Vezzoli, Ceschin, Diehl, & Kohtala, 2015; Williams, 2006). Others suggest that PSS focus on how to fulfil customer needs and create customer value (Lindahl and Olundh, 2001). Within this system, customers are released from the obligation of product ownership to meet their needs. This shift is beneficial for the consumer because it will reduce initial investment and risk of ownership as they purchase the product.

Shifting ownership leads to a change in the relationship between customer and company. In the current system, product purchasing brings consequences for consumer who becomes fully responsible for the product throughout the remainder of its life cycle. Following the change of this property, the interaction between consumer and business becomes more intensive, since transactions may occur anytime during the product life cycle. Consumers become more engaged in product-related decision-making together with the company (e.g. Cavalieri & Pezzotta, 2012; Vezzoli et al., 2015; Williams, 2006). This feature supports previous argumentation in PSS typology, that product-oriented business models could be irrelevant in a PSS framework, and therefore, this study highlights the shifting ownership in PSS which means PSS within the service-oriented spectrum.

b. Extended material management

For business, the shifting of role and ownership in PSS provides an opportunity to have more control over their product life cycle. Regardless, the definition of product life cycle varies across the literature. For the purposes of the present study, the author refers to the product life cycle definition by Sundin (2009) as “the progress of a product from raw material, through production and use, to its final disposal” as illustrated in Figure 1.

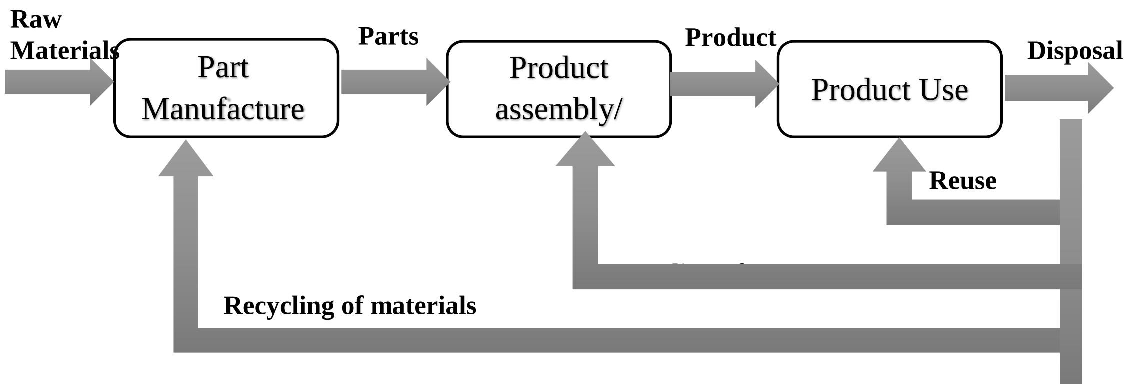


Figure 1. The physical product life-cycle (Sundin, 2009)

In PSS, ideally product ownership rests with the company. Hence, the potential to create value for the company together with the customer arises within the whole lifecycle. Furthermore, under this system, product and material take-back rate is expected to increase significantly. Closed loop material cycles become more attainable under a PSS framework.

1.1.1.1.4. Benefit and Barriers

Various studies have been conducted presenting the benefit and barriers of PSS (Baines et al., 2007; Beuren, Gomes Ferreira, & Cauchick Miguel, 2013; O. K. Mont, 2002; UNEP, 2002). Literatures commonly categorize the PSS benefit based on the stakeholder, including environmental benefits. Table 4 presents PSS benefits summarized from various literature.

Table 4. Summary of PSS benefits

	PSS benefits	***References***
Consumer	Improvement in total value and quality; greater diversity of choices; personalized and customized offers; released from ownership responsibilities; lower cost and problems associated with product ownership.	(Baines et al., 2007; Beuren et al., 2013; Goedkoop et al., 1999; O. K. Mont, 2002; UNEP, 2002)
Company	Creating competitive advantage; opportunities to innovation; increase market development; increase operating efficiencies; better feedback of consumer needs.	(Baines et al., 2007; Beuren et al., 2013; O. K. Mont, 2002; UNEP, 2002)
Environment	Reduced waste; reduced resource used; closing material cycle.	(Baines et al., 2007; O. K. Mont, 2002)

Regarding barriers to implementation, the discussion evolves around consumer readiness, industry readiness, and hesitation with regards to the benefit of the system. It has been argued that consumer-related barriers refer to the necessity of cultural shifts in consumer behaviour. Several studies mentioned that consumers seem to be less enthusiastic about ownerless consumption (e.g., Baines et al., 2007; O. K. Mont, 2002). While companies are more concerned about their capability and the organizational transition required to deliver combined product-service to the customer (e.g., (Beuren et al., 2013; Cavalieri & Pezzotta, 2012). There have only been a few examples of PSS uptake, resulting in a less empirical studies that evaluate the benefit of PSS. Lack of empirical evidence arguably leads to company hesitation to adopt this system (Cavalieri & Pezzotta, 2012; O. K. Mont, 2002). Table 5 presents the summary of PSS barriers from literature.

Table 5. Summary of PSS barriers to implementation

PSS barriers	***References***
Consumer related - Consumers not enthusiastic about ownerless consumption; lack of engagement and awareness related to PSS	(Baines et al., 2007; Cavalieri & Pezzotta, 2012; Mahut, Daaboul, Bricogne, & Eynard, 2015; O. Mont, n.d.)
Company related - Firms concern to process capability and infrastructure which assumes to be need of high investment; lack expertise in designing and delivering the services; organizational changes	(Baines et al., 2007; Beuren et al., 2013; Cavalieri & Pezzotta, 2012; Mahut et al., 2015; O. K. Mont, 2002; Sakao, Panshef, & Dörsam, 2009; Williams, 2006)
Benefit uncertainty - Socio-environmental benefits not always significant; uncertain profitability for company; unclear benefit for consumer	(Cavalieri & Pezzotta, 2012; O. K. Mont, 2002)

1.1.2 Motivation, Objective and Definition of Energy Product Service Systems

Energy Product-Service Systems (EPSS) are a specific subset of the field of PSS where it intersects with energy systems. Hamwi et al. (Hamwi, Lizarralde, Legardeur, Izarbel, & France, 2016) first introduced the term of Energy Product Service Systems as a concept of new business models that incorporate Product-Service Systems into the energy system. Later, the research direction focused on Demand-Response business models (Hamwi & Lizarralde, 2017; Hamwi, Lizarralde, & Legardeur, 2020) which is different from EPSS in this study.

The underlying motivation of EPSS in this study is the understanding that energy is a form of "derived demand", in that end-users do not typically want energy itself, rather they require a certain performance level in terms of an energy-provided service (e.g. cooling (a service) at a set temperature (performance level) rather than the input electricity or gas and the cooling device). Considering that consumption of energy and products are more likely derived demand in the context of energy, hence they should ideally be delivered as energy service performance for end-consumers to avoid wasteful consumption. Satisfying households` derived demand for energy service performance with resources and products arguably worsens the effect of consumer cognitive bias in making informed decisions for electricity and product consumption. Electricity provision being commoditized, makes it more difficult for consumers with bounded rationality to make decisions based on the information provided (Council of European Energy Regulators (CEER), 2016). In the context of electrical appliance purchases as well, evidence shows that consumers tend to be myopic and do not view appliance purchases as long-term investments, thus often fail to choose highly efficient appliances (Gaspar & Antunes, 2011; Hori, Kondo, Nogata, & Ben, 2013). As a consequence, the market suffers from inefficiency due to consumer decision 'mistakes'. Moreover, consumers` failure to optimize their decision in purchasing and operating appliances, and consuming electricity results in excessive use of resources and creating more waste. For this reason, the EPSS framework aims to improve resource efficiency while maintaining consumption benefits for society.

EPSS is defined as a "system" that releases household consumers from appliance ownership and delivers electricity service performance using energy, products and operation of dwellings by incorporating its basic functional systems for a household that is designed to have higher benefit economically and environmentally, compared to typical energy and product-oriented systems (EPOS). Without appliance ownership, consumer costs and risks associated with ownership are anticipated to be lower (O. K. Mont, 2002). Additionally, consumers may be able to obtain more value from customization or higher quality of performance (Baines et al., 2007; O. K. Mont, 2002). For businesses, service-oriented provision arguably create opportunities from offering more consumer value, thus increasing competitiveness (Scherer, Kloeckner, Ribeiro, Pezzotta, & Pirola, 2016; Tukker & Tischner, 2006; Van Ostaeyen, Van Horenbeek, Pintelon, & Duflou, 2013). It is also anticipated that EPSS will result in better consumer feedback (Lindkvist & Sundin, 2016), and therefore, improve satisfaction. Furthermore, consumers shifting from buying products to buying services allows the company to extend their control of products (Lindkvist & Sundin, 2016) and use them strategically to achieve both the desired performance and business objectives. For society, the potential advantage of EPSS could be bolstered by improving the environmental performance, notably the reduction of resource consumption, waste and emissions.

1.1.3 The difference between EPSS and overlapping systems

1.1.3.1 The Difference between EPSS and EPOS

EPSS, which are characterized by shifting tangible resource ownership from customers to producers and omitting the requirement of appliance ownership, allows companies to elaborate various service designs that focus on providing energy service performance for the households. This is different from the incumbent system, which we refer as Energy and Product-Oriented Systems (EPOS), where households must purchase the appliance and the electricity to operate it and deliver and control the service by themselves to get the expected results. That being said, the main difference between incumbent and EPSS is the value proposition or simply stated, the offering.

In EPOS, consumers are left to transform the product purchase into something that effectively fulfils their need. The standard approach in EPOS is that a company produces goods, trades it with the user and receives payment. EPOS consumers are left alone and given freedom to finance the purchase, to learn how to use and extract the benefit from the product. Consumers are also required to organise maintenance, including purchasing complementary parts or components if needed. This depicts the transfer of ownership followed by the subsequent transfer of the risks and benefits of the product from provider to customer, including the failure and quality of the service that are created by the customer himself/herself. In contrast, in EPSS there is no obligation for households to purchase the service resources (i.e. appliances and energy), because EPSS delivers a result or functional unit of consumption. Thus, product ownership belongs to the service provider. An EPSS business model enables the customer to focus on the quality of the service instead of expecting some product quality that might be less or beyond their needs.

From the perspective of design, with respect to its contribution to address environmental problem from industry, the proposed method in EPOS provides only part of the solution, due to its focus on products (Roy, 2000). Each solution has its strength and also limitations to minimize environmental impact. However, when those methods are integrated into a system, sub-optimal solutions may occur and reduce the method’s efficiency in addressing environmental issues (Berndt & Wood, 1975). Moreover, those methods emphasize on tackling upstream issues and pay less attention to downstream, while at the same time industries are challenged with more sophisticated demands related to energy efficiency and material flows (O. K. Mont, 2002). On the other hand, EPSS is designed considering problems in production and consumption, with the aim to improve resource productivity and efficiency in consumption through the combination of products and services to satisfy customers' needs.

1.1.3.2 The Difference between EPSS and Typical Product-Service Systems

EPSS and other PSS are similar, in that both offer service performance for end-customers. Typical PSS can also have intersections with energy system technologies and approaches such as smart grids, energy management systems and demand-response program. Despite the similarities, there are two major distinctions between EPSS and typical PSS i.e. 1) system's primary entity and 2) consumers' ability to recognize benefit (Kusumaningdyah, McLellan, & Tezuka, 2019b).

The major difference between EPSS and PSS lies in the system entities. PSS is envisioned primarily for manufacturing product (e.g. (Manzini & Vezzoli, 2003; O. K. Mont, 2002; Morelli, 2006; Muto, Kimita, & Shimomura, 2015; Salazar, Lelah, & Brissaud, 2015; A. Vasantha & Vijaykumar, 2011)) in which the resource input can be observed clearly. On the other hand, EPSS considers energy as the main ingredient of the service to enable material or product operation. PSS focuses on increasing material productivity in production systems through alternative scenarios of product use and thereby reducing material consumption. At the operational level, its ultimate goal is to close the material cycle by implementing product ownership shifts from customer to service provider (e.g., (O. K. Mont, 2002; Roy, 2000).). Vercalsteren and Geerken (Vercalsteren & Geerken, 2006) provided extensive examples of PSS for households, which reveals that PSS tend to focus on a single product in designing the service, such as carpet leasing, renting toys and laundry services. Therefore, the network involves only the specific product/service provider and customer. Moreover, only a few studies have proposed PSS framework designs for energy services (Muto et al., 2015; Vercalsteren & Geerken, 2006). Energy was presented as a case study to show that service-oriented models can reduce the ownership costs of renewable energy power generating facilities, thus supporting energy accessibility in remote areas (Bacchetti, 2017; Bacchetti, Vezzoli, & Landoni, 2016). Another study designed PSS by offering ancillary services in addition to energy supply service to reduce emissions for industrial customers (Mourtzis, Boli, Alexopoulos, & Różycki, 2018). Despite proposing different ideas of PSS design, all of these studies emphasized on designing PSS for electricity supply service in systems separated from the broader system. Nonetheless, those frameworks exhibit typical PSS design in which the focus is on improving energy supply services without considering the broader energy system.

Meanwhile, given the nature of energy system, EPSS have broader scope involving different stakeholders from multiple sectors. A simple energy system in a household, for example space heating system, requires at least an energy provider, heating machine provider, heating service provider and household as customer. A more comprehensive system might include a housing construction company, house leasing company and policy makers in the network of a space heating system. The extensive network of actors results in higher risk and most likely higher investment. However, the anticipated efficiency and environmental benefit is also greater.

1.1.3.3 The Difference between EPSS and Energy Services Contracting

There is another parallel discussion in the field of energy, commonly referred to as Energy Services Contracting provided by Energy Service Company (ESCO). EPSS and ESCO are alike in the way that the business integrates the energy consumption system to provide immediate results of energy system performance to customers (Benedetti, Cesarotti, Holgado, Introna, & Macchi, 2015; Bertoldi, Hinnells, & Rezessy, 2006; Bertoldi, Rezessy, & Vine, 2006; Vine, 2005). However, EPSS that is characterized with shifting resource ownership distinguishes it from the common conception of an ESCO. The shift of appliance ownership is a critical factor for EPSS because it is expected to boost customer economic benefit and enable the producer to better-manage maintenance, recovery and operation in order to improve profitability while increasing market competitiveness. This is not common for ESCO, which require consumers to invest significantly in energy efficient projects, such that it is hard to gain wider market dissemination (Bertoldi, Hinnells, et al., 2006; Bertoldi, Rezessy, et al., 2006).

1.1.4 EPSS design problem

EPSS introduction, as an energy service-oriented system, is hampered with multi-dimensional barriers that arise from the current market, because energy systems are deeply intertwined with the overall structure of society (Geels, 2004; Goldthau, 2014), whereas infrastructure, technology, and multiple societal actors are already locked-in to product-oriented systems. The system transition requires new development pathways that cover multiple aspects, including technology (e.g. electricity generation, transmission, and distribution), organization (e.g. manufacturing industries, retailer, bank, energy market), natural resources, informational elements, legislation, and human factors (e.g. perception, value, beliefs, and norms) (R. P. Lee & Gloaguen, 2015; Unruh, 2000). Therefore, it is impossible to implement the method in EPOS for EPSS because the form of EPSS itself is unknown in a set context.

On the other hand, nobody knows how the EPSS should ideally be constructed to ensure performance under real conditions. The only clear idea about EPSS is to provide energy service performance and release the consumer from appliance ownership. Meanwhile, the required ingredients (i.e. information, equipment, process) to deliver a well-performing energy service that can satisfy consumers` demand and other stakeholders' interests is still questionable. For this reason, setting the performance measurement requires EPSS to be compared with EPOS. Nonetheless, the performance comparison between both systems is also challenging because it involves two different systems with different actor behaviour that responds differently depending on the product/service provision. In addition, normally the designer already has a system design in mind which is believed to have better performance considering previous evidence, in which accordingly a prototype is developed and evaluated on a small scale to verify the hypothesis. In the case of EPSS, prototyping any kind of design requires significant capital, and the performance measurement can only be done after a long period of time.

Hence, it can be summarized that EPSS design process faces two major challenges, including: 1) EPSS and EPOS comparison to evaluate EPSS design behaviour and performance, and, 2) information scarcity to establish and design well-performing EPSS. Therefore, the EPSS design process requires a specific method to design a system that involves multiple interacting actors in socio-technical complex under limited knowledge.

1.2 Research Questions and Objectives

From EPSS design problems arise a number of research questions that need to be answered:

1. What method and technique are suitable to address the EPSS design problems?
2. How to utilize the method for EPSS design?
3. What is the performance of the method to address EPSS design problems?

To answer these questions, this study is structured into two parts. The first part of the study aims to develop a method to design EPSS, and the second part is dedicated to demonstrating and evaluate the utilization of the method to design EPSS using hypothetical cases to achieve three purposes, comprising of:

1) identification of key factors for EPSS design to reduce emissions and total cost of consumption without sacrificing consumer satisfaction,
2) investigating enablers for EPSS design to achieve win-win solutions for all stakeholders in liberalized electricity markets,
3) investigating preconditions for EPSS design to achieve sustainable renewable energy market.

1.3 Research Steps

The study is conducted in two main parts. The first part is to develop the Simulation-Based Design and evaluation framework, and the second part is to demonstrates the utilisation of the framework to achieve certain goals of EPSS design, whereas the design focuses on three elements of the systems, including tangible products (i.e. electrical appliance), information, and energy (represented by electricity).

1. *Development of Simulation Based Design and Evaluation Framework for EPSS*

This study utilises Simulation-Based Design as the main instrument to design and evaluate EPSS. SBD is beneficial to provide an image of a system with limited available knowledge because the designer does not have sufficient knowledge about the system. In this case, simulation results provide the designer with more information about the unknown characteristics of the systems. Additional technique may be required to design and evaluate the performance of proposed design depending on the context.

2. *Demonstrating the utilisation of Simulation-Based Design for EPSS Design*

Simulation-Based Design is demonstrated to evaluate the flow changes of three elements of the systems toward expected system performance, including tangible product flow, information flow, and energy flow. Changing appliance ownership status leads to changing interaction between economic agents and tangible product. It also effects on the changes of information provision and the flow of information between agents. Moreover, there's also opportunity to manage supply-demand energy, especially electricity, differently from incumbent systems. The method, therefore, is implemented to evaluate the performance of EPSS design caused by changes of systems' element and compare it to incumbent system as the baseline of the system's arrangement. Given the characteristics of the element and or interaction between economic agents and the element, additional technique may be required to be incorporated with SBD to obtain the expected research goal. Figure 2 shows the steps of the research and how they are incorporated in the thesis.

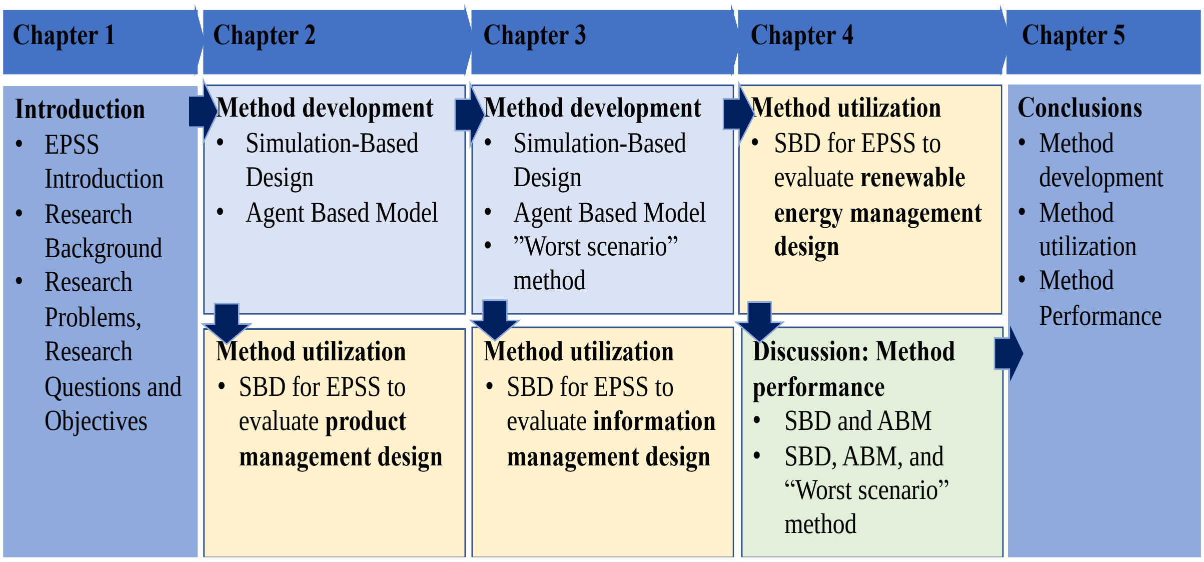


Figure 2. Flow of the thesis

1.4 Object of the study

A hypothetical market is used to demonstrate the implementation of SBD to design EPSS. The electricity market has evolved at different rates and directions in each country. The market, therefore, is constructed from different actors that have different roles and responsibilities. Kisrchen and Strbac (Kirschen & Strbac, 2004) clarified the types of companies and organizations that play a role in these markets. Those actors are responsible for electricity generation, transmission, and distribution, retailer, and consumer. In addition, regulators, market operators, and independent system operators are required to ensure the fair and efficient operation of the power system. Consumers are categorized into small and large consumers. Small consumers buy electrical power from the retailer, while large consumers actively participate in the market by buying electricity directly through the market.

In the existing system, electrical appliances are distinguished from the electricity market, although electrical appliances, in terms of specification and operation, have a major contribution to material and electricity consumption from households. Various factors influence electricity demand from households but are currently difficult to manage.

To demonstrate the method, this study illustrates a market consisting of appliance producers and electricity retailers in liberalized electricity markets that serve a community of household consumers as shown in Figure 3.

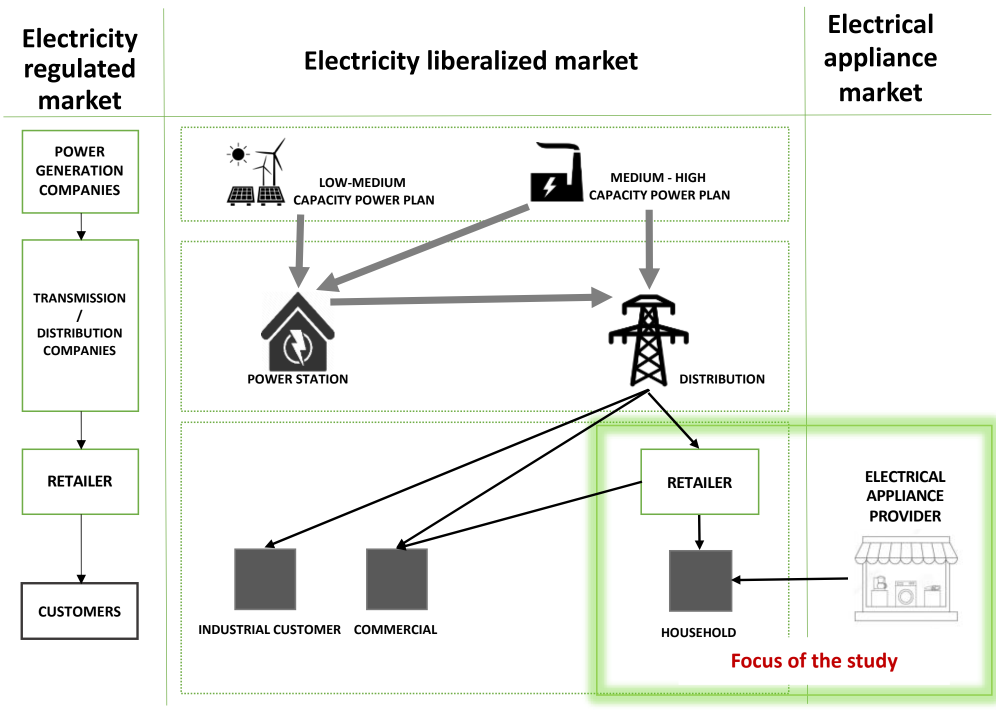


Figure 3. The boundary of the study object

In reality, a range of factors cause consumers to create demand for electricity service performance. The consumer creates demand due to environmental stimuli that cause uncomfortable conditions or reduction in productivity, such as insufficient light, uncomfortable room temperature, or unhealthy room humidity. Lifestyle also triggers consumers to create electricity service performance. For example, some people use home entertainment more than others. Particularly in this study, consumer demand for electricity service performance is triggered by an environmental stimulus. To be precise, consumer demand is a comfortable room temperature caused by low outdoor temperature in winter.

In term of electricity, household consumption is influenced by various factors, that can be categorized into three groups, i.e. 1) demographic factors (e.g. (Hara, Uwasu, Kishita, & Takeda, 2015; Shiraki, Nakamura, Ashina, & Honjo, 2016)(Long et al., 2019; Pombeiro, Pina, & Silva, n.d.)) , 2) operation system (e.g.(Delzendeh, Wu, Lee, & Zhou, 2017; Mizobuchi & Takeuchi, 2016; Young, 2008)), and 3) lifestyle (e.g.(Delzendeh et al., 2017; Ozawa, Furusato, & Yoshida, 2016; Zhang, Bai, Mills, & Pezzey, 2018)). Demographic factors include but are not limited to family size, appliance numbers in-use, income level, and dwelling size. The operation system of service delivery represents the environment including the appliance in-use to deliver service performance. In terms of heating service demand, building and appliance specification contributes to the amount of heating demand. Lifestyle has a major contribution to household demand for electricity consumption. For example, households in which most members spend more time at home require more electricity consumption than those whose members are predominately outside the home. However, this study is only interested to observe the influence of the operating system toward electricity demand as the main consideration to design EPSS, especially appliance efficiency and building structure, which is indicated by coefficient of heating resistance (r-value). Figure 4 depicts the factors that contribute to a household's service demand in the observed market.

1.4.1 Actors' attributes and behaviour

This section describes the attributes of the actors and how it influences their decision-making process given the choices.

1.4.1.1 Household consumers

Consumers are known to have cognitive bias in decisional processes, which is caused by bounded rationality. Herbert A. Simon coined the term bounded rationality where economic agents 'satisfice'[1] due to their limited knowledge and computational capacity (Simon, 1997), time (Gigerenzer & Selton, 2002) and will power (OECD, 2017). These economic agents are not equipped with the capability to compute complex information (Simon, 1955, 1956), causing them myopic and not being able to assess long-term risks or benefits from their decisions (OECD, 2017). Satisficed decision-makers use simple heuristics to make decisions (Gigerenzer, Todd, & the ABC Research Group, 1996; Kahneman & Tversky, 1979; Wilson & Dowlatabadi, 2007) using simple relations, like causality, attributes and similarity between new information and memories that serve as cues (Kahneman, 2011).

The effect of consumer's bounded rationality can be observed in various cases. It was suggested that energy labels do not necessarily influence consumer choice (OECD, 2017; Waechter, Sütterlin, & Siegrist, 2015) and that consumers make systematic mistakes when purchasing energy-using durables, including electrical appliances (Allcott, 2016). The evaluation of imperfect information and inattention in the light bulb market for example, showed that most consumers still prefer inefficient light bulbs even after being well-informed of the lifetime benefits (Allcott & Taubinsky, 2015). Information treatment using energy labels does not affect the share of high efficiency appliance adoption (Datta & Gulati, 2014). A study explored consumer knowledge resulting from the EU Energy Consumption Labelling

[1] The term 'satisfice' originated from the word 'satisficing', first introduced by Simon (1947) in his book *Administrative Behaviour* (Simon, 1956). He uses the term to explain the behaviour of economic agent behaviour in decisional process to accept available options as satisfactory instead making effort to achieve optimum satisfaction.

Framework shows that consumer knowledge about appliance energy class is low for all type of appliances (Mills & Schleich, 2013). Mixed results were found in the case of air conditioners. A model of fully-informed and rational consumers found that consumers value future savings from high-efficiency air conditioner units (Rapson, 2014). Meanwhile, another survey identified that consumers prioritize affordable prices more than other factors (Gaspar & Antunes, 2011). On the other hand, there are a few cases where consumers make informed choices based on the information provided. For example, in the case of vehicles, the weight of evidence suggested that if there's any systematic mistakes in consumer choice, they are minimal (Busse, Knittel, & Zettelmeyer, 2013; Datta & Gulati, 2014; Sallee, West, & Fan, 2016). In clothes washers as well, it was found that the information treatment using energy labels can increase the technology adoption (Datta & Gulati, 2014).

In terms of electricity consumption, consumers are said to have an interest in minimizing costs. However, it was found that consumers in the electricity market do not even remember the electricity rate (Frederiks, Stenner, & Hobman, 2015a; Yamamoto, Suzuki, Fuwa, & Sato, 2008), although the information is readily accessible. Concerning the energy market, a model of the retailer's contract for the energy mix market found that the optimal contract strategy is distorted under asymmetric information. The market distortion is smallest for risk-averse consumers, and largest for risk-taker type consumers (Y. Chen et al., 2018). Bounded rationality may also lead to rebound effect. An experiment exhibited that myopic and loss-averse consumers' behaviour in electric car purchases and driving behaviour can triple the renewable electricity price (Safarzy & Bergh, 2018).

In electricity purchases, despite easy access to information, some consumers were found not to be willing to exercise their freedom to choose in a liberalized market. Three cognitive biases have been identified as the causes of inertia in liberalized electricity markets, including status quo bias, loss-aversion bias and social influence (Council of European Energy Regulators (CEER), 2016). Status quo bias created by previous monopolies promotes consumer loyalty through long-term relationships (Wieringa & Verhoef, 2007; Yang, 2014), which results in habitual behaviour and cognitive comfort. It appears that such comfort results in feelings of satisfaction with the incumbent provider (Wieringa & Verhoef, 2007). For this reason, households rarely search for alternative retailers, but when they search, households perceive more advantages in the incumbent (Hortaçsu, Madanizadeh, & Puller, 2017).

Closely related to the status-quo bias, consumers on average are either risk averse or loss averse. In electricity-related markets, it was found that typical consumers refuse to consider different options because either they afraid that they will lose some benefit compared to the current situation (risk-averse) or they have the perception that there is insignificant economic benefit compared to the cognitive cost from changing their choice (loss-averse) (Frederiks et al., 2015a). Evidence has showed that “lose if you don’t purchase” frames are no better than “save if you purchase” frames to promote goods that require initial investment like solar panels, even if household consumers are aware and believe that the purchase will benefit them in the long run (Gamliel & Herstein, 2011).

Social influence has also been identified as a cause of consumer inertia. It was argued that consumers do not exercise their choice because the social standard is not to switch (Council of European Energy Regulators (CEER), 2016). While not always negative, social standards have been found to effect efficiency of peer network energy consumption (Jain, Gulbinas, Taylor, & Culligan, 2013). It has also been observed that household consumers following social influences depending on the influencer. For example, rich villagers negatively impact on the conformity of households to adopt biogas, in contrast to the positive influence of neighbours and relatives (Zeng, Zhang, & He, 2019). In some cases, the strength of relations between individuals is more important than the number of connections in influencing the individual’s choice (Du et al., 2016; Zeng et al., 2019).

Many suggested to address the present bias by providing low cost of access to information (e.g. (Hortaçsu et al., 2017) (Council of European Energy Regulators (CEER), 2016)). Unfortunately, providing information can only eliminate imperfect information, but it doesn’t affect or identify the present bias. On the other hand, offering fixed price contracts could address the present bias due to bounded rationality, but it will not affect the imperfect information problem (Allcott, 2016). In addition to that, controlling behaviour in product-oriented system using taxes may be either ineffective, or welfare reducing (Ulph & Ulph, 2018).

In the present market model, consumers are divided into two major groups which are characterized by their willingness to switch, comprised of alternative seekers and inert consumers. Alternative seekers are those who are willing to exercise their choice by seeking and evaluating alternatives considering their interests. As described in the section on bounded rationality, alternative seekers make decisions using heuristics and rely on simple, recognized, information to make choices.

Meanwhile, the model assumes inert consumers to be caused by of three types of cognitive bias, i.e. status quo bias, risk-aversion, and social influence. Each consumer adopts a preference reflecting their interest in electricity consumption, as one of cost-oriented, environmental-oriented, or performance-oriented consumers. These consumers make decisions based on their bias. The flow of consumer behaviour and decisional processes in EPOS and EPSS, are described in Figure 5.

In a market wherein EPSS is not available as an option, consumer's demand for service leads to the demand for appliances and electricity supply. Accordingly, EPOS consumers make 2 decisions regarding electrical appliances, comprised of 1) decision to choose appliance, and 2) decision to replace and recycle appliance. EPOS consumers` choice of appliances are influenced by their characteristics and preferences. The model assumes that consumers have different preferences as considerations to choose appliances, including appliance price, and reviews from other consumers. Consumers whose purchasing is constrained by willingness to pay/ cost consider purchasing appliances whose price is closest to their budget. On the other hand, consumers who use market influence as a consideration, choose the most used appliance in the market.

EPOS consumers replace appliances for various reasons. Ideally, consumers are expected to replace an appliance to upgrade it with the latest appliance technology. However, typical consumers tend to prolong device lifetimes, such as air conditioners, until they are broken (*Energy Effic. Househ. Appliances*, 1999; Frederiks, Stenner, & Hobman, 2015b), which indicates that the appliance must be replaced. For this reason, EPOS consumers in this model use machine failure as a consideration to replace appliances. Probability of machine failures increase with age of the appliance, especially after the appliance has been used for more than 10 years (Fenaughty & Parker, 2018).

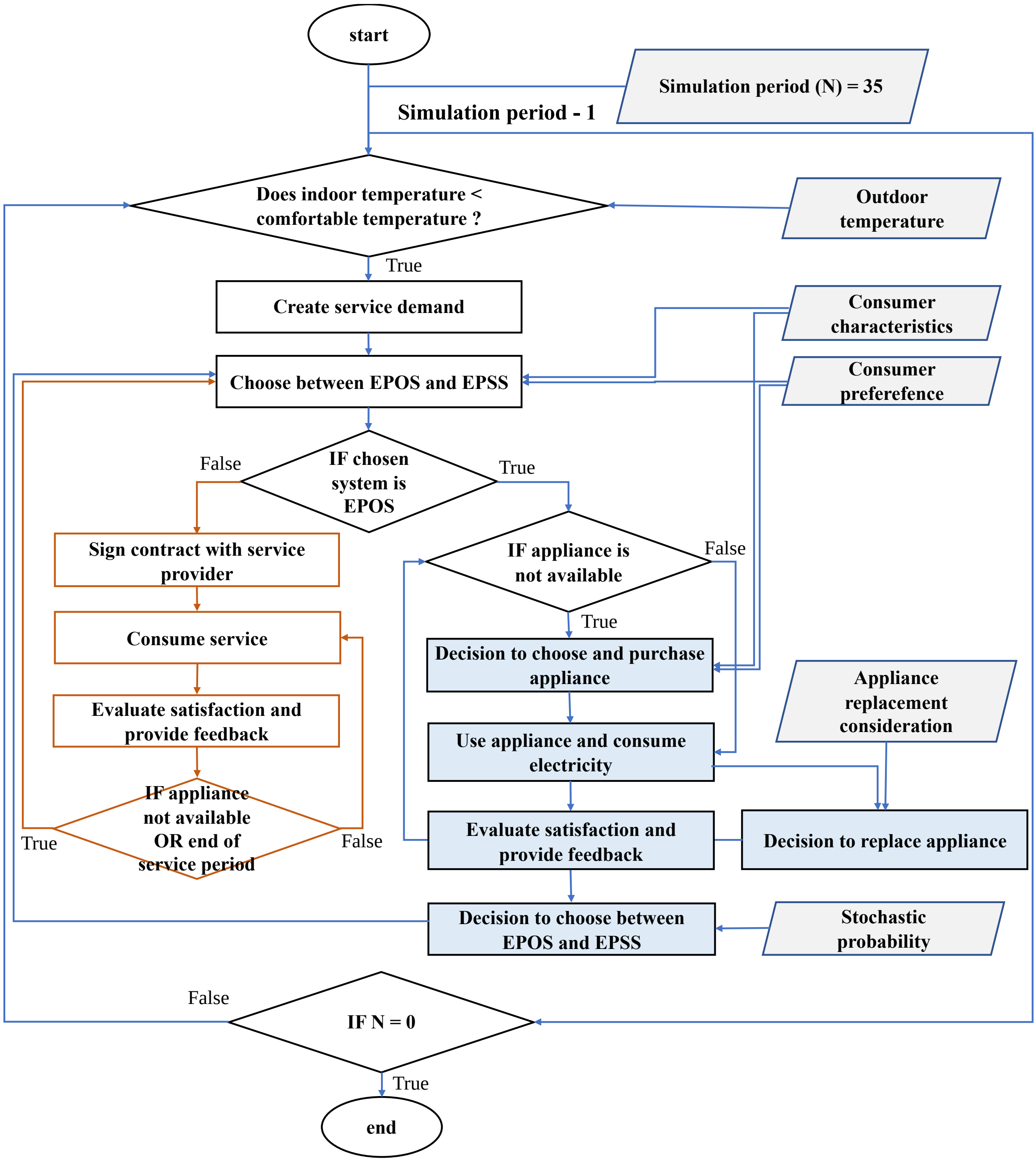


Figure 4. Consumer decision flow

Meanwhile, in the market where the incumbent system (EPOS) competes with EPSS, alternative-seeker consumers are first to develop the intention to choose EPSS. These consumers use available information to predict the benefit of adopting EPSS and compare it with the benefit they experience in EPOS. On the other hand, inert consumers will eventually consider switching to EPSS if there's information that addresses their cognitive bias. Consumers with a status quo bias choose EPSS if there is no choice other than to choose EPSS. This event occurs when companies decide to switch to EPSS for some reason. Loss/risk averse bias customers switch to EPSS if market reviews provide evidence that EPSS service is more satisfying than subscribing to EPOS retailers. Consumers with social proof bias decide to switch to EPSS when most of the closest agents in their network choose EPSS.

Within the simulation period, EPSS consumers evaluate their choice when the service contract ends, i.e. when an appliance is replaced. While EPOS consumers consider switching to EPSS randomly at each period. When they consider choosing, however, the decision is not always to switch. Finally, consumers in both systems provide feedback to the market by reviewing their satisfaction from consumption every period.

1.4.1.2 Companies (electricity retailers and appliance producers) behaviour

Firms exhibit different behaviour in investing in new technology. Some companies strive for innovation and introduce new provisions to the market, while others are found to be risk-averse to making new investments (e.g.(Petitet, 2016)).

In this study, companies in EPOS and EPSS are competing to satisfy consumer demand through energy. In the model, an electricity retailer initiates the adoption of EPSS, in which an appliance producer supplies the equipment and technology. Other companies who are risk-averse do not invest in the new system, unless there's evidence that the new investment will have more advantages than maintaining the status quo.

1.5 Structure of the thesis

This thesis aims to develop a method to design EPSS and to demonstrate its utilisation to achieve the goals of EPSS design. The layout of the thesis is as follows:

Following the first section, the method development for EPSS design framework is explained on *Chapter 2*. A novel approach to design EPSS, namely Simulation-Based Design (SBD) for EPSS is developed, following the discussion of approaches used to address EPSS design challenges. The method incorporates Agent-Based Simulation to depict the interaction between multiple actors on certain socio-technical environment. The step by step explanation of conducting SBD for designing EPSS is clarified afterward. This chapter also presents the implementation of the method for designing EPSS that minimize total cost and emission generation from households' electricity consumption without sacrificing consumer satisfaction. EPSS releases consumer from appliance ownership enable company to make decisions regarding appliance selection, operation, replacement and appliance reprocessing after end-of-life product. Given the mechanism, this chapter demonstrates the method to identify the conditions for EPSS to achieve the goal. For the purposes of the study, conditions derived from combinations of market variables are simulated and analysed. The selected variables include

EPSS service level, Recycling Law enactment, reprocessing rate, and appliance replacement policy. Managerial implications are provided based on research findings.

Chapter 3 improves the method developed in chapter 2 by incorporating the "Worst case" method to address the issue of uncertain input design. The method is then used to investigate enablers for EPSS design to achieve win-win solutions for all stakeholders. The underlying background of this study is suboptimality in incumbent systems that harms the benefit of consumers, electricity retailers, and appliance producers. EPSS with service provision allows the modification of information-sharing mechanism that differs from current systems. The modified information-sharing mechanism is expected to deliver win-win solution for all the involved actors. However, the proposed approach will only deliver expected results if it is preferentially taken-up by actors in competition against existing system. Therefore, it is important to identify the conditions required for information-sharing mechanisms to achieve EPSS design objectives. SBD for EPSS is used to evaluate EPSS design under different market environment. Three scenarios of information-sharing mechanisms are evaluated within several market conditions which characterized by share of alternative seeker consumers, share of dominant consumer preference and policy measures.

In *Chapter 4*, SBD for EPSS is implemented for designing EPSS in the context of energy transition. Energy transition is a complex mechanism that involve socio-technical dimensions of the society, whereas the transition is challenged with two major problems associated with lock-in, and sustainable renewable energy market design. To address lock-in, policy makers are expected to develop measures that also consider human dimension of energy systems, while also focusing on physical aspects of the systems (e.g. infrastructure, technology and organization). Concerning renewable energy markets, integrating renewable energy markets into current electricity markets will destroy power prices in the marginal cost-based wholesale spot market. It creates problems for future energy market sustainability, since the market cannot rely on wind and PV to refinance renewable energy development. It was suggested that future energy markets must be designed to achieve efficient balance of supply demand by steering the installation capacity and by sending signals through revenue gain for more investment in renewable energy production and supporting facilities. EPSS providing services allows a company to control and manage appliance usage and operation and demonstrates greater flexibility from the demand side to respond to supply uncertainties. To achieve service excellence, EPSS providers also invest in storage as reserve capacity for when demand for highest service performance is required. Moreover, instead of electricity trading, EPSS creates its main revenue from service value generated from appliances and electricity performance.

With zero operational cost, EPSS business model is projected to generate more revenue than merely trading electricity. Three conditions that lead to the worst performance for renewable energy market in the short-run and long-run have been identified in this study. This chapter also provides discussion regarding the performance of the method. This chapter reviews the performance of techniques incorporated to the method in addressing EPSS design problems, as well as improvements required for the method. Also, research implications from the method development are proposed here.

Ultimately, *Chapter 5* concludes the research by clarifying the development of the novel method and incorporated techniques to design EPSS. This chapter also verifies the performance of the method in addressing design problems for the designated goals. Moreover, conclusions based on the findings from method implementation are also clarified, including the research and managerial implications resulted from the findings.

Chapter 2

Methodology: Simulation-Based Design for Energy Product-Service-Systems

This chapter presents the development of the method using Simulation-Based Design (SBD) for Energy Product-Service Systems design and evaluation. This chapter also demonstrates the implementation of the framework to identify the conditions for EPSS to minimize service cost and emission from household service consumption without sacrificing consumer satisfaction.

2.1 Related Studies

The method to design and evaluate the performance of Energy Product-Service Systems is developed by incorporating SBD with Agent-Based Model (ABM). This section justifies the compatibility of SBD and ABM to address EPSS design problems based on the utilisation from previous studies.

2.1.1 Simulation-Based Design

Simulation-Based Design (SBD) has been utilized in many areas, mainly on product design (e.g. (Negrão & Hermes, 2011; Waltrich, Hermes, & Melo, 2011), marine study (Oh, Min, Cho, Bae, & Kim, 2016; Sandvik, Lønnum, & Asbjørnslett, 2019; Vernengo, Gaggero, & Rizzuto, 2016), and building and environment design ((Bueno, Wilson, Sunkara, Sepúlveda, & Kuhn, 2020; Cossentino, Fortino, Gleizes, & Pavón, 2010; Dhariwal & Banerjee, 2018; Henry et al., 2019).

Particularly in energy-related systems, SBD has been implemented for various purposes. In associate with product design, SBD is used to design parts of electrical appliances to achieve the goal of the design (Negrão & Hermes, 2011; Waltrich et al., 2011). The product design is an improvement from the existing design, and the simulation was developed based on prior knowledge. SBD is used to test the performance of the design under various environments. Still in a product-centric system, a study implemented SBD to illustrate the environmental impact of electronic waste. The thoroughness of the simulation is useful to estimate the true environmental impact of various reprocessing procedures for electrical appliances (Reuter, van Schaik, & Gediga, 2015). Other studies used SBD to optimize systems under uncertainty due to intermittent renewable energy supply (Gürtler & Paulsen, 2018; Mohammadi, Hoes, & Hensen, 2020). To achieve this, performance-based design support was proposed, and a simulation framework is presented to conduct the performance assessment. Simulation for performance assessment was also used to evaluate the interactive effect between photovoltaic applications and traditional passive houses (X. Chen, Huang, Yang, & Peng, 2019).

Generally, previous studies of SBD have emphasized the use of simulation as a tool to design, to evaluate product design, and to analyze systems. It uses simulation as the primary tool for system evaluation and verification. It is applied to areas with systems that require comprehensive analysis to predict the outcomes before consuming resources, effort, and time by eliminating risks of design failure as soon as possible (Klitkou, Bolwig, Hansen, & Wessberg, 2015). Some The simulation will typically require modeling and computational tools, and potentially virtual reality environments, and infrastructure for collaborative engineering and integration technologies and tools (Barazza & Strachan, 2020; Mercure, Pollitt, Bassi, Viñuales, & Edwards, 2016).

SBD has been implemented to address various design problems. Some problems related with complex system and multidisciplinary actors (Lalic, Cosic, & Anisic, 2005; Suzuki, Yahyaei, Jin, Koyama, & Kang, 2012), as well as to identify and to address the design issues that involves multi-actor within design environment (Huang, Seck, & Fumarola, 2012). A study utilized SBD for the sole purpose of finding the shortest way to deliver product design and production to meet every consumer demand (Lalic et al., 2005). The problem can be very specific to each case, such that some problem requires additional approach for SBD to achieve its research purpose. Table 6 shows the various approaches, techniques and tools that are incorporated to support SBD implementation.

Moreover, the literature review provides an image of SBD utilisation for different purposes including design optimization (e.g., (X. Chen et al., 2019; Dhariwal & Banerjee, 2018; Huang et al., 2012; Mohammadi et al., 2020; Oh et al., 2016; Shi, Fonseca, & Schlueter, 2017; Waltrich et al., 2011)), and to build knowledge management system (Cossentino et al., 2010; Reuter et al., 2015; Suzuki et al., 2012). SBD is used to optimize the performance of building design by using incremental integrated design approach and experimental design method (Dhariwal & Banerjee, 2018). Another deploys a genetic optimization algorithm for product design and to select the best design that satisfy the design objective (Waltrich et al., 2011). Optimization in SBD is advantageous for a system design with minimum uncertainties and well established knowledge. On the other hand, there many design process that are not about finding the optimal result, but to gain understanding about the actors and the problem within the system. SBD is used as an instrument to collect knowledge about the behaviour of the system design and accordingly make decision that are acceptable, instead the best, to suffice the requirement (Huang et al., 2012). This feature is suitable for EPSS design framework as a system without previous experience and with limited available knowledge, wherein instead finding the optimal design, EPSS evaluation framework is intended to provide a knowledge about the actors' behaviour, the problem of the design, the inter-connection between actors and how it influences the overall system behaviour and performance. Moreover, SBD is endowed with the flexibility to include various design parameters under various spaces (Cossentino et al., 2010), as well as instrument to generate dashboard performance that allows for the quick comparison of multiple design variants and within multiple design environment. This capability satisfies to the requirement of EPSS design and evaluation framework to compare design performance and incumbent systems.

Table 6. Approaches, Technique and Tools integrated to Simulation-Based Design

Research Field	**Integrated Approaches/ Techniques/ Tools**	**Authors**
Product design	Integration of new computer technologies and tools, including CAD and CAE to enable the application of simulation-based design into product design in general.	(Bossak, 1998), (Sephard, Beall, O'Bara, & Webster, 2004)
Product design	A genetic optimization algorithm was used to design condenser and evaporator	(Waltrich et al., 2011), (Negrão & Hermes, 2011)
Sustainable Faecal Sludge Management System	Agent Based Model	(Mallory, Crapper, & Holm, 2019)
Business process management	Process Modeling Technology	(Suzuki et al., 2012)
Resource efficiency and recycling systems	Process simulation (HSC Sim 1974-2014, Outotec's design tool) and environmental software (GaBi 2014) to quantify resource efficiency (RE)	(Reuter et al., 2015)
Energy related systems	A joint modelling platform consisting of EnergyPlus, JEPlus, R and GenOpt is developed to conduct different sensitivity and optimization analyses with adaptive variation of key parametric settings to compare the optimization of the passive building design with and without integrated PV systems.	(X. Chen et al., 2019)
Engineering support of offshore plant equipment industries	Advanced simulation-based design, namely "Feedback Loop Design" incorporates the software integration framework, including Remote Component Environment (RCE) (DLR, Germany), and the analysis tool used is the commercial software, DAFUL & ANSYS, for verification of the developed concept	(Oh et al., 2016)

2.1.2 Agent-Based Model

Agent-Based Modelling (ABM) is considered a better approach compared to equilibrium models to design EPSS that involves the interaction of heterogeneous actors with various interests, characteristics, and constraints, as well as to capture the impacts of the decision-making process on EPSS design performance. Agent-Based Simulation (ABS) is often applied to simulate energy systems considering economic agents with bounded rationality. It is advantageous to replicate the dynamics of liberalized electricity markets and energy transition progress by incorporating heterogeneous actors' behavior (Barazza & Strachan, 2020; O. Kraan, Kramer, & Nikolic, 2018). It also allows the exploration of the role of community players with their cognitive bias in energy transitions (Oscar Kraan, Dalderop, Kramer, & Nikolic, 2019). The exploration of plausible trajectories of energy transitions given uncertain socio-technical conditions is also possible with ABS (Kwakkel & Yücel, 2014; Yücel & van Daalen, 2012). These advantages are suitable for EPSS design, wherein multiple interacting market players with heterogenous characteristics and behaviors have anticipated impacts on the design performance.

In contrast to ABM, equilibrium models are static and only consider rational, utility-maximizing actors (Klitkou et al., 2015), different from the reality in energy systems, where actors often exhibit bounded rationality. Also, equilibrium models emphasize optimization, which often fails to capture the interaction between agents, and does not consider the fact that path-dependency often arises from actors' non-optimal decisions (Barazza & Strachan, 2020; Mercure et al., 2016).

2.2 Development of Simulation-Based Design framework for EPSS

A novel method is developed by incorporating ABM into SBD to evaluate and compare the performance of two systems consist of heterogeneous agent that exhibits different behaviour depending on the provision. Due to the limited available knowledge, the EPSS design process must use the information available in incumbent systems as the design baseline. The design process is conducted by making incremental changes to the value of the current system's parameters and to evaluate the impact of the changes through the comparison with the baseline system. Figure 6 shows the steps to conduct SBD for designing EPSS.

The first thing to do in SBD is to determine the goal of design and to decide the performance criteria as measurements of goal achievement. The performance criteria are determined based on the requirements of the stakeholders, considering current or future needs. Besides, the desired performance level must be quantifiable to measure the success of system design.

Next, the system causality that captures the dynamic interaction between actors and their entities and their influence to system performance is constructed based on the knowledge in the existing systems. The system designer sets up the system boundary, which can be referred to as the market where actors are interacting to achieve their goal. For initial development, the system boundary is set as simple as possible and similar to the current system. The system designer can later gradually expand and evaluate the effect of the system boundary on system performance. The system designer predicts the attributes, behavior, and decisional processes of each actor that are expected to influence goal achievement. For EPOS, the information is selected based on the knowledge/evidence in current energy markets. On the other hand, the information related with EPSS behaviour is determined based on the knowledge of existing systems with similar characteristics and not necessarily based on the energy market. In parallel, EPSS business models are designed to deliver the provision that suits consumers' needs by creating several scenarios of EPSS service. Each scenario is distinguished by the service level provided by the provider to consumers. Other criteria may also be applied to differentiate EPSS service designs. Eventually, exogenous factors that influence actors' behavior and decisional process in existing system, such as the direction of market policy or certain market characteristics, can be elaborated.

The next step is to compare the performance of EPSS and the incumbent system, the effect of changing combinations of parameters toward system performance is investigated. Parameters here refer to actors' behaviour, decisional processes and attributes, and the influencing exogenous factors. Sensitivity analysis is then conducted to investigate the correlation between each parameter, and the effect of individual parameters toward system performance. Market conditions are derived from the combination of actors' attributes and exogenous factors, which include controlled variables and uncontrolled variables. To select which parameters are to be evaluated in combination with others, the magnitude of the impact on system performance, or the key stakeholders' interests may be utilised as justification. For the evaluation of each condition, it is important to consider the minimum run of simulations that represents a sufficient sample size (J. S. Lee et al., 2015). The process is then iterated until the designer gains sufficient insight into the behavior of the observed systems. This level is considered to be met when the designer can identify the conditions where the system performs well or worst in the simulation through a comparison between incumbent performance and the modified system.

Eventually, build a simulation model to depict the behavior and performance of EPOS and EPSS using an Agent-Based Model (ABM), which is developed using *Python 3.8* language programming, particularly Mesa, an agent-based modeling framework in *Python 3.x* (Masad & Kazil, 2015). The analysis is conducted by focusing on the conditions that have significant impact on the results, either expected results or unexpected results. Afterward, the managerial implications are evaluated based on the findings.

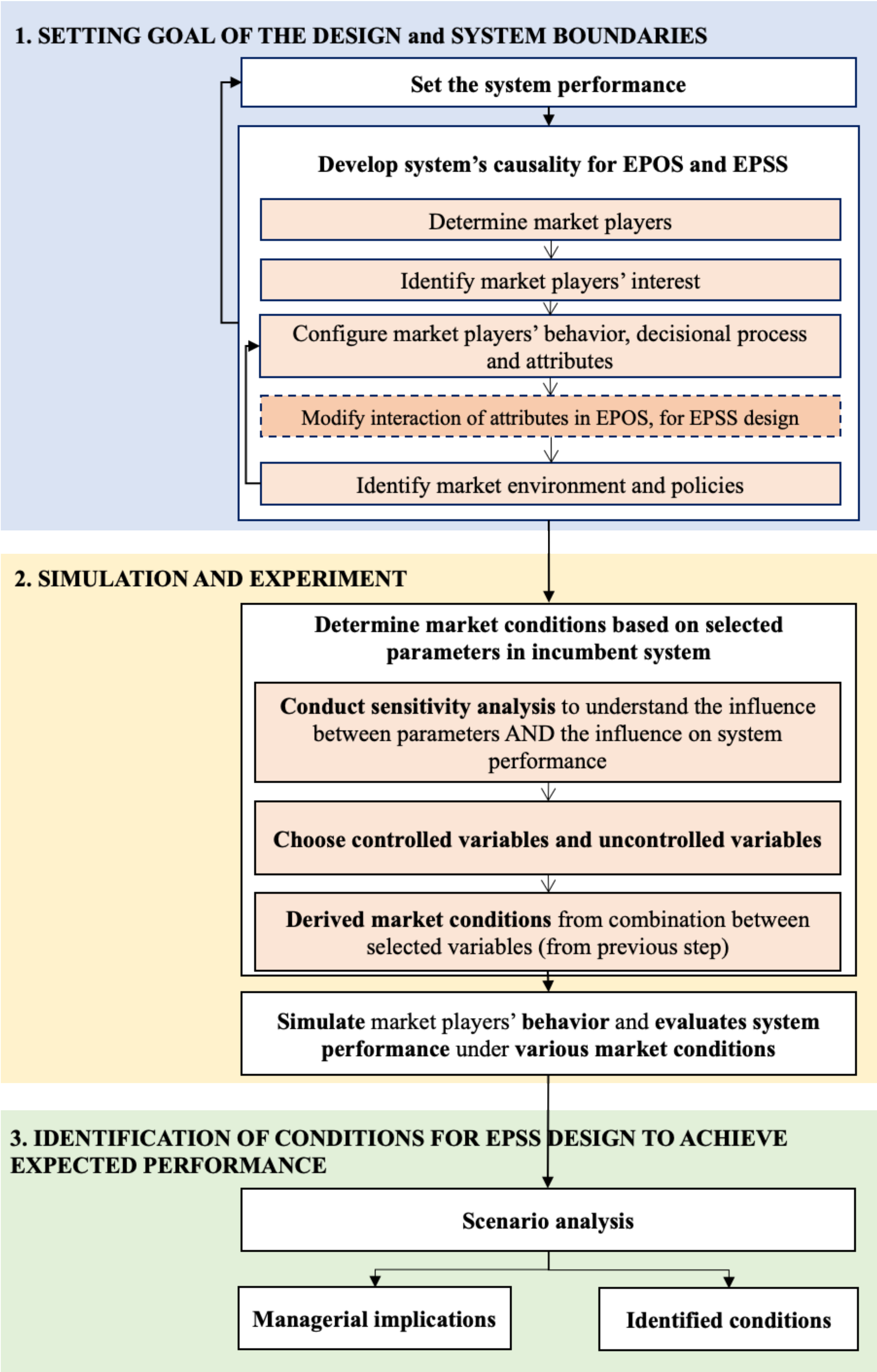


Figure 5. Simulation-Based Design for EPSS design

2.3 The method implementation to identify conditions for EPSS design to reduce emissions and total cost of consumption without sacrificing consumer satisfaction

The effort to minimize emission seems to be challenged with the trade-off between economic and environmental advantages. For example, the significant emission reduction from renewable energy deployment may harm the business profitability and economic sustainability of the current electricity market, which is a marginal-cost based market (Agora Energiewede, 2013). Another study shows a utility company providing wood chip-based heating service for a community faces challenge transitioning to carbon neutrality because was heating the company and its consumer do not willing to use less heat during winter, to reduce peak load demanded from the system so that provisioning with non-burning alternatives becomes attainable (Vadén et al., 2019). For this reason, this chapter demonstrates SBD for EPSS to design EPSS that reduce emissions while minimizing total cost to satisfy household consumer's demand without sacrificing satisfaction.

2.3.1 Object of the study

Chapter 1 has set a system baseline for EPSS design, consisting of household consumers, appliance producers, and electricity retailers. Particularly in this chapter, consumers preference is set to be cost-oriented. Moreover, the cognitive bias of inert consumers is caused by either risk-averse or loss-averse, wherein consumers refuse to consider different options because either they afraid that they will lose some benefit compared to the current situation (risk-averse) or they have the perception that there is an insignificant economic benefit compared to the cognitive cost from changing their choice (loss-averse) (Frederiks et al., 2015a). While alternative-seeker consumers willing to exercise their choice by making simple relations based on the recognized cue from information provision, inert consumers makes choice when there's sufficient positive feedback from early EPSS adopters. Figure 7 describes the actors` behaviour to satisfy consumers' demand in the market.

Regarding the provision, as previously described, EPOS and EPSS satisfy consumer demand differently. In EPOS, consumers are obliged to possess the appliance and connect to the electricity grid to satisfy their demand. Meanwhile, EPSS provides service as a bundle including the electrical appliance and electricity supply to deliver expected performance for household consumers in a constant monthly rate. In an attempt to minimize the operational cost of service delivery, this chapter evaluates three types of EPSS that are distinguished by service level as shown in Table 7.

Table 7. EPSS design service for evaluation

EPSS design	Service design characteristics
EPSS type 1	Company provides electricity service performance without appliance ownership; the service includes regular maintenance
EPSS type 2	Similar to EPSS type 1; with additional service where provider chooses appliances that minimize total cost of service delivery and provide maintenance; the aim is to minimize electricity demand to deliver service
EPSS type 3	Similar to EPSS type 1; in addition service provider increases the building heating resistance to minimize the occurrence of service demand.

The first service design is the simplest type of EPSS, which is similar to EPOS in a way that consumers are allowed to choose appliances based on their preference. The difference is that EPSS service releases consumers from appliance ownership and provides regular maintenance to maintain the appliance performance and to slow down the performance degradation rate and expectedly prolongs the product lifetime. In the second type of service level the company also chooses electrical appliances for the consumer to minimize electricity demand to deliver the service, which is expected to minimize the operation costs. Meanwhile, the third type of EPSS emphasizes the operating environment of the appliances by increasing the coefficient of heating resistance of the building to minimize the occurrence of service demand. For this type of service, the provider allocates more capital to improve building insulation and chooses the most cost-efficient appliance.

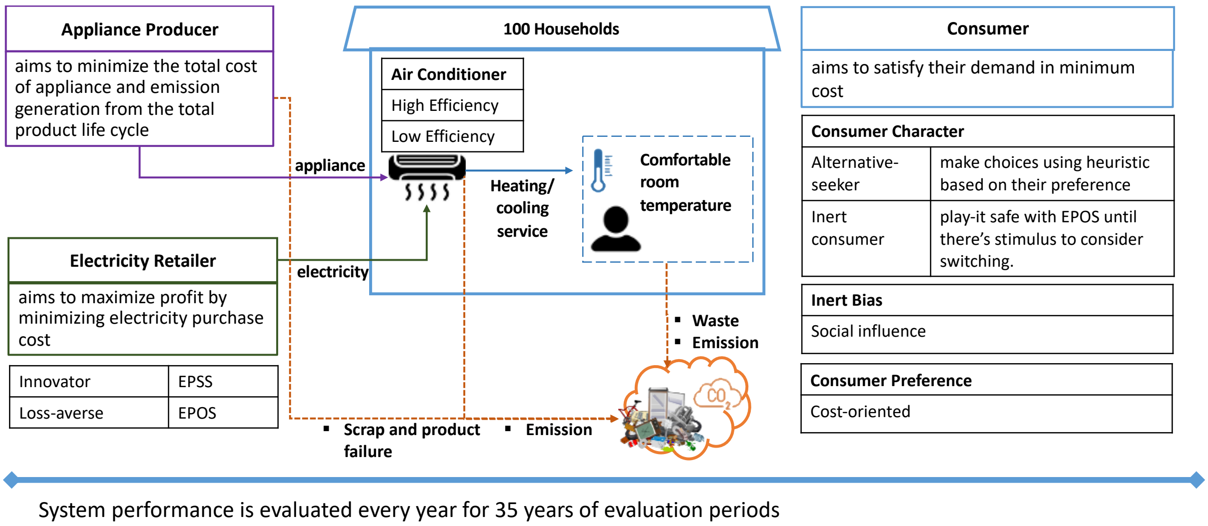


Figure 6. Description of actors` attributes and behaviour in the model

At the end of product lifetime, returned appliances are sent for further reprocessing procedures. The existing system incorporates various reprocessing procedures into their supply chain, including product recovery, component recovery, material recovery, and waste disposal (Krikke, Pappis, Tsoulfas, & Bloemhof-ruwaard, 2001; Rashid, Asif, Krajnik, & Nicolescu, 2013; Shimada & Van Wassenhove, 2019). To minimize the total cost of the system, the company responsible for returned appliances aims to maximize revenue from obsolete products to compensate for the cost of the forward supply chain. Accordingly, the company must determine the optimal amount of returned appliances that will simultaneously minimize appliance cost and emission generation. In the present study, all of the collected appliances in EPOS are sent for recycling by the manufacturer, while EPSS has more options for reprocessing and re-use, including product recovery, product sales to the second-hand market, and recycling.

The model also considers that the enactment of a Recycling Law influences the effort of minimizing cost from material consumption. The law aims at resource conservation and reduction of the environmental burden caused by material flows, especially for the production and disposal of home electrical appliances (Tasaki, Terazono, & Moriguchi, 2005). The law usually affects three actors in the system who participate in the recycling process, i.e. households, home appliance retailers, and home appliance producer (PETEC'S, n.d.), except that this study does not involve home appliance retailers.

2.3.2 System performance measurement

In the present case, the design objective is clear, such that it can be used as a performance indicator of the system. The total cost is estimated based on total cost of appliance and electricity by companies, instead of the total cost incurred from the consumer side. This is because consumer costs do not reflect the real cost to deliver the service. In terms of appliance cost, the purchase price includes the company's margin which is difficult to isolate from public data. Moreover, consumers typically pay their electricity consumption at a fixed rate, which does not represent the price in the electricity market. In this sense, the total cost to deliver the service is estimated based on total appliance procurement, operational cost to deliver service and end-of-life costs, which are borne by appliance producer. Operational cost is calculated based on electricity consumption to deliver service. Appliances are procured in two conditions, i.e. new or second-hand products, while electricity consumption depends on the consumer service demand and the efficiency of appliance in-use. By the end of the product life cycle, the assigned cost includes repurposing or reprocessing cost of obsolete appliances. Reprocessing of the returned appliance is intended to obtain not only environmental benefit but also economic value from the used appliance. To obtain the benefit, three procedures of the obsolete appliance are considered in this study: 1) product recovery before being sent back to the company for re-use, 2) selling obsolete appliances to the second-hand market, and 3) recycling.

Accordingly, the total cost of service delivery is estimated considering total production cost (Z), total product recovery cost (V), total electricity cost (C), and total revenue from recycling revenue (L) and second-hand market sales (S). Hence, the total cost of service delivery (T) is given by

$$T = Z + V + C - L - S \tag{1}$$

While total product recovery cost (V) and revenue from end-of-life products (L, S) are calculated simply based on the multiplication between unit product and value per unit, total production cost and electricity cost are computed considering two variables with a different value for each variable. The computation is given below.

$$Z = \text{a}.x_1 + \text{b}.x_2 \tag{2}$$

$$V = r'_1.y_1 \tag{3}$$

$$C = c_1.z_1 + c_2.z_2 \tag{4}$$

$$L = r_2.y_2 \tag{5}$$

$$S = r_3.y_3 \tag{6}$$

Where

a, b	: Production cost of highly efficient appliance and low efficient appliance	(JPY)
x_1,x_2	: Production number of highly efficient appliance and low efficient appliance	(units)
c_1,c_2	: Electricity price in the day-ahead market and spot market	(JPY/KwH)
z_1,z_2	: Electricity purchase in the day-ahead market and spot market	(KwH)
r'_1	: Product recovery cost	(JPY/unit)
r_2	: Recycling revenue	(JPY/unit)
r_3	: Second-hand product price	(JPY/unit)
y_1	: Numbers of product recovered	(units)
y_2	: Number of unit recycled	(units)
y_3	: Numbers of product sold to second-hand market	(units)

In terms of emissions, the total emissions (E) are calculated considering emissions from appliance (ε1), emissions from electricity (ε2). Given e_0 , e_1 , e_2 , e_3, e_4 represent emissions generated from production per unit, from recovery process per unit, from recycling process per unit, from second-hand market sales per unit, and from electricity consumption consecutively, hence

$$E = \varepsilon 1 + \varepsilon 2 \quad (7)$$

Where

$$\varepsilon 1 = e_0\ (x_1 + x_2) + e_1.y_1 + e_2.y_2 + e_3.y_3 \quad (8)$$

$$\varepsilon 2 = e_4\ (z_1 + z_2) \quad (9)$$

2.3.3 Actors' behavior and the decisional process

2.3.3.1 Consumer behavior and the decisional process

Figure 8 presents the behavior and decisional process of EPOS and EPSS consumers. In EPOS, the demand for service leads to the demand for appliances and electricity supply. Accordingly, EPOS consumers make 2 major decisions, comprising of 1) decision to choose appliance, and 2) decision to replace and recycle appliance. The model assumes that consumer has two different consideration to choose an appliance depend on their characteristics. Alternative seeker consumers make decisions by comparing price, while inert consumers choose based on influences from other consumers. In EPOS, alternative seeker consumers' purchases are constrained by willingness to pay for appliances. Consumers choose appliances whose price is the closest to their budget. On the other hand, consumers that use market influences as a consideration, choose the most used appliance in the market.

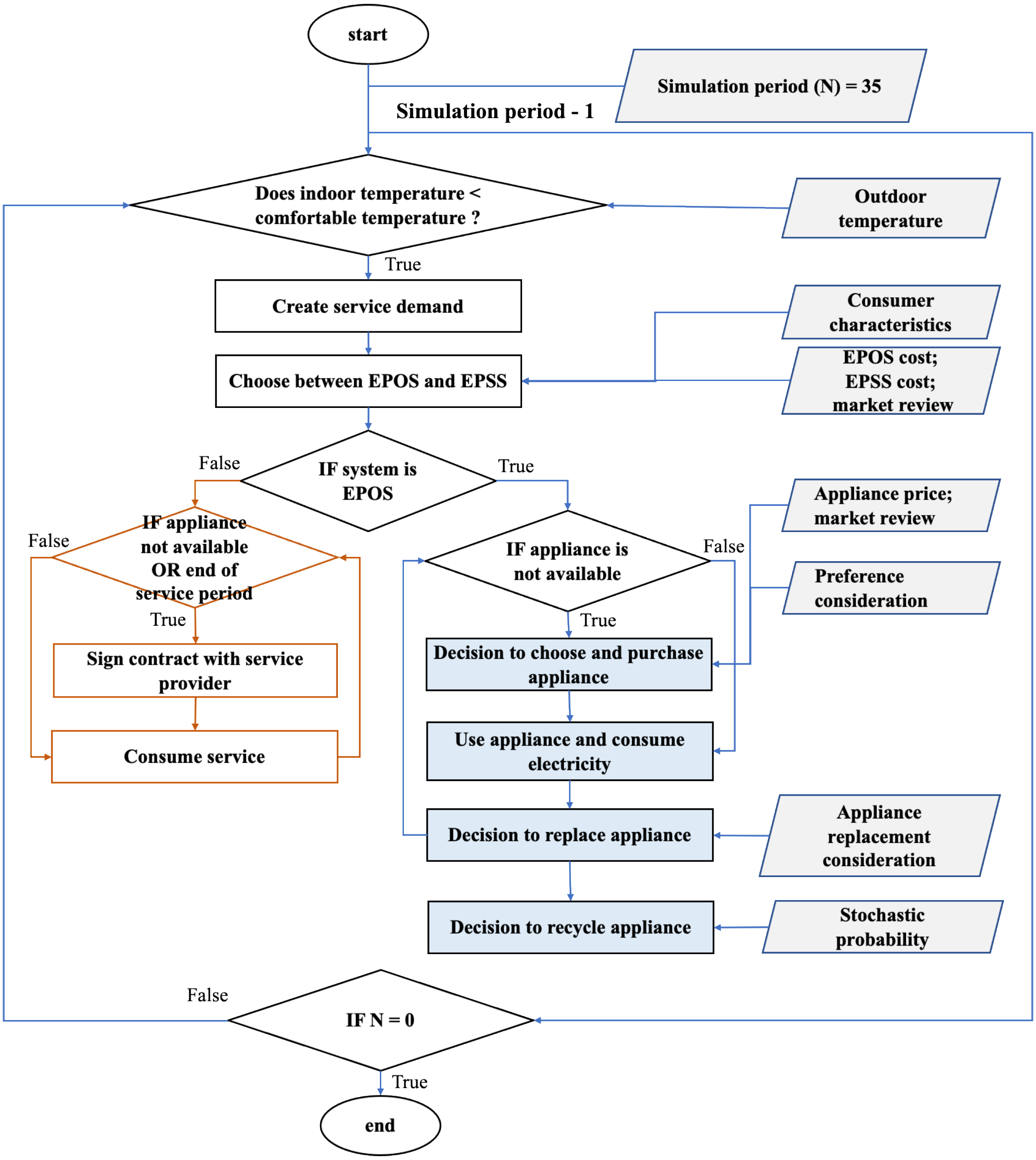


Figure 7. Consumer behavior and decision flow

EPOS consumers replace appliances for various reasons. Ideally, consumers are expected to replace the appliance to upgrade it with the latest appliance technology. However, typical consumers tend to prolong air conditioner lifetime until it's broken (*Energy Effic. Househ. Appliances*, 1999; Frederiks et al., 2015b), which indicates that the appliance must be replaced. For this reason, EPOS consumers in this model use machine failure as a consideration to replace appliance. Probability of machine failures increases following age of appliance, especially after appliance is used more than 10 years (Fenaughty & Parker, 2018).In the model the probability of machine failures is set into 50% once its age reach 10 years, and is increased 10% every year, until 15 years when it is predetermined to be replaced by the system.

After making a replacement decision, the consumer decides whether to send the old appliance to the collection center to be recycled or to give the appliance to the ragmen. Giving appliances to ragmen means that the appliance is illegally disposed. The reason for consumers not sending the appliance is uncertain. Some argue because the recycling fee is too expensive for certain households (Amemiya, 2018; Shimada & Van Wassenhove, 2019). In this model, the decision to recycle is made by stochastic probability, where the probability that a consumer sends an appliance to the collection center is higher. The model assumes that a penalty occurs for each appliance that fails to reach the collection center to be recycled. The penalty represents the environmental cost that must be borne by the total system for this recycling failure.

Meanwhile, in EPSS, the demand is satisfied with the service supply, where EPSS consumers follow two scenarios. In the case where EPSS is designed for a market without barriers to adoption, given that there's only one option of EPSS available in the hypothetical market, the only decision that must be made by the EPSS consumer is to sign a contract with the EPSS provider when demand occurs. However, in the case where EPSS is designed for a market which is locked-in to EPOS, consumers first decide between adopting EPOS or EPSS, where the decision is influenced by their characteristics, whether they are alternative seekers or inert consumers. Alternative seeker consumers compare the expected cost of service between EPOS and EPSS, whilst inert consumers depend on market feedback to assess and compare the benefit between EPOS and EPSS. In the end of product or service life span, EPSS consumers are not responsible for the obsolete product, because the service provider decides when to replace an appliance and to decide the further process.

2.3.3.2 Appliance Producer behavior rule

The model assumes that appliance producers are rational enough to make decisions based on optimization. The behavior of the appliance producer is motivated by the goal to minimize the total cost of appliances and emissions generation from the total product life cycle. Figure 9 provides a complete description of appliance behavior and decisional flow to minimize cost and emissions from appliances.

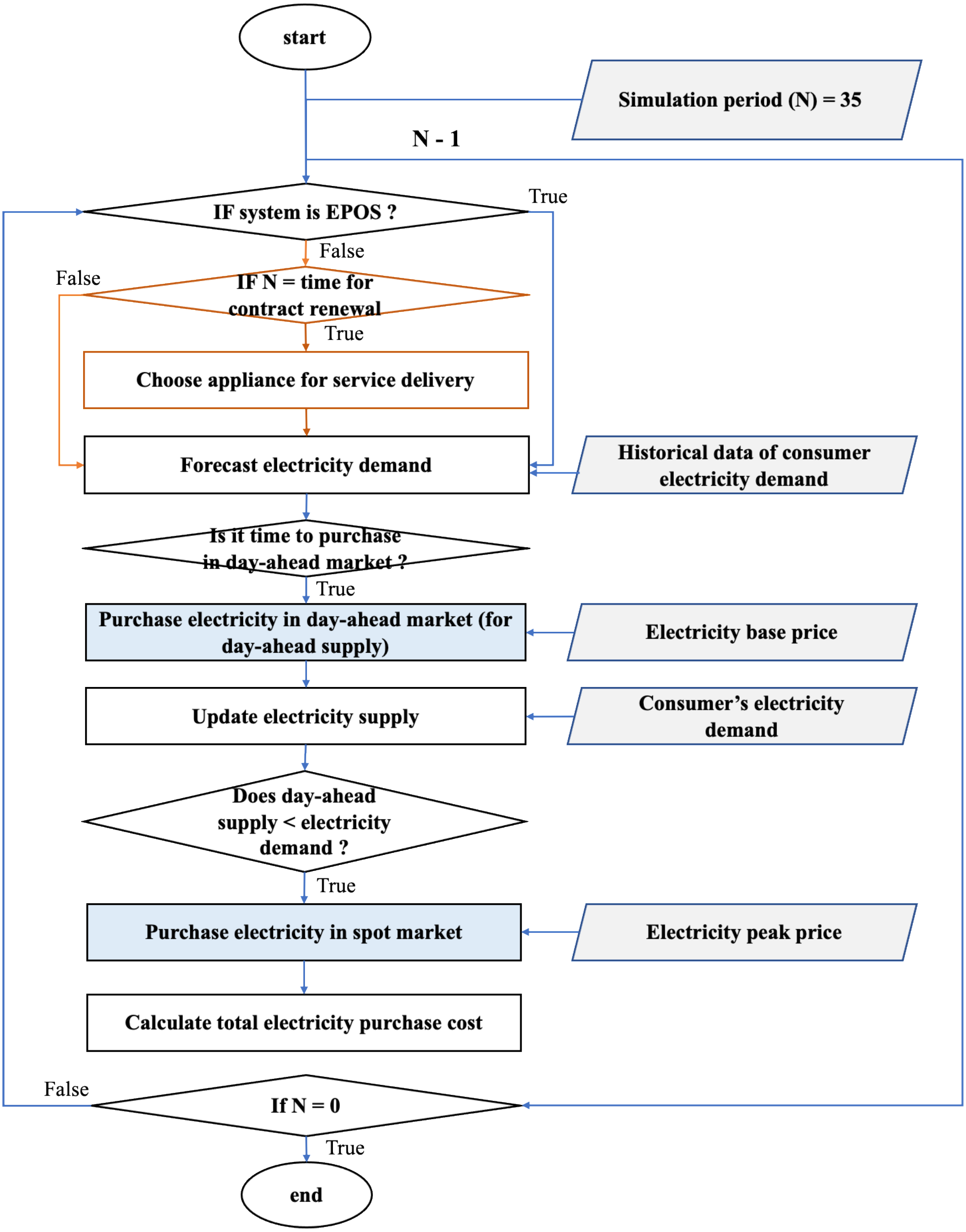


Figure 8. Appliance producer behavior and decision flow

In an attempt to achieve the goal, appliance producers makes two crucial decisions, i.e. 1) to minimize product procurement costs, and 2) to maximize profit while minimizing emissions generation from end-of-life products. To minimize production cost *(Z)*, the producer must

determine the optimal production number of high efficient appliance (x_1) and low efficient appliance (x_2), considering several constraints as shown below.
Objective function:

$$\text{Minimize} \qquad Z = \text{a}.x_1 + \text{b}.x_2 \qquad (10)$$

Subject to:

$$x_1 + x_2 \geq (dx_1 - i_1) + (dx_2 - i_2) \qquad (11)$$

$$x_1 \geq (dx_1 - i_1) \qquad (12)$$

$$x_2 \geq (dx_2 - i_2) \qquad (13)$$

$$x_1 \geq 0, x_2 \geq 0 \qquad (14)$$

Where,

a, b	: Production cost of high efficient appliance and low efficient appliance	(JPY)
dx_1, dx_2	: Forecast demand of high efficient and non-efficient appliance	(units)
i_1, i_2	: Inventory level of high efficient and non-efficient appliance	(units)

Besides minimizing production costs, company also aims to maximize revenue from end-of-life products to compensate for the total cost of products to satisfy consumer demand. In maximizing revenue from end-of-life products, EPOS company collects as much as a possible obsolete appliance from households' consumers to be recycled following recycling law. Despite reprocessing options, company recycles all of the returned appliances for cost efficiency because of the high uncertainty of conditions and quantity of appliance, and therefore, all appliances are recycled.

However, in EPSS, it is possible to manage the condition of the collected appliance through regular maintenance and replacement policy. All appliances used in EPSS are provided with regular maintenance to maintain the machine performance, which leads to a slower degradation rate than those which not getting regular maintenance. Air conditioner efficiency degradation is calculated based on formula (15) below (Fenaughty & Parker, 2018).

$$Efficiency_{degrade} = Efficiency_{nominal} * (1- M)^{Age} \qquad (15)$$

Where M is the *Maintenance factor*, 0.01 for expertly maintained equipment and 0.03 for unmaintained; and *Age* is appliance age in years.

The simulation applies two types of replacement policy for EPSS, including replaced based on appliance performance and scheduled replacement. Replacement based on appliance performance is intended to prolong the product lifespan, thus expectedly reduced the production requirement. On the other hand, scheduled replacement shortens the appliance usage time before replacement, which aim to maintain the appliance performance on a range where it is feasible for product recovery and reuse. In this study, the schedule replacement follows the service contract period.

End-of-life appliances are categorized into two groups based on the performance when it was collected. The first category, referred to as *grade-one*, consists of appliance with good performance (machine efficiency is at least 85% from initial efficiency). The second category, *grade-two,* consists of appliances which efficiency decreases by more than 15%. The grade-one appliances have more reprocessing/ repurposing options, including product recovery, sold to the second-hand market, and recycling. On the other hand, grade two appliances can only be recycled.

The decisional process in this stage is to maximize revenue (*R*), while at the same time minimize emission (*E)* from the process. Thus, the optimization approach uses a multi-objective optimization program with the decision variable comprising of the total appliances from grade-one category to be recovered (y_1), recycled (y_2), and sold to second-hand market (y_3).

Hence,

Objective function:

Maximize $$R = r_1 . y_1 + r_2 . y_2 + r_3 . y_3 \quad (16)$$

Minimize $$E = e_1 . y_1 + e_2 . y_2 + e_3 . y_3 \quad (17)$$

Subject to:

$$r_1 = 0.5 * a \quad (18)$$

$$r_2 = \alpha * \beta * \gamma \quad (19)$$

$$y_1 + y_2 + y_3 \geq \text{Y} \quad (20)$$

$$y_1 \geq 0, y_2 \geq 0, y_3 \geq 0 \quad (21)$$

Where,

r_1 : production cost saving from product recovery (JPY)

r_2 : recycling revenue per unit product (JPY)

r_3 : revenue from the second-hand market per unit product (JPY)

$e_1,\ e_{2,}\ e_3$: emission from product recovery, recycling, and second-hand sales (CO_2.kg)

Y : total of *grade one* appliances (units)

α : scrap price (JPY)

β : appliance weight per unit (kg)

γ : recycling rate (%)

2.3.3.3 Electricity retailer behavior rule

Figure 10 shows the behavior and decisional process of electricity retailers, either in EPOS and EPSS. In this case, the retailer decides the optimal amount of electricity purchased in the day-ahead market to satisfy consumer demand over a certain period of time at a minimum cost. The optimal amount depends on forecast of consumer electricity demand, considering the base price in day-ahead market, and uncertain spot price, given the probability (Kirschen & Strbac, 2019). Hence,

Objective function

Minimize $$C = c_1.z_1 + p_2.c'_2.z_2 + p_3.c'_3.z_3 \quad (22)$$

Subject to:

$$z_1 + z_2 + z_3 \geq D \quad (23)$$

$$C \leq (D * P) \quad (24)$$

$$x_1, x_2, x_3 \geq 0 \quad (25)$$

Whereas:

z_1 : Total power supply purchased on day-ahead market (KWh)

z_2 : Total power supply purchased on spot market for scenario 1 (KWh)

z_3 : Total power supply purchased on spot market for scenario 2 (KWh)

C : Expected electricity purchase cost (JPY)

D : Forecast electricity demand (KWh)

P : Electricity selling rate per (constant rate) (JPY/KWh)

c_1 : Electricity rate of day-ahead market (JPY/KWh)

c'_2 : Predicted electricity rate at spot market for scenario 1 (JPY/KWh)

c'_3 : Predicted electricity rate at spot market for scenario 2 (JPY/KWh)

p_2 : Probability of electricity rate at spot price occurs for scenario 1

p_3 : Probability of electricity rate at spot price occurs for scenario 2

In addition, for company that provides EPSS service, the attempt to minimize total cost of service includes designing the service level for consumers. Assumes that electricity retailer provides EPSS service, hence its business process includes service planning.

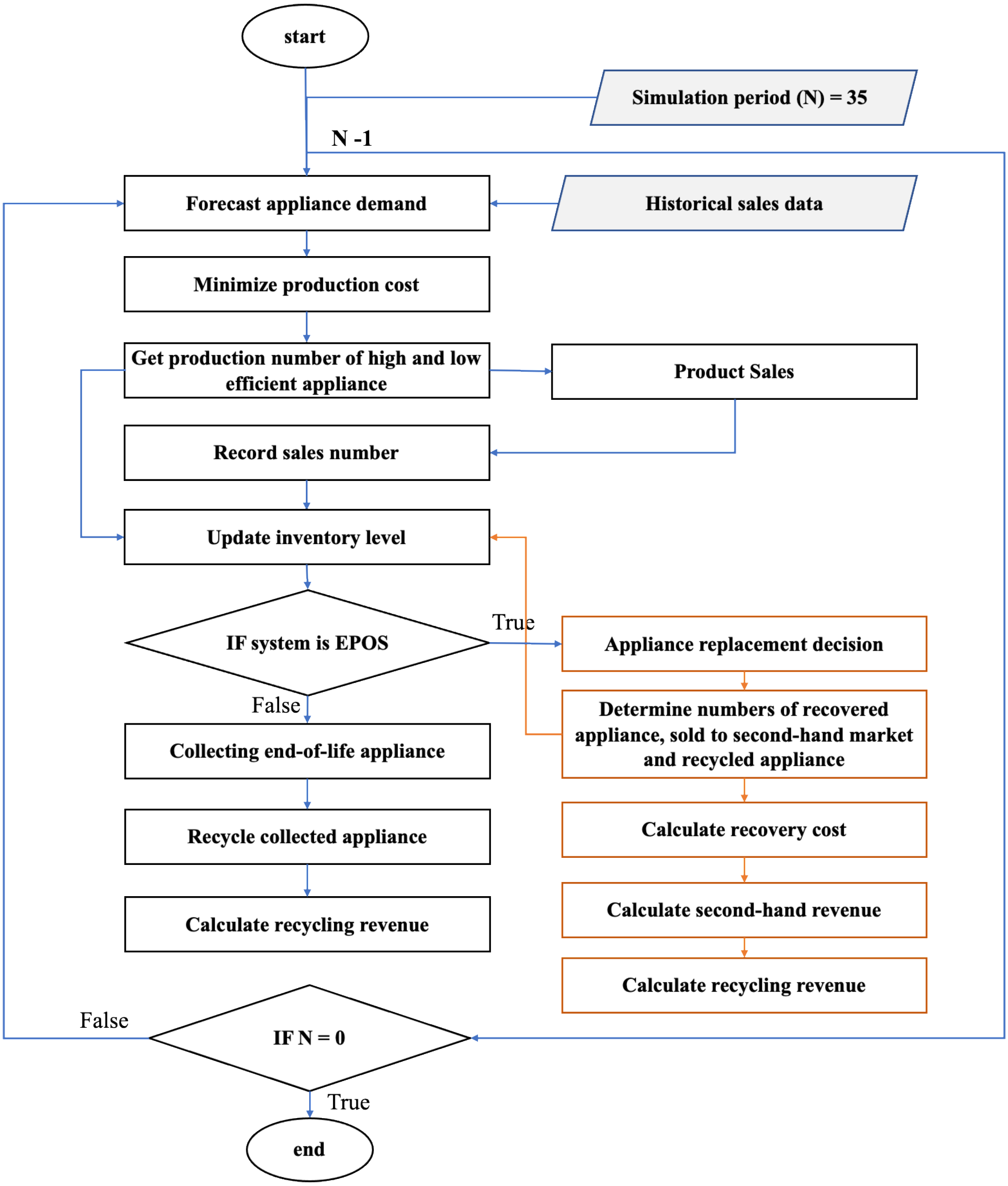


Figure 9.Electricity retailer producer behavior and decision flow

2.3.4 Development of System Causalities

Given the system boundary and the design performance criteria, system causality is developed to depict the interaction between actors in the observed market and how it impacts on the system performance. The causality is used as a reference for the simulation model. Figure 11 partly shows the interaction between variables that influence emission generation from the system. Total emissions as the design objective are presented with an orange box, which has a positive linear relation to the number of emissions from appliances and emissions from electricity consumption (in a blue box). To minimize those variables actors must determine the optimum number of the appliance for each process and minimize electricity consumption to deliver the service. The minimization needs the actors to make an optimal decision and control the related parameters. The complete causalities, which also exhibit causalities to minimize the total cost of systems are presented in Appendix I-A.

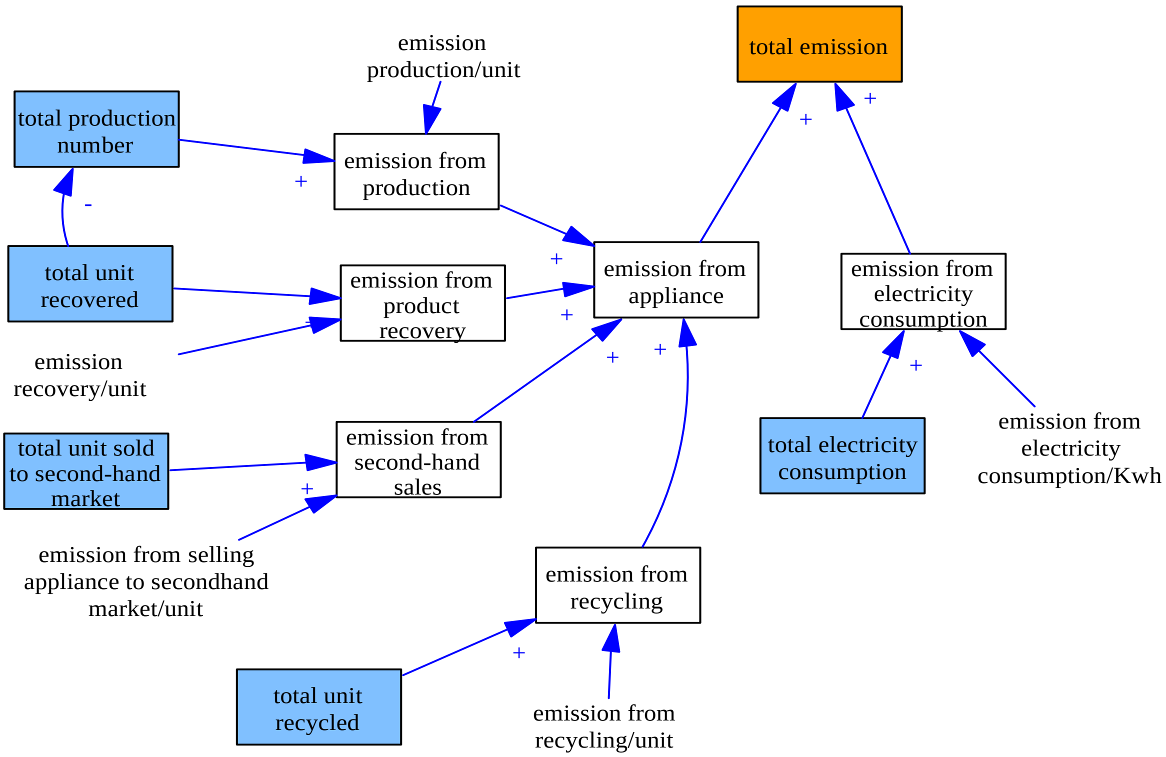


Figure 10. Example of parameter causalities of total emission generation

2.3.5 Simulation development and Design Experiment

The simulation aims to identify conditions of EPSS design performance by understanding the behavior of EPSS under various conditions. Actors' behavior and decisional process are motivated by minimizing total cost to deliver service and total emissions.

The present simulation has two objectives. The first simulation is to understand the behavior under the EPSS market, whereas all consumers are willing to adopt EPSS to satisfy their demand. This step investigates the required conditions of system operations for EPSS, not only related to the actors' attributes but also attributes of the market (i.e. market policy). The simulation focuses on observing the influence of a combination of variables in the market, including EPSS service level, recycling law enactment, appliance replacement policy, and composition of reprocessing rate.

Firstly, EPOS as a baseline system is simulated, and performance is measured within the setting system. The model is simulated following the life span of the housing, by assuming that households do not move, and maintain their lifestyle and preferences during the evaluation period. Building life span varies among regions range from 20 years to 50 years (Kirschen & Strbac, 2019; Saputra & Isnaeni, 2018; Vanvari & Mhaske, 2018). In this study, the system evaluation period (N) is set to 35 years, following building age in Japan, where the general data for the hypothetical market are extracted. Afterward, the values of the selected variables are incrementally changed to understand its performance and the effect on system behavior. The selected variables and their value are described below.

1. Recycling law enactment is important for EPOS to improve the collection rate of the obsolete appliance. However, in EPSS, the law may hamper the company seeking to maximize its economic benefit from the obsolete appliance. This is because the enactment of the recycling law prohibits the company from selling the collected appliance to the second-hand market to avoid illegal disposal in the future. In contrast, without the recycling law, the company has options on whether to sell appliances to the second-hand market or for obsolete product recovery. Given that the company not only aims for economic benefit but is also obligated to minimize emissions from appliances, the decision may vary depending on the selling price of the second-hand product in the market, and the saving from product recovery and recycling. For this reason, it is interesting to investigate whether not implementing the recycling law influences the total cost of service delivery.
2. Considering the previous variables, the profit comparison is expected to influence the company's decision to maximize economic benefit while minimizing emissions from end-of-life appliances, without the recycling law. The profit comparison obtained from the second-hand market and product recovery and recycling are evaluated in the model to gain understanding about the company's decision when combined with other variables. Three variances of values that describe the profit comparison per unit product and material between recycling and thesecond-hand market are introduced in the simulation. The first condition is when profit from second-hand sales per unit is estimated to be equal to savings from product recovery and recycling (i.e. profit comparison = 1:1). The second condition

is when profit from second-hand sales per unit is estimated to be higher than savings from product recovery and recycling (i.e. profit comparison = 2:1). And the last condition is when profit from second-hand sales per unit is estimated to be lower than savings from product recovery and recycling (i.e. profit comparison = 1:2).

3. Finally, the simulation applies two types of replacement policy for EPSS, including replacement based on appliance performance and scheduled replacement. Replacement based on appliance performance is intended to prolong the product lifespan, thus expectedly reduced the production requirement. In the model, appliances are replaced when the efficiency reduction reaches 15% compare to the initial efficiency. The value of 15% is interpolated from the typical AC technician suggestion (e.g. (Matulka, 2012)) to replace appliances when between 10 years to 15 years to save 20% - 40% on electricity costs, with the efficiency degradation calculated based on (Fenaughty & Parker, 2018). On the other hand, scheduled replacement shortens the appliance usage time before replacement, to maintain the appliance performance on a range where it is feasible for product recovery and reuse. In this model, the scheduled replacement is based on the service contract, i.e. 7 years, which is determined considering the results of sensitivity analysis (see Appendix II).

The investigated variables for EPSS design are summarized in Table 8. The evaluated conditions derived from a combination of variables, as well as the parameter and variables value of the simulation are presented in Appendix I-B.

Table 8. Investigated variables and values for EPSS design

Variable	**Value**
EPSS service level	{type1, type2, type3}
Recycling Law	{with, without}
Reprocessing Rate Composition, represented by (benefit from recovery: benefit from second hand)	{(1: 1), (2: 1), (1: 2)}
Appliance Replacement Policy	{appliance efficiency, scheduled replacement}

The second simulation aims to investigate the key factors of EPSS design considering EPOS consumer behavior. It particularly investigates the influence of consumer characteristic and preference on EPSS uptake in the market. There are two retailers and an appliance producer that serves 100 household consumers. One of the retailers provides service and another one delivers electricity supply service. Consumers are provided with information that EPSS design can reduce the total cost of service delivery, hence the cumulative service rate is more economical compared to EPOS. The information provided may be useful for alternative seeker consumers' decisional process. On the other hand, inert consumers seek market feedback to consider switching. The experiment evaluates two types of consumer's inclination to trust the source of feedback. The first is where consumers trust the market review from information available online, and the second is where consumers put more trust in their closest network offline. The model interprets "the closest" as neighbouring agents located one radius from the agent's location in the simulation.

The experiment is conducted to observe how long it takes for EPSS to penetrate the EPOS market given the percentage of alternative-seekers consumers available in the market and the source of feedback of inert consumers. Table 9 shows the simulation variables for EPSS. The simulation results analysis includes EPSS market share, required time for EPSS to penetrate the EPOS market, the total cost of the system, and emission generation.

Table 9. Description of simulation variables and value

Variable	**Value**
% of alternative-seeker consumers	{ 0.01, 0.03, 0.05, 0.1, 0.2, 0.4 }
Inert consumer's source of feedback	{online, offline}

2.3.6 Simulation Results and Analysis

2.3.6.1 EPSS design for EPSS market

Figure 12 shows the results of the total cost required to satisfy consumer demand for electricity service performance. From the figure, we can observe which conditions of EPSS result in the best and worst performance. Conditions that are characterized with EPSS type 3, which includes the operating environment of the appliance as consideration to design the service (condition of EPSS17 to EPSS24) consistently results in significantly lower total cost compare to EPOS and other EPSS. A passive house appears to be the closest system to represent this type of EPSS. Evidence shows that passive houses can minimize energy demand from households (Johnston, Siddall, Ottinger, Peper, & Feist, 2020; Wang, Yang, & Sun, 2020). Nonetheless, note that this study estimates the total cost only from appliance and electricity cost. Incorporating EPSS into the real estate business can be more expensive if we thoroughly calculate the material cost required to improve the insulation and design of the building. This kind of EPSS design is not suitable for households where the building has been established. And that to introduce this business model probably is not preferable for appliance producers because it is arguably will cause demand for certain electrical appliances to decline. Another option is to have improvement to the current building structure under budget constraints and investigate its effects on the total cost of service. However, it will be interesting for further research to investigate the system behavior that incorporates real estate within the system boundary to minimize the total cost of electricity service delivery.

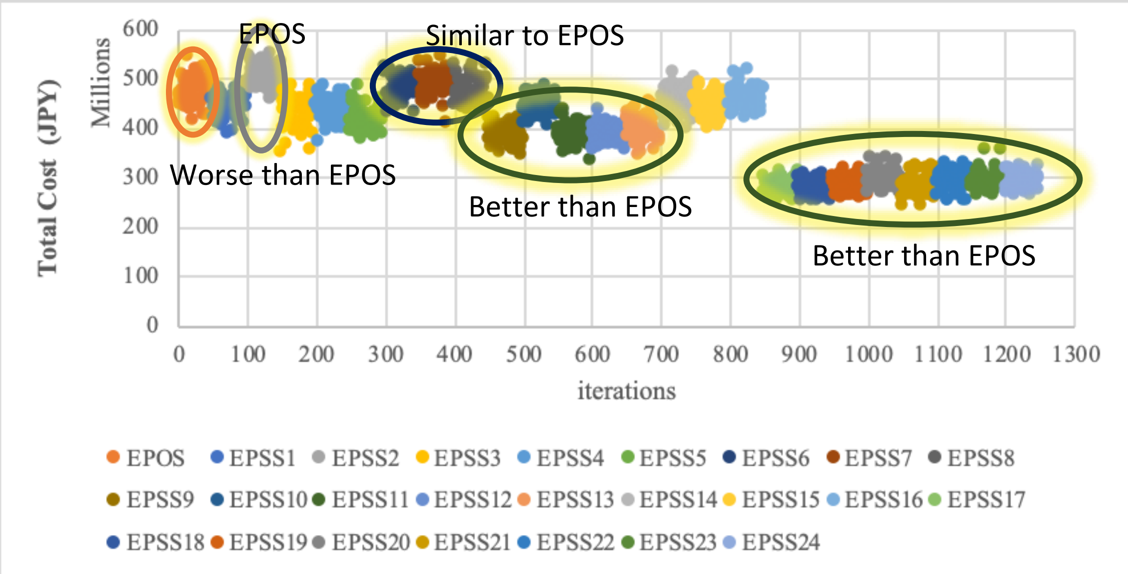


Figure 11. Comparison of total cost to deliver electricity service performance for consumers

Other conditions that lead to lower cost compared to EPOS are by simply applying maintenance and replacing the appliance when its efficiency reaches the performance threshold (i.e., 15% efficiency degradation). The combination of appliance maintenance and extending the appliance life span can minimize not only the requirement for new appliance production, but also reduce electricity consumption. This result is actually predictable. But in reality, it can only be achieved when the owner of the appliance has the capacity to maintain and optimize the operation of the appliance in-use. Such capacity is more readily attainable when appliance ownership is transferred to company.

The worst result is shown by the condition of EPSS2, which resulted from combined market conditions where service only includes appliance maintenance (EPSS type 1), the appliance is replaced based on the replacement schedule before its end-of-life cycle, and when recycling law is enacted. The figure also shows the condition where results are similar cost with EPOS, which are represented with EPSS14 to EPSS16. Those conditions are similar to the previous ones, except that EPSS is designed as type 2, where the service provider chooses appliances to minimize cost and emissions. In these cases, appliance replacement takes place before its end-of-life product, to be reprocessed in an attempt to recover its performance to initial conditions. The appliance in-service is then replaced with another appliance in prime performance or a new one. The problem is that the method to forecast demand for production planning still uses a conventional approach which causes the cost of production volume to increase higher than EPOS. This result suggests the importance of production planning that incorporates the schedule of product recovery and upgraded appliances into appliance production planning within a closed-loop system to avoid overproduction. The increased cost is worsened with the enactment of the recycling law, where companies lose the opportunity to optimize the profit from obsolete products through various ways of capturing economic benefit. It is different to the case where recycling law is not implemented, when there's a higher chance that the producer sells the appliance to the second-hand market. Ultimately, the cost of service delivery resulting from combined conditions of appliance scheduled replacement and recycling law enactment increases to higher or similar to EPOS.

Moreover, it is also found that although highly efficient appliances are used, it does not effectively reduce electricity costs. Highly efficient appliances indeed reduce electricity consumption for the same level of service demand. However, electricity cost reduction using highly efficient appliances will only be effective for cost minimization if the intensity of electricity demand is high or the electricity rate is significantly expensive.

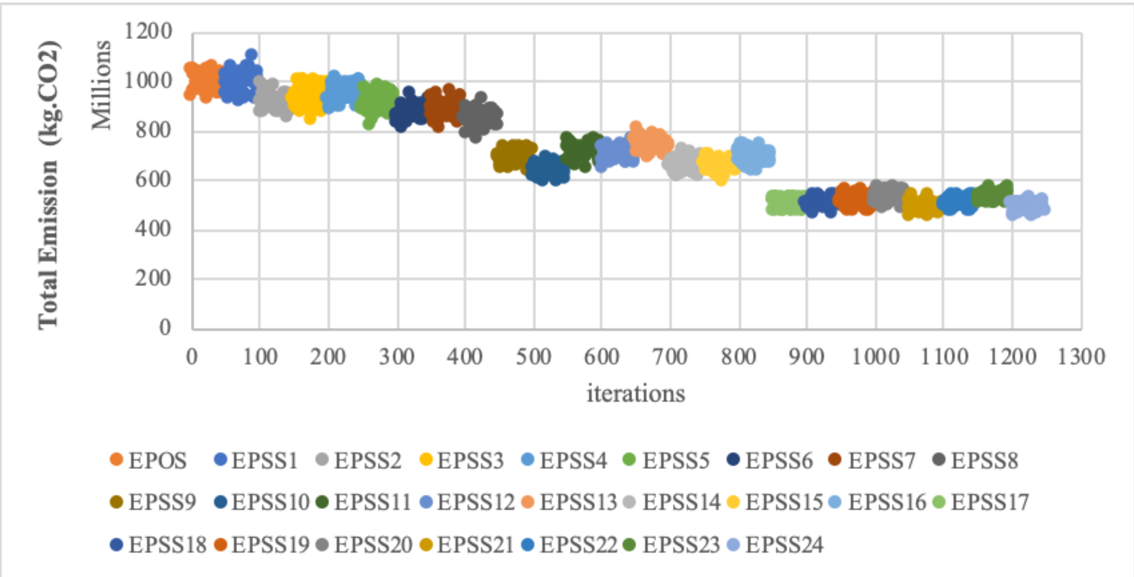


Figure 12. Comparison of the total emission generation from service consumption

In terms of emissions, the result is predictable. Figure 13 exhibits that EPSS for all types of service design consistently results in lower emissions compared to EPOS. Note that electricity used in this model is considered to be generated from 100% fossil fuels. In consequence, the emissions from electricity consumption are higher than the emission from the obsolete appliance per unit. Therefore, although in some cases EPSS appliance production is higher than EPOS, electricity consumption is much lower, leading to lower emissions generation from EPSS consumption.

Summarizing the results above, the conditions that contribute to EPSS performance to minimize cost and emissions from household electricity service consumption in EPSS market have been identified, including:

1. Maximizing the total cost reduction from appliance and electricity consumption can be achieved by considering the operating environment of the service.
2. Simply implementing maintenance of appliances, combined with replacing appliances based on the performance, leads to reduced new product costs and increased profit from end-of-life products, which eventually results in lower total cost compare to EPOS.
3. The scheduled replacement policy when combined with the enactment of recycling law causes total cost of service delivery higher than is expected.
4. Using highly efficient appliances combined with a scheduled replacement only effective to reduce total cost when electricity demand intensity is high or electricity rate per kWh is significantly more expensive compared to the price of the highly efficient appliance.

2.3.6.2 EPSS introduction to EPOS market

In this section, the simulation aims to study the interaction between EPSS variables and consumer's decision variables to understand the critical factors that influence EPSS adoption in the EPOS-logic market. Alternative-seeker consumers represent the EPSS initial adopters. The simulation investigates the effect of initial uptake effect on the period required for EPSS penetration in the market considering consumer's behavior in making choices.

From Figure 14, it is observed that given the market size (i.e. 100 consumers), there is no significant difference between the result of consumers being influenced by online market review or closest network review. In this simulation, a simple relationship between market trends and consumer decisions is demonstrated, where the market trends are viewed based on the online community or real life community. The result indicates that there's no difference in terms of the range of influence between online and offline review relative to the consumer numbers in the target market. This finding suggests that it is important to identify the most effective and efficient influencer from the market to address consumers with social proof bias.

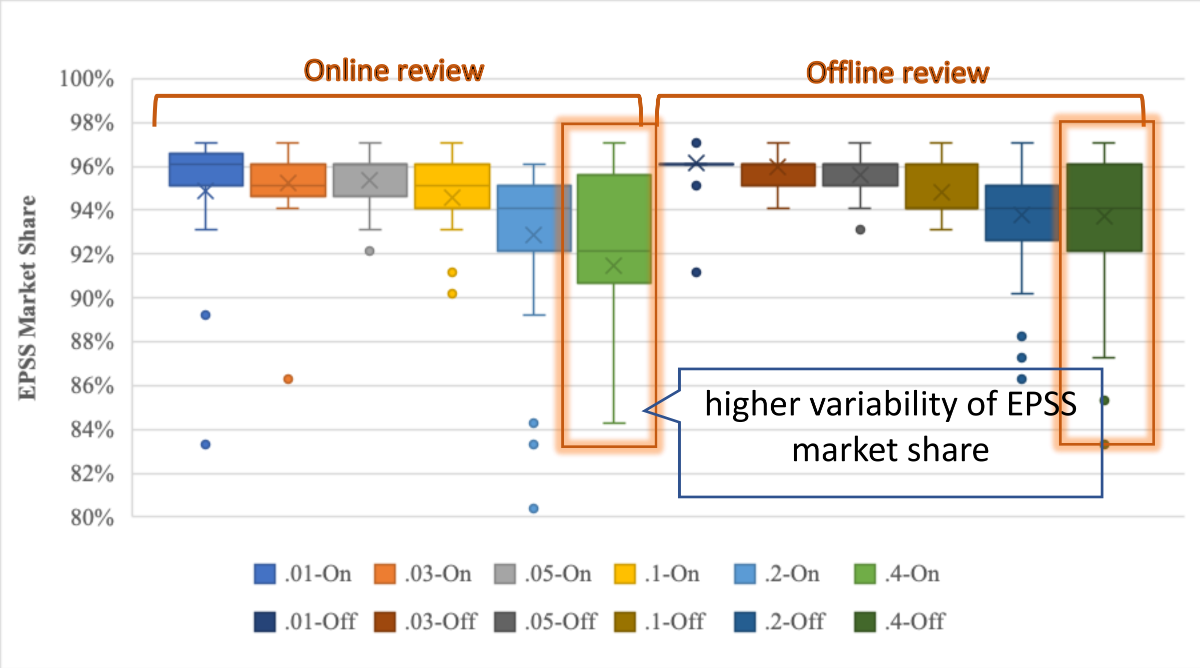


Figure 13. Comparison of EPSS market share from various market conditions

Moreover, a higher fraction of alternative-seeker consumers in the market is followed by higher variability of EPSS market share at the end of the evaluation period (see .3-On, .4-On, .3-Off, and 4-Off), which signifies that more decision makers are independent from the market influence and justify the performance of the service purely based on the cost. On the other hand, the more inert consumers whose decision depends on market influence, results in uniform choices. Hence, in the case where EPSS cost is perceived as lower than EPOS, it is easier for EPSS in this particular market characteristic to have a higher market share.

In terms of market transition, the time for EPSS penetration to dominate the EPOS market is shorter when most consumers are inert consumers with social influence bias (Figure 8). As much as 3% of initial adopters are optimal in this study, to achieve a shorter time for EPSS to dominate a market of 100 household consumers. It is suggested that the market only needs a few alternative seekers to influence the choice of the rest of the market that consist of inert consumers. In contrast to where more consumers are alternative-seekers, the market transition takes more time to achieve, since most consumers actively assess the performance of the provision in deciding for themselves.

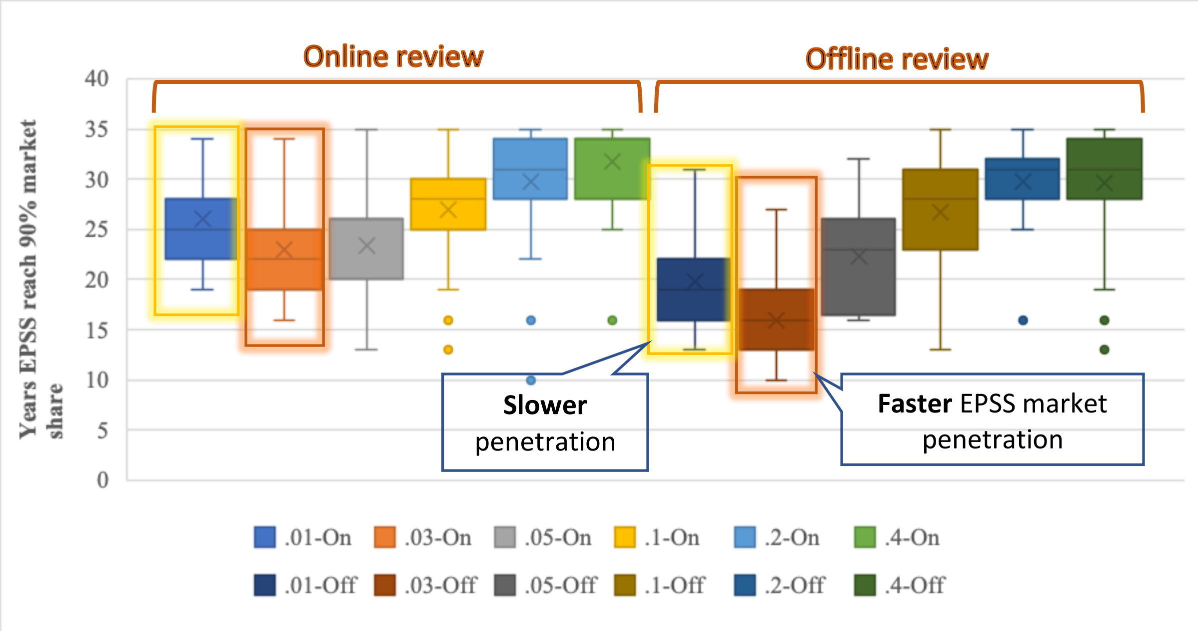


Figure 14. Comparison of time required for EPSS dominates market share

Result presented by Figure 15 suggest that having sufficient numbers of consumers with bias whose choices are influenced by the market, shortens the time required for EPSS penetration. In this study, the fastest time for EPSS market domination is achieved by a market with 3% alternative seeker consumers. The time required for EPSS market domination increases following the group size of alternative seeker consumers in the market. However, it is interesting to observe that the fewer alternative seeker consumers at some point causes slower market penetration, which in this case occurred when alternative seekers are only 1% of 100 household consumers. This finding suggests that determining the optimum initial adopter is crucial to accelerate EPSS market penetration. For a new system transition, it points out the importance of policy measures to reinforce initial uptake of the new system in any way to escape from incumbent system lock-in together with consumer bias consideration.

2.3.7 Managerial implications

The findings from the first simulation suggest the importance of incorporating the schedule of product recovery into production planning together with improving the forecast method. Especially for EPSS service with scheduled appliance replacement, aligning the schedule of product recovery together with the production line becomes indispensable. Blockchain technology can be introduced to EPSS operation system to enable the integration of information system for appliance life cycle management, that covers new products, product recovery, part recovery, and material recovery, and accordingly develops flexible scheduling decision methods to support the appliance production planning and inventory control that minimized cost and emission (Leng et al., 2020).

Another aspect to be considered in EPSS design is the trade-off between upfront cost and operational cost throughout the service lifetime. The research finding indicates that investing in highly efficient appliances for service delivery does not necessarily minimize the total cost of service. EPSS should be able to determine the optimum price of appliances in-use for service delivery considering electricity rate and demand intensity. This finding has implications for existing policy measures, wherein policies to minimize electricity consumption through the uptake of highly efficient appliances, appear to be contradictory to the aim of market liberalization to achieve affordable electricity price rate for consumers. In EPOS, it is better to implement multiple policies rather than just focusing on one policy, because regulation is designated for a society with multiple cognitive biases. Meanwhile, for EPSS these policies are expected to be achievable, because decisional processes of service delivery and consumption are made by decision makers who have capability to optimize their decisions considering predetermined constraints. Moreover, the EPSS business model provides an opportunity to create various sources of profit, more than in EPOS.

The result iterates the argument of the importance to design regulation considering the characteristics, cognitive processes and interest of the targeted actors. Accordingly, a different approach is required for EPSS implementation to minimize total cost of service delivery and emissions generation from electricity consumption. System designers and regulators may need to expand the system boundary by including product and energy life cycle cost from material procurement until end-of service life (instead of end-of product life) to identify the suitable policy to optimize the result. Dealing with economic agents with clear economic objectives and better rationality allows regulators to include a sophisticated system with higher complexity to achieve optimum results. The downside of this approach is that it requires higher bargaining power of government to enforce the policy with firms.

Research findings from EPSS introduction to a market with barriers to adoption also has implications for system transition policies. Despite the fact that EPSS may address consumer bias in appliance selection and electricity consumption, consumer bias for EPOS occurs. The simulation results reveal the importance of sufficient initial uptake of the new system in the market where social influence bias is prevalent. To achieve the target of initial uptake, a measure that aims for a specific community appears to be more feasible, instead of targeting a large scale, diverse market. Moreover, it is easier to identify consumer bias of a certain community so that appropriate measures can be formulated to avoid consumer mistakes in decision-making processes and to achieve the goal of the system design.

2.4 Closing Remarks

This chapter has implemented SBD for designing EPSS to reduce emissions and total cost of service delivery without sacrificing consumer satisfaction. The experiments provide us with insight regarding conditions that contribute to EPSS design and introduction to the incumbent system, which are concluded as below.

1. EPSS implementing maintenance of appliances, combined with replacing appliances based on the performance, leads to a reduced new product costs and increased profit from end-of-life products, which eventually results in lower total cost in EPOS.
2. EPSS design must consider the trade-off between appliance cost and electricity cost throughout the service lifetime, since investing in highly efficient appliances for service delivery does not necessarily minimize the total cost of service. In the case where the electricity price rate is inexpensive or demand intensity is low, the expensive-highly efficient appliance may reduce the service cost competitiveness.
3. EPSS actors should incorporate the schedule of product recovery into production planning together with improving the forecast method to mitigate the risk of overproduction, which violates the objective of EPSS.
4. Policy measures for the EPSS transition must be properly introduced to the right actors considering their characteristics, interest, and present bias, to enable and accelerate the transition.

Chapter 3

Investigating Enablers for EPSS Information Sharing Mechanisms to Achieve Win-win Solutions for All Stakeholders in a Liberalized Electricity Market

3.1 Introduction

Suboptimal results from actors' interaction in current electricity-related markets have been observed. Imperfect information provision has been identified as the cause of market failure, with the consequence on suboptimal results for household consumers, both environmentally and economically. Information is the basis for economic agents to make informed decisions. The information is derived from the attributes of the object or provision shared with the decision-maker. However, economic agents in the market exhibit different behaviour in terms of information acquisition and processing for decision-making processes. Some agents are identified to have bounded rationality, relying on simple heuristics for decision-making process. Meanwhile other economic agents can perform complex computations under predetermined constraints. Efforts have been made to improve information provision to support the decision-making process of bounded rational agents. Nonetheless, it appears that the results are still far from optimal.

Low quality decision in the market consequences on suboptimal market performance. In many liberalised electricity retail markets, the market mechanism fails to suppress the electricity price rate (AEMC, 2017; Morey & Kirsch, 2016; Toyoda, 2016) and electricity retailers experience profit squeezes. In electrical appliance markets, slow adoption results of highly efficient products (Fullerton, Wolfram, & Davis, 2014; Hesselink & Chappin, 2019; Nicole Buccitelli, Elliott, Schober, & Yamada, 2015) result in low incentives for innovation and production of such appliances. This is because consumers predominately consider appliance initial costs rather than efficiency in making their appliance choice (e.g. (Gaspar & Antunes, 2011)). Moreover, consumers with bounded rationality cannot minimize the cost of appliance ownership and fail to optimize the benefit from their purchase and consumption. Consumers exhibit certain preferences in their consumption which are influenced by lifestyle, habit, and income level. Despite their preferences, it has been said that in existing products/services the customer pays a cost that does not reflect the real benefit because of most customers are poor electricity shoppers with a lack of knowledge and information regarding service plans and technology (Cramton, 2017a). Consumers` bounded rationality also impacts on failure to choose highly efficient appliances (Allcott & Taubinsky, 2015; Cohen, Glachant, & Söderberg, 2017; Myers, 2019; Rapson, 2014), and being irresponsible in disposing obsolete appliance, makes it more challenging for the effort to minimize waste and emission generation. Not to mention unpredictable consumer demand toward electrical appliance and electricity, leads to the unplanned growth encouraging unstoppable increased in production capacities. Ultimately, the mismatch between production and consumption, and excessive consumption eventually affects the effort to address resource scarcity problems, as well as waste and emissions reduction.

EPSS providing electricity service performance changes the interaction among actors in energy-related markets, leading to the possibility of altered information-sharing mechanisms. EPSS, as service-oriented systems, expect actors to deliver and to acquire different information and behave differently from current energy-related systems. The present study implements SBD to identify enablers for EPSS information-sharing mechanisms under various market conditions to achieve win-win solutions for all market players. However, although it is possible to observe a group of individuals responds to certain arrangement of information provision through experiments, to observe the effect of changing information provision in real market environment is almost impossible. It is because consumer exhibits various cognitive bias, and the identification of present bias is very difficult (Allcott, 2016). To this point, there's hardly available evidences of how the market will react to certain information provision, and therefore, it is difficult to estimate the system parameter associated with information provision and or consumer behaviour responds to information provision that will contributes to EPSS system performance.

Simulation-Based Design (SBD) is used to simulate and evaluate the information-sharing mechanism design performance under various market conditions. Nonetheless, the performance measurement is challenged with uncertain response of market actors toward the information provision. Accordingly, this chapter develops a method to identify key factors of information-sharing mechanisms to achieve win-win solutions in EPSS. The "worst scenario" method is incorporated into SBD to tackle the design problem uncertainty.

3.2 Worst scenario method to design EPSS information sharing mechanism

Various methods are available to address the model uncertainty problems, including input uncertainty, such as fuzzy and stochastic modeling. Among the well-known methods, stochastic models have been extensively used to model energy system uncertainties (e.g. (Jain et al., 2013; Kharrati, Kazemi, & Ehsan, 2016; Otsuka, 2018)). Nonetheless, stochastic models require information about the statistical distribution of the data, which is difficult to obtain for EPSS, considering its unknown inputs.

The “worst scenario” method is introduced as a novel approach for EPSS design to address problems associated with unknown design inputs due to limited available knowledge. The method searches for the most “unfavourable” inputs among uncertain input data in the range of available information (Hlaváˇcek, Chleboun, & Babuška, 2004). Modelers only need to set the bound for the input data, and therefore it is useful for a problem where probabilistic data has not yet been established. In the case of EPSS design, available information from the incumbent system can be used as the starting point. Simulation-Based Design with the worst scenario method calculates the impact of change in multiple variables on the system performance criteria and accordingly identifies the worst situation caused by input data within the scope of uncertain inputs. Figure 16 describes Simulation-Based Design process incorporating the “worst scenario” method to address the design problem.

3.3 Related studies

The sign of healthy competition and innovation in a liberalized market is the retailer’s ability to offer various products and services, coupled with consumer’s ability to compare the offers and make informed decisions (Council of European Energy Regulators (CEER), 2015). The current electricity retail market differentiates the provision through pricing and billing options, the origin source of electricity, and service related to demand response and self-generated electricity, which are considered as a sign of healthy innovation of the market (Council of European Energy Regulators (CEER), 2015). Nonetheless, market outcomes deviate from stakeholders’ expectation, which are signified by suboptimal results achieved by market players. Imperfect information, asymmetric information and consumers` inattention have been suggested as contributor to market failure in liberalized energy markets and electrical appliance markets (Allcott, 2016; Allcott & Knittel, 2019; Allcott & Taubinsky, 2015; Datta & Gulati, 2014).

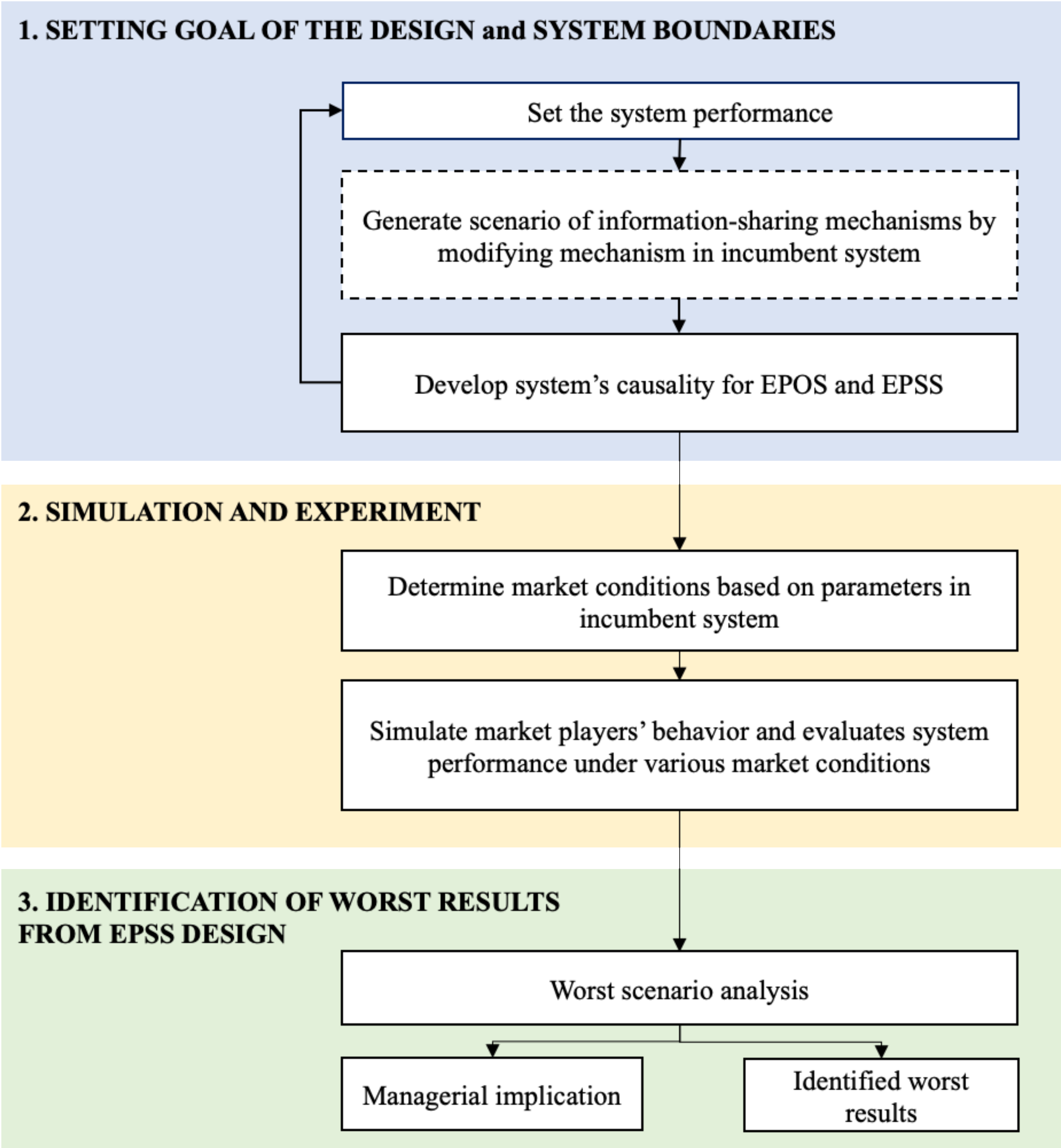


Figure 15. Simulation-Based Design with the "Worst Scenario" method for EPSS design

3.3.1 Policy for addressing EPOS market failures

Policies have been enacted to address market failures due to consumer mistakes in making choices. Typical policies fall into three categories, including standardization, price policies, and information provision. Standardization includes policies enacted to promote minimum energy efficiency standards for home appliances. While price policies fund utility-implemented demand-side management programs, which include subsidized home energy audits, energy efficiency information and subsidies for energy-efficient appliances to influence consumer choice and behaviour in electricity-related consumption (Allcott, 2016). In regard to information provision, government requires appliance manufacturers to have energy efficiency labels for appointed products. Energy efficiency labels are considered as a method to deliver information provision for all previously uninformed consumers, and draws attention to desirable information, such as energy costs. A comprehensive energy label guide was proposed by considering consumer opinion collected from a survey to design efficiency labels in Malaysia (Saidur, Sattar, Izudin, & Masjuki, 2006). As the market learned that too much information causes information overload for consumers, it was suggested to simplify the efficiency label through framing, symbols or single letters (Blasch, Filippini, & Kumar, 2019; DECC, 2014; IPSOS & London Economics, 2014; Leenheer, Elsen, Nella, van der Wagt, & Lloyd, 2014; Newell, Siikamäki, Siikamaki, Siikamäki, & Siikamaki, 2013; OECD, 2017). In addition to that, eye tracking experiments were conducted to observe eye movement on appliance information to identify the ideal location to put the energy labels (Waechter et al., 2015).

However, results of the policies vary among regions. The Top Runner Program is one example of best practice where the Japanese government set mandatory energy efficiency standards based on the most efficient products on the market (Kimura, 2010; Session, 2012). It has successfully directed the market trend into providing highly energy efficient products under certain preconditions, such as market structure that are dominated by a limited number of domestic producers, and companies' full compliance with the mandatory standards even without strict sanctions (Kimura, 2010). Without those preconditions, other countries have been found struggling to achieve the expected results from appliance standardization. Hence, efficiency labels are expected to be impactful to address market failures caused by consumers' mistakes in making choices.

The evidence from the literature in energy-using appliances and energy markets are mixed (e.g.(Allcott & Knittel, 2019; Aydin, Brounen, & Kok, 2018; Myers, 2019; Sallee et al., 2016)). Studies revealed that consumers are found to make rational choices in terms of energy efficiency in the automobile market (Sallee, 2013; Sallee et al., 2016). Nonetheless, other studies suggest different evidence, where consumers exhibited myopic behaviour regarding future fuel costs for automobiles (Busse et al., 2013). More studies provided evidence that consumers exhibit myopic behaviour, not only in automobiles, but also in home appliance selection (Allcott & Taubinsky, 2015). These evidences imply that consumers experience bounded rationality hindering the decision-making process considering information provision.

Another factor of unsuccessful policies is the presence of consumer inertia, where consumers are unwilling to exercise their choice to respond to the policy introduction.

3.3.2 System lock-in and path dependencies for EPSS

The lock-in mechanism is an important issue for introduction of systems like EPSS. Current energy systems are deeply intertwined with the overall structure of society, involving a multitude of societal actors (Geels, 2004; Goldthau, 2014) that are designated for product-oriented systems. In energy systems, the source of lock-in comes from multidimensional aspects including technology (e.g. electricity generation, transmission, and distribution), organization (e.g. manufacturing industries, retailer, bank, energy market), natural resources, informational elements, legislation and human factors (e.g. perception, value, beliefs, and norms) (R. P. Lee & Gloaguen, 2015; Trencher, Rinscheid, Duygan, Truong, & Asuka, 2020; Unruh, 2000). The deep rooted influence of societal structure in product-oriented systems leads to resistance to fundamental changes and the occurrence of new system lock-in (Unruh, 2000, 2002) that can hinder transition to new service-oriented systems like EPSS.

To escape from the current system locked-in, it was argued that exogenous forces are required (Unruh, 2002), such as new technologies (Arthur, 1989). However, to achieve sustainable success in overcoming lock-in in socio-technical systems, policy maker is expected to develop measures by focusing not only on the physical aspects of the systems (e.g. infrastructure, technology and organization) (Hirsh & Jones, 2014), but also on the human dimension of energy systems (Ã & Geels, 2007; Geels, 2004; Goldthau, 2014). To address the suboptimal problem, therefore, EPSS design must consider not only information-sharing mechanisms but also to determine effective measures for escaping system lock-in.

3.4 Object of the study

The market, which aims to satisfy consumer demand of electricity service performance is limited to a liberalized market consisting of electricity retailers providing electricity services for household consumers` demand for electricity service performance. Electrical appliance producers are included to provide appliances for consumers. In addition, the market model also covers policy makers` interest in the sustainability of the system. Figure 17 describes the market model as well as actors’ characteristics and attributes that drive their behaviour and decision-making process.

These actors interact according the market structure, which regulates the material and information flows to satisfy their interests. In this model, each actor attempts to achieve a “win” situation, to improve suboptimality resulting from the incumbent system.

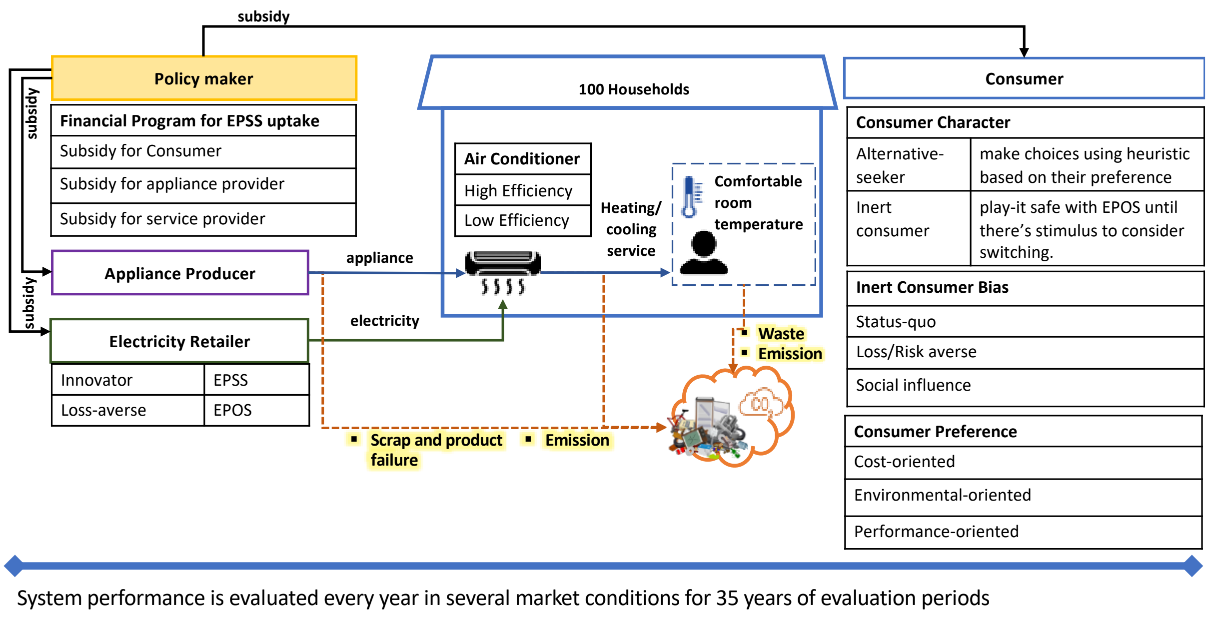


Figure 16. Description of actors` attributes and behaviour in the model

4.4.1 "Win" situation for each actor

One of the objectives of liberalization is to maintain electricity prices at the level of marginal costs, by promoting innovation to deliver affordable and better-quality electricity services. Nevertheless, evidence has showed that in many cases market liberalization has no obvious effect on price reduction (Morey & Kirsch, 2016; Toyoda, 2016). In fact, the price of retail choices may be higher on average compared to traditional markets (AEMC, 2017; Morey & Kirsch, 2016). Although the electricity price is influenced by multiple factors, it broadly follows fuel prices (Morey & Kirsch, 2016). The increase of fossil fuel and gas prices make it harder to maintain lower wholesale prices. Also, retailers experience profit squeeze due to electricity being highly commoditized, which leads to competitive price reduction. It has been argued that consumers face difficulties in trying to differentiate between providers, such that they fail to respond to price stimulus (Matthyssens & Vandenbempt, 2008). Therefore, electricity retailers aim to maximize profit by minimizing purchasing costs of electricity from the wholesale market through the introduction of Demand Response Management (DRM) to manage consumer's demand for electricity. DRM is provided as an additional service which consumers can choose to purchase or not.

Concerning the appliance market, producers do not typically gain any direct incentive from innovation and production of highly efficient appliances. In an attempt to minimize environmental impacts from the industry, appliance producers may aim to reduce energy consumption in the usage stage (Haase, 1997), but this is not of direct benefit to the producer.

Currently a variety of technologies are available in the market, including appliances, whose main feature is energy consumption reduction. If all other things were equal, manufacturers would produce the most efficient appliance. But usually, other things are not equal, and therefore the most efficient appliance usually costs more to produce. Unfortunately, myopic consumers do not view appliance purchases as a long-term investment, thus they often fail to choose highly efficient appliances (Gaspar & Antunes, 2011; Hori et al., 2013). Considering that manufacturers have more interest in maximizing profit, insufficient numbers of efficient appliance sales lead to little incentive for innovation and development of appliances. For this reason, a win situation for appliance producers is when the highly efficient appliance uptake dominates the market share.

Evidence shows that consumer's bounded rationality may harm their own benefit in electricity consumption systems, where they cost occurs does not reflect the real benefit as consumer expected. Accordingly, consumer satisfaction becomes the main indicator of the consumer's win situation. Consumers measure their satisfaction based on company's feedback regarding the consumption, especially information associates to consumers' preferences (such as electricity bill, total consumption, and emission generation from consumption).

Besides economic performance, policy makers also have an interest in the environmental aspects of system performance. Environmental problems are the extended effect of inefficiency in current markets. It is because industries have been over-using natural resources such as material, mineral, energy, and water (Ernst Ulrich von Weizsäcker, Lovins, & Lovins, 1998; Raworth, 2017; *Vision 2050: The new agenda for business*, 2010), leads to resources scarcity. Herewith, policy maker has interest in total cost of the system to satisfy consumer demand and emission generation from the product/service consumption. Table 10 summarizes the win situation for each market player.

Table 10. The "win" situation for each market player

Market player	**Expected win situation**
Electricity retailer	Minimize electricity purchase cost from wholesale market.
Appliance producer	Maximize incentive from highly efficient appliances
Household consumer	Consumer satisfaction, estimated based on information (if any) shared by company to consumer that can be used as performance measurement based on their preference
Policy maker	Total cost of the system to satisfy consumer demand and emissions generation from the product/service consumption.

4.4.2 Causality Diagram

The previous section describes the attributes of the market players and the objective of their behaviour (i.e. win situations) in the observed market. A causality diagram is developed accordingly, to structure the interaction among actors and their decision-making process considering their attributes and objectives as partly shown in Figure 18. The model causality is used as a reference for the simulation model. The complete system causalities are presented in Appendix I-D.

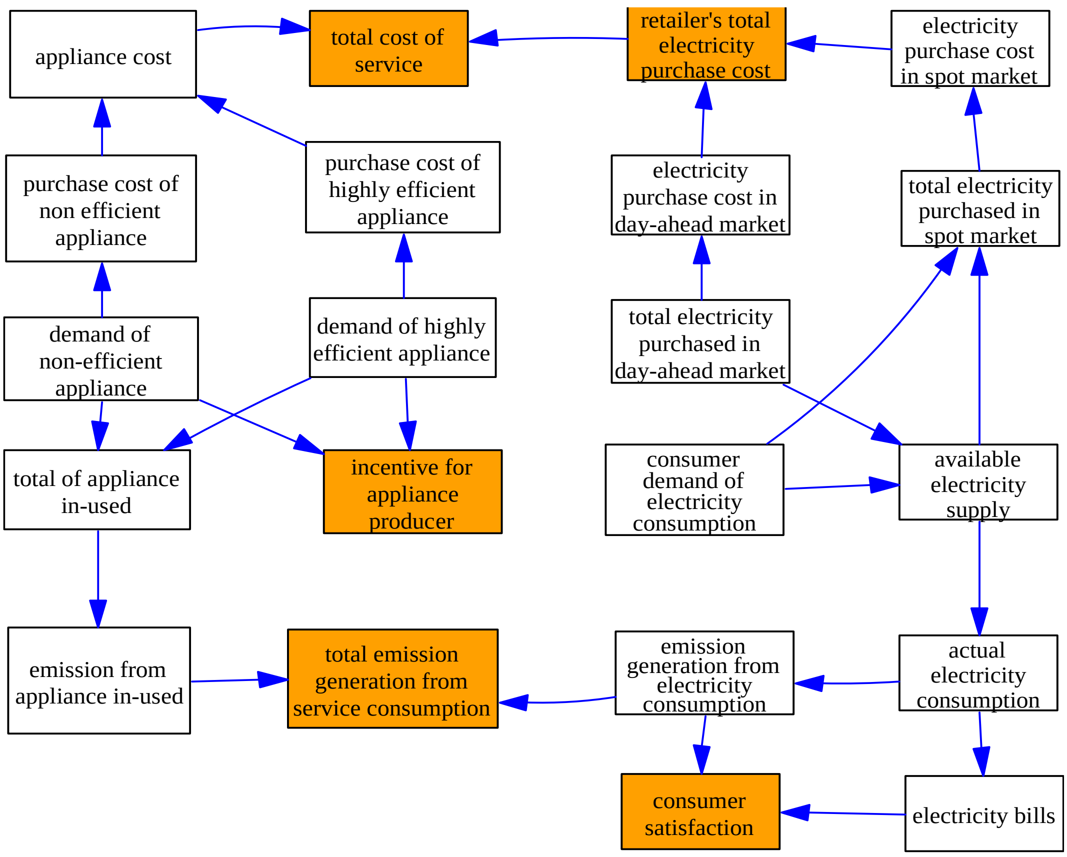


Figure 17. Example of causality depicting interactions that influence win-win solution

4.4.3 Agents' decision-making processes to achieve their win situation

4.4.3.1 Electricity retailer

Given price uncertainty in the spot price market, retailer`s decision-making processes aim to minimize electricity purchase costs with expectation to improve profit. To achieve this objective, there are two important decisions for retailers to make, including the decision to choose between EPOS and EPSS, and electricity purchase decision in the wholesale market.

Retailers that strive for innovation choose to develop EPSS, while risk-averse retailer remains with providing electricity supply for consumers. Conventional retailers` decision to switch to EPSS depends on the system's increasing returns. The present model determines increasing return based on the number of consumers that adopt the system. Initially, EPOS increasing returns (r_{EPOS}) are much higher than EPSS because all of the consumers are involved in EPOS. Every time step of the simulation, conventional retailers evaluate and compare EPSS increasing returns (r_{EPSS}) with EPOS. EPSS return increases for every additional consumer choosing EPSS, while it decreases when a consumer decides to switch back to EPOS. EPOS return also increases following the number of adopters and decrease when consumers leave the system. Nonetheless, the return value differs between EPOS and EPSS. Since EPOS has reached saturation point, the return value is less than EPSS return value. Conventional retailers decide to switch to EPSS when EPSS increasing return reaches the point higher than EPOS, indicating the potential advantage of adopting EPSS. Hence, retailer's decision to switch from EPOS to EPSS is stated as

$$Ret_{EPOS \to EPSS} = True, if\ r_{EPSS} > r_{EPOS} \quad (26)$$

Meanwhile, EPSS retailers decide to switch to EPOS when there are no more adopters during the evaluation period, therefore

$$Ret_{EPSS \to EPOS} = True, if\ N_{EPSS} = 0 \quad (27)$$

Both EPOS and EPSS retailers make operational decision to optimize the amount of electricity purchased in the day-ahead market to satisfy consumers` demand over a certain period of time at a minimum cost. The optimal amount depends on the forecast of consumer electricity demand, considering the base price in the day-ahead market, and uncertain spot price, with a given probability (Kirschen & Strbac, 2019). It is assumed that the electricity price in the spot market tends to be higher than the day-ahead market. Hence,

Objective function

Minimize $$C = c_1.z_1 + p_2.c'_2.z_2 + p_3.c'_3.z_3 \quad (28)$$

Subject to:

$$z_1 + z_2 + z_3 \geq D \quad (29)$$

$$C \leq (D * P) \quad (30)$$

$$x_1, x_2, x_3 \geq 0 \quad (31)$$

Where:

z_1 : Total power supply purchased on day-ahead market (KWh)

z_2 : Total power supply purchased on spot market for scenario 1 (KWh)

z_3 : Total power supply purchased on spot market for scenario 2 (KWh)

C : Expected electricity purchase cost (JPY)

D : Forecast electricity demand (KWh)

P : Electricity selling rate per (constant rate) (JPY/KWh)

c_1 : Electricity rate of day-ahead market (JPY/KWh)

c'_2 : Predicted electricity rate at spot market for scenario 1 (JPY/KWh)

c'_3 : Predicted electricity rate at spot market for scenario 2 (JPY/KWh)

p_2 : Probability of electricity rate at spot price occurs for scenario 1

p_3 : Probability of electricity rate at spot price occurs for scenario 2

4.4.3.2 Appliance producer

The behavior of the appliance producer is motivated by the goal to improve the incentive from highly efficient appliances. Appliance producer make the decision to choose between serving for EPOS or EPSS before making operational decisions to increase the sales of highly efficient appliances. A risk taker manufacturer initiates to serve EPSS, while a risk-averse producer chooses the status quo to avoid loss. Risk-averse producers decide to switch to EPSS if the estimated future demand of highly efficient appliances from EPSS is higher than EPOS, hence $Mfg_{EPOS \to EPSS} = True, if\ D^*_{EPSS} > D^*_{EPOS}$. Concerning EPSS producers, they switch to EPOS when all consumers switch to EPOS, which can be stated as $Mfg_{EPSS \to EPOS} = True, if\ N_{EPSS} = 0$.

Concerning highly efficient appliance sales, efforts have been made to increase their leverage through labelling and information framing. However, the sales fully depend on consumer choices, in EPOS or service provider choices in some EPSS services. By the end of the simulation period, the model estimates the incentive of highly efficient appliances based on high efficiency product sales relative to total sales during the simulation period, which is represented as $Incentive_{eff} = \frac{Sales_{eff}}{Total\ Sales}$.

4.4.3.3 Consumer

Despite the limitation to optimizing their choice, consumers aim for satisfaction from service consumption. The satisfaction is estimated based on their preference. The very first decision to make to get the expected result is choosing between EPOS and EPSS. Alternative seeker consumers are the initial adopters of EPSS, before they finally evaluate the EPSS and EPOS performance for further adoption. On the other hand, inert consumers play-it safe with the incumbent system until there's stimulus that will encourage them to consider switching.

Alternative seeker consumers make choices based on their preference, and information provided by the company. In the case where no information is recognized by consumers, alternative seekers make a random choice (Gigerenzer, Peter M. Todd, & and the ABC Research Group, 1999). In certain EPSS mechanisms, consumers are provided with information related with their preference. The EPSS company provides information about EPOS average cost and EPSS service rate to be compared by cost-oriented consumers. Environmental-oriented consumers are provided with information about aggregate emissions` generation from households under EPOS and estimations of emissions` generation from the EPSS service. The EPSS company also provides information about service features that may influence service results for performance-oriented consumers.

In some scenarios, consumers choose appliances by themselves, whether in EPOS or EPSS. Similar to choosing the system, consumers make decisions based on their characteristics and preferences. Only alternative seekers are willing to compare recognized information, while inert consumers wait for the market signal that suits their present bias to make a choice.

Based on their choices, consumer consumes products and energy, and evaluate their satisfaction periodically. In EPOS, cost-oriented consumers feel happy if their current electricity bill is lower compared to the previous month`s bill. Meanwhile, environmental-oriented consumers in EPOS will never be satisfied, because they cannot measure the emissions generation resulting from their consumption. On the other hand, performance-oriented consumers will typically be satisfied because they have full control over appliance usage and service consumption. respectively, therefore, EPOS consumer satisfaction on $\text{year} - \text{t}$ is represented as

$$S_{i,ecost}^{EPOS} = \begin{cases} 1, if\ c_{i,t} < \ c_{i,t-1} \\ 0, if\ c_{i,t} \geq \ c_{t-1} \end{cases} ;\ S_{i,env}^{EPOS} = 0\ ;\ S_{i,perf}^{EPOS} = 1 \tag{32}$$

Where

c_t : consumer's electricity bill at $-t$

c_{t-1}: consumer's electricity bill at $-(t-1)$

In EPSS, however, consumers compare their satisfaction with EPOS. The company provides information about the performance to be compared with average system performance, including EPOS and EPSS. Cost-oriented consumers in EPSS will be happier if their expenditure is lower than the average of the system. Environmental-oriented consumers will be satisfied when the report of emissions generation from their consumption is lower than the average of the system. Meanwhile, performance-oriented consumer is unhappy when their service level is different than their expectation, either in time fulfilment or comfort temperature. Hence, EPSS consumer satisfaction of cost-oriented, environmental-oriented and performance-oriented consumers-i are $S_{i,cost}, S_{i,env}$ and $S_{i,perf}$, which can be stated as below.

$$S_{i,cost}^{EPSS} = \begin{cases} 1, if\ c_{i,t} < \bar{c}_t \\ 0, if\ c_{i,t} \geq \bar{c}_t \end{cases} ;\ S_{i,env}^{EPSS} = \begin{cases} 1, if\ e_{i,t} < c \\ 0, if\ e_{i,t} \geq \bar{e}_t \end{cases} ;\ S_{i,perf}^{EPSS} = \begin{cases} 1, if\ \partial_{i,t} = \dot{\partial}_t \\ 0, if\ \partial_{i,t} \neq \dot{\partial}_t \end{cases} \quad (33)$$

Where

c_t : consumer's monthly expense at $-t$

$\bar{c}_t$: average consumer's expense in the system at t

e_t : emission generation at $-t$

$\bar{e}_{t_t}$: average emission generation of consumers in the system at t

$\partial_{i,t}$: service level demand at $-t$

$\dot{\partial}_t$: service level supply t

4.4.3.4 Policy Maker

Policy makers are interested to minimize emissions generation and total cost of the system to deliver electricity service performance for household consumers. Total cost is estimated based on total appliance procurement, operational cost to deliver service, and end-of-life cost. Operational cost is calculated based on electricity consumption to deliver service, while end-of-life cost includes recycling cost. Recycling of the returned appliance is intended to obtain not only environmental benefit but also economic value from the used appliance. Accordingly, the total cost of service delivery is estimated considering total production cost (*Z*), total electricity cost (*C*), and total revenue from recycling revenue (*L*). Hence, the total cost of service delivery (T) is given by

$$T = Z + C - L \quad (34)$$

While total product recovery cost (V) and revenue from end-of-life products (L, S) are calculated simply based on the multiplication between units of product and value per unit, total production cost and electricity cost are computed considering two variables with different values for each variable. The computation is given below.

$$Z = \text{a}.x_1 + \text{b}.x_2 \quad (35)$$

$$C = c_1.z_1 + c_2.z_2 \quad (36)$$

$$L = r_1.y_1 \quad (37)$$

Where

a, b : Production cost of highly efficient appliance and low efficient appliance (JPY)

x_1,x_2 : Production number of highly efficient and low efficient appliance (units)

c_1,c_2 : Electricity price in the day-ahead market and spot market (JPY/KwH)

z_1,z_2 : Electricity purchase in the day-ahead market and spot market (KwH)

r_1 : Recycling revenue (JPY/unit)

y_1 : Numbers of product recycled (units)

In terms of emissions, the total emissions (E) are calculated considering emissions from appliances (ε_1), emissions from electricity (ε_2), whereas electricity is generated from fossil fuel, which is generated using Natural-Gas-combined cycle. Given e_0 , e_1 , e_2 represent emissions generated from production per unit, from recycling processes per unit, and from electricity consumption respectively, hence

$$\text{E} = \varepsilon_1 + \varepsilon_2 \quad (38)$$

Where

$$\varepsilon_1 = e_0\ (x_1 + x_2) + e_1.y_1 \quad (39)$$

$$\varepsilon_2 = e_3\ (z_1 + z_2) \quad (40)$$

4.4.4 EPSS provision

The present study introduces four types of EPSS, which are differentiated by the features and performance level as shown in Table 11.

Table 11. Description of EPSS provision

EPSS design	Design subject	Service design characteristics
EPSS type 1	Typical consumers	Consumers choose and operate appliances by themselves.
EPSS type 2	Cost-oriented consumers	Service provider chooses and operates appliance that minimize total cost of service delivery
EPSS type 3	Environmental-oriented consumers	Service provider chooses and operates appliance that minimize total emission from consumption
EPSS type 4	Performance-oriented consumers	Service provider chooses and operates appliance to maximize consumer satisfaction

The first type of EPSS is the basic form of the service, where consumers are simply released from appliance ownership, but are still authorized to choose the appliance and have full control to use the appliance based on their liking. The role of the service provider is providing expert maintenance for the appliance to sustain its efficiency at its best performance during the service lifespan. The maintenance slows the appliance degradation rate compared to those without proper maintenance (Fenaughty & Parker, 2018).

The second type of EPSS design is intended for cost-oriented consumers, whose interest is to minimize the total cost of service consumption. These consumers are willing to compromise the performance level of the service to limit their consumption costs. To satisfy their requirements, the service provider invests in technology to obtain and deliver information about real time electricity demand and control the usage to minimum performance when service demand occurs during peak times.

EPSS type 3 is designated for environment-oriented consumers, which aims to minimize emissions generation from service consumption. For environment-oriented consumers service providers invest in highly efficient appliances and technology to monitor real time electricity demand and control the service performance in the case demand occurs during peak time.

For consumers who are performance-oriented, service providers prepare EPSS type 4. This type of EPSS satisfies consumer demand for premium service, where consumers do not want curtailment or postponement of demand fulfilment, and costs are not a limitation for them to purchase the service. For these consumers, the company invests on highly efficient appliances, and allows consumers to have full control over operation and use at all times.

EPSS contract between consumer and company ends when the appliance needs to be replaced. In EPSS an appliance is replaced when its efficiency degrades by more than 15% from the initial condition.

4.4.5 Information-sharing mechanism in competing market

The information-sharing mechanism follows the market rules, which are arranged following EPSS provision. The information-sharing mechanism of EPOS and EPSS in the present market model are shown in Figure 19 and Figure 20, consecutively. In EPOS appliance producers typically share information about appliance prices, user guidance and product specifications including efficiency of the appliance. In reverse, appliance producers can extract information about consumer preferences for appliances from historical demand. At the same time, electricity retailers provide information about electricity pricing plans, together with complementary services and sometimes with information regarding the electricity source. In return, retailers can extract aggregate information of electricity demand. While delivering the service for themselves, consumers generate habits in appliance usage, and develop preferences in consumption based on their lifestyle, as well as acknowledging their willingness to pay for a certain provision.

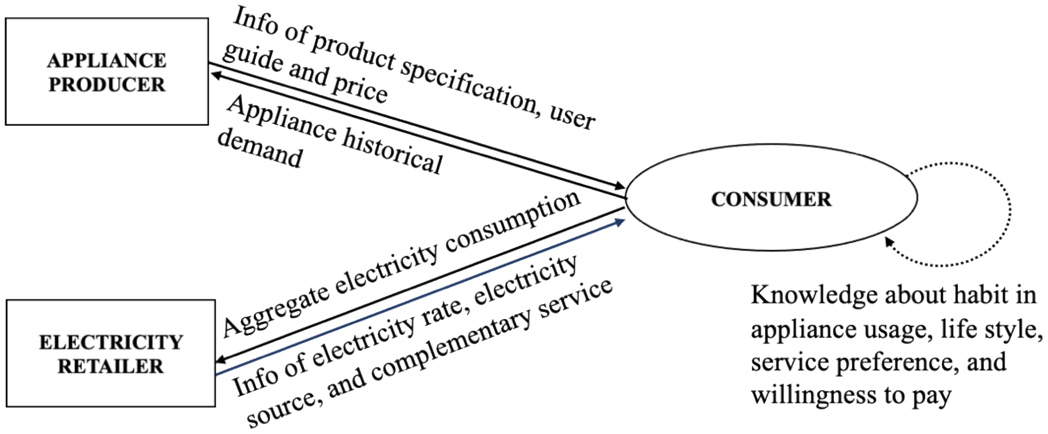


Figure 18. Information-sharing mechanism in EPOS

Despite information provided by companies, consumers only recognize appliance price when considering purchasing an appliance, while ignoring other information (Gaspar & Antunes, 2011). In terms of electricity, consumers hardly consider information provision from the company in making daily decisions on electricity consumption. Consumers' consumption is more likely influenced by lifestyle, environmental stimulus and preference in consumption. Some consumers consider cost to limit their consumption. On the other hand, electricity retailers and appliance producers rely on aggregate information of historical demand to optimize their decision in electricity purchasing and appliance production.

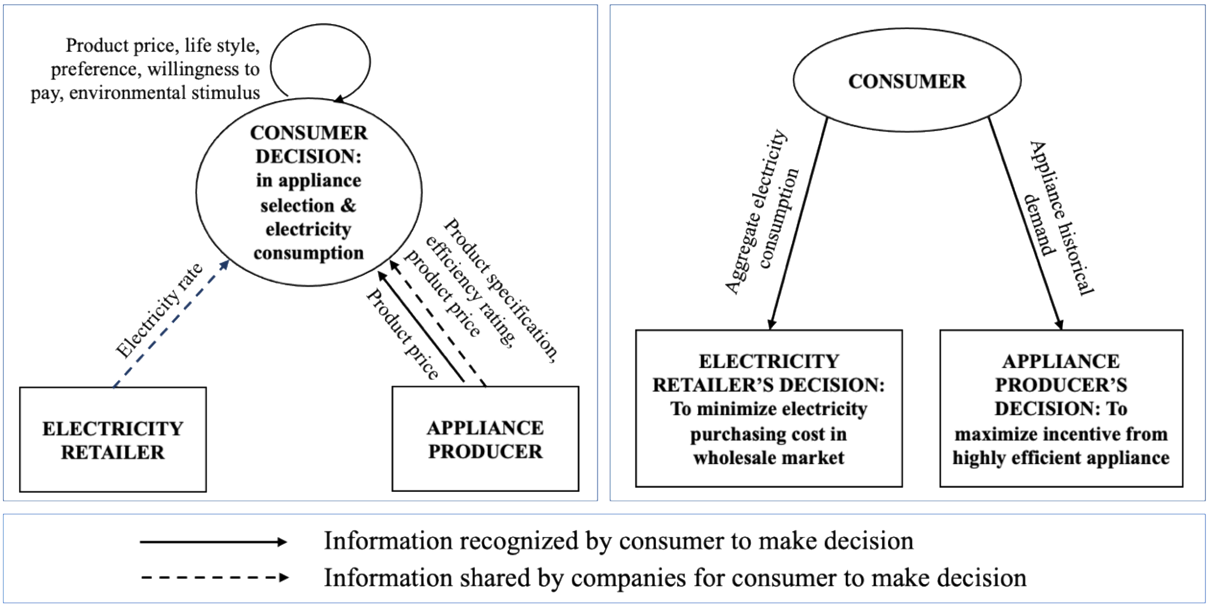


Figure 19. Agents' information acquisition and processing for decision-making process in EPOS

As mentioned earlier, providing electricity service performance through a bundle of appliance and electricity supply allows the market to alter the information-sharing mechanism to improve consumer decisions and market outcomes in general. As shown in Figure 21, EPSS consumers can simplify their decisions through interaction only with the service provider. In addition, information provision can be designed based on consumer's recognized information. A certain EPSS type can set a fix service rate per month if the consumer allows the company to partly control electricity consumption in response to price signals to simplify the information provision.

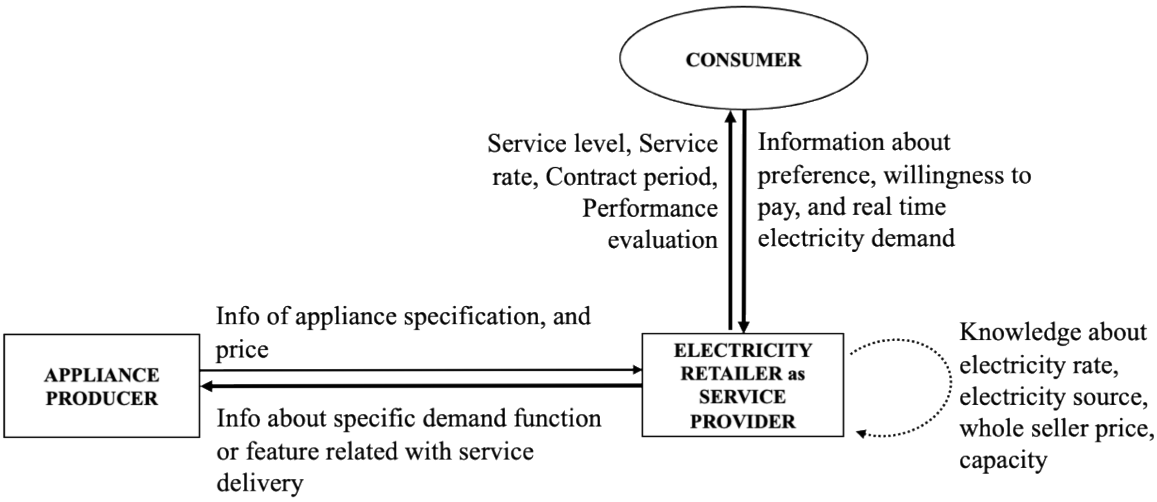


Figure 20. Example of information-sharing mechanism design for EPSS

4.4.6 Policy measures for EPSS introduction

Beside policy measures that have been enacted in the incumbent system, the present model introduces three types of measures for EPSS introduction, which will be separately tested in the simulation. Financial programs are used to stimulate three market actors to accelerate EPSS uptake in the market to improve efficiency in electricity consumption and emissions reduction. The first measure is to provide financial support for household consumers to adopt EPSS. The financial support provides discounted prices for consumers on the initial investment. The second measure is providing incentives for electricity retailers that purchase highly efficient appliances to deliver EPSS service. And the last is providing incentives for appliance producers for each sale of highly efficient appliances.

4.4.7 Simulation and Design Experiment

The model developed in this study explores the dynamics of competing systems with multiple interacting agents aiming to satisfy their own interests. The simulation is used as an instrument to design and compare EPSS performance with the incumbent system, given different conditions. Simulation results are used to identify key factors of EPSS information-sharing mechanisms to achieve win-win situations for all actors. Interaction between actors in competing systems are simulated, and the win situation of each actor is measured within the setting system. Similar to the previous chapter, the system evaluation period (N) is set for 35 years, which represents average building age in Japan.

For the purpose of the study, EPOS information-sharing mechanisms are modified resulting in three mechanisms, which are characterized by EPSS provision. The content of information shared between actors and delivered by EPSS provision are shown in Table 12. Basically, the information sharing mechanisms are distinguished by the information extracted from consumers, which has consequences for the type of EPSS services available in the market. In the first scenario, there is no information extracted from consumers except the historical demand of electricity consumption and appliances purchased. The information is then used to predict future demand trends, both for electricity and appliances. In the second scenario, information regarding consumers` preferences is extracted from the market, and the result is aggregated to determine the majority of consumers' preferences, with this information used to design and deliver EPSS services. In the last scenario, service is delivered based on individual preference. In this case, the company acquires personal information from each individual consumer to satisfy their preferences. Accordingly, there are various types of EPSS in the market following consumers' preferences.

Table 12. Influential factors in consumer's decision-making behaviour

Information-sharing scenario	Description	Content of information	
		Information extraction from targeted consumers	Information provision from service provider to consumer
Without information sharing	Mechanism to deliver EPSS type 1, which service is delivered without taking consumer's interest into consideration. Hence, consumers choose and operate appliances by themselves.	None	Service rate (depends on selected appliances, Service contract, Emissions generation)
With aggregate information	Mechanism to deliver one of EPSS provision among type 2, or type 3 or type 4. Service is designed considering aggregate consumer interest and mass produced based on majority preference in the targeted market.	Aggregate information, collected using sample survey about consumer preference in service consumption	Service rate (depends on selected appliances, Service contract, Emissions generation)
With personalized information	Mechanism to deliver customized EPSS provision, by taking account of individual interests in service delivery. Hence, there will be EPSS type 2, type 3 and type 4 following individual interest on targeted market.	Personalized information, can be collected using individual interviews about consumer preferences in service consumption	Service rate depends on selected appliances, Service contract, Emissions generation)

These mechanisms are then evaluated under various market conditions given different values of market variables (presented in Table 13). The selected variables in combination with information-sharing mechanism include fraction of alternative-seeker consumers in the market, the dominant preference, and policy measures to promote EPSS adoption.

We have previously mentioned the percentage of alternative-seeker consumers. This variable represents the group of consumers who are expected to be the initial adopters of EPSS that will influence inert consumers` decisional process to switch to EPSS.

The majority consumer preference is also selected to signify the market characteristics. This variable is anticipated to significantly influence consumer's satisfaction, and cost of service delivery. In this model, as much as 60% of consumers in the market are assumed to have the same preference representing the dominant preference in the market.

Finally, policy measures to promote EPSS adoption are evaluated in the model. The measures used here are to provide subsidies for economic agents who are willing to adopt EPSS. The measures are distinguished by the subsidy beneficiary, which could be household consumers, electricity retailers, or appliance providers. Consumers are provided with a discount on the initial instalment when first signing on to EPSS. Meanwhile, electricity retailers and appliance providers are provided with financial support for delivering EPSS. The value of the subsidy is equal per consumer adopter for all beneficiaries.

The combined parameters resulting in 108 scenarios, where each scenario is iterated until we obtain a sufficient number of samples for further analysis (Ju-Sung Lee, Tatiana Filatova, Arika Ligmann-Zielinska, Behrooz Hassani-Mahmooei, Forrest Stonedahl, Iris Lorscheid, Alexey Voinov, J. Gary Polhill, 2015).

Table 13. Selected variables to tested in simulation

Variables	Value
Information-sharing mechanism	{without information, with aggregate information, with personalized information}
Share of alternative-seeker consumers*)	{0.15, 0.25, 0.35}
Share of dominant preference (i.e. as much as 60% of consumers in the market is dominated by one of these preferences)	{cost-oriented, environmental-oriented, performance-oriented}
Policy measure	{without subsidy for EPSS, subsidy for EPSS consumer, subsidy for EPSS appliance producer, subsidy for EPSS provider

*) The rest are inert consumers who are each endowed with one of status quo bias, social influence bias and loss-averse bias. The distribution of consumer for each bias is equal.

3.5 Simulation Results and Analysis

The model was simulated and results in high dimensional data containing the information about the win situation of each actor given the market conditions. Simulation results indicating the win situation of each actor are plotted in scatter plots, which can be visually observed to identify the conditions that lead to the worst results. The results highlight that path dependence emergence and lock-in effect are largely driven by conditional characteristics of the market environment.

3.5.1 EPSS market penetration

It will be useful for further analysis to first observe market characteristics and system behaviour impact on EPSS market share. Figure 22 exhibits whether the selected variables individually impact on EPSS market share. It was revealed that the selected variables individually impact on EPSS market share, except for the dominant consumer preference in the market.

In the presented case, the more alternative-seeker consumers in the market, the more likely that the simulation results in higher EPSS market share. This figure iterates the previous chapter`s conclusion, that a sufficient amount of initial EPSS uptake is indispensable to create momentum to accelerate EPSS market penetration. The problem is that to reach sufficient initial uptake can be very challenging. In this case, to begin with a small community and address the cognitive bias on the small scale could be more impactful rather than targeting the whole market. Replicating the process for different communities or a larger market, however, can be another challenge for a region with diverse culture, interests, and demographic conditions. Although, it is arguably that the replication process can be effective for behavioural changes in a region with a homogenous society. To this point, the research finds hints that initial consumer uptake is crucial to escape from status-quo lock-in. Nevertheless, its effectiveness to influence the rest of the targeted market needs further investigation.

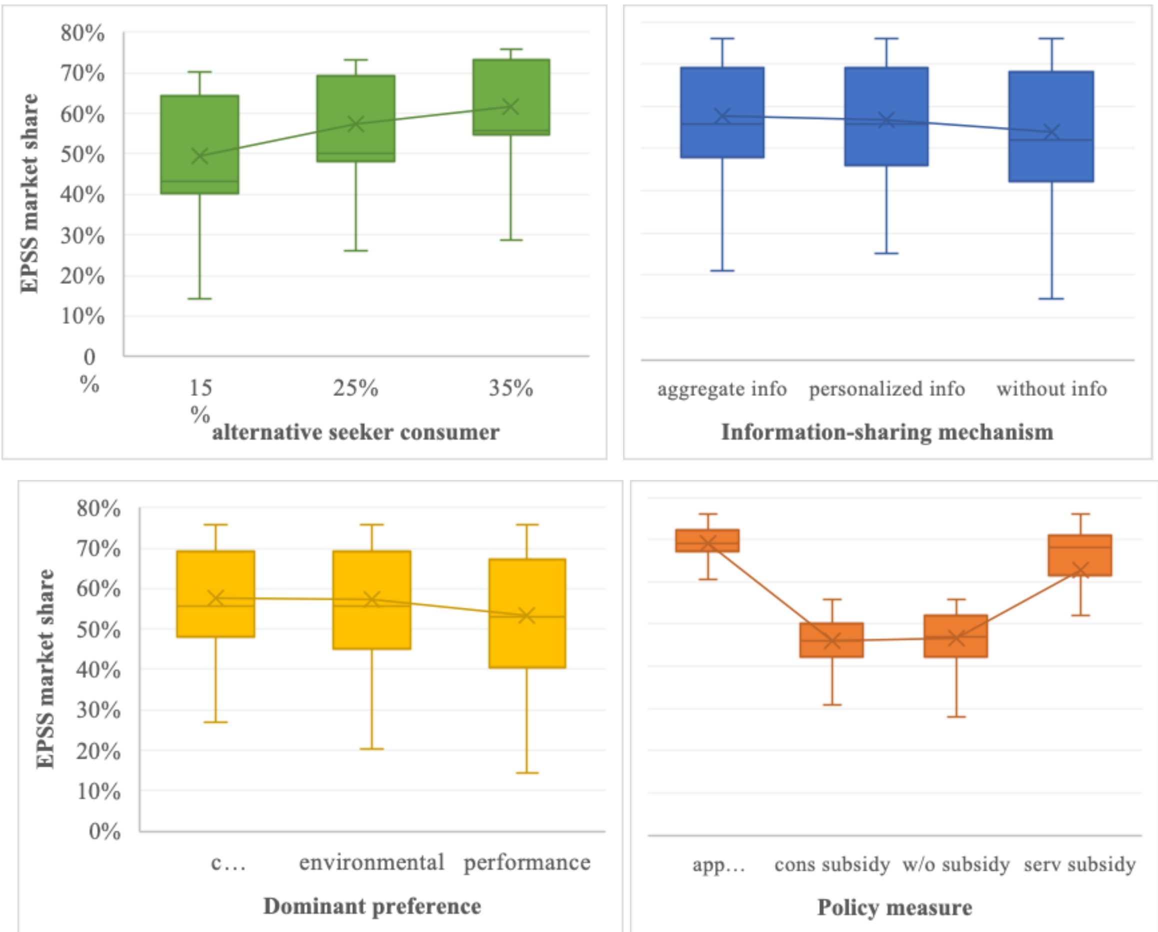


Figure 21. Evaluated variable impact on EPSS market share

Concerning information-sharing mechanism, this strategy aims to address imperfect information provision to improve consumer choice. Hence, it is predictable that providing EPSS without taking account of consumers' interests risks the system transition being slower. On the other hand, improving information provision associated with economic benefit is not necessarily relevant to address consumer's cognitive bias. While at the same time, providing comprehensive information in an attempt to address unidentified diverse biases also hampers consumers making informed choices. For this reason, not only simplified information, but also close relationships between consumers and the company that allows immediate feedback and capture of individual bias becomes necessary to guide EPSS transition.

Regarding policy measures, the results emphasize that the system transition resulting from providing subsidies for consumers is not better than without subsidies. This result suggests that in general, providing benefits to improve economic decisions is more effective if provided for economic agents who has clear economic objective and able to optimize rather than agents that are 'satisficed' with bounded rationality. Therefore, policy makers need to formulate different approaches to stimulate behavioural changes in household's energy consumption rather than simply providing economic benefit, because modifying individual behaviour and choice is not as simple as educating and offering economic benefit or loss, considering that individual behaviour and decision-making processes are driven by various motives and interest, beyond economic aspects. That's being said, it is more feasible to shift complicated decisional processes which impact on the greater good to the economic agents who are endowed with a clear motive and sufficient resources to deliver high quality decisions, such as companies.

Consumer preferences in the market show relatively similar impacts on EPSS market share. Although the range of market penetration resulting from markets dominated by performance-oriented consumers vary more than others. It is because performance-oriented consumers possess fewer constraints in their consumption, therefore EPSS service is not necessarily better for them, when compared to EPOS. These individual impacts, however, may be distorted when combined with other variables. Nonetheless, it is worth noting for analysis of the combined effect toward win-win situations.

Figure 23 shows that the year where the EPSS market share begins to stabilize are found vary between samples. This implies that there are no certain influencing factors for when the lock-in occurs after the first observation of path creation. However, the developed method can predict which conditions are more likely to cause slow market penetration within a given period, as shown in Figure 24.

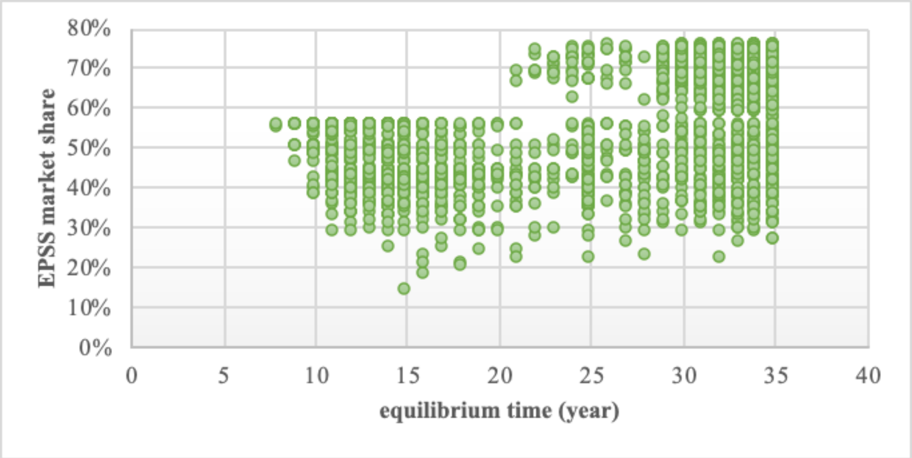


Figure 22. Gap years until EPSS market share stabilized

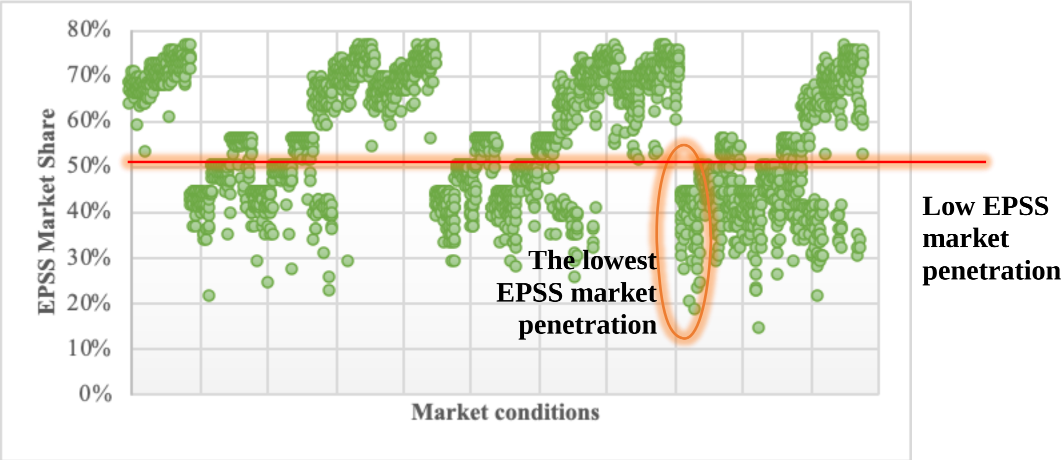


Figure 23. Worst conditions for EPSS market penetration

All conditions that lead to low EPSS market share within an evaluation period are characterized with the domination of performance-oriented consumers, and mostly consist of the fewest alternative-seeker consumers. Still aligned with individual variable impacts, the information-sharing mechanism without information extraction from the consumer has a higher chance to hold EPSS market penetration. In addition, half of the conditions that lead to lowest EPSS market share occur when a subsidy is provided for consumers. Combined variables with negative effects on EPSS market share have the highest probability to cause the slowest EPSS lock-in within the 35 years of the evaluation period.

The result once again justifies that policy enactment utilizing an economic approach to influence individual consumer's decision-making process is not effective. Information provision focusing on price competitiveness, subsidies for consumers to influence their choice, and fewer alternative seeker consumers are a series of conditions that reveal ineffectiveness of economic influences for society. This finding strengthens previous arguments that policy emphasizing on economic benefits seems to be more effective for economic agents with clear motivation for economic benefit, such as firms.

3.5.2 Win-win results of market actors

Figure 25 depicts the shares of highly efficient appliance sales relative to total appliance sales, which represents the incentive from innovating and producing highly efficient appliances. The higher the percentage of sales means the higher the benefit for appliance producers.

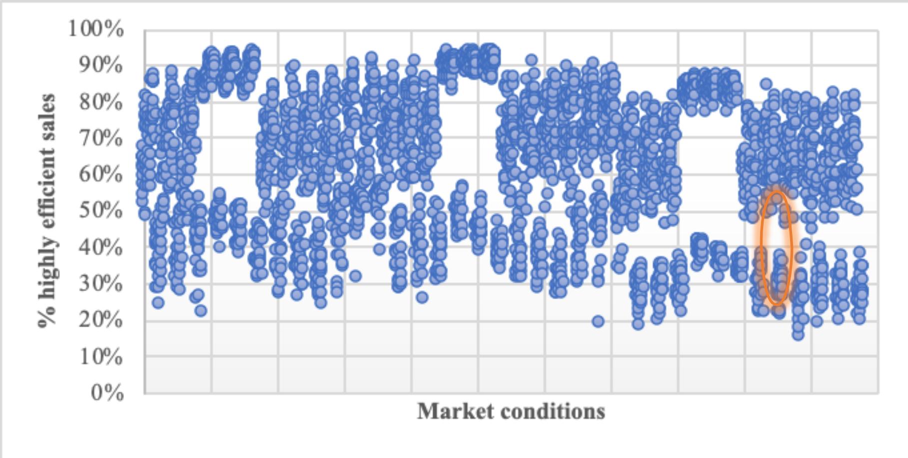


Figure 24. Percentage incentive for highly efficient appliances

From Figure 26 it can be observed that the lowest incentive for appliance producers occurs (with probability 83%) when EPSS type 1 is delivered in a market without any subsidy for EPSS adopters and with 35% of alternative-seeker consumers. Those conditions are identified to have 30% to 50% of EPSS market share. The major influencing factor of the worst result is that consumers in EPOS and EPSS are allowed to choose their own appliances. Without subsidies, the appliances selected in EPSS will be similar to those with an EPOS market. As a consequence, the sales of highly efficient appliances do not improve, which is a disincentive for appliance producers.

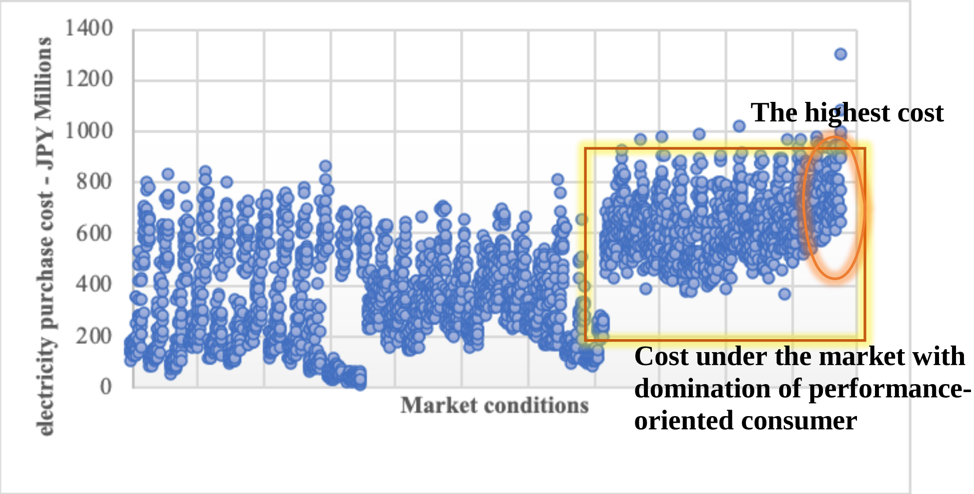


Figure 25. Highly electricity purchase cost of retailer

It is observable from Figure 27 that there is a chance of electricity purchase cost being higher in EPSS. This event occurs when EPSS type-1 is delivered without information extraction from consumers and is provided in the market where performance-oriented consumers dominate with subsidies given for EPSS providers. We can also observe that in general, a market dominated with performance-oriented consumers results in higher electricity purchase costs for retailers, which indicates that the main cause of higher operational cost in EPSS is that demand is uncontrollable. Highly efficient appliances and maintenance are not effective to minimize operational costs without limiting the service demand.

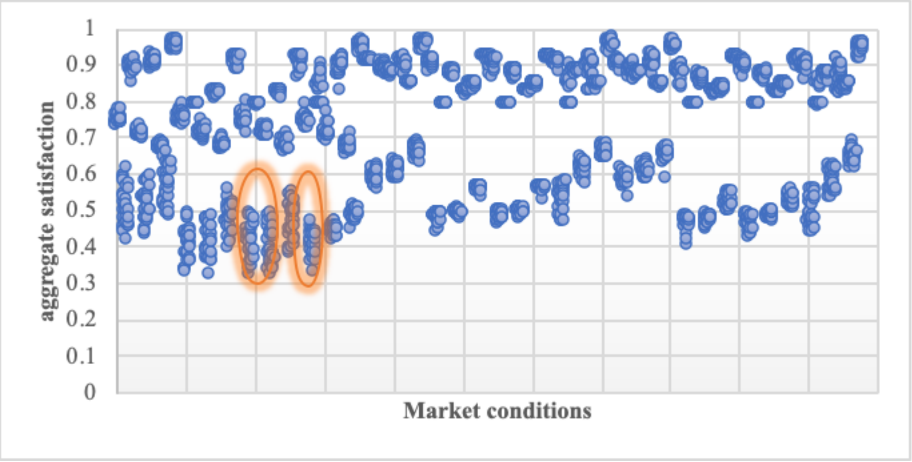


Figure 26. Worst situation for consumer satisfaction

From Figure 28, it can be observed that aggregate consumer satisfaction reaches the lowest (range from 32% to 49%) when EPSS is designed based on aggregate information, and where the market is dominated by environmental-oriented consumers. With only 15% alternative-seeker consumers it results in average 48% EPSS market share, which means that 48%

purchase service designated as environmental-oriented despite their preferences. EPSS designed for environmental-oriented consumers using highly efficient appliances and allowing service providers to limit their consumption to an acceptable level for the sake of emissions reduction causes a conflict of interest with cost-oriented and performance-oriented consumers. The majority of inert consumers who choose based on the market influence are again, making mistakes in choosing products/services that are not suited with their preference.

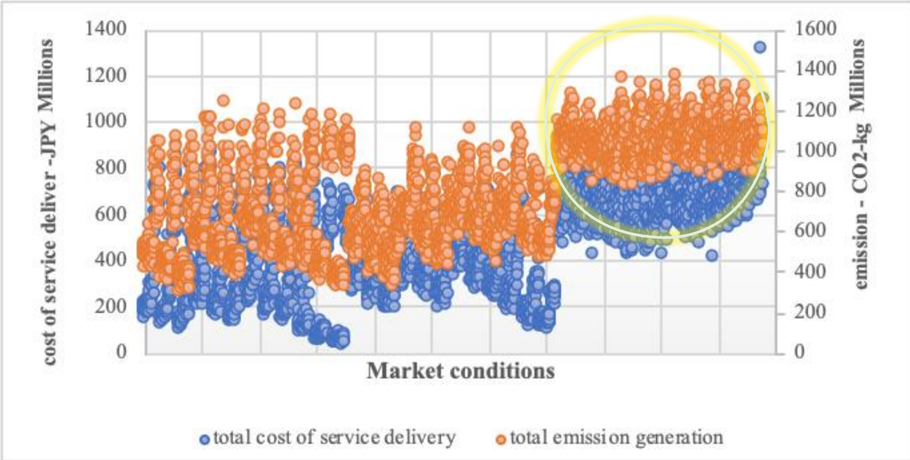


Figure 27. Worst conditions for policy maker

Policy makers' interests to minimize costs and emissions generation is threatened when EPSS is delivered without considering consumers' interest for a market dominated by performance-oriented consumers at all levels of alternative-seeker consumers and all types of policy measures (Figure 29).The result suggests that the domination of performance-oriented consumers in the market, which represents unsupervised consumption, may cause rebound effect for the effort to minimize service cost and emission. The above results reveal that the worst conditions in general occurs when services are either delivered without information sharing from consumers or designed and delivered based on aggregate information. Ultimately, the conditions representing input designs that lead to the worst results for each stakeholder have been identified, comprising of:

1. A market wherein EPSS service is delivered without company's interference in appliance selection and usage, and EPSS is introduced without any subsidy for EPSS adopters may lead to similar results as in the EPOS market, if not worse, for appliance producers
2. Providing consumers with subsidies to influence their choice has minimum effect on consumer decision-making processes due to their myopic view.

3. Markets dominated with performance-oriented consumers result in higher electricity purchase costs for retailers. It implies that retailers tend to spend more on operational costs (i.e. electricity cost) to deliver EPSS to serve a market where demand is uncontrollable.
4. Providing EPSS based on aggregate information extracted from the market harms consumer satisfaction, especially when the service is designed to be environmentally friendly, whereas service consumption is controlled and appliance in-used are the highest efficient appliance the service cost.
5. Unsupervised and uncontrolled consumption may cause rebound effect on EPSS strategy to minimize emission cost and emission.

3.6 Managerial implications

Identification of worst conditions revealed the key factor for EPSS information sharing mechanism to achieve win-win solution. One of the keys is to take into account individual interests in service delivery, in which this mechanism requires company to manage close relationship with consumers so that company can extract necessary information. It suggests the importance of managing close relationships between the company and consumer in EPSS to achieve win-win solution for all stakeholders. Moreover, it demonstrates that disregarding consumer interest to deliver EPSS hampers the effort to achieve win-win solutions, not only for consumers but also for other market players. On the other hand, the findings also suggested to avoid providing consumers with subsidies to influence their choice and behaviour. It has been acknowledged that most energy policies are designed to be economic minded. However, there has been much evidence that influencing individual consumer behaviour and decisional processes using economic loss and benefit often leads to failures. The case is different when economic-oriented policies, such as taxation or subsidies, are applied to companies. Policy compliance is manageable as long as the economic benefit is justified. On the other hand, when the policy appears to hinder the firms' interest to maximize profit, the response is obvious, where companies will cut business investment. The Top Runner Program provides a good example of how economic-oriented policy is well directed to companies, instead of consumers. Accordingly, financial support can be directed for companies to maintain close relationships with consumers to address their cognitive bias and to support consumers to make informed decisions.

The research also finds that EPSS serves market wherein performance-oriented consumers domination may lead to rebound effect. In reality, it reflects the consumption of households from higher income levels, with less environmental awareness. This condition creates tradeoffs with other stakeholders` win situations (e.g. policy measures which aiming for emission reduction), and therefore additional measures are required. For example, to set higher prices instead minimizing cost for these groups of consumers may be necessary to control the consumption.

Lastly, although exogenous shocks are required to trigger change, the research finding suggests that the magnitude of the effect is different for each market actors depending on their attributes and decision-making process, and therefore influence the acceleration of the new system lock-in at different rates. For this reason, it is important to choose the right market players for policy target to accelerate the path dependence. In addition, this study emphasizes that initial consumer uptake is also crucial to create momentum to accelerate the system transition.

However, it remains unclear why organizations or society sometimes are successfully locked into a system, and some other times they are not. The lock-in occurrence from path dependence can only be observed after it happens. The creation of path dependence can only predict lock-in but cannot tell when it will occur (Vergne & Durand, 2010). Therefore, it cannot be said that lock-in has not occurred, because there is no specification of the time limit of when it is supposed to occur after path dependence is observed. For this reason, any empirical evidence of system lock-in based on ex-post case study observation is bound to remain questionable (Liebowitz & Margolis, 1995) because it appeals to the subjective interpretation of the observer of what is the long-run equilibrium. SBD for EPSS identifying the worst scenario is useful to provide hints of situational characteristics of the market environment that may lead to the longest gap of lock-in after path creation is observed. Therefore, the method can be implemented to study the path dependencies of systems in general.

3.7 Closing Remarks

The Simulation-Based Design has been successfully demonstrated to identify the sufficient conditions for EPSS information-sharing mechanism so that it can achieve win-win solutions for the stakeholders. The method effectively addresses uncertain input designs for EPSS by using available information from incumbent system and emphasizing on the worst results, which reflecting the most dangerous input (represented with combined market conditions and EPSS provision), even if the probability of the occurrence is low.

From the simulation results, the major finding shows that the introduction of policy measures to enable EPSS transition by disregarding actors' interest and cognitive bias results in failure in achieving the purpose of measures itself. Decisional processes in energy systems and consumption involve high level cognitive process and therefore are difficult for consumers with bounded rationality. This study suggests directing the economic-based policy for firms, whose economic motivation is clear and have more resources to optimize their decision considering various factors and predetermined constraints. The policy is intended to manage close relations between company and consumer to extract important information from consumers, in an attempt to address consumer's cognitive bias and to support them to make informed decisions in energy consumption.

Chapter 4

Investigating Preconditions for Sustainable Renewable Energy Product-Service Systems in Retail Electricity Markets

4.1 Research background

It has been acknowledged that energy transitions are challenged with carbon lock-in from the incumbent socio-technical regime. Transitioning energy systems requires social commitment, involving producers, users, financial support, and political will from various actors. Without commitment, investment, and innovation to enable it, the transition cannot be realized. Policies have been introduced to stimulate renewable energy technology installation and escape system lock-in. Nonetheless, the effectiveness of such policies varies among regions, depending on actors' behavior and decision-making process. Therefore, policy makers are expected to consider the human dimensions of energy systems alongside the technological and organizational dimensions.

On the other hand, while some countries show progress in transitions and have begun to successfully cut emissions, higher renewable energy uptake may harm the economic sustainability of future energy markets. The more renewable electricity generated, the lower the operational cost of the generation facility, thus price levels are set in accordance to the levels of wind and sun. For this reason, zero-marginal cost energy markets integrated to marginal-cost based markets may destroy electricity prices and squeeze revenue, which results in refinancing and supply security becomes impossible (Agora Energiewede, 2013). Ultimately, there's a strong need for new energy market designs for renewable energy. The market should be designed to achieve an efficient balance of supply with demand and to instigate more investment through revenue generation.

Energy Product-Service Systems (EPSS) with renewable energy (Re-EPSS) is suggested as an alternative sustainable renewable market mechanism. EPSS aims to improve resource efficiency while maintaining benefits for society by providing electricity service performance using energy, products, and operation of dwellings for a household. Service provision releases consumers from the requirement to purchase and possess electrical appliances to satisfy their needs. Consumers shifting from buying products to buying services allows the company to extend their control of products and use them strategically to achieve both the desired performance and business objectives.

EPSS is theoretically matched with the requirement for sustainable future renewable markets. EPSS providing service allows the company to control and manage appliance usage and operation, demonstrates greater flexibility from the demand side to respond to supply uncertainties. To achieve service excellence, the EPSS provider also invests in storage as reserve capacity for when demand for service is required. Moreover, EPSS creates its revenue from service value generated from appliances and electricity performance. With zero operational costs, the EPSS business model is projected to generate more revenue rather than merely trading electricity sources.

Nonetheless, evidence shows that human cognitive bias and bounded rationality hinder the energy transition and harms the efficiency of the retail market. While it is possible to address the present bias in society, to identify the bias is difficult (Allcott, 2016). Therefore, instead of attempting to develop a specific market design, this study aims to identify the required preconditions for EPSS to achieve a sustainable renewable energy market design.

4.2 Related Literature

4.2.1 Escaping carbon locked-in

Energy transitions are a complex phenomenon that involves multiple dimensional aspects ranging from technological and economic feasibility, resource availability, political willingness, and social acceptability (Sovacool, 2017; Vadén et al., 2019) (Trencher et al., 2020). State interventions in the energy sector have been iteratively identified to cause lock-in (e.g. (Ćetković & Buzogány, 2020)). The low diversity of decision-making actors and a skewed distribution of power contributes to political decisions that influence energy transitions (Trencher et al., 2020). For example, governments in Asian countries appear to be risk-averse towards energy transitions. Most are reluctant to reframe renewable energy as an electricity supply system for energy security due to its high uncertainties reflecting the lack of successful transition experience in other countries (Mori, 2018). Emerging countries in Asia which eventually increase the renewable energy market share, especially for wind and solar PV, have gained confidence after substantial experience and industry leadership has been built-up elsewhere (Gosens, Binz, & Lema, 2020). The importance of foreign technology absorption and experience to build domestic capability for energy transitions have also been emphasized . Concerning social and market acceptability, some communities are not convinced about the importance of the energy transition for decarbonization and to address climate change (Colvin, 2020).

Policies have been introduced to stimulate renewable energy technology installation. Most countries rely on feed-in-tariffs (FiT) as a measure to promote renewable energy development (e.g.(Bouznit, del P. Pablo-Romero, & Sánchez-Braza, 2020; Chapman, McLellan, & Tezuka, 2016; Li, Edwards, Hosseini, & Costin, 2020; Lu et al., 2020; Poruschi, Ambrey, & Smart, 2018)). It offers a profit guarantee for long-term contracts (typically ranging from 15 to 20 years) to renewable energy developers. Until now, FIT policies are considered the most successful measure to promote renewable energy around the world, notably in Germany (García-Alvarez & Mariz-Pérez, 2012). FiTs are considered more effective to influence PV installation compared to other measures, such as renewable energy certificates (Chapman et al., 2016). Nonetheless, it was also found that in certain cases, FiTs correspond to a great number of electricity disconnections from the grid (Poruschi et al., 2018). Despite its drawbacks, many countries depend on FiTs in promoting energy transitions (Sawin et al., 2012), which signifies the importance of citizen participation to support high investment in renewable energy technology. One implication may be that less economic support from grassroots users in the energy transition may hamper FiT effectiveness to promote renewable energy investment. Net energy metering (NEM) is considered to be an alternative for regions where the community has a lack of urgency concerning the energy transition. Instead of charging consumers, NEM provides the option to obtain economic benefit from installing small-scale renewable energy generation. Despite its economic benefit (Crossborder Energy, 2013; Energy and Environmental Economics (E3), 2014; Energy Environmental Economics, 2014), it promotes less renewable energy investment, compared to FiTs policy.

Despite countries struggling with carbon locked-in, some have shown impressive progress in the energy transition. The combination of timing and impact of socio-political alignment of endogenous and exogenous events creates the catalyst and support for the transition. In Germany, political stability, the coordinated policy making style, and grassroots support, combined with suitable policies, have enabled a vast deployment of wind power and photovoltaics to replace power from coal (Cheung, Davies, & Bassen, 2019a, 2019b; Dehmer, 2013). Simultaneous external pressures and the recognition of performance problems in the incumbent systems can weaken the system lock-in and create urgency towards the energy transition (Di Lucia & Ericsson, 2014).

The above description shows the importance of human dimensions of energy systems to overcome lock-in in socio-technical systems. Therefore, while it is important to focus on the physical aspects of the systems (e.g. infrastructure, technology, and organization), policy makers are expected to develop measures that also consider human dimensions of energy systems (Ã & Geels, 2007; Geels, 2004; Goldthau, 2014; Hirsh & Jones, 2014).

4.2.2 Future renewable energy market

Renewable energy, especially wind power and photovoltaics, is expected to form the basis of future, low carbon energy system. Wind power and PV facilities are characterized by high investment costs and marginal costs that are close to zero. These characteristics of renewable energy bring issues for future sustainable energy markets. At present, feed-in-tariffs provide long-term guarantees to compensate for the profit risk from electricity price uncertainty. Nonetheless, when renewable energy uptake dominates the total energy mix, wind and PV will reduce electricity market prices and the operating time of fossil-based power stations. Integrating renewable energy markets into current electricity markets which are marginal-cost based will destroy power prices in the marginal-cost based wholesale spot market (Agora Energiewede, 2013). Despite the objective of market deregulation to hold down electricity prices, to achieve almost zero electricity price through renewable energy transitions creates a problem for future energy market sustainability, since the market cannot rely on wind and PV to finance and refinance[2] renewable energy development. The more wind and PV facilities are built and produce electricity concurrently, the lower the electricity market price, and the worse its effect on economic sustainability. It was suggested that future energy markets should be designed to achieve an efficient balance of supply and demand by steering the installation capacity and by sending signals for more investment in renewable energy production and supporting facilities (Agora Energiewede, 2013).

To achieve sustainable renewable energy markets, several options are proposed including "power-only" markets and markets with Capacity Remuneration Mechanism (CRM) (Agora Energiewede, 2013; Oscar Kraan, Jan, Nikolic, Chappin, & Koning, 2019). Others suggest business models that appear to be suitable for renewable energy. Service mobility, load management, and storage are repeatedly mentioned for renewable energy business models (e.g. (Engelken, Römer, Drescher, Welpe, & Picot, 2016)). Yet, the exact configuration of the new market and business model requires further study.

[2] Refinancing is a mechanism to take an existing, operating renewable energy facilities and get new loan from the bank, ideally with better term since the risk of the project decreases. However, under marginal cost-based market, higher deployment of renewable energy electricity price destroys electricity price, putting company's profitability into higher risk. And therefore, refinancing becomes more difficult.

4.2.3 Promoting Energy Product-Service Systems for sustainable energy market design

This study suggests Energy Product-Service Systems (EPSS) for sustainable renewable energy markets. EPSS is expected to provide opportunities to create value-added services for retail consumers, to ensure the benefit from the market is distributed to consumers through prices and service quality attributes that match with consumers' values and preferences (Joskow & others, 2008). A well-functioning liberalized market also expects retailers' ability to offer various service options to be coupled with consumers' ability to compare and make informed choices (Council of European Energy Regulators (CEER), 2016). Nonetheless, as a highly commoditized product, electricity provisions are difficult to differentiate. Current retail markets distinguish their offers through pricing plans or billing. It may also include ancillary services, though society appears to not be ready to adopt this generally.

Benefit has been recognized from market liberalization, but mostly for the supplier side (Joskow, 2000; Joskow & others, 2008). On the other hand, lower electricity prices, as an expected benefit for household consumers have not always been achieved. In fact, there are times, where liberalized electricity prices are higher than monopolistic markets (AEMC, 2017; Morey & Kirsch, 2016). Market imperfections, such as complexity of information provision and switching cost, have been identified as the cause of retail electricity market failures (Defeuilley, 2009; Hortaçsu et al., 2017; Von Der Fehr & Hansen, 2008). Electricity retail consumers are poor electricity shoppers because their cognitive processes are limited with computational capability, time and will power (Gigerenzer & Selton, 2002; OECD, 2017; Simon, 1955, 1956, 1997). These cognitive biases influence their valuation of retailer's provision in power-only markets with distinguished pricing plans.

Others have argued that one of the critical preconditions for retail consumers to obtain benefit from a liberalized electricity market, is for them to be able to see and to respond to real-time price changes (Joskow & others, 2008). Once consumers (demand side) can actively participate and react to variations of market prices, full integration of demand side responses to energy prices and reliability criteria can be achieved, leading to market efficiency (Joskow & others, 2008). For this reason, there is hope that the expanded development and use of smart devices and smart home technologies will materialize the required preconditions (Cramton, 2017b). Unfortunately, consumers are also bad shoppers for highly efficient technology. Myopic consumers who are incapable of assessing long-term risks or benefits of their choices (OECD, 2017) have been widely identified in investigations on the highly efficient appliance and technology as well (Allcott, 2016; OECD, 2017; Waechter et al., 2015). Therefore, expecting consumers to choose the latest technology, which is more expensive, despite being potentially more efficient, may lead to other buying “mistakes”.

EPSS releasing consumers from ownership allow the company to control, choose appliances and electricity sources. It is suitable for renewable energy futures and liberalized retail markets where demand side participation is indispensable for supply-demand balance to achieve market efficiency. It appears that EPSS characteristics align with the requirements of liberalized electricity retail markets and renewable energy markets.

4.3 Object of the study

A hypothetical market, focusing on the retail market is developed to demonstrate the identification of required preconditions for Re-EPSS market design. The market consists of an appliance producer and electricity retailers that purchase and sell electricity to the wholesale market, which serves a community of 100 households. Some retailers and consumers exhibit loss-averse behavior, where they avoid exposure to risky choices due to uncertain results. These types of retailers and consumers represent late adopters of new system mechanisms. On the other hand, innovative retailers initiate the deployment of Re-EPSS mechanisms to satisfy consumer demand, and alternative-seeker consumers are identified in liberalized markets as early adopters of the new system due to their awareness toward switching cost (Wieringa & Verhoef, 2007). In this market, consumers are endowed with one of the preferences, including cost-oriented consumers, performance-oriented consumers, and environmental-oriented consumers, which reflects their preference toward supply reliability. Moreover, three cognitive biases are assumed to influence consumer decision processes, comprising of loss aversion bias, status quo bias, and social proof (Council of European Energy Regulators (CEER), 2016).

Consumers demand three types of services, comprising of food preservation, heating/cooling services, and laundry services. For each type of service demand, appliance producers provide two groups of appliances, which are categorized based on their efficiency. Each group of appliances consists of several appliance specifications which are distinguished by price. However, in general, the price of highly efficient appliances is set to be more expensive than that of low efficient appliances.

For the purpose of this study, the market also covers the wholesale market as a power-only market, where fossil fuel and renewable electricity is exchanged. The wholesale market satisfies the demand from EPOS and EPSS. For simplicity in capturing the market response to price signals, all electricity demand from EPOS is satisfied in the spot market. Spot prices in the wholesale market are determined by the renewable energy mix in total energy consumption.

The power-only market is equipped with a capacity market, to secure electricity supply when needed. Re-EPSS providers also invest in demand response and storage capacity to deliver services, depending on consumer preferences and cost constraints in service consumption. In a market with EPSS, Virtual Power Plant (VPP) is incorporated to manage and control electricity supply-demand balances for EPSS consumers. Electricity generation and storage are used by prioritizing EPSS consumers before VPP dispatches any excess electricity to balance the demand from the EPOS market. Figure 29 summarizes the market players in the observed market.

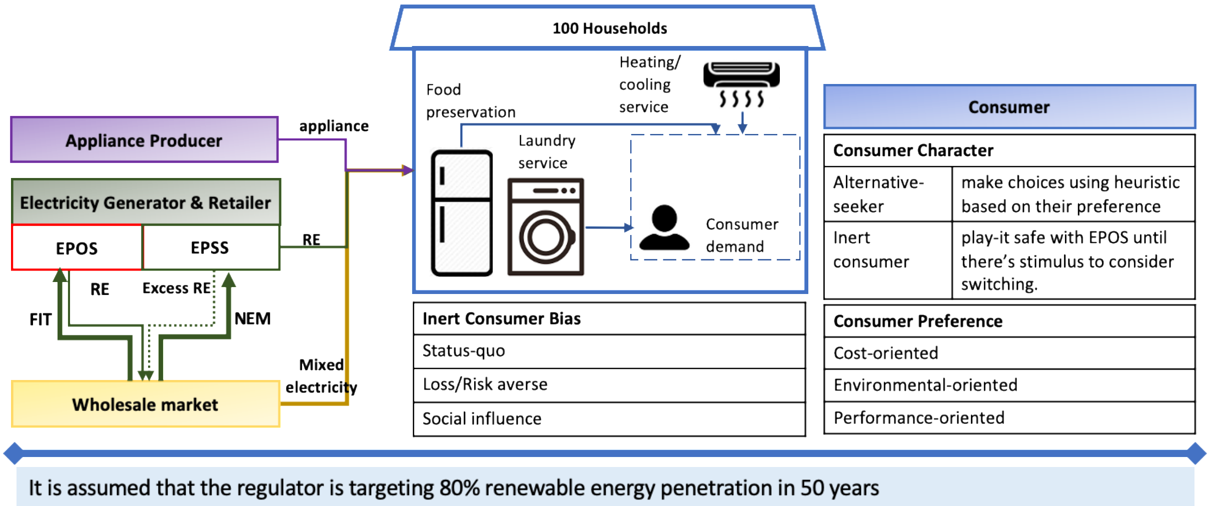


Figure 28. Market players' interaction in the observed market

4.3.1 Market players' behavior and decision-making process

Both retailers in EPOS and EPSS behavior are motivated to maximize revenue from renewable energy investment. Ultimately, the critical decision for both retailers is investment decisions on PV facilities. Investment decisions are influenced by prospective benefits in the future, which in this study is signaled by demand trends and revenue trends. In addition, for EPSS retailers, their investment decision involves electricity storage for reserve supply when needed.

EPOS and EPSS retailers have different sources of revenue. In EPOS the revenue is derived from electricity sales in the wholesale market and retail market, and profit depends on both FiT and wholesale prices. The bigger PV installed capacity, the higher volume of electricity sales. Meanwhile, EPSS retailers rely on a constant service rate which is billed periodically (e.g. monthly) from the consumer. Another profit source of EPSS retailers also includes excess electricity sales in the wholesale market.

Consumer behavior is intuitively directed by their needs and preferences. In EPOS, consumers are required to choose and purchase appliances, create service demand based on environmental stimuli, pay electricity bills of an amount depending on the consumption, unconsciously evaluate satisfaction, provide feedback when asked, and decide on appliance replacement. EPOS consumers are assumed to voluntarily pay the surcharge cost of renewable electricity but are not interested to purchase ancillary services because it requires high investment with uncertain benefits. In a market where EPOS and EPSS compete, however, consumers first decide whether to switch to EPSS or remain with the status quo, based on their characteristics and preferences. Only alternative-seeker consumers compare attributes of products/services based on their interest to choose a system or appliance. Inert consumers, on the other hand, postpone their decision until the market provides signals that address their bias in decision-making. And eventually, every period, wholesale electricity prices, and FiT rates are adjusted, considering the renewable energy mix in total electricity consumption.

Market players decisions contribute to the renewable energy market efficiency in the short-run and long-run. In the simulation, decisional processes that affect market efficiency include consumer decisions on consumption, retailer decisions on EPOS and EPSS operation, and the wholesale market determines electricity price rate, while the regulator sets the Feed in Tariff rate.

4.3.1.1 Electricity retailer behaviour and decision-making process

The series of processes conducted by electricity retailers in EPOS who also generate renewable energy are described in Figure 30. On the other hand, EPSS generation capacity focuses to satisfy demand from EPSS consumers. The decisional flow of EPSS retailers are described in Figure 31.

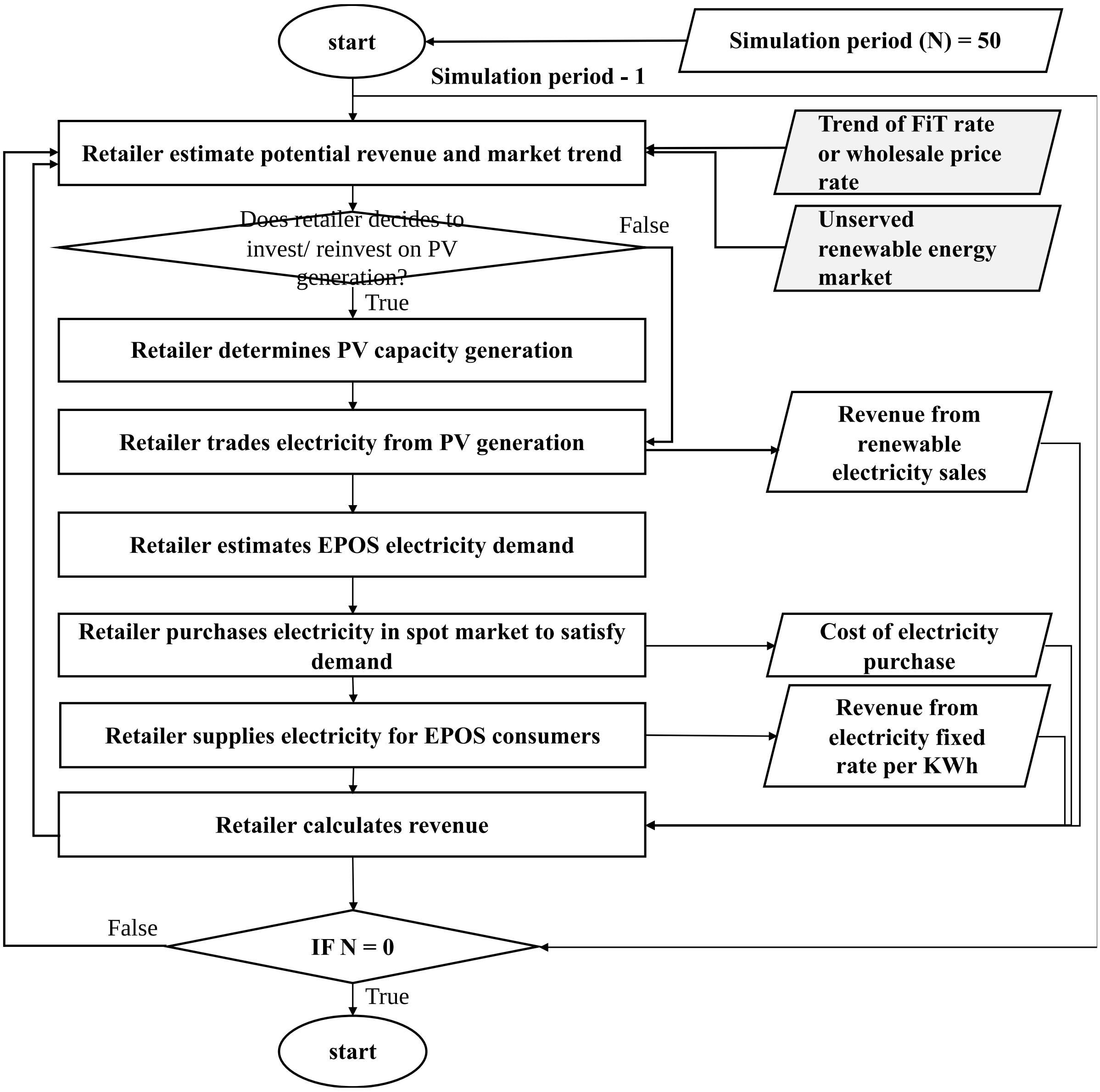


Figure 29.EPOS retailer behaviour and decision flow

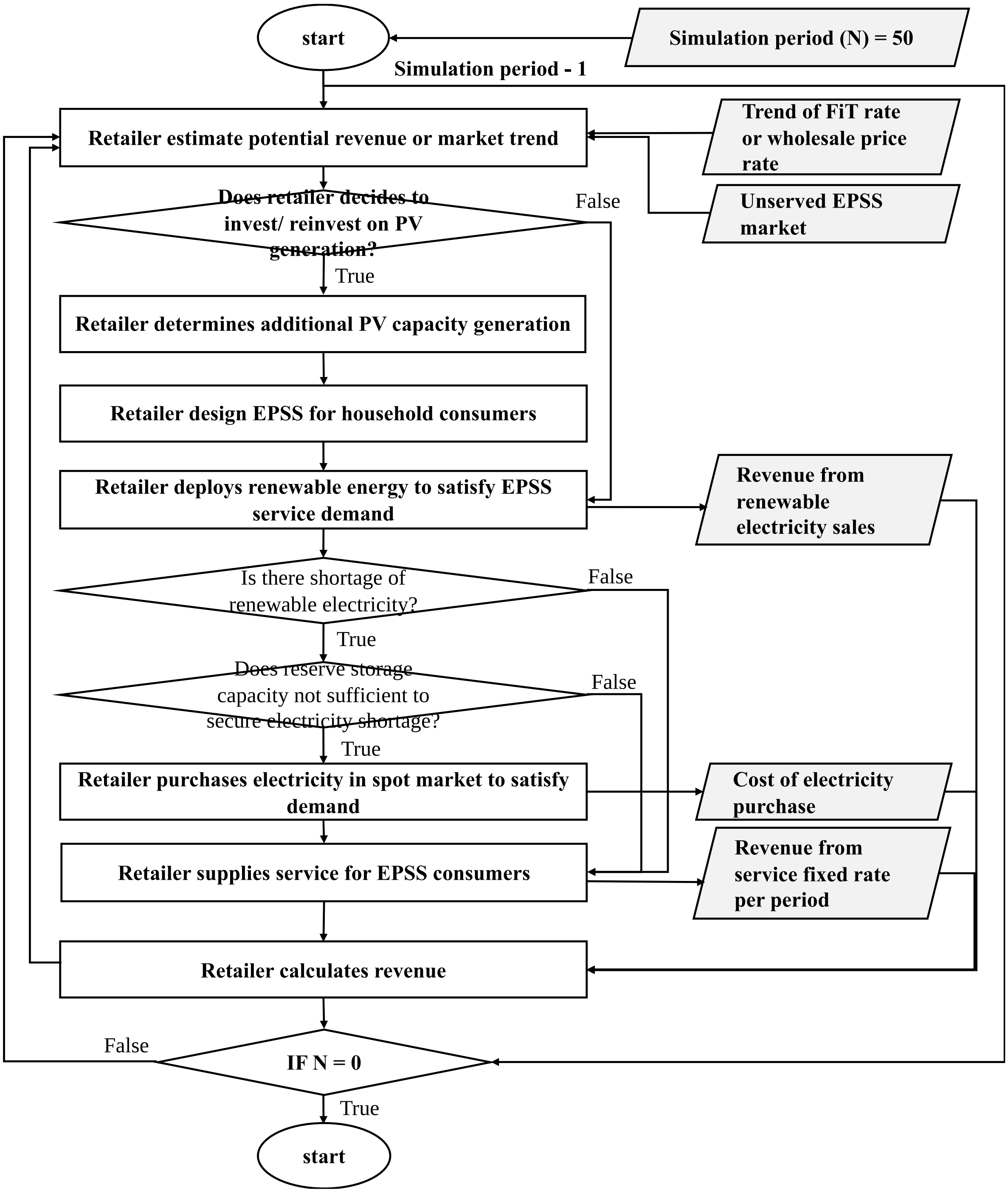


Figure 30.EPSS retailer behaviour and decision flow

In the first period, both EPOS and EPSS retailers decide to invest in PV considering the benefit from the FiT rate. For the first investment, initial installed PV capacity is intended to satisfy electricity demand of half of potential consumers, indicated by the share of alternative seekers. Future investment, however, is determined considering potential revenue and or renewable energy demand trends. Estimation of future revenue is a function of the unserved market and current FiT rate or wholesale price rate (depending on the FiT enactment). If estimated future revenue or market trend is predicted to be promising, retailers invest more in PV, increasing generation capacity.

Assuming that PV specifications in-use for power generators are uniform, and the entire area gets the same amount of sunlight, electricity generation per period is a stochastic process depending on sunlight intensity during the time. Electricity generated from PV is then traded in the wholesale market by EPOS retailers, where they gain revenue from the FiT rate. On the other hand, EPSS retailers deploy the electricity to deliver services. In EPSS, excess electricity is used to charge the storage for reserve capacity. When batteries are fully-charged, and electricity generation is less than electricity demand, surplus electricity is dispatched to the main grid, and the company obtains revenue from it. In contrast, when electricity shortages takes place, reserve capacity is used to secure renewable electricity supply. When reserve capacity is not sufficient to supply service demand, if possible, the service provider adjusts service demand to reduce electricity demand. Nonetheless, in the case where even after service adjustment, electricity shortage is still unavoidable, the service provider purchases electricity from the spot market. The whole process of managing supply demand balance and bridging electricity transmission from EPSS community with the main grid is conducted as a Virtual Power Plant.

The next step is to calculate retailer revenue to send a signal to the market for inciting more renewable energy investment. EPOS retailer revenue is a function of revenue from renewable energy trading in wholesale market, revenue from electricity sales in the retail market, and cost of electricity purchase in the spot market to satisfy EPOS demand in the retail market. Meanwhile, EPSS revenue is calculated considering revenue from fixed rate of service sales in the retail market, revenue from electricity trading in the wholesale market, minus EPSS appliance investment. While operating, companies keep evaluating market trends and potential revenue to determine future renewable energy investment. Ultimately, the EPSS retailer provides feedback to consumer by reporting their emissions generation compared to average emissions generation of households in the community.

4.3.1.2 Other market players

Additional mechanisms in the observed market include the FiT rate and wholesale price rate update. The Feed in Tariff is also updated every period considering renewable energy mix of total consumption. The regulator aims for 80% renewable energy mix from total community consumption in 50 years. Initially, the FiT rate is set to 40 JPY/kWh. The rate is gradually decreased when renewable energy share from total consumption reaches 25%, and 60% and ultimately revoked when it reaches 80%. The wholesale market updates the electricity price rate every period based on the composition of electricity from renewable energy and fossil fuel trades in the market.

4.3.2 EPSS provision

EPSS provides service as a bundle of electrical appliances and electricity supply to deliver expected performance for household consumers. The present study introduces three types of EPSS, which are differentiated by performance level to serve different consumer's preferences.

The first type of EPSS design is intended for cost-oriented consumers, whose interest is to minimize the total cost of service consumption. These consumers limit their consumption costs and are willing to compromise the performance level of the service. To satisfy the requirement, service providers invest in technology to obtain and deliver information about real-time electricity demand and control the usage for minimum performance when service demand occurs during peak times. The second EPSS type is designated for environmental-oriented consumers, whose aim is to minimize emissions generation from service consumption. For environmental-oriented consumers, the service provider invests in highly efficient appliances and technology to monitor real time electricity demand and control the service performance in the case that demand occurs during peak times. For performance-oriented consumers, the service provider prepares EPSS type 3. This type of EPSS satisfies consumer demand for premium service demand, where consumers do not want curtailment or postponement of demand fulfilment, and cost does not limit them to purchase the service. For these consumers, the company invests in highly efficient appliances and allows consumers to have full control over the operation and use whenever it is needed. The EPSS contract between the consumer and company ends when an appliance needs to be replaced. In EPSS the appliance is replaced when its efficiency degradation reaches more than 15% of than initial condition.

The services are categorized into two groups, which are characterized by the reliability performance, i.e. 1) negotiable vs non-negotiable services, and 2) deferrable and non-deferrable services. The first and second types of services are categorized into negotiable and deferrable services. Cost-oriented and environmental-oriented consumers are willing to adjust the heating and cooling temperatures to an acceptable level and shift the time to do laundry if required, to satisfy their consumption constraints. Meanwhile, performance-oriented consumers are not willing to compromise the performance level and the time of demand fulfilment, and ultimately non-negotiable and non-deferrable service as in type 3 is provided.

Table 14.EPSS type and description

EPSS design	Design subject	Service design characteristics
EPSS type 1	Consumer-oriented consumers	Negotiable and deferrable
EPSS type 2	Environmental-oriented consumers	Negotiable and deferrable
EPSS type 3	Performance-oriented consumers	Non-negotiable and non-deferrable

While inert consumers` decisions strongly depend on the network, alternative-seeker bias can be addressed by providing low cost of information provision (Council of European Energy Regulators (CEER), 2016; Hortaçsu et al., 2017). EPSS not only alters the provision but also changes the information-sharing mechanism between actors. EPOS information-sharing mechanism modification results in two mechanisms for EPSS, which are characterized by information extraction from consumers for service delivery, as shown in Table 14. EPSS offering fixed-price contracts are expected to address the present bias due to bounded rationality (Allcott, 2016).

Table 15. The influential factor of consumer's decisional behavior

Information-sharing scenario	Content of information	
	Information extraction from targeted consumers	Information provision from service provider to consumer
With aggregate information	Aggregate information, collected using sample survey about consumer preference in service consumption	Service rate Service feature (e.g. emission generation, performance level) Service contract period
With personalized information	Personalized information, can be collected using individual interview about consumer preference in service consumption	Service rate Service feature (e.g. emission generation, performance level) Service contract period

4.3.3 Market performance measurements

Regulators seek a market design that provides reliable electricity at the minimum cost for consumers through renewable energy generation. This objective is indicated by efficiency in the short-run and long-run. Short-run efficiency aims to satisfy the present demand with available resources considering consumer preferences for reliability. In this case, consumer satisfaction is the best representation of short-run performance measurement. Long-run efficiency, on the other hand, is reflected through revenue generation to promote more investment in generation capacity to secure supply reliability in the market. The present study indicates long-run efficiency with retailer revenue considering the renewable energy mix in total consumption.

This study assumes that consumers can measure their satisfaction if information concerning their interests is available. Cost-oriented consumers measure their satisfaction based on the cost spent to satisfy their demand. Environmental-oriented consumers measure their satisfaction based on the emissions released from their consumption. While EPSS provides information about the consumer's emissions, the consumer in the incumbent systems has no information about it. Concerning performance-oriented consumers, their satisfaction is measured based on the performance level of the service. They prefer to choose products/services that can satisfy their demand as it is, without curtailment or postponement. When information to assess their satisfaction is not available, consumer satisfaction is recorded as zero.

Let satisfaction of cost-oriented, environmental-oriented, and performance-oriented consumers-i be $S_{i,cost}$, $S_{i,env}$ and $S_{i,perf}$ respectively, therefore, EPOS consumer satisfaction is represented as

$$S_{i,ecost}^{EPOS} = \begin{cases} 1, if\ c_{i,t} < c_{i,t-1} \\ 0, if\ c_{i,t} \geq c_{i,t-1} \end{cases} ;\ S_{i,env}^{EPOS} = 0\ ;\ S_{i,perf}^{EPOS} = 1 \quad (41)$$

In EPSS, however, consumers compare their satisfaction with EPOS. The company provides information about the performance to be compared with average system performance, including EPOS and EPSS. Cost-oriented consumers in EPSS will be happy if their expenditure is lower than the average of the system. Environmental-oriented consumers are satisfied when the report of emissions generated from their consumption is lower than the average of the system. Meanwhile, performance-oriented consumers are unhappy when their service level is different than their expectations, either in time or comfort temperature. Hence, EPSS consumer satisfaction measurement can be stated as below.

$$S_{i,cost}^{EPSS} = \begin{cases} 1, if\ c_{i,t} < \bar{c}_t \\ 0, if\ c_{i,t} \geq \bar{c}_t \end{cases} ;\ S_{i,env}^{EPSS} = \begin{cases} 1, if\ e_{i,t} < \bar{e}_t \\ 0, if\ e_{i,t} \geq \bar{e}_t \end{cases} ;\ S_{i,perf}^{EPSS} = \begin{cases} 1, if\ \partial_{i,t} = \dot{\partial}_t \\ 0, if\ \partial_{i,t} \neq \dot{\partial}_t \end{cases} \quad (42)$$

Concerning long-run efficiency, it was mentioned before that retailers in EPOS and EPSS have different sources of profit. EPOS retailers with PV generation gain revenue from renewable energy sales, both in the wholesale market and retail market. EPOS retailer revenue (R_{EPOS}), therefore, is formulated as follows.

$$R_{EPOS} = \sum_{t=0}^{T} \varphi_t.\left(x_1.P_t + x_2.\hat{P}_t\right) + \delta_t.\left(p + S - \hat{P}_t\right) \quad (43)$$

Subject to:

$$x_1 = \begin{cases} 1, if\ P_t > \hat{P}_t \\ 0, if\ P_t \leq \hat{P}_t \end{cases}; \qquad x_2 = 1 - x_1 \quad (44)$$

Meanwhile, EPSS revenue (R_{EPSS}) is derived from monthly fixed service rates and sales of excess electricity. The fixed rate reflects service cost and appliance investment including demand response and electricity storage. Hence,

$$R_{EPSS} = \sum_{t=0}^{T} \dot{c}\, N_{EPSS,t} + (\varphi_t - \delta_t).\hat{P}_t - \sum_{t=0}^{T} I.N_{EPSS} \quad (45)$$

Where

$c_{i,t}$	: consumer's -i electricity bill at $-t$	(JPY)
$c_{i,t}$	: consumer's -i electricity bill at $-t$	(JPY)
$\overline{c_t}$	: average consumers electricity bill at $-t$	
$e_{i,t}$	: consumer's -i emission at $-t$	(CO_2.kg)
$\bar{e}_t$	: aggregate consumers' emission at −t	(CO_2.kg)
$\partial_{i,t}$	: consumer's demand for service performance at $-t$	
$\dot{\partial}_t$	: actual of service performance at $-t$	
φ_t	: renewable electricity generation at $-t$	(GW)
δ_t	: electricity sales at $-t$	(GW)
x_1, x_2	: variable decision of applied electricity price rate in wholesale market	
P_t	: Fit-in-tariff rate	(JPY/KWh)
$\hat{P}_t$	: Wholesale price rate	(JPY/KWh)
p	: Electricity rate for EPOS consumer in retail market	(JPY/KWh)
S	: Surcharge cost for renewable energy	(JPY/KWh)
$\dot{c}$	: Service rate for EPSS consumer retail market	(JPY/period)
I	: Investment for appliance and EPSS facility	(JPY)
N_{EPSS}	: Number of EPSS consumers	

4.3.4 Simulation and Scenario Design

Interaction between actors in the renewable electricity market is simulated, and its impact on market performance is measured. Initially, there is 0% of renewable energy mix in total consumption before retailers which are also power PV generation companies enter the market. To stimulate investment, the regulator implements a FiT and NEM. Due to the nature of their business model electricity generators in EPOS apply for the FiT, and Re-EPSS apply for NEM. It is assumed that the regulator is targeting 80% renewable energy penetration in 50 years, considering that many socio-technical transitions take 40 – 120 years (Cheung et al., 2019b).

The present study is interested to observe the impact of decision processes of uncertain consumer bias on the performance of the renewable energy market. Re-EPSS designs are then evaluated under 36 market conditions which are derived from selected market variables as shown in Table 16.

Table 16. Selected variables for scenario design

Variables	Value
Market design	{power-only market, competing market with EPSS}
Information-sharing mechanism	{with aggregate information, with personalized information}
Share of alternative-seeker consumer*)	{0.15, 0.25, 0.35}
Share of dominant preference (i.e. as much as 60% of consumers in the market is dominated by one of these preferences)	{cost-oriented, environmental-oriented, performance-oriented}

*) The rest are inert consumers who are each is endowed with one of status quo bias, social influence bias, and loss-averse bias. The distribution of consumers for each bias is equal.

4.4 Simulation Results and Analysis

4.4.1 The impact of heterogeneous consumer bias and market competition toward renewable energy market

The probability of a market with the incumbent system to achieve the target of the renewable energy mix is higher than that of a market with Re-EPSS introduction (i.e. 97% and 69% for incumbent and competing market, consecutively). The conditions that lead to the worst results were identified to be those conditions where alternative-seeker consumers are less than 35% (shown in Figure 32). Fewer alternative-seeker consumers are associated with slower EPSS market penetration. It appears that in a competing market between a power-only market and EPSS (which is similar to an ancillary market), slow and low EPSS market penetration affects loss-averse investors in the power-only market. EPSS introduction amplifies uncertainty of future revenue, due to uncertain consumer choice to remain engaged with the incumbent system or switch to the service-oriented market. The slow penetration hampers renewable energy investment for EPSS, while at the same time exposing EPOS companies to revenue risk from the declining market share. As a result, both EPOS and EPSS companies suppress additional investment which leads to an even lower renewable energy mix from total consumption.

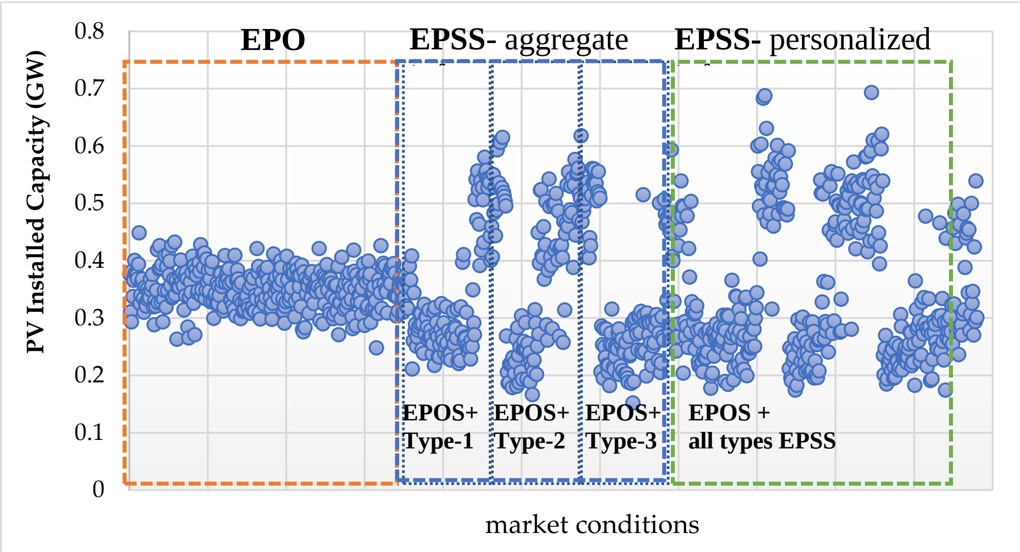


Figure 31. Market conditions affect PV installed capacity

On the other hand, EPSS deploying batteries as part of their service impacts on the increasing storage capacity in the long run. Figure 33 shows that lower storage capacity is associated with low EPSS market share. It suggests that EPSS not only stimulates investment in PV facilities but also in electricity storage. The more EPSS uptake in the market the more reserve capacity available that will be advantageous for supply security.

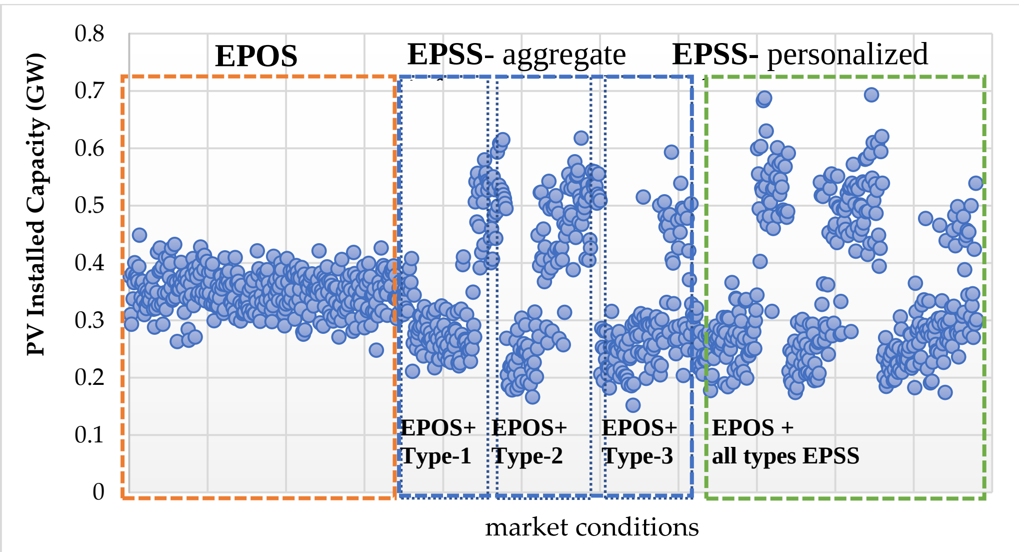


Figure 32. Market conditions affect the storage capacity

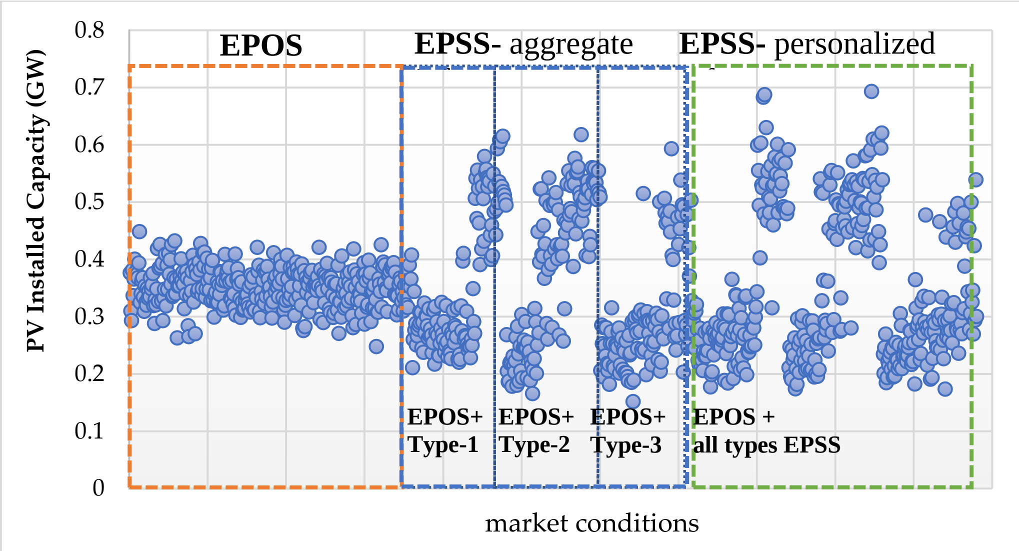


Figure 33. Market conditions affect aggregate consumer satisfaction

Figure 34 shows the impact of various market conditions toward aggregate consumer satisfaction. The worst results are caused by the conditions presented in Table 17. There's a higher probability of consumer satisfaction being lower than the incumbent system where EPSS uptake in the market is relatively high. The result signifies that consumers make mistakes in their choices, similar to the incumbent system. Instead of making informed decisions considering their preferences, these consumers decide to follow social networks and market trends to avoid risk. Although consumers demonstrate similar behavior in both market mechanisms, satisfaction toward EPSS is more likely higher because consumers perceive more advantages to the incumbent (Hortaçsu et al., 2017).

Table 17. Worst conditions result in lowest consumer satisfaction

Market design	**Information sharing mechanism**	**Share of alternative-seeker consumer**	**Share of dominant preference**
Competing market	with_aggregate	0.25	Environmental-oriented
Competing market	with_aggregate	0.35	Cost-oriented
Competing market	with_aggregate	0.35	Environmental-oriented
Competing market	with_custom	0.25	Environmental-oriented
Competing market	with_custom	0.35	Cost-oriented
Competing market	with_custom	0.35	Environmental-oriented

Visual analysis of Figure 35 shows that markets with EPSS generate more revenue compared to power-only markets. This result is predictable given the nature of the EPSS business model. However, the EPSS mechanism is challenged with locked-in effects from the incumbent system. Other than carbon lock-in, EPSS faces barriers from a society that has been deeply rooted in product-oriented systems. With energy as the main entity, moving from product-oriented systems into service-oriented systems requires not only socio-technological transitions in the energy market system but also actors from different sectors associated with energy consumption, such as manufacturing and housing companies. Different measures are required to enable system transition from EPOS to EPSS to achieve sustainable markets for renewable energy.

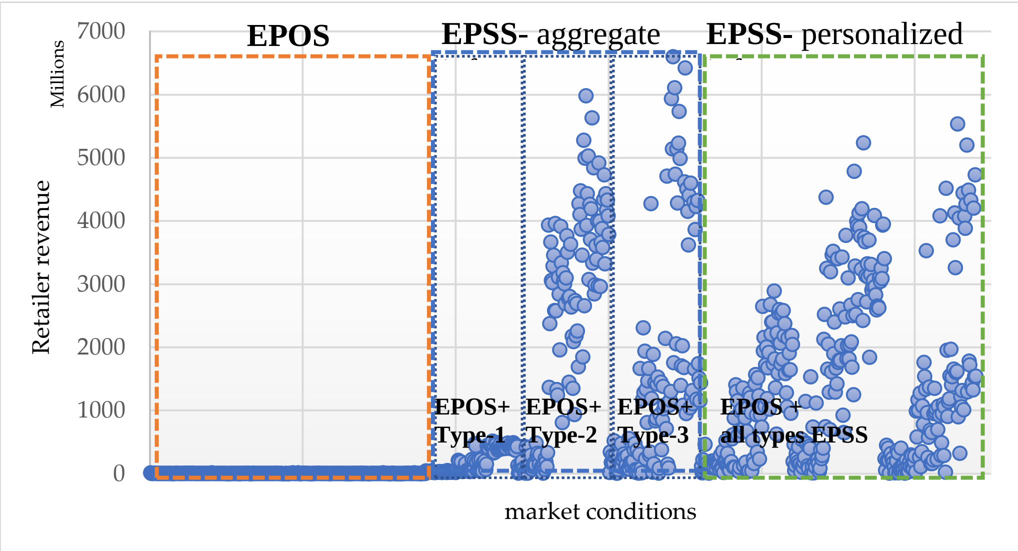


Figure 34. Market conditions affect retailer revenue

Accordingly, we can summarize the necessary conditions for Re-EPSS to achieve sustainable renewable energy markets as below.

1. In terms of renewable energy investment, the result supports previous studies that emphasize the importance of certainty for business profitability. In the case of competing market mechanisms between EPOS (as the power-only market) and EPSS (which are similar to the ancillary market), it seems better to induce measures that distinguish the market segmentation during EPSS introduction, so that the initial growth of the EPSS market doesn't amplify market uncertainty around renewable energy investment in the EPOS market.
2. Simulation results of aggregate consumer satisfaction repeat the results of the incumbent system, where consumers are 'satisficed' with their choice. It implies that consumers` decision process contributes to their mistakes in choosing providers. In the simulation, it was assumed that consumer consideration in the decision process is static

over time. However, in reality, there could be learning processes when feedback mechanisms to evaluate their choice is available.

3. Retailer revenue for EPSS is predictably higher than EPOS due to its business nature. Revenue optimization from the EPSS mechanism faces barriers from product-oriented systems lock-in. Previous studies provide hints of specific market characteristics for EPSS that require a longer time to take effect. However, further study is necessary to investigate preconditions for EPSS in renewable electricity markets.

4.4.2 Managerial implications

Based on the research findings, recommendations are provided to satisfy the requirements of EPSS to achieve market efficiency. Prospective benefits are important to accelerate renewable energy investment under uncertainty. It is particularly important for loss-averse business actors in power-only markets when they have to compete with EPSS business models that involve ancillary services. While EPSS transitions are challenged with path dependency of the current system, investment in power-only markets may be affected by market competition. On the other hand, investing in EPSS appears to be more profitable compared to incumbent mechanisms. For this reason, it is better to set clear boundaries to distinguish consumer segmentation for power-only markets and ancillary markets. In addition, different policy measures become indispensable for EPSS transitions. It is because participation from different sectors associated with energy market systems is required to deliver EPSS, which means that there will be more players involved in the new energy market system. Previous studies revealed the conditions required for EPSS lock-in including to secure the profit of previously product-oriented companies that switch into service-oriented provision. Incentives for appliance producers that suit their interests will likely accelerate the EPSS lock-in effect.

Consumer preference for reliability is supposedly well captured in EPSS market mechanisms. However, simulation results reveal that consumers demonstrate similar cognitive bias that leads to even lower satisfaction than with the incumbent, due to the inertia effect. However, attempts to optimize consumer satisfaction can be directed to design feedback mechanisms from service consumption, involving close relationships between consumers and service providers, in anticipating consumer learning processes to choose services that suit their preferences. In this case, the low switching cost is important, so that consumers can exercise their learning processes.

4.5 The performance of SBD for EPSS design

The study has developed a novel method to design EPSS, namely SBD for EPSS. It is a simulation framework that incorporates Agent-Based Modelling and Worst scenario methods to design EPSS, which represents a new system with multiple interacting actors under limited available knowledge. Using a hypothetical market, the method has been successfully implemented to design a system with different purposes. Insights regarding the method performance are obtained after the implementation.

Simulation-Based Design (SBD) plays a significant role in the evaluation and comparison of EPSS design performance with incumbent market mechanisms under various conditions. The conditions in this study refer to the market environment which is derived from combined market characteristics comprising of consumer characteristics, bias, and preference, company's characteristics, and market policy. SBD emphasizes on the use of simulation as a tool to design, to evaluate, and to analyse a system design is beneficial for EPSS that requires comprehensive analysis to predict the outcomes before consuming resources, effort, and time by eliminating risks of design failure as soon as possible. This approach allows the use of hypothetical environments, as well as infrastructure for collaborative engineering and integration technologies and tools. Nonetheless, the SBD approach is challenged with the requirement of a systematic approach to find the optimal combination of variables to be evaluated within the system boundary. It is because the more actors and variables considered in the design process, the higher the number of variable combinations that need to be evaluated.

Agent-Based Model (ABM) is indispensable to model EPSS, wherein multiple interacting market players with heterogenous characteristics and behaviors have anticipated impacts on EPSS performance. ABS is advantageous to replicate the dynamics of liberalized electricity markets and energy transition progress by incorporating heterogeneous actors' behavior. Particularly to depict the dynamic of decisional process induced by agent's characteristics, bias and preferences in economic activity. It also allows the exploration of the role of market players with their cognitive bias and rationality level in energy transitions. The exploration of plausible trajectories of energy transitions given uncertain socio-technical conditions is also possible with ABS. The model at some point manages to capture the unpredictable results or system behaviour given the interaction of market players. Nonetheless, the Agent Based Model applied in this study has not been able to capture the occurrence of new, unpredicted behaviour of the market players. In short, incorporating SBD with ABM is beneficial in providing an understanding of the future system behavior so that the designer can avoid making careless assumptions about the behavior of the actors and the systems that may cause the design failure.

Finally, the “Worst Scenario” method has effectively addressed uncertain input design for EPSS by using available information from the incumbent system and emphasizing the worst results. It also has effectively identified the ‘unfavourable’ conditions which reflect the most dangerous input (represented with combined market conditions and EPSS provision). Instead of seeking the design with the best performance, embedding the “worst scenario” method is effective to identify the worst conditions, that should be avoided, even if the probability of the occurrence is low.

4.6 The Future with EPSS

This section briefly describes some of the potential implications of a widespread uptake of EPSS, although this is speculative, due to the significant uncertainties.

EPSS could facilitate the adoption of advanced and more efficient technology in society faster than EPOS. This is because the company chooses the technology and they are expected to choose more efficient appliances in order to maximise their own profit.

Under EPSS, the industry will shift from mass production to achieve economies of scale into customized production. As a consequence, there would be high demand for technologies to cut delivery time from product and service design to consumer delivery, such as 3D printing. Digital twin technology will be implemented not only for large machines and equipment but also in small household electrical devices and equipment. In EPSS, this technology plays an important role in controlling appliances and collecting information of product usage behaviour to satisfy consumer’s demand. As a consequence, there will be an explosion in data creation following the information collection regarding individual behaviour in appliance usage and electricity consumption. In this sense, electricity demand is shifted from household consumption to company consumption for data storage and processing. The society may consume more electricity than in the EPOS era to run servers for data processing and transmission. Blockchain technology is also useful for EPSS operations to enable the integration of information systems for appliance life cycle management, covering new products, product recovery, part recovery, and material recovery, and accordingly can be used to develop flexible scheduling decision methods to support appliance production planning and inventory control that minimizes costs and emissions.

With the deployment of highly efficient technology, the industrial size, particularly those industries that are related to EPSS is likely to shrink. But resources may be more evenly distributed under market competition. However, there is also the possibility that resources to support service delivery may be monopolized by certain market players.

With EPSS, decentralized electricity generation is expected to be more rapidly introduced. For this reason, EPSS could potentially enable the development of smart cities as satellite towns for bigger cities with self-sufficient electricity resources. The quality of life could increase with minimum belongings but an improved environment and service performance. It is uncertain how EPSS will alter human behaviour. But closer relationships and better communication between consumers and companies will result in better understanding of individual preferences and interests in consuming electricity service performance. Such understanding is important for society because it is projected that in the near future, most of human's daily activities will be supported by using electrical appliances.

4.7 Closing Remarks

This study demonstrates the implementation of SBD to design EPSS for the sustainable renewable energy market. Worst scenarios that lead to unexpected results have been identified as well. Accordingly, it can be concluded from the study the preconditions required for EPSS design to achieve the objective of efficient market design, both in short-run and long-run, for the renewable energy market, as below.

1) In the case of the renewable energy market, it is necessary to set a clear boundary to distinguish consumer segmentation for power-only market and EPSS market (for ancillary service), to facilitate loss-averse investor.
2) The finding emphasizes the importance of managing the close relationship between company and consumer in an attempt to extract consumer interest and create a feedback mechanism to facilitate the learning process and addressing consumer cognitive bias. EPSS with a better information sharing mechanism enables the service provider to build a closer relationship with the consumers.

Iterating previous study, introducing low switching cost in EPSS is indispensable for the consumer to exercise their learning process to make an informed decision in the retail market.

Chapter 5

Research Conclusions

This research aims to develop a method to design EPSS and how to utilize it for designing EPSS. This study proposed a method to design EPSS, which is challenged with limited knowledge, input design uncertainty, and involve multiple interacting actors within a socio-technological complex. To address the design problems, the method is developed using Simulation-Based Design, and incorporating the "Worst Scenario" method and Agent-Based Model. From the study, four major aspects regarding the method and the result from method implementation can be concluded as below.

1. A method to design EPSS is developed by comparing the performance of incumbent systems with EPSS design performance under various market characteristics with limited available knowledge. The key of the method is to determine the design objective of the new system and the model structure. The process of structuring the model includes selecting the market actors and their attributes, followed by structuring causalities between actors' behaviour and system performance, which is predicted based on existing knowledge in current systems. Based on the model causalities, simulation model is developed to evaluate the performance of EPSS design before consuming resources, effort, and time by eliminating risks of design failure as soon as possible and compare it with the EPOS performance.Agent-Based Modelling is applied to model interacting heterogenous actors with various interest and cognitive bias and has been useful to replicate the dynamics of liberalized electricity markets and energy transition progress given the actors' characteristics and behaviour. The "Worst Scenario" method has been incorporated to address uncertain correlation between system input and system performance, whereas modelers only need to set the bound for the input data and searches for the most "unfavorable" output, and therefore it is useful for a problem where probabilistic data has not yet been established.
2. SBD for EPSS is developed using *Python 3.8* Programming Language, with the main module namely MESA for Agent Based Simulation. A hypothetical market is developed to demonstrate the utilisation of the method consisting of electricity retailers and appliance producers serving a community of 100 households that demand electricity service performance. Different types of EPSS design to deliver the service are introduced into a

community with different preferences and characteristics, which influence their decisional process. The detail of the market characteristics varies between cases.

3. From the method demonstration, it also can be concluded that Simulation-Based Design (SBD) plays a significant role in the evaluation and comparison of EPSS design performance with incumbent market mechanisms under various conditions, while Agent-Based Model (ABM) is indispensable to model EPSS, wherein multiple interacting market players with heterogenous characteristics and behaviors have anticipated impacts on EPSS performance. The model at some point manages to capture the unpredictable results or system behaviour given the interaction of market players. Nonetheless, the Agent Based Model applied in this study has not been able to capture the occurrence of new, unpredicted behaviour of the market players. By incorporating the "worst scenario" method , the model simulates and identify the worst scenario for a market where characteristics is predetermined, and the range of the input data is assumed to be known beforehand based on evidence or observation in the existing market. The simulation results provide knowledge about the system behaviour and possible outcomes of system design given various market characteristics. On the other hand, given the nature of the unknown input, accuracy of prediction from the simulation results becomes a weakness of the method.

References

Ã, G. V., & Geels, F. (2007). The ongoing energy transition : Lessons from a socio-technical , multi-level analysis of the Dutch electricity system (1960 – 2004). *Energy Policy*, *35*, 1025–1037. https://doi.org/10.1016/j.enpol.2006.02.010

Abdelaziz, E. a., Saidur, R., & Mekhilef, S. (2011). A review on energy saving strategies in industrial sector. *Renewable and Sustainable Energy Reviews*, *15*(1), 150–168. https://doi.org/10.1016/j.rser.2010.09.003

Adrodegaria, F., Alghisia, A., Ardolinoa, M., & Saccania, N. (2015). From ownership to service-oriented business models: a survey in capital goods companies and a PSS typology. *Procedia CIRP 30*, 245–250.

AEMC. (2017). *2017 AEMC Retail Energy Competition Review*. Sydney. Retrieved from http://www.aemc.gov.au/getattachment/006ad951-7c42-4058-9724-51fe114cabb6/Final-Report.aspx

Agora Energiewede. (2013). *12 Insights on Germany ' s Energiewende 12 Insights on Germany ' s*.

Allcott, H. (2016). Paternalism and Energy Efficiency: An Overview. *Annual Review of Economics*, *8*, 145–176. https://doi.org/10.1146/annurev-economics-080315-015255

Allcott, H., & Knittel, C. (2019). Are consumers poorly informed about fuel economy? Evidence from two experiments. *American Economic Journal: Economic Policy*, *11*(1), 1–37. https://doi.org/10.1257/pol.20170019

Allcott, H., & Taubinsky, D. (2015). Evaluating Behaviorally-Motivated Policy: Experimental Evidence from the Lightbulb Market. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2676158

Amemiya, T. (2018). Current State and Trend of Waste and Recycling in Japan Original Reports Open Access. *Int J Earth Environ Sci IJEES, an Open Access Journal*, *3*, 155. https://doi.org/10.15344/2456

Annarelli, A., Battistella, C., & Nonino, F. (2016). Product service system: A conceptual framework from a systematic review. *Journal of Cleaner Production*, *139*, 1011–1032. https://doi.org/10.1016/j.jclepro.2016.08.061

Arthur, W. B. (1989). Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *The Economic Journal*, *99*(394), 116. https://doi.org/10.2307/2234208

Aydin, E., Brounen, D., & Kok, N. (2018). *Information Asymmetry and Energy Efficiency: Evidence from the Housing Market*.

Bacchetti, E. (2017). A Design Approach with Method and Tools to Support SMEs in Designing and Implementing Distributed Renewable Energy (DRE) Solutions Based on Sustainable Product-Service System (S.PSS). *Procedia CIRP*, *64*, 229–234. https://doi.org/10.1016/j.procir.2017.03.064

Bacchetti, E., Vezzoli, C., & Landoni, P. (2016). Sustainable Product-Service System (S.PSS) applied to Distributed Renewable Energy (DRE) in Low and Middle-income Contexts: A Case Studies Analysis. *Procedia CIRP*, *47*, 442–447. https://doi.org/10.1016/j.procir.2016.03.085

Baines, T. S., Braganza, A., Kingston, J., Lockett, H., Martinez, V., Michele, P., … Wilson, H. (2007). State-of-the-art in product service-systems. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *221*(Part B), 1543–1552. https://doi.org/10.1243/09544054JEM858

Barazza, E., & Strachan, N. (2020). The impact of heterogeneous market players with bounded-rationality on the electricity sector low-carbon transition. *Energy Policy*, *138*(March 2019), 111274. https://doi.org/10.1016/j.enpol.2020.111274

Benedetti, M., Cesarotti, V., Holgado, M., Introna, V., & Macchi, M. (2015). A proposal for energy services' classification including a product service systems perspective. *Procedia CIRP*, *30*, 251–256. https://doi.org/10.1016/j.procir.2015.02.121

Berndt, E. R., & Wood, D. O. (1975). Technology, Prices, and the Derived Demand for Energy. *The Review of Economics and Statistics*, *57*(3), 259. https://doi.org/10.2307/1923910

Bertoldi, P., Hinnells, M., & Rezessy, S. (2006). Liberating the power of Energy Services and ESCOs in a liberalised energy market. *EEDAL06 International Energy Efficient Domestic Appliances and Lighting Conference (London)*, (November), 13.

Bertoldi, P., Rezessy, S., & Vine, E. (2006). Energy service companies in European countries: Current status and a strategy to foster their development. *Energy Policy*, *34*(14), 1818–1832. https://doi.org/10.1016/j.enpol.2005.01.010

Beuren, F. H., Gomes Ferreira, M. G., & Cauchick Miguel, P. A. (2013). Product-service systems: A literature review on integrated products and services. *Journal of Cleaner Production*, *47*, 222–231. https://doi.org/10.1016/j.jclepro.2012.12.028

Blasch, J., Filippini, M., & Kumar, N. (2019). Boundedly rational consumers, energy and investment literacy, and the display of information on household appliances. *Resource* *and Energy Economics*, *56*, 39–58. https://doi.org/10.1016/j.reseneeco.2017.06.001

Bond, R. (2005). Group size and conformity. *Group Processes and Intergroup Relations*, *8*(4), 331–354. https://doi.org/10.1177/1368430205056464

Bossak, M. A. (1998). Simulation based design. *Journal of Materials Processing Technology*, *76*(8), 11. https://doi.org/10.1524/teme.2012.0177

Bouznit, M., del P. Pablo-Romero, M., & Sánchez-Braza, A. (2020). Measures to promote renewable energy for electricity generation in Algeria. *Sustainability (Switzerland)*, *12*(4), 1–17. https://doi.org/10.3390/su12041468

Bueno, B., Wilson, H. R., Sunkara, S., Sepúlveda, A., & Kuhn, T. E. (2020). Simulation-based design of an angle-selective and switchable textile shading system. *Building and Environment*, *184*(February), 107227. https://doi.org/10.1016/j.buildenv.2020.107227

Busse, M. R. ., Knittel, C. R. ., & Zettelmeyer, F. (2013). American Economic Association Are Consumers Myopic ? Evidence from New and Used Car Purchases. *The American Economic Review*, *103*(1), 220–256.

Cavalieri, S., & Pezzotta, G. (2012). Product–Service Systems Engineering: State of the art and research challenges. *Computers in Industry*, *63*(4), 278–288. https://doi.org/10.1016/j.compind.2012.02.006

Ćetković, S., & Buzogány, A. (2020). Between markets, politics and path-dependence: Explaining the growth of solar and wind power in six Central and Eastern European countries. *Energy Policy*, *139*(February). https://doi.org/10.1016/j.enpol.2020.111325

Chapman, A. J., McLellan, B., & Tezuka, T. (2016). Residential solar PV policy: An analysis of impacts, successes and failures in the Australian case. *Renewable Energy*, *86*, 1265–1279. https://doi.org/10.1016/j.renene.2015.09.061

Chen, X., Huang, J., Yang, H., & Peng, J. (2019). Approaching low-energy high-rise building by integrating passive architectural design with photovoltaic application. *Journal of Cleaner Production*, *220*, 313–330. https://doi.org/10.1016/j.jclepro.2019.02.137

Chen, Y., Wei, W., Liu, F., Shafie-khah, M., Mei, S., & Catalão, J. P. S. (2018). Optimal contracts of energy mix in a retail market under asymmetric information. *Energy*, *165*, 634–650. https://doi.org/10.1016/j.energy.2018.09.139

Cherubini, S., Iasevoli, G., & Michelini, L. (2015). Product-service systems in the electric car industry: critical success factors in marketing. *Journal of Cleaner Production*, *97*, 40–49. https://doi.org/10.1016/j.jclepro.2014.02.042

Cheung, G., Davies, P. J., & Bassen, A. (2019a). In the transition of energy systems: What lessons can be learnt from the German achievement? *Energy Policy*, *132*(May), 633–

646. https://doi.org/10.1016/j.enpol.2019.05.056

Cheung, G., Davies, P. J., & Bassen, A. (2019b). In the transition of energy systems: What lessons can be learnt from the German achievement? *Energy Policy*, *132*(April), 633–646. https://doi.org/10.1016/j.enpol.2019.05.056

Cohen, F., Glachant, M., & Söderberg, M. (2017). Consumer myopia, imperfect competition and the energy efficiency gap: Evidence from the UK refrigerator market. *European Economic Review*, *93*, 1–23. https://doi.org/10.1016/j.euroecorev.2017.01.004

Colvin, R. M. (2020). Social identity in the energy transition: an analysis of the "Stop Adani Convoy" to explore social-political conflict in Australia. *Energy Research and Social Science*, *66*(November 2019), 101492. https://doi.org/10.1016/j.erss.2020.101492

Company Overview of Local Motors, Inc. (2016). Retrieved January 1, 2016, from http://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapId=117638330

Cossentino, M., Fortino, G., Gleizes, M. P., & Pavón, J. (2010). Simulation-based design and evaluation of multi-agent systems. *Simulation Modelling Practice and Theory*. https://doi.org/10.1016/j.simpat.2010.07.007

Council of European Energy Regulators (CEER). (2015). *Position paper on well-functioning retail energy markets*. Belgium.

Council of European Energy Regulators (CEER). (2016). CEER Report on commercial barriers to supplier switching in EU retail energy markets, Ref: C15-CEM-80-04.

Cramton, P. (2017a). Electricity market design, *33*(4), 589–612. https://doi.org/10.1093/oxrep/grx041

Cramton, P. (2017b). Electricity market design. *Oxford Review of Economic Policy*, *33*(4), 589–612.

Crossborder Energy. (2013). The Benefits and Costs of Solar Distributed Generation for Arizona Public Service, (510). Retrieved from http://www.seia.org/sites/default/files/resources/AZ-Distributed-Generation.pdf

Current Scrap Metal Prices. (n.d.). Retrieved August 31, 2020, from https://iscrapapp.com/prices/

Datta, S., & Gulati, S. (2014). Utility rebates for ENERGY STAR appliances: Are they effective? *Journal of Environmental Economics and Management*, *68*(3), 480–506. https://doi.org/10.1016/j.jeem.2014.09.003

DECC. (2014). *Evaluation of the DECC and John Lewis energy labelling trial - Publications - GOV.UK*. Retrieved from https://www.gov.uk/government/publications/evaluation-of-the-decc-and-john-lewis-energy-labelling-trial

Defeuilley, C. (2009). Retail competition in electricity markets. *Energy Policy, 37*(2), 377–386. https://doi.org/10.1016/j.enpol.2008.07.025

Dehmer, D. (2013). The German Energiewende: The First Year. *Electricity Journal*, *26*(1), 71–78. https://doi.org/10.1016/j.tej.2012.12.001

Delzendeh, E., Wu, S., Lee, A., & Zhou, Y. (2017). The impact of occupants' behaviours on building energy analysis: A research review. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.05.264

Dhariwal, J., & Banerjee, R. (2018). Simulation based mixed mode building design. *Materials Today: Proceedings*, *5*(11), 23391–23403. https://doi.org/10.1016/j.matpr.2018.11.079

Di Lucia, L., & Ericsson, K. (2014). Low-carbon district heating in Sweden - Examining a successful energy transition. *Energy Research and Social Science*, *4*(C), 10–20. https://doi.org/10.1016/j.erss.2014.08.005

Du, F., Zhang, J., Li, H., Yan, J., Galloway, S., & Lo, K. L. (2016). Modelling the impact of social network on energy savings. *Applied Energy, 178,* 56–65. https://doi.org/10.1016/j.apenergy.2016.06.014

Energy and Environmental Economics (E3). (2014). Evaluation of Hawaii's Renewable Energy Policy and Procurement, (January).

Energy Efficiency in Household Appliances. (1999). *Energy Efficiency in Household Appliances*. https://doi.org/10.1007/978-3-642-60020-3

Energy Environmental Economics. (2014). Nevada Net Energy Metering Impacts Evaluation preparted for state of Nevada Public Utilities Commission. Retrieved from http://puc.nv.gov/uploadedFiles/pucnvgov/Content/About/Media_Outreach/Announcements/Announcements/E3 PUCN NEM Report 2014.pdf?pdf=Net-Metering-Study

Engelken, M., Römer, B., Drescher, M., Welpe, I. M., & Picot, A. (2016). Comparing drivers, barriers, and opportunities of business models for renewable energies: A review. *Renewable and Sustainable Energy Reviews, 60,* 795–809. https://doi.org/10.1016/j.rser.2015.12.163

Ernst Ulrich von Weizsäcker, Lovins, A. B., & Lovins, L. H. (1998). *Factor Four: Doubling Wealth—Halving Resource Use: A New Report to the Club of Rome*. Earthscan.

Fenaughty, K., & Parker, D. (2018). *Evaluation of Air Conditioning Performance Degradation: Opportunities from Diagnostic Methods*. *2018 ACEEE Summer Study on Energy Efficiency in Buildings*.

Frederiks, E. R., Stenner, K., & Hobman, E. V. (2015a). Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour. *Renewable and Sustainable Energy Reviews*, *41*, 1385–1394. https://doi.org/10.1016/j.rser.2014.09.026

Frederiks, E. R., Stenner, K., & Hobman, E. V. (2015b). Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour. *Renewable and Sustainable Energy Reviews*, *41*, 1385–1394. https://doi.org/10.1016/j.rser.2014.09.026

Fullerton, D., Wolfram, C., & Davis, L. W. (2014). *Evaluating the Slow Adoption of Energy Efficient Investments*. *The Design and Implementation of US Climate Policy*. https://doi.org/10.7208/chicago/9780226921983.003.0020

Gaiardelli, P., Resta, B., Martinez, V., Pinto, R., & Albores, P. (2014). A classification model for product-service offerings. *Journal of Cleaner Production*, *66*, 507–519. https://doi.org/10.1016/j.jclepro.2013.11.032

Gamliel, E., & Herstein, R. (2011). To save or to lose: Does framing price promotion affect consumers' purchase intentions? *Journal of Consumer Marketing*, *28*(2), 152–158. https://doi.org/10.1108/07363761111115999

García-Alvarez, M. T., & Mariz-Pérez, R. M. (2012). Analysis of the Success of Feed-in Tariff for Renewable Energy Promotion Mechanism in the EU: Lessons from Germany and Spain. *Procedia - Social and Behavioral Sciences*, *65*, 52–57. https://doi.org/10.1016/j.sbspro.2012.11.090

Garetti, M., Rosa, P., & Terzi, S. (2012). Life Cycle Simulation for the design of Product-Service Systems. *Computers in Industry*, *63*(4), 361–369. https://doi.org/10.1016/j.compind.2012.02.007

Gaspar, R., & Antunes, D. (2011). Energy efficiency and appliance purchases in Europe: Consumer profiles and choice determinants. *Energy Policy*, *39*(11), 7335–7346. https://doi.org/10.1016/j.enpol.2011.08.057

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems Insights about dynamics and change from sociology and institutional theory. *Research Policy*, *33*, 897–920. https://doi.org/10.1016/j.respol.2004.01.015

Gigerenzer, G., Peter M. Todd, & and the ABC Research Group. (1999). *Simple heuristics that make us smart*. New York, Oxford: Oxford University Press. https://doi.org/10.1002/(SICI)1099-0771(200004/06)13:2<161::AID-BDM348>3.0.CO;2-P

Gigerenzer, G., & Selton, R. (2002). *Bounded Rationality: The Adaptive Toolbox*. (G.

Gigerenzer & R. Selton, Eds.). Cambridge, Massachusetts: The MIT Press.
Gigerenzer, G., Todd, P. M., & the ABC Research Group. (1996). *Simple Heuristics That Make Us Smart*. (S. Stich, Ed.) (1st Ed.). New York: Oxford University Press.
Goedkoop, M. J., Van Halen, C. J. G., Te Riele, H. R. M., & Rommens, P. J. M. (1999). *Product Service systems , Ecological and Economic Basics*. *Economic Affairs* (Vol. 36). https://doi.org/10.1111/j.1365-294X.2004.02125.x
Goldthau, A. (2014). Rethinking the governance of energy infrastructure: Scale, decentralization and polycentrism. *Energy Research and Social Science*, *1*, 134–140. https://doi.org/10.1016/j.erss.2014.02.009
Gong, Y., & Yu, Q. (2019). Evolution of conformity dynamics in complex social networks. *Symmetry*, *11*(3). https://doi.org/10.3390/sym11030299
Gosens, J., Binz, C., & Lema, R. (2020). China's role in the next phase of the energy transition: Contributions to global niche formation in the Concentrated Solar Power sector. *Environmental Innovation and Societal Transitions*, *34*(March 2019), 61–75. https://doi.org/10.1016/j.eist.2019.12.004
Gürtler, M., & Paulsen, T. (2018). The effect of wind and solar power forecasts on day-ahead and intraday electricity prices in Germany. *Energy Economics*, *75*, 150–162. https://doi.org/10.1016/j.eneco.2018.07.006
Haase, H. P. (1997). Impact of Energy and Environmental Issues on the Globalisation of the Industry and Markets. In P. Bertoldi, A. Ricci, & B. H. Wajer (Eds.), *Energy Efficiency in Household Appliances* (pp. 14–16). Florence, Italy.
Hamwi, M., & Lizarralde, I. (2017). A Review of Business Models towards Service-Oriented Electricity Systems. In *Procedia CIRP* (Vol. 64, pp. 109–114). The Author(s). https://doi.org/10.1016/j.procir.2017.03.032
Hamwi, M., Lizarralde, I., & Legardeur, J. (2020). Demand response business model canvas: a tool for flexibility creation in the electricity markets. *Journal of Cleaner Production*, (xxxx), 124539. https://doi.org/10.1016/j.jclepro.2020.124539
Hamwi, M., Lizarralde, I., Legardeur, J., Izarbel, T., & France, B. (2016). Energy Product Service Systems as core element of energy transition in the household sector : The Greenplay project. In *22nd International Sustainable Development Research Society Conference*. Lisbon, Portugal. https://doi.org/10.13140/RG.2.2.30854.37448
Hara, K., Uwasu, M., Kishita, Y., & Takeda, H. (2015). Determinant factors of residential consumption and perception of energy conservation: Time-series analysis by large-scale questionnaire in Suita, Japan. *Energy Policy*, *87*, 240–249.

https://doi.org/10.1016/j.enpol.2015.09.016
Henry, D., Zani, A., Richardson, H. D., Tono, A., Schiavon, S., Arens, E., … Berkeley, U. C. (2019). A simulation-based design analysis for the assessment of indoor comfort under the effect of solar radiation, 0–8.
Hesselink, L. X. W., & Chappin, E. J. L. (2019). Adoption of energy efficient technologies by households – Barriers, policies and agent-based modelling studies. *Renewable and Sustainable Energy Reviews*, *99*(September 2018), 29–41. https://doi.org/10.1016/j.rser.2018.09.031
Hirsh, R. F., & Jones, C. F. (2014). History's contributions to energy research and policy. *Energy Research and Social Science*, *1*, 106–111. https://doi.org/10.1016/j.erss.2014.02.010
Hlaváˇcek, I., Chleboun, J., & Babuška, I. (2004). *Uncertain Input Data Problems and the Worst Scenario Method*. *Elsevier* (1st ed.).
Hori, S., Kondo, K., Nogata, D., & Ben, H. (2013). The determinants of household energy-saving behavior: Survey and comparison in five major Asian cities. *Energy Policy*, *52*, 354–362. https://doi.org/10.1016/j.enpol.2012.09.043
Hortaçsu, A., Madanizadeh, S. A., & Puller, S. L. (2017). Power to choose? An analysis of consumer inertia in the residential electricity market. *American Economic Journal: Economic Policy*, *9*(4), 192–226. https://doi.org/10.1257/pol.20150235
Huang, Y., Seck, M. D., & Fumarola, M. (2012). A simulation based design framework for large scale infrastructure systems design (pp. 194–201). Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84898799100&partnerID=40&md5=2377a67b5a6714f3c81afa080c6847f5
IPSOS, & London Economics. (2014). *Study on the impact of the energy label and potential changes to it – on consumer understanding and on purchase decisions*.
Jain, R. K., Gulbinas, R., Taylor, J. E., & Culligan, P. J. (2013). Can social influence drive energy savings? Detecting the impact of social influence on the energy consumption behavior of networked users exposed to normative eco-feedback. *Energy and Buildings*, *66*, 119–127. https://doi.org/10.1016/j.enbuild.2013.06.029
Johnston, D., Siddall, M., Ottinger, O., Peper, S., & Feist, W. (2020). Are the energy savings of the passive house standard reliable? A review of the as-built thermal and space heating performance of passive house dwellings from 1990 to 2018. *Energy Efficiency*. https://doi.org/10.1007/s12053-020-09855-7
Joskow, P. L. (2000). *Deregulation and Regulatory Reform in the U.S. Electric Power*

Sector. *Center of Energy and Environmental Policy Research*.

Joskow, P. L., & others. (2008). Lessons learned from electricity market liberalization. *The Energy Journal*, *29*(2), 9–42. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol29-NoSI2-3

Ju-Sung Lee, Tatiana Filatova, Arika Ligmann-Zielinska, Behrooz Hassani-Mahmooei, Forrest Stonedahl, Iris Lorscheid, Alexey Voinov, J. Gary Polhill, Z. S. and D. C. P. (2015). The Complexities of Agent-Based Modeling Output Analysis. *Journal of Artificial Societies and Social Simulation*, *18*((4) 4). Retrieved from http://jasss.soc.surrey.ac.uk/18/4/4.html

Kahneman, D. (2011). *Thinking, Fast and Slow* (Kindle). New York: Farrar, Straus and Giroux.

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica*, *47*(2), 263–291. https://doi.org/10.2307/1914185

Kharrati, S., Kazemi, M., & Ehsan, M. (2016). Equilibria in the competitive retail electricity market considering uncertainty and risk management. *Energy*, *106*, 315–328. https://doi.org/10.1016/j.energy.2016.03.069

Kimura, O. (2010). Japanese Top Runner Approach for energy efficiency standards. *SERC Discussion Paper*, 14.

Kirschen, D. S., & Strbac, G. (2004). *Fundamentals of Power System Economics* (Kindle). Manchester, UK: John Wiley & Sons Ltd.

Kirschen, D. S., & Strbac, G. (2019). *Fundamentals of Power System Economics* (2nd Editio). London: John Wiley & Sons Ltd.

Klitkou, A., Bolwig, S., Hansen, T., & Wessberg, N. (2015). The role of lock-in mechanisms in transition processes: The case of energy for road transport. *Environmental Innovation and Societal Transitions*, *16*, 22–37. https://doi.org/10.1016/j.eist.2015.07.005

Kraan, O., Kramer, G. J., & Nikolic, I. (2018). Investment in the future electricity system - An agent-based modelling approach. *Energy*, *151*, 569–580. https://doi.org/10.1016/j.energy.2018.03.092

Kraan, Oscar, Dalderop, S., Kramer, G. J., & Nikolic, I. (2019). Jumping to a better world: An agent-based exploration of criticality in low-carbon energy transitions. *Energy Research and Social Science*, *47*(August 2018), 156–165. https://doi.org/10.1016/j.erss.2018.08.024

Kraan, Oscar, Jan, G., Nikolic, I., Chappin, E., & Koning, V. (2019). Why fully liberalised electricity markets will fail to meet deep decarbonisation targets even with strong carbon pricing. *Energy Policy*, *131*(May), 99–110. https://doi.org/10.1016/j.enpol.2019.04.016

Krey, V., Masera, O., Blanforde, G., Bruckner, T., Cooke, R., Fish-Vanden, K., … Zwickel, T. (2014). *Annex II: Metrics & Methodology. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_annex-ii.pdf

Krikke, H. R., Pappis, C. P., Tsoulfas, G., & Bloemhof-ruwaard, J. (2001). *Design Principles for Closed Loop Supply Chains*.

Kusumaningdyah, W., McLellan, B., & Tezuka, T. (2019a). Designing and Evaluating Energy Product-Service Systems for Energy Sector (EPSS) in Liberalized Energy Market: A Case Study in Space Heating Services for Japan Household. *Challenges*, *10*(1), 18. https://doi.org/10.3390/challe10010018

Kusumaningdyah, W., McLellan, B., & Tezuka, T. (2019b). Designing and Evaluating Energy Product-Service Systems for Energy Sector (EPSS) in Liberalized Energy Market: A Case Study in Space Heating Services for Japan Household. *Challenges*, *10*(1), 18.

Kwakkel, J. H., & Yücel, G. (2014). An exploratory analysis of the dutch electricity system in transition. *Journal of the Knowledge Economy*, *5*(4), 670–685. https://doi.org/10.1007/s13132-012-0128-1

Lalic, B., Cosic, I., & Anisic, Z. (2005). Simulation based design and reconfiguration of production systems. *International Journal of Simulation Modelling*, *4*(4), 173–183. https://doi.org/10.2507/IJSIMM04(4)2.047

Lee, J. S., Filatova, T., Ligmann-Zielinska, A., Hassani-Mahmooei, B., Stonedahl, F., Lorscheid, I., … Parker, D. C. (2015). The complexities of agent-based modeling output analysis. *Journal of Artificial Societies and Social Simulation*, *18*(4), 1–27. https://doi.org/10.18564/jasss.2897

Lee, R. P., & Gloaguen, S. (2015). Energy Research & Social Science Path-dependence , lock-in , and student perceptions of nuclear energy in France : Implications from a pilot study. *Energy Research & Social Science*, *8*, 86–99. https://doi.org/10.1016/j.erss.2015.05.001

Leenheer, J., Elsen, M., Nella, M., van der Wagt, M., & Lloyd, L. (2014). *Study on the effects on consumer behaviour of online sustainability information displays*. https://doi.org/10.2759/52063

Leng, J., Ruan, G., Jiang, P., Xu, K., Liu, Q., Zhou, X., & Liu, C. (2020). Blockchainempowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey. *Renewable and Sustainable Energy Reviews*, *132*(July), 110112. https://doi.org/10.1016/j.rser.2020.110112

Li, H. X., Edwards, D. J., Hosseini, M. R., & Costin, G. P. (2020). A review on renewable energy transition in Australia: An updated depiction. *Journal of Cleaner Production*, *242*, 118475. https://doi.org/10.1016/j.jclepro.2019.118475

Liebowitz, S. J., & Margolis, S. E. (1995). Path dependence, lock-in, and history. *Journal of Law, Economics, and Organization*, *11*(1), 205–226. https://doi.org/10.2139/ssrn.1706450

Lindkvist, L., & Sundin, E. (2016). The role of Product-service Systems Regarding Information Feedback Transfer in the Product Life-cycle Including Remanufacturing. *Procedia CIRP*, *47*, 311–316. https://doi.org/10.1016/j.procir.2016.03.088

Long, Y., Yoshida, Y., Meng, J., Guan, D., Yao, L., & Zhang, H. (2019). Unequal age-based household emission and its monthly variation embodied in energy consumption – A cases study of Tokyo , Japan. *Applied Energy*, *247*(March), 350–362. https://doi.org/10.1016/j.apenergy.2019.04.019

Lu, Y., Khan, Z. A., Alvarez-Alvarado, M. S., Zhang, Y., Huang, Z., & Imran, M. (2020). A critical review of sustainable energy policies for the promotion of renewable energy sources. *Sustainability (Switzerland)*, *12*(12), 1–30. https://doi.org/10.3390/su12125078

Mahut, F., Daaboul, J., Bricogne, M., & Eynard, B. (2015). Survey on Product-Service System applications in the automotive industry. *15th IFAC/IEEE/IFIP/IFORS Symposium - Information Control Problems In Manufacturing*, *48*(3), 840–847. https://doi.org/http://dx.doi.org/10.1016/j.ifacol.2015.06.188

Mallory, A., Crapper, M., & Holm, R. H. (2019). Agent-Based Modelling for Simulation-Based Design of Sustainable Faecal Sludge Management Systems. *International Journal of Environmental Research and Public Health*, *16*(1125), 2–19. https://doi.org/10.3390/ijerph16071125

Manzini, E., & Vezzoli, C. (2003). A strategic design approach to develop sustainable product service systems: Examples taken from the "environmentally friendly innovation" Italian prize. *Journal of Cleaner Production*. https://doi.org/10.1016/S0959-6526(02)00153-1

Masad, D., & Kazil, J. (2015). Mesa: An Agent-Based Modeling Framework. *Proceedings of the 14th Python in Science Conference*, (April), 51–58. https://doi.org/10.25080/majora-7b98e3ed-009

Matthyssens, P., & Vandenbempt, K. (2008). Moving from basic offerings to value-added solutions: Strategies, barriers and alignment. *Industrial Marketing Management*, *37*(3), 316–328. https://doi.org/10.1016/j.indmarman.2007.07.008

Matulka, R. (2012). You Asked, We Are Answering: Your Home Efficiency Questions. Retrieved June 19, 2020, from https://www.energy.gov/articles/you-asked-we-are-answering-your-home-efficiency-questions

Mercure, J. F., Pollitt, H., Bassi, A. M., Viñuales, J. E., & Edwards, N. R. (2016). Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Global Environmental Change*, *37*, 102–115. https://doi.org/10.1016/j.gloenvcha.2016.02.003

Mills, B., & Schleich, J. (2013). Analysis of Existing Data: Determinants for the Adoption of Energy-Efficient Household Appliances in Germany. In B. Brohmann, T. Clamor, K. Rennings, B. Brohmann, J. Nentwich, J. Schleich, … R. Wüstenhagen (Eds.), *Sustainable Energy Consumption in Residential Buildings* (1st ed., pp. 39–67). Physica-Verlag Heidelberg. https://doi.org/10.1007/978-3

Mizobuchi, K., & Takeuchi, K. (2016). Replacement or additional purchase : The impact of energy-efficient appliances on household electricity saving under public pressures. *Energy Policy*, *93*, 137–148. https://doi.org/10.1016/j.enpol.2016.03.001

Mohammadi, Z., Hoes, P. J., & Hensen, J. L. M. (2020). Simulation-based design optimization of houses with low grid dependency. *Renewable Energy*, *157*, 1185–1202. https://doi.org/10.1016/j.renene.2020.04.157

Mont, O. (n.d.). Product Service System Concept as a Means of Reaching Sustainable Consumption? In *Proceedings of the 7th European Roundtable on …* (pp. 1–21). Lund, Sweden. Retrieved from http://www.score-network.org/files/821_13.pdf

Mont, O. (2001). Introducing and developing a Product-Service System (PSS) concept in Sweden. *IIIEE Reports*, (January), 1–150. Retrieved from http://www.researchgate.net/publication/228863029_Introducing_and_developing_a_Product-Service_System_(PSS)_concept_in_Sweden/file/72e7e515b4851098f8.pdf

Mont, O. K. (2002). Clarifying the concept of product-service system. *Journal of Cleaner Production*, *10*(3), 237–245. https://doi.org/10.1016/S0959-6526(01)00039-7

Morelli, N. (2006). Developing new product service systems (PSS): methodologies and operational tools. *Journal of Cleaner Production*, *14*(17), 1495–1501. https://doi.org/10.1016/j.jclepro.2006.01.023

Morey, M. J., & Kirsch, L. D. (2016). *Retail Choice in Electricity : What Have We Learned* *in 20 Years ?* https://doi.org/10.1016/j.enpol.2007.06.022

Mori, A. (2018). Socio-technical and political economy perspectives in the Chinese energy transition. *Energy Research and Social Science*, *35*(October 2017), 28–36. https://doi.org/10.1016/j.erss.2017.10.043

Mourtzis, D., Boli, N., Alexopoulos, K., & Różycki, D. (2018). A Framework of Energy Services: From Traditional Contracts to Product-Service System (PSS). *Procedia CIRP*, *69*(May), 746–751. https://doi.org/https://doi.org/10.1016/j.procir.2017.11.118

Muto, K., Kimita, K., & Shimomura, Y. (2015). A Guideline for Product-Service-Systems Design Process. *Procedia CIRP*, *30*, 60–65. https://doi.org/10.1016/j.procir.2015.02.188

Myers, E. (2019). Are home buyers inattentive? Evidence from capitalization of energy costs. *American Economic Journal: Microeconomics*, *11*(2), 165–188. https://doi.org/10.1257/pol.20170481

Negrão, C. O. R., & Hermes, C. J. L. (2011). Energy and cost savings in household refrigerating appliances: A simulation-based design approach. *Applied Energy*, *88*(9), 3051–3060. https://doi.org/10.1016/j.apenergy.2011.03.013

Newell, R. G. R. ., Siikamäki, J., Siikamaki, J., Siikamäki, J., & Siikamaki, J. (2013). Nudging Energy Efficiency Behavior. *RFF Discussion Paper*, (July), 44. https://doi.org/10.3386/w19224

Nicole Buccitelli, Elliott, C., Schober, S., & Yamada, M. (2015). *2015 U .S. Lighting Market Characterization*. Retrieved from energy.gov/eere/ssl/solid-state-lighting

OECD. (2017). Using behavioural insights to increase energy conservation and energy efficiency. In *Tackling Environmental Problems with the Help of Behavioural Insight* (pp. 45–89). Paris: OECD Publishing.

Oh, J., Min, C., Cho, S., Bae, D., & Kim, H. (2016). Concept of an advanced simulation-based design for engineering support of offshore plant equipment industries and its realization method. *Ocean Engineering*, *121*, 369–381. https://doi.org/10.1016/j.oceaneng.2016.05.028

Otsuka, A. (2018). Regional determinants of energy efficiency: Residential energy demand in Japan. *Energies*, *11*(6), 1–14. https://doi.org/10.3390/en11061557

Ozawa, A., Furusato, R., & Yoshida, Y. (2016). Determining the relationship between a household's lifestyle and its electricity consumption in Japan by analyzing measured electric load profiles. *Energy and Buildings*, *119*, 200–210. https://doi.org/10.1016/j.enbuild.2016.03.047

PETEC'S, P. E. T. C. (n.d.). Japanese Home Appliance Recycling Law | Panasonic Eco

Technology Center (PETEC) | Panasonic Global. *Panosonic Corporation*. Retrieved from https://panasonic.net/eco/petec/recycle/

Petitet, M. (2016). Effects of risk aversion on investment decisions in electricity generation: What consequences for market design? *International Conference on the European Energy Market, EEM*, *2016-July*, 1–5. https://doi.org/10.1109/EEM.2016.7521346

Pombeiro, H., Pina, A., & Silva, C. (n.d.). Analyzing Residential Electricity Consumption Patterns Based on Consumer's Segmentation.

Poruschi, L., Ambrey, C. L., & Smart, J. C. R. (2018). Revisiting feed-in tariffs in Australia: A review. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2017.09.027

Rapson, D. (2014). Durable goods and long-run electricity demand: Evidence from air conditioner purchase behavior. *Journal of Environmental Economics and Management*, *68*(1), 141–160. https://doi.org/10.1016/j.jeem.2014.04.003

Rashid, A., Asif, F. M. a., Krajnik, P., & Nicolescu, C. M. (2013). Resource Conservative Manufacturing: an essential change in business and technology paradigm for sustainable manufacturing. *Journal of Cleaner Production*, *57*, 166–177. https://doi.org/10.1016/j.jclepro.2013.06.012

Raworth, K. (2017). *Doughnut economics : seven ways to think like a 21st century economist*. Vermont: Chelsea Green Publishing.

Reuter, M. A., van Schaik, A., & Gediga, J. (2015). Simulation-based design for resource efficiency of metal production and recycling systems: Cases - copper production and recycling, e-waste (LED lamps) and nickel pig iron. *International Journal of Life Cycle Assessment*, *20*(5), 671–693. https://doi.org/10.1007/s11367-015-0860-4

Rolls Royce. (2014). *Rolls-Royce Holdings plc Annual Report 2014*. Retrieved from http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/investors/annual-reports/2014-annual-report-v2.pdf

Roy, R. (2000). Sustainable product-service systems. *Futures*, *32*(3–4), 289–299. https://doi.org/10.1016/S0016-3287(99)00098-1

Safarzy, K., & Bergh, J. C. J. M. Van Den. (2018). A higher rebound effect under bounded rationality : Interactions between car mobility and electricity generation. *Energy Economics*, *74*, 179–196. https://doi.org/10.1016/j.eneco.2018.06.006

Saidur, R., Sattar, M., Izudin, A., & Masjuki, H. (2006). Developing a comprehensive energy guide label for household appliances through consumers research survey. *Journal of Energy & Environment*, *5*(May), 77–93.

Sakao, T., Panshef, V., & Dörsam, E. (2009). Addressing Uncertainty of PSS for Value-Chain Oriented Service Development. In *Introduction to Product/Service-System Design* (pp. 137–157).

Salazar, C., Lelah, A., & Brissaud, D. (2015). Eco-designing product service systems by degrading functions while maintaining user satisfaction. *Journal of Cleaner Production*, *87*(C), 452–462. https://doi.org/10.1016/j.jclepro.2014.10.031

Sallee, J. M. (2013). Nber Working Paper Series Rational Inattention and Energy Efficiency. Retrieved from http://www.nber.org/papers/w19545

Sallee, J. M., West, S. E., & Fan, W. (2016). Do consumers recognize the value of fuel economy? Evidence from used car prices and gasoline price fluctuations. *Journal of Public Economics*, *135*, 61–73. https://doi.org/10.1016/j.jpubeco.2016.01.003

Sandvik, E., Lønnum, O. J. J., & Asbjørnslett, B. E. (2019). Stochastic bivariate time series models of waves in the North Sea and their application in simulation-based design. *Applied Ocean Research*, *82*(June 2018), 283–295. https://doi.org/10.1016/j.apor.2018.11.010

Saputra, A., & Isnaeni, H. (2018). Building Rejuvenation Approach Through Revitalization, Rehabilitation and Redevelopment - Case of Vertical Housing in Jakarta. *E3S Web of Conferences*, *67*. https://doi.org/10.1051/e3sconf/20186704036

Sawin, J. L., Bhattacharya, S. C., Galan, E. M., McCrone, A., Moomaw, W. R., Sims, R., … Sverrisson, F. (2012). Renewables 2012 Global Status Report. REN21 Secretariat, Paris. *Ren21*, 1–172. Retrieved from http://www.ren21.net/REN21Activities/GlobalStatusReport.aspx

Scherer, J. O., Kloeckner, A. P., Ribeiro, J. L. D., Pezzotta, G., & Pirola, F. (2016). Product-Service System (PSS) design: Using Design Thinking and Business Analytics to improve PSS Design. *Procedia CIRP*, *47*, 341–346. https://doi.org/10.1016/j.procir.2016.03.062

Schuh, G., Gudergan, G., Feige, B. a., Buschmeyer, a., & Krechting, D. (2015). Business Transformation in the Manufacturing Industry - How Information Acquisition, Analysis, usage and Distribution Affects the Success of Lifecycle-Product-Service-Systems. *Procedia CIRP*, *30*, 335–340. https://doi.org/10.1016/j.procir.2015.02.133

Sephard, M. S., Beall, M. W., O’Bara, R. M., & Webster, B. E. (2004). Toward simulation-based design. *Finite Elements in Analysis and Design*, *40*, 1575–1598. https://doi.org/10.1016/j

Session, S. (2012). *Impact of Top-Runner Program in Japan and its Perspective*.

Shi, Z., Fonseca, J. A., & Schlueter, A. (2017). A review of simulation-based urban form generation and optimization for energy-driven urban design. *Building and Environment*, *121*, 119–129. https://doi.org/10.1016/j.buildenv.2017.05.006

Shimada, T., & Van Wassenhove, L. N. (2019). Closed-Loop supply chain activities in Japanese home appliance/personal computer manufacturers: A case study. *International Journal of Production Economics*, *212*(April 2013), 259–265. https://doi.org/10.1016/j.ijpe.2016.11.010

Shiraki, H., Nakamura, S., Ashina, S., & Honjo, K. (2016). Estimating the hourly electricity profile of Japanese households – Coupling of engineering and statistical methods. *Energy*, *114*, 478–491. https://doi.org/10.1016/j.energy.2016.08.019

Simon, H. A. (1955). A Behavioral Model of Rational Choice Author. *The Quarterly Journal of Economics*, *69*(1), 99–118. Retrieved from http://www.jstor.org/stable/1884852

Simon, H. A. (1956). Rational Choice and the Structure of the Environment. *Psychological Review*, *63*(2), 129–138. https://doi.org/10.1037/xge0000013

Simon, H. A. (1997). *Models of Bounded Rationality* (vol. 3). Cambridge, MA: MIT Press.

Sovacool, B. K. (2017). Contestation, contingency, and justice in the Nordic low-carbon energy transition. *Energy Policy*, *102*(December 2016), 569–582. https://doi.org/10.1016/j.enpol.2016.12.045

Stang, D. J. (1976). Group size effects on conformity. *Journal of Social Psychology*, *98*(2), 175–181. https://doi.org/10.1080/00224545.1976.9923388

Sundin, E. (2009). Life-Cycle Perspectives of Product/Service-Systems: In Design Theory. In M. Sakao, T and Lindahl (Ed.), *Introduction to Product/Service-System Design* (1st ed., pp. 31–70). New York: Springer. https://doi.org/10.1007/978-1-84882-909-1

Suzuki, Y., Yahyaei, M., Jin, Y., Koyama, H., & Kang, G. (2012). Simulation based process design: Modeling and applications. *Advanced Engineering Informatics*, *26*(4), 763–781. https://doi.org/10.1016/j.aei.2012.06.002

Tasaki, T., Terazono, A., & Moriguchi, Y. (2005). Effective assessment of Japanese recycling law for electrical home appliances four years after the full enforcement of the law. *IEEE International Symposium on Electronics and the Environment*, (June), 243–248. https://doi.org/10.1109/ISEE.2005.1437035

Toyoda, M. (2016). *Impact, Electricity Market Reform and its impact on energy market in Japan*.

Trencher, G., Rinscheid, A., Duygan, M., Truong, N., & Asuka, J. (2020). Revisiting carbon lock-in in energy systems: Explaining the perpetuation of coal power in Japan. *Energy*

Research and Social Science, *69*(August), 101770. https://doi.org/10.1016/j.erss.2020.101770

Tukker, A. (2004). Eight Types of Product –. *Bus. Strat. Env*, *260*(13), 246–260. https://doi.org/10.1002/bse.414

Tukker, A., & Tischner, U. (2006). *New Business for Old Europe: product-service development, competitiveness and sustainability* (1st ed.). Sheffield: Greenleaf Publishing Ltd.

Ulph, A., & Ulph, D. (2018). Environmental policy when consumers value conformity. *Journal of Environmental Economics and Management*, 1–23. https://doi.org/10.1016/j.jeem.2018.09.001

UN Global Compact. (2013). *The UN Global Compact-Accenture CEO Study on Sustainability - Architects of a Better World*. *UN Global Compact Reports* (Vol. 5). https://doi.org/10.5848/UNGC.5720.2014.0015

UNEP. (2002). The Role Of Product Service Systems in a Sustainable Society. Retrieved from h

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, *28*, 817–830. https://doi.org/10.1016/S0301-4215(01)00098-2

Unruh, G. C. (2002). Escaping carbon lock-in. *Energy Policy*, *30*(4), 317–325. https://doi.org/10.1016/S0301-4215(01)00098-2

Vadén, T., Majava, A., Toivanen, T., Järvensivu, P., Hakala, E., & Eronen, J. T. (2019). To continue to burn something? Technological, economic and political path dependencies in district heating in Helsinki, Finland. *Energy Research and Social Science*, *58*(March), 101270. https://doi.org/10.1016/j.erss.2019.101270

Van Ostaeyen, J., Van Horenbeek, A., Pintelon, L., & Duflou, J. R. (2013). A refined typology of product–service systems based on functional hierarchy modeling. *Journal of Cleaner Production*, *51*, 261–276. https://doi.org/10.1016/j.jclepro.2013.01.036

Vanvari, V., & Mhaske, S. (2018). Redevelopment of buildings in Mumbai city: Risks and challenges. *International Journal of Engineering and Technology(UAE)*, *7*(3), 91–94. https://doi.org/10.14419/ijet.v7i3.29.18468

Vasantha, A., & Vijaykumar, G. (2011). a Framework for Designing Product- Service Systems. *Quality*, (August).

Vasantha, G. V. A., Komoto, H., Hussain, R., Rajkumar, R., Tomiyama, T., Evans, S., … Williams, S. (2013). A manufacturing framework for capability-based product-service systems design. *Journal of Remanufacturing*, *3*(8), 1–32. https://doi.org/10.1186/2210-

4690-3-8

Vercalsteren, A., & Geerken, T. (2006). Need Area 5: households. In A. Tukker & U. Tischner (Eds.), *New Business for Old Europe: product-service system development, competitiveness and sustainability* (pp. 303–336). Sheffield.

Vergne, J. P., & Durand, R. (2010). The missing link between the theory and empirics of path dependence: Conceptual clarification, testability issue, and methodological implications. *Journal of Management Studies*, *47*(4), 736–759. https://doi.org/10.1111/j.1467-6486.2010.00913.x

Vernengo, G., Gaggero, T., & Rizzuto, E. (2016). Simulation based design of a fleet of ships under power and capacity variations. *Applied Ocean Research*, *61*, 1–15. https://doi.org/10.1016/j.apor.2016.09.003

Vezzoli, C., Ceschin, F., Diehl, J. C., & Kohtala, C. (2015). New design challenges to widely implement 'Sustainable Product–Service Systems.' *Journal of Cleaner Production*, *97*, 1–12. https://doi.org/10.1016/j.jclepro.2015.02.061

Vine, E. (2005). An international survey of the energy service company ESCO industry. *Energy Policy*, *33*(5), 691–704. https://doi.org/10.1016/j.enpol.2003.09.014

Vision 2050: The new agenda for business. (2010). *World Business Council for Sustainable Development*. https://doi.org/10.1111/j.1530-9290.2009.00117.x

Von Der Fehr, N. H. M., & Hansen, P. V. (2008). Electricity retailing in Norway. https://doi.org/10.5547/issn0195-6574-ej-vol31-no1-2

Waechter, S., Sütterlin, B., & Siegrist, M. (2015). Desired and undesired effects of energy labels - An eye-tracking study. *PLoS ONE*, *10*(7), 1–26. https://doi.org/10.1371/journal.pone.0134132

Waltrich, M., Hermes, C. J. L., & Melo, C. (2011). Simulation-based design and optimization of refrigeration cassettes. *Applied Energy*, *88*(12), 4756–4765. https://doi.org/10.1016/j.apenergy.2011.06.020

Wang, F., Yang, W. J., & Sun, W. F. (2020). Heat transfer and energy consumption of passive house in a severely cold area: Simulation analyses. *Energies*, *13*(3). https://doi.org/10.3390/en13030626

Watari, T., McLellan, B. C., Giurco, D., Dominish, E., Yamasue, E., & Nansai, K. (2019). Total material requirement for the global energy transition to 2050: A focus on transport and electricity. *Resources, Conservation and Recycling*, *148*(May), 91–103. https://doi.org/10.1016/j.resconrec.2019.05.015

Wieringa, J. E., & Verhoef, P. C. (2007). Understanding Customer Switching Behavior in a

Liberalizing Service Market. *Journal of Service Research*, *10*(2), 174–186. https://doi.org/10.1177/1094670507306686

Williams, A. (2006). Product-service systems in the automotive industry: The case of micro-factory retailing. *Journal of Cleaner Production*, *14*(2), 172–184. https://doi.org/10.1016/j.jclepro.2004.09.003

Wilson, C., & Dowlatabadi, H. (2007). Models of Decision Making and Residential Energy Use. *Annual Review of Environment and Resources*, *32*(1), 169–203. https://doi.org/10.1146/annurev.energy.32.053006.141137

Yamamoto, Y., Suzuki, A., Fuwa, Y., & Sato, T. (2008). Decision-making in electrical appliance use in the home. *Energy Policy*, *36*(5), 1679–1686. https://doi.org/10.1016/j.enpol.2008.01.022

Yang, Y. (2014). Understanding household switching behavior in the retail electricity market. *Energy Policy*, *69*, 406–414. https://doi.org/10.1016/j.enpol.2014.03.009

Young, D. (2008). When do energy-efficient appliances generate energy savings? Some evidence from Canada. *Energy Policy*, *36*(1), 34–46. https://doi.org/10.1016/j.enpol.2007.09.011

Yücel, G., & van Daalen, C. (2012). A simulation-based analysis of transition pathways for the Dutch electricity system. *Energy Policy*, *42*, 557–568. https://doi.org/10.1016/j.enpol.2011.12.024

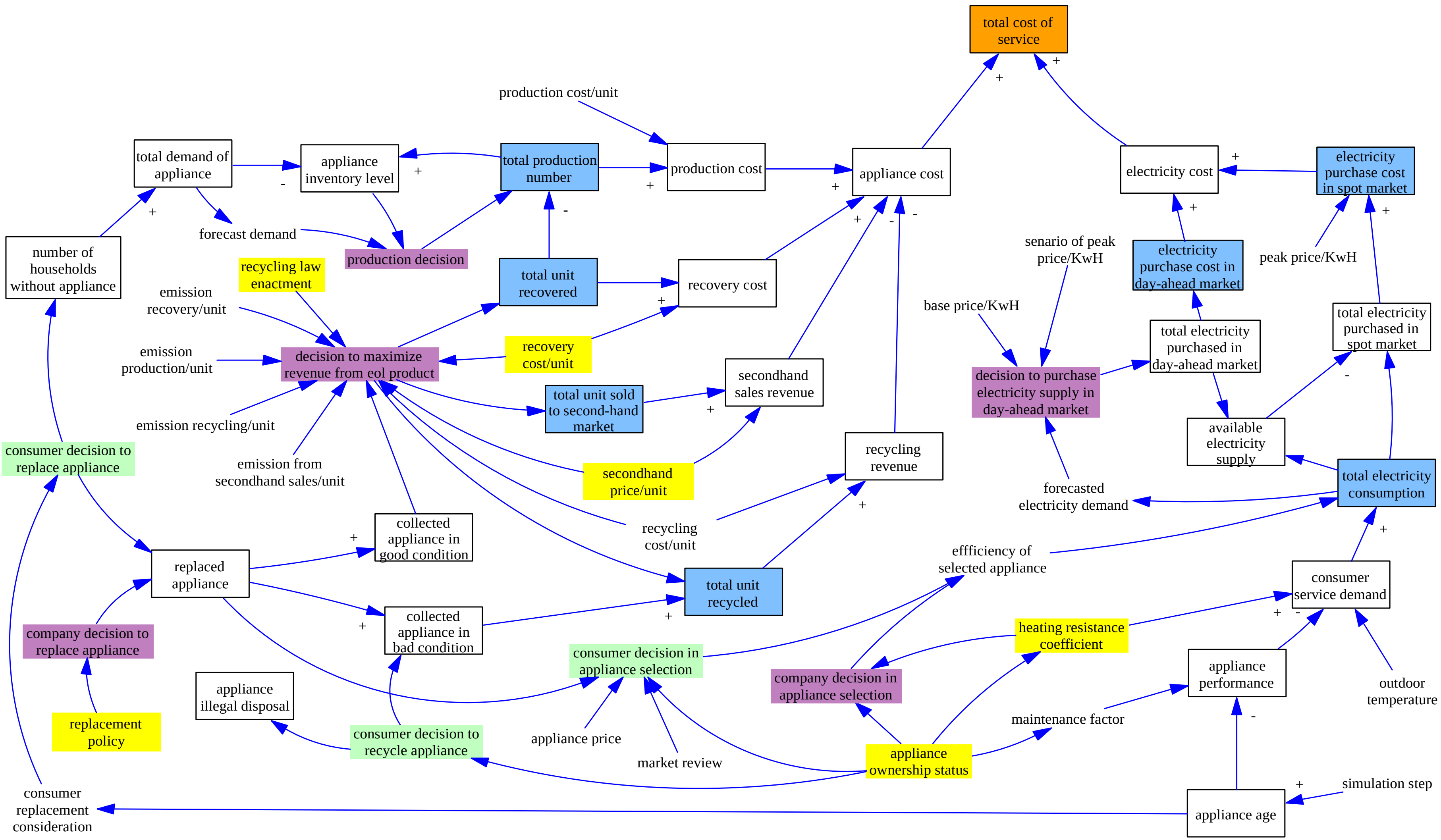
Zeng, Y., Zhang, J., & He, K. (2019). Effects of conformity tendencies on households' willingness to adopt energy utilization of crop straw: Evidence from biogas in rural China. *Renewable Energy*, *138*, 573–584. https://doi.org/10.1016/j.renene.2019.02.003

Zhang, Y., Bai, X., Mills, F. P., & Pezzey, J. C. V. (2018). Rethinking the role of occupant behavior in building energy performance: A review. *Energy and Buildings*. Elsevier B.V. https://doi.org/10.1016/j.enbuild.2018.05.017

Zheng, M., Fang, R., & Yu, Z. (2016). Life Cycle Assessment of Residential Heating Systems: A Comparison of Distributed and Centralized Systems. *Energy Procedia*, *104*, 287–292. https://doi.org/10.1016/j.egypro.2016.12.049

Appendix I. Model causalities, parameter, and variables

Appendix I- A. System causality that determines total cost of service delivery



Remarks

Orange box	:	Represents the objective function
Blue box	:	Represents the main decision variable in the systems that contributes to emission and total cost
Purple box	:	Represents decisional process by companies
Green box	:	Represents decisional process by consumers
Yellow box	:	Represents independent variables, which value is incrementally changed. Serve as treatment for the simulation.
Box with line	:	Represents dependent variable, which value changes depend on other variables or parameters
Box without line	:	Represents auxiliary parameters/variables

Appendix I-B. Simulation Parameters Value

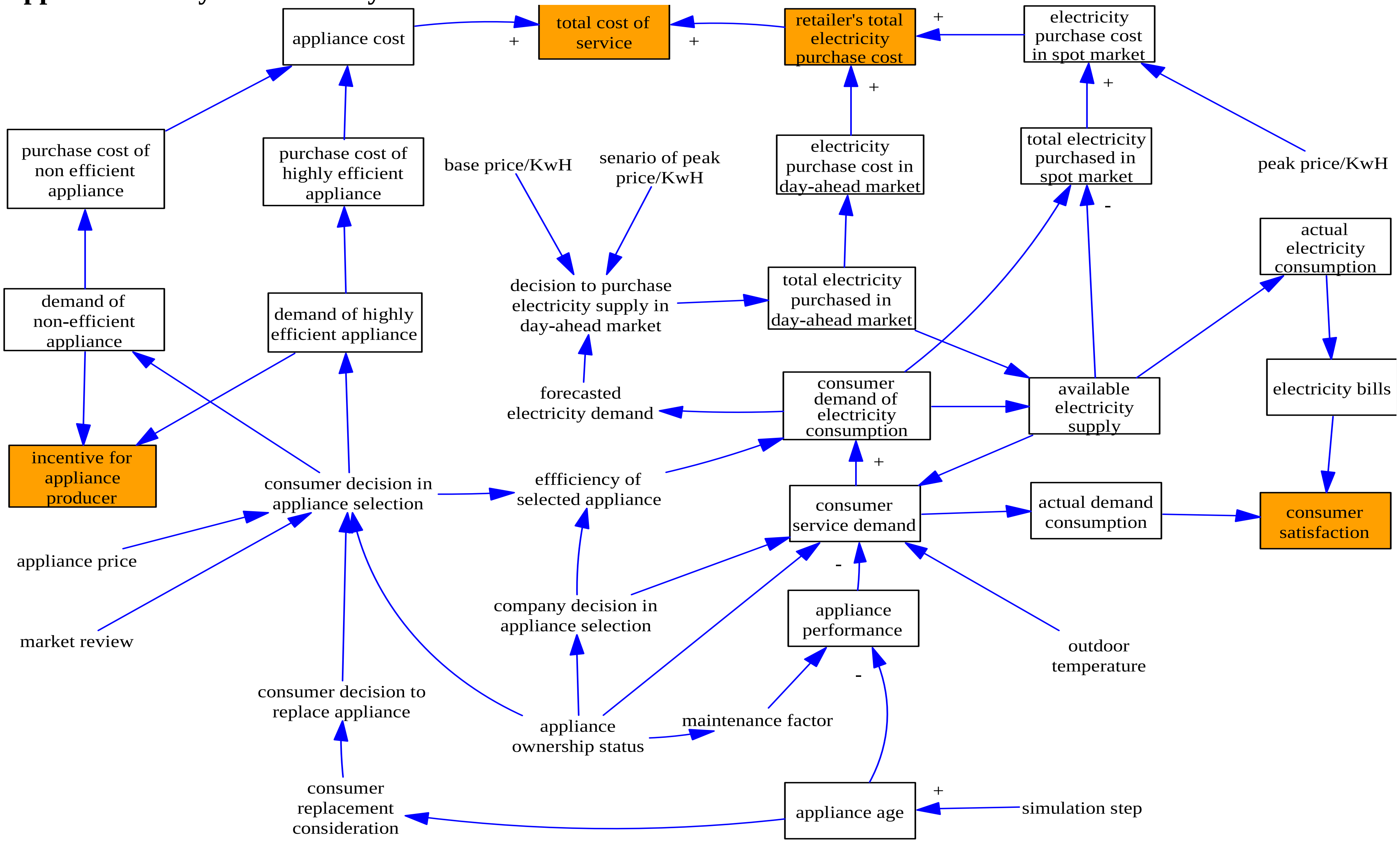
Parameter	Value	Unit	Remarks
Outdoor Temperature			
minimum temperature	2	º Celsius	
maximum temperature	12	º Celsius	
Temperature at time	random.integer (minimum temperature, maximum temperature)		
Consumer Attributes			
preference	{cost-oriented, market review}		
characteristic	{risk averse, risk adverse}		
building attributes			
floor area	1750	$feet^2$	
Height ceiling	3	m	
Wall area	perimeter * height ceiling		
product/service demand			
willingness to pay	random.integer (minimum appliance price, maximum appliance price)	JPY/unit	
minimum appliance price	230.000	JPY/unit	
maximum appliance price	500.000	JPY/unit	
comfort temperature demand	random integer (minimum temperature, maximum temperature)	º Celsius	
minimum temperature	20	º Celsius	
maximum temperature	30	º Celsius	
Electricity Retailer			
Electricity base price	30	JPY/KWh	
Electricity peak price	60	JPY/KWh	
electricity emission	170	kg-CO2	Source: (Krey et al., 2014)
EPSS			
service contract	7	years	
acceptable efficiency for operation	> = 85% from initial efficiency		

Parameter	Value	Unit	Remarks
Appliance Producer			
Air Conditioner Data			
Highly efficient production cost	300.000	JPY/unit	
Low efficient production cost	200.000	JPY/unit	
Highly efficient product price	random (400000, 500000)	JPY/unit	
low efficient product price	random (250000, 350000)	JPY/unit	
High EER product	random uniform (10, 12)		
Low EER product	random uniform (7, 9)		
appliance ID	{A1, A2, A3, B1, B2, B3}		
Appliance Emission			
production emission	106,9	kg-CO2	
Recovery emission	41,73	kg-CO2	Source: (Zheng, Fang, & Yu, 2016)
Recycling emission	106,9	kg-CO2	Source: (Zheng et al., 2016)
Second-hand emission	106,9	kg-CO2	
End-of-Life Product			
Appliance weight	0,046	tons/unit	
Recycling rate	0,90		
Scrap price	0,105	JPY/tons	Source: (“Current Scrap Metal Prices,” n.d.)

Appendix I-C. Variables for EPSS design for EPSS market

	EPSS service level	Recycling Law	Appliance Replacement Policy	Reprocessing Rate Composition
	{type1, type2, type3}	{with, without}	{app_efficiency, scheduled replacement}	{benefit from recovery : benefit from secondhand } = {(1 : 1), (1 : 2), (2 : 1)}
1	type1	TRUE	efficiency	-
2	type1	TRUE	contract	-
3	type1	FALSE	efficiency	(1:1)
4	type1	FALSE	efficiency	(2:3)
5	type1	FALSE	efficiency	(2:1)
6	type1	FALSE	contract	(1:1)
7	type1	FALSE	contract	(2:3)
8	type1	FALSE	contract	(2:1)
9	type2	TRUE	efficiency	-
10	type2	TRUE	contract	-
11	type2	FALSE	efficiency	(1:1)
12	type2	FALSE	efficiency	(2:3)
13	type2	FALSE	efficiency	(2:1)
14	type2	FALSE	contract	(1:1)
15	type2	FALSE	contract	(2:3)
16	type2	FALSE	contract	(2:1)
17	type3	TRUE	efficiency	-
18	type3	TRUE	contract	-
19	type3	FALSE	efficiency	(1:1)
20	type3	FALSE	efficiency	(2:3)
21	type3	FALSE	efficiency	(2:1)
22	type3	FALSE	contract	(1:1)
23	type3	FALSE	contract	(2:3)
24	type3	FALSE	contract	(2:1)

Appendix I-D. System causality that influence win-win solution



Remarks

Orange box	:	Represents the criteria of win-win situation
Box with line	:	Represents dependent variable, which value changes depend on other variables or parameters
Box without line	:	Represents auxiliary parameters/variables

Appendix II. Model Sensitivity Analysis

Appendix II- A. Variables effect on system behaviour and performance

Simulation-Based Design incorporating Agent-Based Simulation is developed using Mesa for Agent-Based Model Framework, to observe the effect of agents' attributes to the system performance. The agent-based model is built consisting of a two-dimensional grid to locate consumer agents, market agents and agent schedulers. The grid size is as much as the market size. Each grid cell contains a consumer agent with overlapping grid locations for consumer agents prohibited. These consumer agents are located randomly in the space, regardless of their attributes (e.g. characteristics, bias, and preference). The simulation is scheduled to be evaluated for 35 steps, in which each step represents one year. For each step, the agent behaves and makes decisions based on their type, attributes and the market environment.

1. Market size effect on system performance

The system performance is measured based on total cost of service delivery and total emissions. Both indicators are calculated according to cost and emissions incurred from service delivery borne by the company. In particular, every cost and revenue stream associated with appliances are borne by appliance producers, whilst costs associated with electricity is attributable to the electricity retailer.

This section evaluates the effect of market size toward the system performance. Given the parameters used to construct the performance indicator, market size does not have a direct effect on the system performance. However, the amount of consumers in the observed market is expected to influence the performance because it depends on the consumers` decision to choose between EPOS and EPSS. Considering that EPSS performs better economically and environmentally, the higher EPSS uptake, the better the system performance. Given the market condition (see Table II-1), which is expected to influence the consumer's choice, Figure II-1 exhibits an example result of total cost and emission generation dynamics throughout the evaluation time (i.e. every year for 35 years).

Table II-1. Parameters of the system

EPSS type	**Type 2**
Profit ratio of obsolete product reprocessing and secondhand sales	1:1
Recycling Law	w/ Recycling Law
% of alternative seeker	40%
Trusted source of inert consumers	Offline

The figure reveals that the cost for individual consumers is slightly higher when appliance replacement policy is based on the service contract. The peak occurs from new appliance production cost, to satisfy new appliance demand. Note that EPSS demand for appliances can be satisfied not only using the new appliances but also used appliances, as long as the efficiency is within the stipulated threshold (i.e. minimum 85% of initial performance). The forecast method only considers historical demand, without incorporating reprocessing appliance planning. As a consequence, the accuracy of appliance demand is extremely low, leading to excessive production numbers and high production costs. On the other hand, replacement based on efficiency usually leads to obsolete appliances being recycled. Therefore, the demand for new appliances is mostly satisfied using new appliances. Assuming that market size and household demand is constant during the evaluation period, such conditions result in stable, and predictable new appliance demand. The figure also shows that the peak of cost increases with the market size, depicting the increased cost caused by error forecast following the appliance demand.

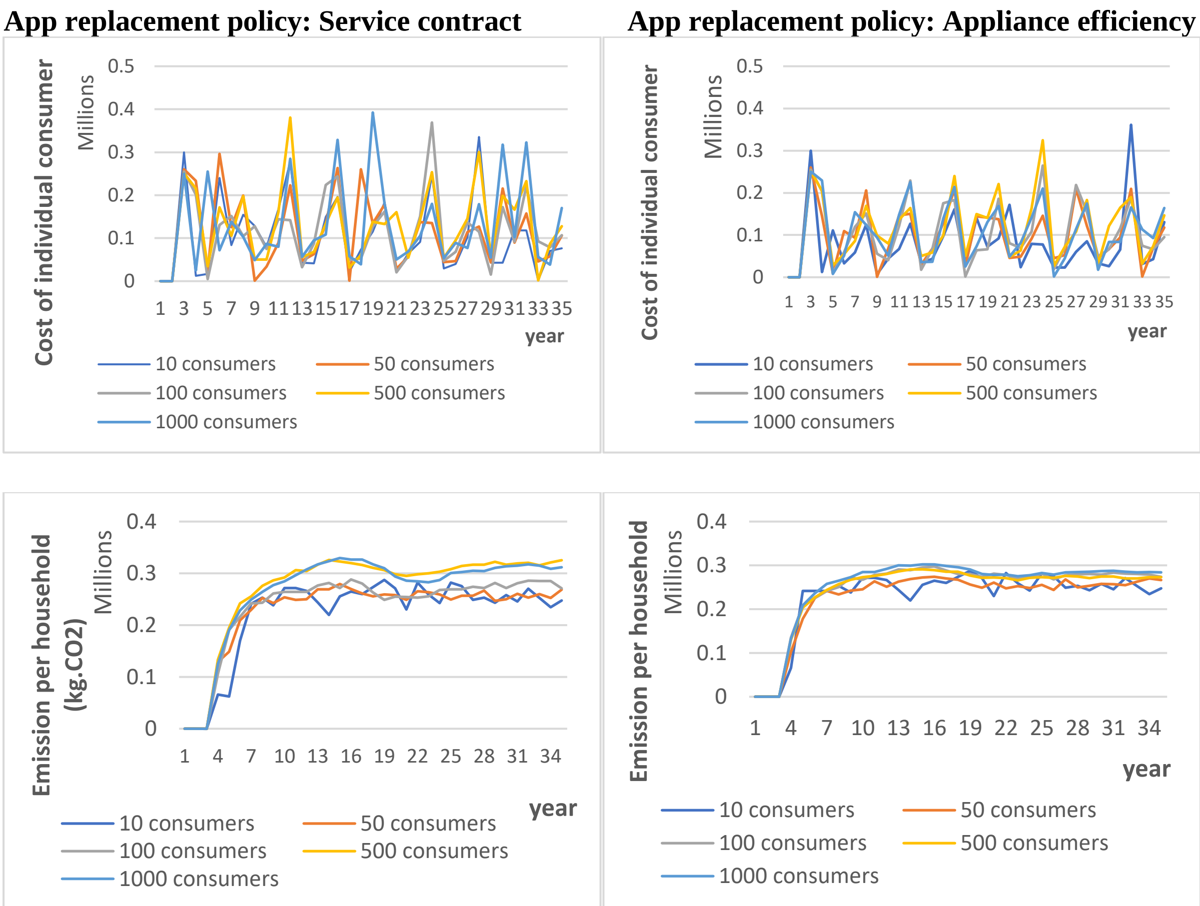


Figure II-1. Example of consumer's number effect on the dynamics of system performance

Regarding emissions, there is no significant difference between appliance replacement policies from the sample. By isolating consumption patterns, the result shows that consumer choice of system (between EPOS and EPSS) and consumer choice of appliance in EPOS are not different given different appliance replacement policies.

2. Variable effect on EPSS market share and penetration time

The effect of combinations of variables toward EPSS market share and penetration time are observed in this section. The effect of combinations of appliance replacement policy and another factor were observed by isolating the market conditions derived from the combinations as shown in Table II-2.

Table II-2. System parameters for the observed market

EPSS type	**Type 2**
Profit ratio of obsolete product reprocessing and secondhand sales	1:1
Recycling Law	w/ Recycling Law
% of alternative seeker	40%

Appliance replacement policy AND **trusted source of inert consumer** effect on **EPSS market share** and **time for market penetration**

This section observes the effect of combined appliance policy replacement and trusted source for inert consumers. Figure III-2 reveals EPSS market share progress every year given different appliance replacement policies when inert consumers' choices are influenced by the offline community.

Replacement policy: scheduled replacement　　Replacement policy: appliance efficiency

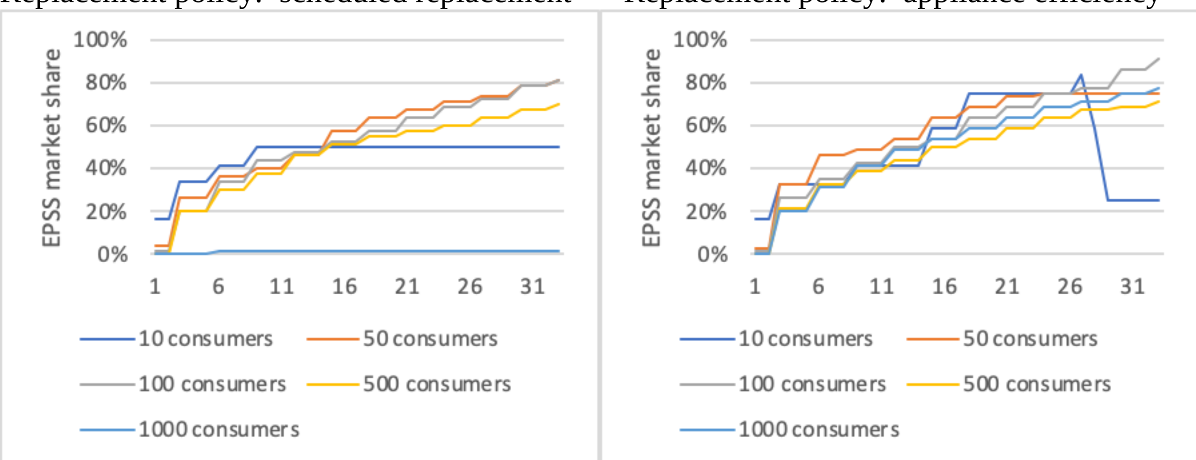


Figure III-2. Example of combined effect of consumer number, appliance replacement policy and trusted source for inert consumers toward EPSS market share

From the two figures above, it is observed that in general, EPSS market progresses similarly in each year for every market size, where EPSS market share incrementally increases when inert consumers use offline recommendations to make their choice, except for a market with 10 consumers and 1000 consumers. A market with 10 consumers shows different progress, where appliances are replaced based on the service contract the trend is flattened in the very early stage, whilst if appliances are replaced based on efficiency the sample result shows a collapse in market share. The flattened curve of market share (on the left hand figure) happens because of the small size of market share, thus it is faster to reach equilibrium state. In the case of 1000 consumers, EPSS immediately reaches equilibrium with 1% market share even lower than the share of alternative seeker consumers. This sample shows that a bigger market size may face a failure for EPSS to penetrate the market under given conditions.

Meanwhile, the right hand figure shows the market share incrementally increases before collapse after it reaches 80%. The market share increases because inert consumers are influenced by the positive review from EPSS alternative seeker consumers that EPSS costs lower than EPOS. However, when EPSS market share dominates, it was found that the expenditure of the remaining EPOS consumers are lower. As a result, alternative seeker consumers switch back to EPSS followed by other inert consumers. The possibility of EPOS costs being lower than EPSS may occur depending on the service demand intensity. When EPOS service demand level is significantly lower than EPSS consumers, even highly efficient appliances in-use would not result in lower electricity consumption and cost. This information is unknown by other consumers, and for this reason alternative seeker consumers switch back to EPSS at the end of service contract, or in this case, when an appliance is replaced due to inefficiency.

Figure II-3 shows EPSS market share changes every year given different appliance replacement policies when inert consumers' choice are influenced by the offline community.

Replacement policy: scheduled replacement   Replacement policy: appliance efficiency

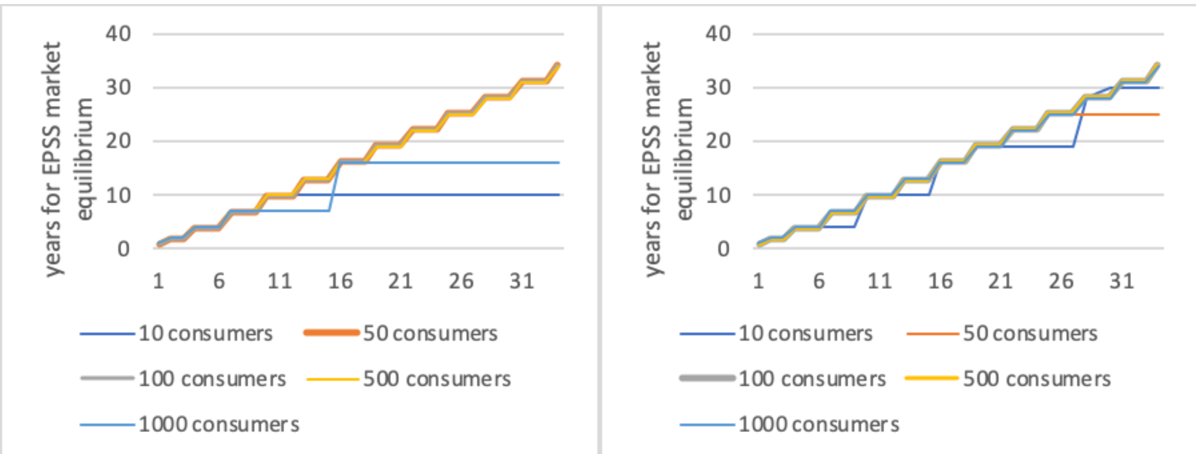


Figure II-3. Example of combined effect of consumers' number, appliance replacement policy and trusted source of inert source toward EPSS penetration time

The above figures illustrate the progression of EPSS each year as the result of different market sizes and policies of appliance replacement used in EPSS. From the right hand figure, it can be observed that for EPSS with Market size 50, 100 and 500 the EPSS market share changes every year, except for Market size 10 and 1000 that show a plateau. This is aligned with the previous figures, where EPSS market share with 10 and 1000 consumers reach equilibrium faster than other market sizes. This result also associates with the social influencing factors of inert consumers, in which the offline community influences the smaller group size and online community influences the bigger group size. Studies show that group size exhibits different effects on conformity (Bond, 2005; Gong & Yu, 2019; Stang, 1976).

Figure II-4 exhibits EPSS market share progress every year given different influencing factors of inert consumers when the appliance replacement policy is based on service contract (scheduled replacement)

Trusted source: offline community Trusted source: online community

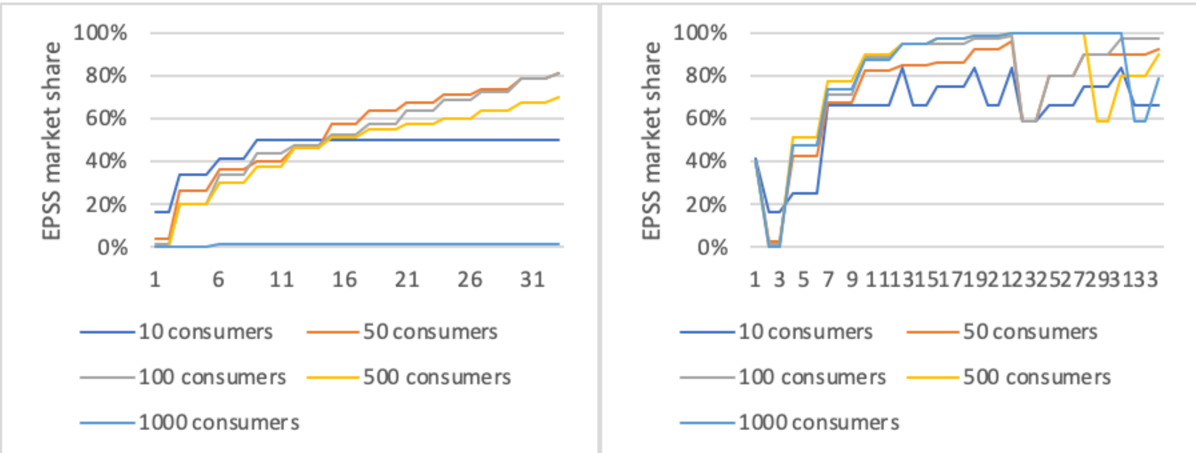


Figure II-4. Example of EPSS market share changes in every year given different inert consumers influencing factors.

Different to previous results, when inert consumers rely on online reviews to make decisions, EPSS market share progress fluctuates, which is different to consumers that rely on their offline closest network in making decisions. The difference between online and offline review lies on the group size of the influencer. For a market where their decision is based on the online review, there's higher variation because the influence comes from a wider market. The online review influences a consumer agent despite the location, which indicates the influence from all consumers in the observed market. The influence may come from online communities discussing their experience about the product/service performance, or influencers reviewing a product/service for sole purpose of advertising. The influencing factors from offline community, on the other hand, only comes from those whose location is the closest (i.e. agent located on the immediate grid) with the agent in question. In real life we can observe this condition where values of people with close proximity tend to heterogenous and usually the ones with different values will get influenced and soon follow the majority. A community that have strong sense of social conformity usually has stable value or perception about things.

Electricity Price Rates effect on EPSS market share

The effect of various electricity price rates toward EPSS market share is shown in Figure II-5. The effect is evaluated for EPSS type 1 in which EPSS consumption pattern similar to EPOS.

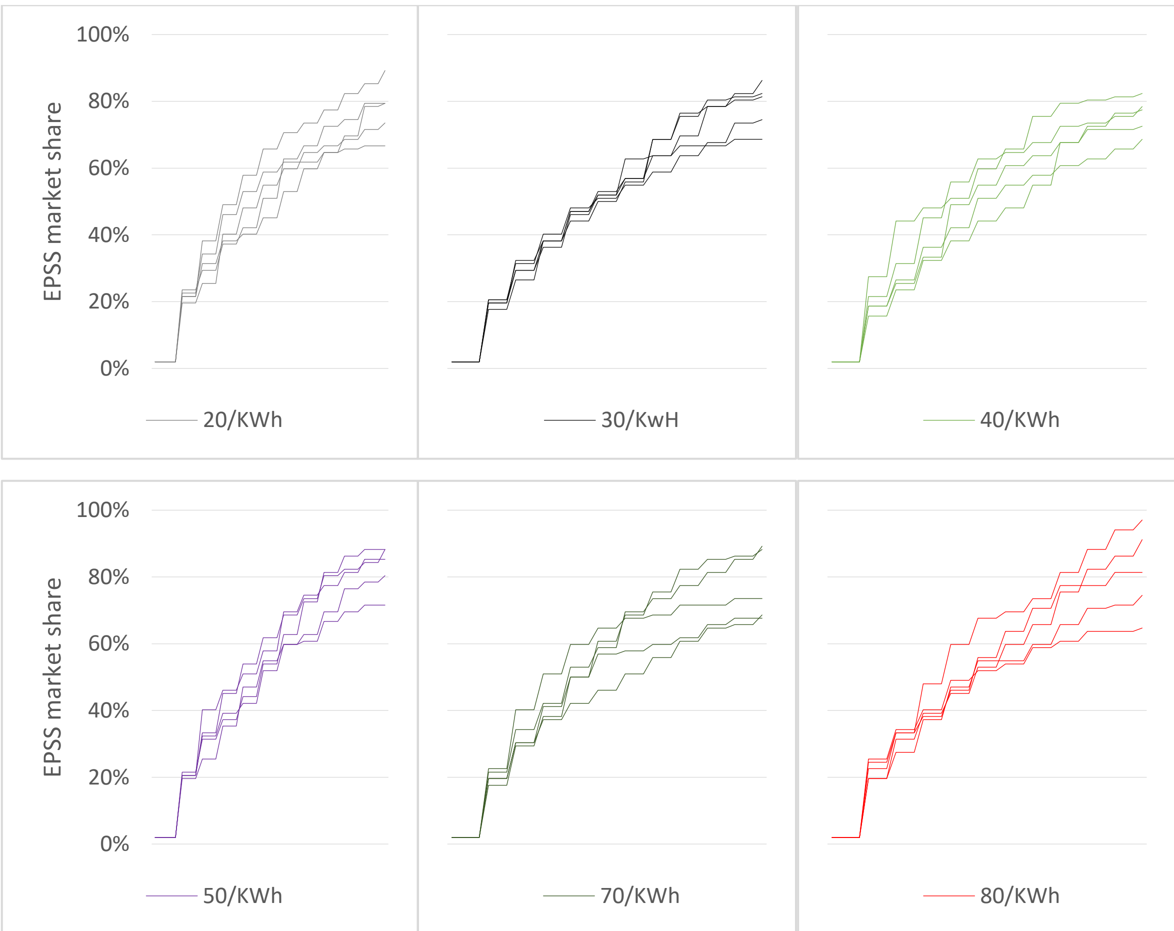


Figure II-5. The effect of electricity price rate toward EPSS market share

Electricity rate per kWh does not affect consumer choice between EPOS and EPSS, which is reflected by EPSS market share not showing a definite pattern given different rates. This is because most of the consumers in the simulation are set to be biased (inert consumers), and therefore their decision making process is not based on price or efficiency. It is also apparent that the alternative seeker consumers who are expected to influence inert consumer's decisional process, need more support to strengthen their influence.

Comparison of electricity rate effect on total cost of service delivery for different EPSS types

As expected, increased electricity price rate per kWh is followed by increased total cost of service delivery. Nonetheless, the cost range resulting from EPSS type 1 is wider than EPSS type 2.

EPSS type 1 **EPSS type 2**

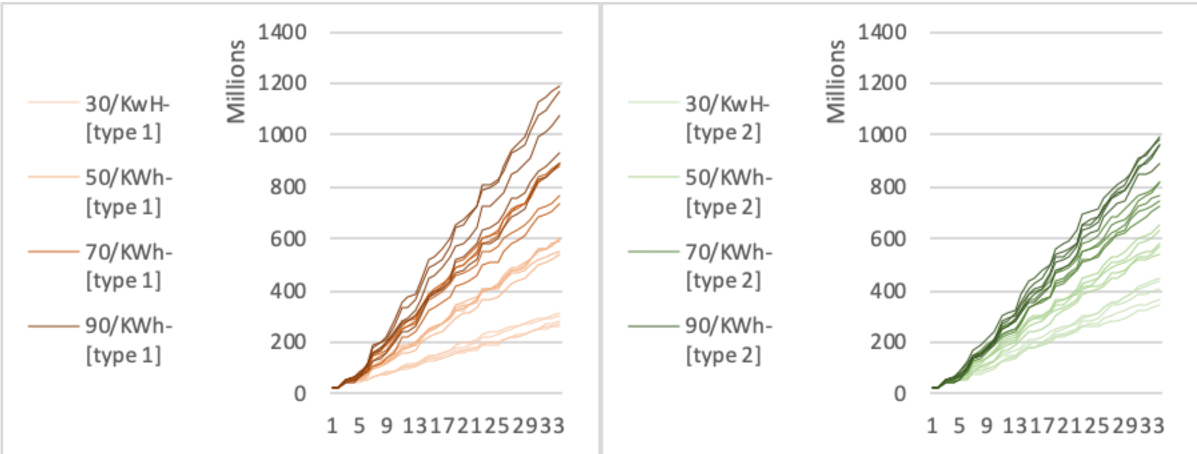


Figure II-6. Example of consumer's

From Figure II-6, it is observed that EPSS type 1 (where consumer chooses their own appliance) results in lower total cost compare to EPSS type 2 (where highly efficient, expensive appliance is selected) when electricity rate is low, and results in higher costs when electricity rate is high. EPSS results in higher cost of service delivery if the upfront cost is more expensive compare to the operational cost, which may occur when the electricity price rate is cheap. On the other hand, EPSS total cost of service delivery is lower than in EPOS when electricity price rate is expensive, because EPSS uses highly efficient appliances that can minimize the total cost of service throughout the service lifetime.

Number of appliances per household per operation effect on total cost of service delivery, based on EPSS type 2

The effect of number of appliances in-used per household toward total cost of service delivery is also evaluated under EPSS type 2, where the service provider chooses highly efficient appliances to deliver the service in an attempt to minimize operational costs. The result is presented in Figure II-7.

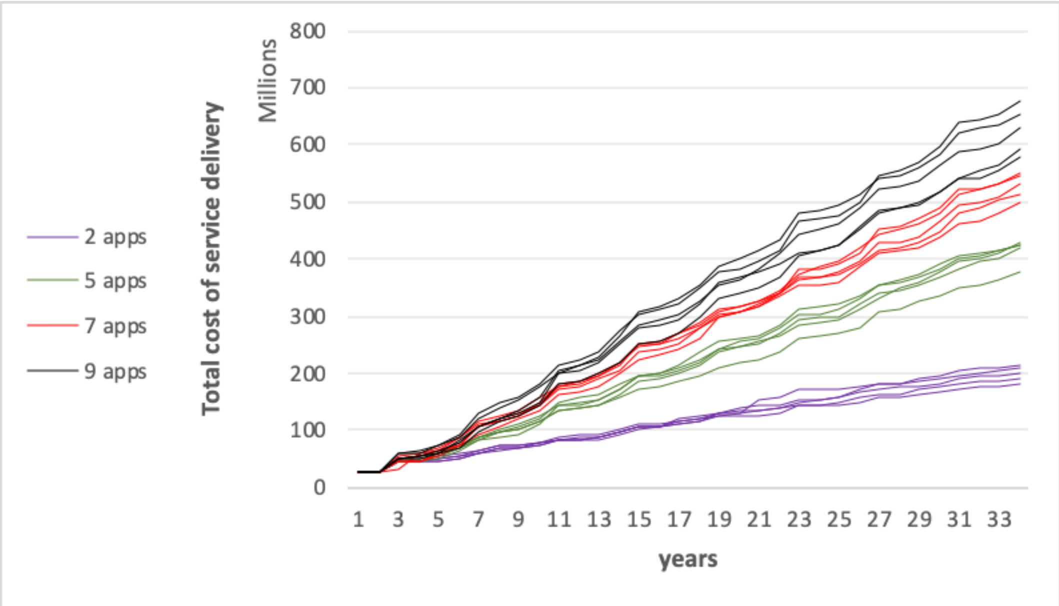


Figure II-7. The effect of number of appliances per household on total cost of service delivery

Figure II-7 reveals that the total cost of service delivery in EPSS increases following the number of appliances in-use per household. In general, this correlation is predictable and the changes of this parameter do not affect the behaviour of the system.

Appendix II-B. Estimated simulation run time for different Market sizes

For further experiment, time to run the simulation using various numbers of consumer agents are also recorded. Simulation run time is required to justify the optimum number of consumers considering required iterations and time limitations.

Scenario - 1	
EPSS type	type 1
Appliance replacement policy	App efficiency
Profit ratio of obsolete product reprocessing and secondhand sales	1 : 1
Recycling Law	w/ recycling law
Scenario - 2	
% of alternative seeker consumer	4%
Trusted sourced of inert consumer	Offline

N consumers	***required simulation time/run***		***total evaluated combination of variables***	***total iteration (@40)***	***estimated required simulation time***	
	minutes	***second***			***hours***	***days***
10	0	8	48	1920	4,26	0,17
50	0	32			17,1	0,71
100	1	8			36,3	1,5
500	5	12			166,4	6,93
1000	10	26			333,9	13,9

Scenario - 1	
EPSS type	type 1
Appliance replacement policy	Service contract
Profit ratio of obsolete product reprocessing and secondhand sales	1 : 1
Recycling Law	w/ recycling law
Scenario - 2	
% of alternative seeker consumer	4%
Trusted sourced of inert consumer	Offline

N consumers	***required simulation time/run***		***total evaluated combination of variables***	***total iteration (@40)***	***estimated required simulation time***	
	minutes	***second***			***hours***	***days***
10	0	9	48	1920	4,80	0,20
50	0	34			18,13	0,76
100	1	3			33,60	1,40
500	7	38			244,27	10,18
1000	13	21			427,20	17,80

Considering previously presented sensitivity analysis and simulation run time per iteration, the experiment will be conducted with a market size of 100 consumers.

Appendix II-C. Selected variables effect on the results of system performance for EPSS introduction without barriers to adoption

1. The influence **of APPLIANCE REPLACEMENT POLICY** toward **TOTAL COST OF SERVICE DELIVERY**

This section exhibits the influence of appliance replacement policy into total of service. Two types of policies are introduced, including scheduled replacement based on service contract, and replacement based on appliance efficiency. In addition, the analysis is conducted by changing EPSS type, and evaluated under market condition derived from parameters presented on Table II-3.

Table II-3. Market condition to evaluate combined effect of appliance replacement policy with other factors

Market size	**100**
Profit ratio of obsolete product reprocessing and secondhand sales	All
Recycling Law	All
% of alternative seeker	All

The combined effect of appliance replacement policy and different types of EPSS service toward total service cost are compared and analysed using box and whisker plot, in which the simulation is run for 40 iterations for each type of EPSS. The box and whisker plot exhibits the distribution of the result from each combination between appliance replacement and EPSS type through the data quartiles, as shown in Figure II-8. The plot shows the maximum (upper whisker), the minimum (the bottom whisker), and median cost value (the cross mark). Meanwhile, there are several dots observed in the figure, which represent the outlier data.

From Figure II-8 we can observe in general that appliance replacement policies based on efficiency tend to result in lower total service cost, except for EPSS type 3 where the cost between both policies are similar. The difference between EPSS type 3 and other EPSS types is that it includes managing operating system environment that trigger the service demand, while other types only consider appliance operation system to manage electricity demand. Note that this study estimates total cost based on upfront cost of appliance and operational cost from electricity consumption. For this reason, EPSS type 3 manages to squeeze the total cost compare to other EPSS types, by managing service demand, instead of managing electricity demand.

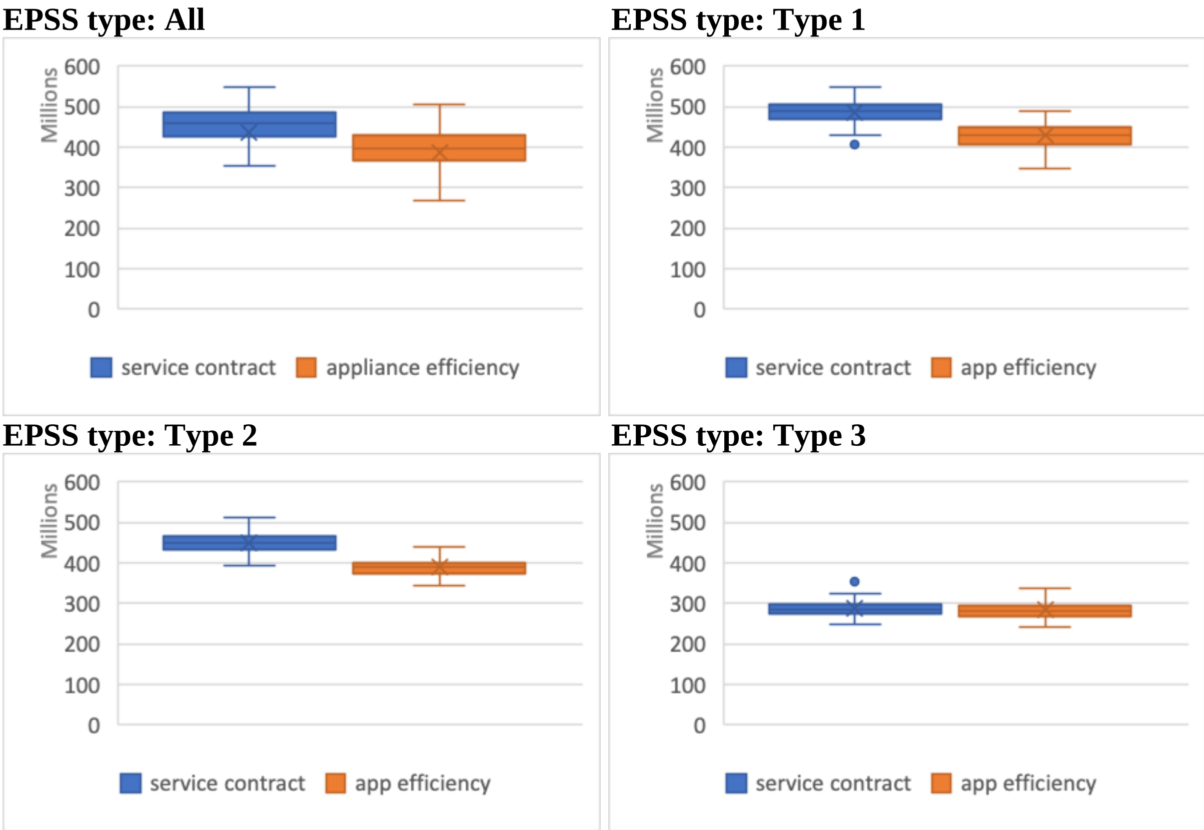


Figure II-8. The effect of combined variables between appliance replacement policy and EPSS service type toward total service cost

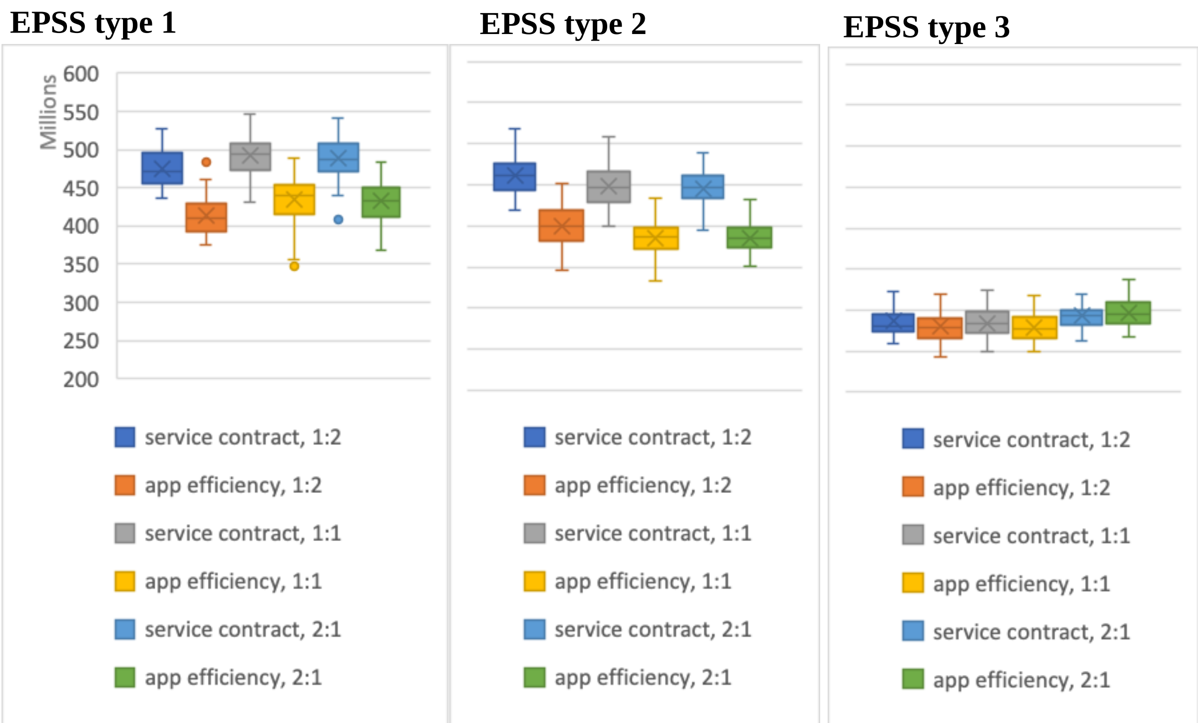


Figure II-9. The effect of combined variables between appliance replacement policy, EPSS type, and profit ratio from obsolete appliance toward total service cost

Further, the combined effect of appliance replacement policy together with EPSS type and profit ratio of obsolete product reprocessing and secondhand sales from obsolete products are also evaluated as shown on Figure II-9, given the market conditions derived from parameters on Table II-3. The figure shows similar results to previous analysis. Given various options of profit ratio from obsolete appliances, the results of efficiency-based appliance replacement tend to be lower than those of scheduled appliance replacement based on service contract.

The next step is to evaluate the combined effect of appliance replacement policy, EPSS type and recycling policy enactment, in which results are presented in Figure II-10. It can be observed that there is no significant difference regarding the effect of appliance replacement policy toward total service cost, even when it is combined with recycling law enactment.

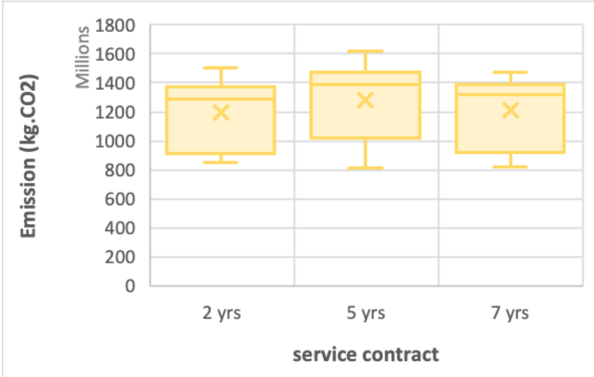
Figure II-10. The effect of combined variables between appliance replacement policy, EPSS type, and recycling law enactment toward total service cost

In addition, the effect of the length of service contract period toward system performance was also analyzed, with the results shown in Figure 6-4. Three periods of service contract are evaluated, including 2 years, 5 years and 7 years of service contract. A slight difference is observed on the distribution of total service cost and emissions among the service contract periods.

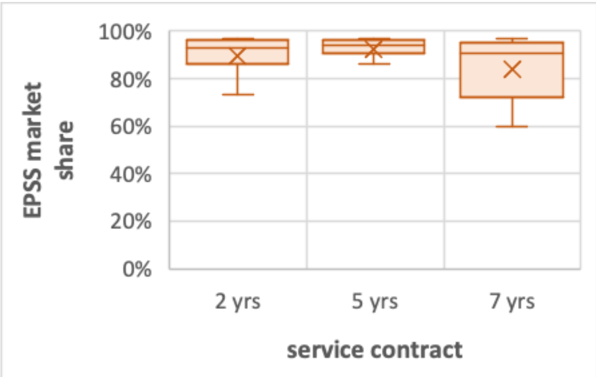
The highest cost incurs from a 5 year contract, followed by 2 years' service contract. The lowest cost is achieved by 7 years of service contract period. This evidence reveals that different service contract period effects the appliance cost (representing upfront cost) and electricity consumption cost (as operational cost) differently in EPSS total cost for different service contract periods (as shown on Figure II-11). Two years` contract cost is less in operation costs compared to 5 years and 7 years' contract, because the appliance is maintained at a high efficiency level, and reprocessed before it is used for another service contract. As a result, electricity consumption is lower for the same level of service demand. On the other hand, production cost of new appliance is higher for 2 years' contract compared to the longer contract period. Nonetheless, in this case, electricity cost has higher contribution than appliance cost, therefore, total cost of 2 years' contract tends to be lower compared to 5 years' contract. The effect is strengthened due to higher share of EPSS market share of 2 years' contract period (see Figure II-11).

Seven years' contract, on the other hand, costs lower than 5 years despite that electricity consumption and production number is similar. The result is influenced by EPSS market share, whereas EPSS market share in the market with 7 years contract period tends to lower than those with 2 years and 5 years. As the result, low efficient production is lower in the market with 7 years contract, which lead to lower production cost.

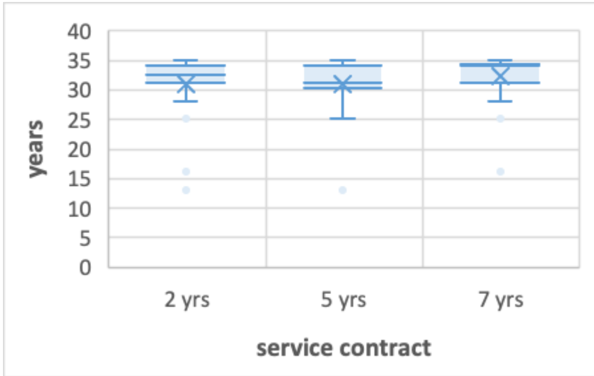
(b) Effect on total cost of service delivery



(a) Effect on emission



(d) Effect on EPSS market share



(c) Effect on EPSS market share

Figure II-11. The effect of combined variables between appliance replacement policy, EPSS type, and recycling law enactment toward total service cost

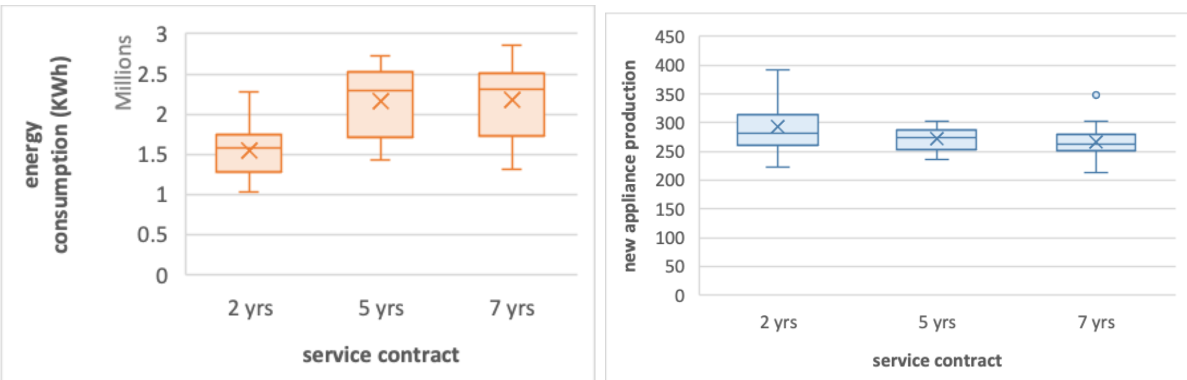


Figure II-12. Energy cost and new appliance production cost effect on total service cost caused by different service contract period

2. The influence of RECYCLING LAW ENACTMENT toward TOTAL OF SERVICE COST DELIVERY

This section analyse the influence of recycling law enactment toward total cost of service delivery combined with other variables. The first analysis of combined variables involves recycling law enactment and EPSS type, for which results are exhibited on Figure II-13

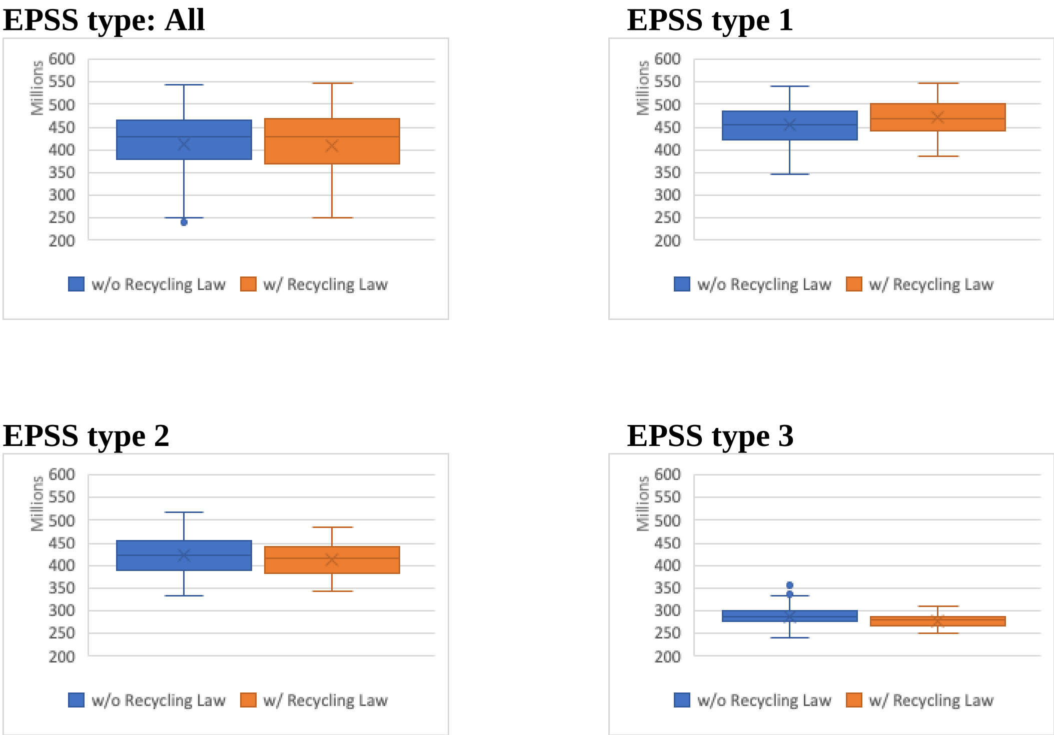


Figure II-13. The effect of combined variables between appliance replacement policy, EPSS type, and recycling law enactment toward total service cost

From the left-hand upper side figure, it can be observed that the cost to deliver service is not so different for all EPSS types whether recycling law is enacted or not. Nonetheless the results among different EPSS type show different patterns. Recycling law enactment leads to relatively higher costs compared to markets without recycling law, when EPSS type 1 is delivered. On the other hand, when a provider decides to deliver EPSS type 2 and EPSS type 3, there is a tendency that the total cost incurred under recycling law enactment becomes lower compared to the market without the recycling law.

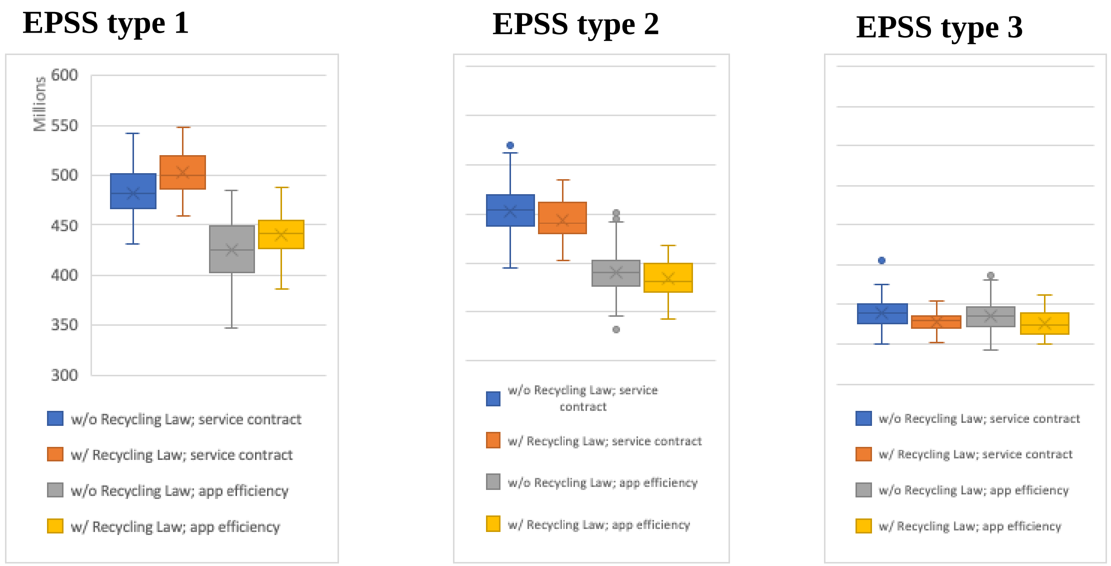


Figure II-14 . The effect of combined variables between appliance replacement policy, EPSS type, and recycling law enactment toward total service cost

In the case where recycling law enactment is combined with the variable of appliance replacement policy, the figure iterates the previous result, where for EPSS type 1, the cost tends to be lower without recycling law enactment, and at the same time the opposite applies to EPSS type 2 and type 3. These figures confirm the previous result, where scheduled replacement based on service contract causes the total cost to be higher compared to efficiency-based appliance replacement.

3. The influence of **EPSS and EPSS TYPE** toward **TOTAL OF SERVICE COST DELIVERY**

The data distribution representing the combined effect of EPSS type with other variables toward total cost of service delivery were also analysed. Figure II-15 exhibits the effect of different types of EPSS in comparison with EPOS. The figure shows that EPSS more likely to generate lower cost compare to EPOS. Based on visual analysis, it is also observed that there is a possibility of EPSS costs being higher than EPOS, especially from EPSS type 1. It possibly happens due to the characteristics of EPSS type 1, which allow consumers to choose and operate appliances similar to EPOS. Nonetheless, further analysis is required to confirm the conditions when EPSS cost performance is worse than EPOS. EPSS type 3, on the other hand, has consistently shown the best cost performance among other types, despite the conditions.

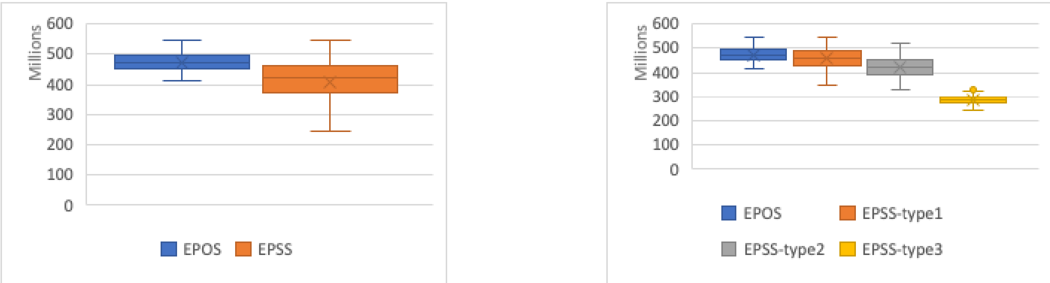


Figure II-15. The effect of EPSS type toward total service cost in comparison with EPOS

Furthermore, analysis was undertaken to investigate the effect of combining EPSS type with recycling law enactment, with appliance replacement policy and also with profit ratio of obsolete appliances. As shown in Figure II-16, the results show that there is no effect observed to the performance of each EPSS type toward total service cost when it is combined with given variables. Either the level of cost performance or data distribution is similar with conditions without combined variables. This result suggests that the influence of EPSS type is more important than the influence of other variables.

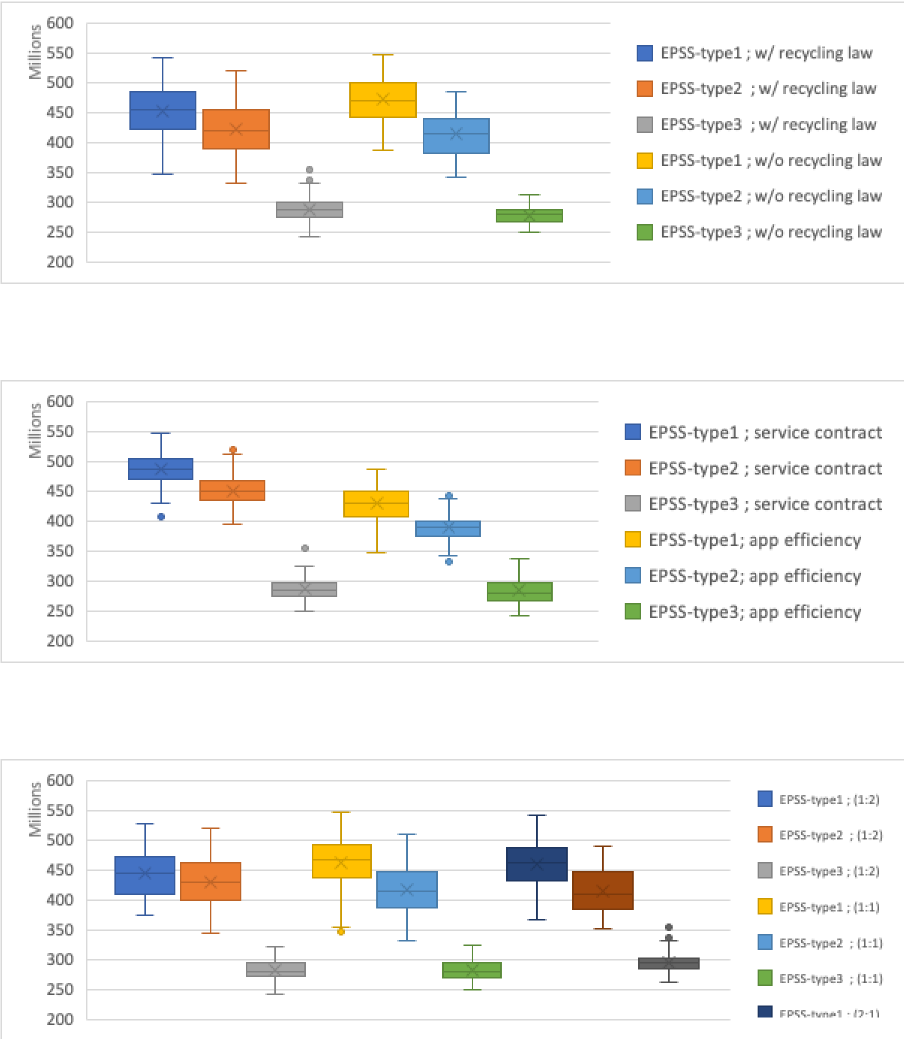


Figure II-16. The effect of combined variables between EPSS type with recycling law enactment, with appliance replacement policies and with profit composition of obsolete appliance, toward total service cost

Publication List

Original Journal Papers (Peer-reviewed)

1. Kusumaningdyah, W., McLellan, B., Tezuka, T. (2019). “Designing and Evaluating Energy Product-Service Systems for Energy Sector (EPSS) in Liberalized Energy Market: A Case Study in Space Heating Services for Japan Household”, Challenges (Switzerland), 10(1) 18. doi:10.3390/challe10010018

2. Kusumaningdyah, W., McLellan, B., Tezuka, T. (2021) “Investigating Preconditions for Sustainable Renewable Energy Product-Service Systems in Retail Electricity Markets”. Energies. *(Accepted)*

3. Kusumaningdyah, W., McLellan, B., Tezuka, T. “Proposing a method to design Energy Product-Service Systems under limited available knowledge: A case study for system design to reduce emissions and total cost of consumption without sacrificing consumer satisfaction”. Journal of Cleaner Production. *(Under Review*)

4. Kusumaningdyah, W., McLellan, B., Tezuka, T. “’Worst scenario’ method to identify key factors for information sharing mechanisms to achieve win-win solutions for all stakeholders in a liberalized electricity market”. Cleaner and Responsible Consumption. *(Under Review)*

Conference papers and presentations

1. Modeling Customers' Switching Behavior from Product-Oriented to Product-Service Systems in a Liberalized Energy Market, Kusumaningdyah, W., McLellan, B., Tezuka, T. Annual Meeting of Japan Society of Energy and Resource (JSER), January 26th, 2016, Tokyo, Japan,

2. Technology options towards a clean and sustainable road transport system in Japan by 2030 R. Iacobucci, W.Kusumaningdyah, N.Kaerkitcha, H.Lin, N.Luangchosiri, R.Motoori, K.Olaniyan, T.Sagawa, K.N.Ishihara. Poster presented at the 7th International Symposium of Advanced Energy Science, Kyoto, September 2016

3. A Framework to Manage Co-creation Process for PSS Considering the Network and Technology. Kusumaningdyah, W., Tezuka, T. Procedia CIRP, 9th CIRP IPSS Conference, Denmark, 19 – 21 June 2017 (doi: 10.1016/j.procir.2017.03.029.)

4. Simulation-Based Design method to design and predict the performance of environmental-oriented Energy-Product-Service Systems (EPSS). Kusumaningdyah, W., McLellan, B., Tezuka, T. 7th International Conference on Sustainable Future for Human Security. Indonesia, October 29-30, 2018