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Business Dynamics Evaluation of Battery Swapping in Electric Vehicle Systems

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SUMMARY OF MASTER'S DISSERTATION

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Title

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Abstract

Electric vehicles (EV) have been in the market for decades as agents of transition to sustainable transportation system. The commercialization of electric vehicle is slow due to its characteristics in terms of limited range, long charging time, and high initial cost compared to incumbent internal combustion engines vehicle but it has the advantages in operation cost, flexible energy sources, and grid integration. Based on the study of over 8 EV business models in Asia, US, and Europe, this paper identifies a system model and evaluates the dynamics of operational and financial interaction within electric vehicle systems using system dynamics methodology. Over time there is a need of battery swapping system to accommodate higher number of electric vehicles; and its business viability has to be evaluated to ensure its sustainability. This paper models the dynamics of passenger growth and business operation; then it simulates the financial performance of the business over the period of 100 business quarters in terms of cash flow, book value, and present value. The purpose of this research is to create a quantitative model to evaluate the viability of an EV business model with battery swapping system. A model is proposed for a battery swapping highway electric bus system in Malaysia. Battery stocks act as a buffer to accommodate the demand change to the system such as increase of vehicle stock and utilization rate. It reduces the need of charging infrastructure upgrade, as the batteries are pre-charged at a normal rate when the battery is in depot. The battery swapping system demonstrates the possible success scenario for EV business model by What-If analysis.

Key Words:

Business Dynamics Evaluation, Simulation Model, System Dynamics

Electric Vehicle, Battery Swap

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Secondly, I am grateful to learn about System Dynamics from my lecturer in my class at Keio University. Assoc. Prof Nobuaki Minato inspires me to learn more about this field and eventually System Dynamics becomes the main methodology for me to complete my research in terms of modeling and simulation. He also encouraged me to present my research paper the System Dynamics conference in the USA. I got to participate in many professional meetings and meet the legendary personnel in the field whose work I often refer to in my studies. This has been my main motivation booster and confidence to further deepen my skill in this field.

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Chapter 1: Introduction

The future of mobility is exciting as there are many new players in automotive industries seek to embrace electric mobility in different products and services to address the energy crisis and climate change. For the past decades, some business failed, some still survive and others learnt the lesson and emerged with another innovative model.

1.1 Research Background

1.1.1 History of Electric Vehicle

Figure 1: Electric Vehicle by Thomas Parker in late 1890s. (Source: Wikipedia Commons Free Media Rights)

Electric vehicles (EV) were actually the first developed in 1834 before Nikolaus Otto patented its practical four-stroke engine in 1876. Thomas Davenport made the first prototype of miniature EV runs in circle on a tabletop. Wilhelm J Sinsteden invented a rechargeable lead oxide battery in 1854. Edison's General Electric laid out the electric power distribution infrastructure in 1880s as the foundation for powering up electric vehicles. Hartford Electric Light Company applied battery swap concept for electric truck with General Vehicle Company (GeVeCo) service in 1910-1924. However, 20th century is the boom for internal combustion engines vehicle and become mainstream of automotive industry[1]. Oil spike in 1970s revives the interest of EV, GM EV1 was launched and recalled in 1990s and EV remerged again with new players in 2000s. The famous documentaries like “Who Killed the Electric Car?” and the sequel “Revenge of Electric Car” have recorded the modern age of the rise of EV lead by some of the incumbents such as Nissan-Renault and entrepreneurial firms like Tesla to be named a few. The EV innovation has struggled and achieved reasonable technological development in 1990s to 2010s. In order to overcome the barrier of EV adoption, it takes more than technology breakthrough i.e. business model innovation for its commercialization success.

1.2 Research Purpose and Target

1.2.1 Purpose of Research

The purpose of this research is to create a model to evaluate the dynamic behavior of a business system by applying systems approach. The evaluation model is then applied on the evaluation battery swapping of electric vehicle business model.

1.2.2 Application Target

1.2.2.1 The Advantages of Battery Swapping

Battery swapping in electric vehicle systems is the main application target. By simply swap the batteries; electric vehicles could immediately take off in full charge in the matter of minutes, same or even faster that the refueling of combustion cars. The battery swap allows battery of today’s technology to achieve fast charging without needing the next generation battery chemistry. By swapping the battery, the power grid system does not have to be reinvested to provide higher power. The spare batteries could be used for off loading at night or support storage of excess of renewable energy. The advancement of battery technology will also make this system become better. Key advantages of battery swap are listed as follows:

- Get full charge faster than combustion vehicles instead of charging them for hours.
- Does not require power grid to upgrade for high power charging.
- Depot batteries could be used as power buffer for off loading or storing excess renewable energy.
- Vehicle and battery ownership could be separated to reduce risk to end consumers.

1.2.2.2 Revival of Once a Failed Business System

However, battery swap technology is not popular yet to most of the electric car. The company (Better Place Inc.) that provides battery swap service to electric vehicle drivers filed for bankruptcy in 2013[2]. The vision of Better Place is plausible in prospective view; the idea gained millions of dollar for a start-up. Shai Agassi, the founder of Better Place were invited to top universities to give business talk and spread his vision of sustainable transport and energy by electric vehicle through batter swap technology to the public. [3].

After the fall of Better Place Inc., the world doubts the feasibility of electric vehicles even with battery swap. Tesla Motors has developed Battery Swap Technology for the Model S car but the service is not available yet as at this time when this thesis is written. The old ‘Better Place’ has pivoted to provide battery swap technology for buses in China[4]. Greenway in Slovakia applies battery swap technology to commercial delivery truck[5]. New company like Gogoro has chosen battery swap service for their smart scooters in Taipei in 2015[6]. As there is a rise of battery swap system, battery-swapping system required a re-evaluation at the system point of view.

1.3 Survey of Past Studies

1.3.1 Reference for Comparing Business Model

Existing business model is unable to accelerate the commercialization of EV due to its inherent consumer perceptions on 1) high initial cost, 2) limited range and 3) uncertainty on battery technology in which affects the used car value. Four business model innovations was proposed: 1) Free Floating All Electric City Car, 2) EV as Company Car, 3) Peer to Peer EV Subscription and 4) Leasing Chain for EV. All these models embrace maximum utilization rate of EV by car-sharing and transfer of ownership to partnering company to lower the risk of user[7]. The innovation aspect for auto-mobility is clearly favors to car-sharing solution to address the trend of increased population density and decreasing of the will vehicle ownership. However, this research does not provide a reference to compare each model. Only by having a reference for comparison, different model could be modeled and tested.

1.3.2 Static Model and Framework

An overview of business model was viewed in categories of a product-service system such as product oriented, use oriented and result oriented[8]. Based on this typology, the EV Business Model is developed into morphological box to view the systemic description for vehicle and batteries, infrastructure and system services[9]. The morphological box for EV business model serves as the reference in the operational model describing the relationship between vehicle, battery and infrastructure and financial describing the relationship of the ownership or access to the assets between customer, company and service partner. Cambridge Service Alliance research group highlights a few business models and provides an analysis framework to evaluate the business based on 2 criteria which are innovations made to address barrier to customer adoption and the ability to capture the value of electric mobility[10]. The morphological box analysis describes the categorization of EV system very and the framework analysis characteristics EV business model, but they are just the "snapshot" of business model. It is static and the behavior of the business model could not be visualized. In order to achieve that, the structure of the business system should be modeled.

1.3.3 Lacking of a Model for Evaluating Business Viability

A qualitative study argues that the lack of organizational innovation and less penetration of EV lies on the strong continuity forces in the automotive industry. This force of continuity e.g. established fueling network, manufacturing supply chain and the lower risk on technology perception is the constraint on the innovation for new technology like the electric vehicle system. Case studies on the business model Tesla Motor Company and Paris Autolib scheme. Government intervention was highlighted on the Tesla "Entrepreneurialism" case as it received USD 465 million loan from US Department of Energy and incentives were given for new electric vehicle purchase, where as in "Public-Private Partnership approach" Autolib case, the state government acts as the investor in this system by paying subsidize on the charging stations on parking spaces, Autolib pays for the parking spaces. Profits will be shared with the municipal when Autolib system is profitable and in the long run, this ecosystem nurtures the car-sharing solution to the society to embrace the circular economy[11]. However, there is a lack of quantitative model to describe the system behavior that makes it difficult to evaluate the viability of the Autolib case in public-private partnership.

1.3.4 Gaps to be filled for Research

From the study of past research, there is a gap to be filled and built upon on the foundation that has been done. A quantitative model in which describes the behavior of business system is required to aid the evaluation process by decision makers. This research aims to model and evaluate the battery swap system with a separate ownership of vehicle and battery as bears the most uncertainties but offers the most opportunities for innovation.

1.4 Research Originality

1.4.1 Technology evaluation in one context

Conventional studies view the viability of a technology on one-dimensional point of view for the simplicity of analysis. They describe the advantages and the disadvantages of some technology which out properly explain in which context. In this research, we are evaluating the viability of battery swap in different context and scenario through building a model to examine its dynamic behavior.

1.4.2 Research Strategy

The research direction is based on an innovation matrix to evaluate the "Architecture Innovation" of EV system in which implementing battery swapping technology on vehicle leasing business model, as opposed to incumbents which pursue vehicle ownership which incrementally improved technology and hoping for a radical next generation battery to make electric vehicle take off. Blue arrow in figure 2 shows the direction of innovation strategy of normal incumbents will pursue. Red arrow shows an alternative innovation strategy path that potentially provides more value to the customer and more opportunity for the company to capture the value.

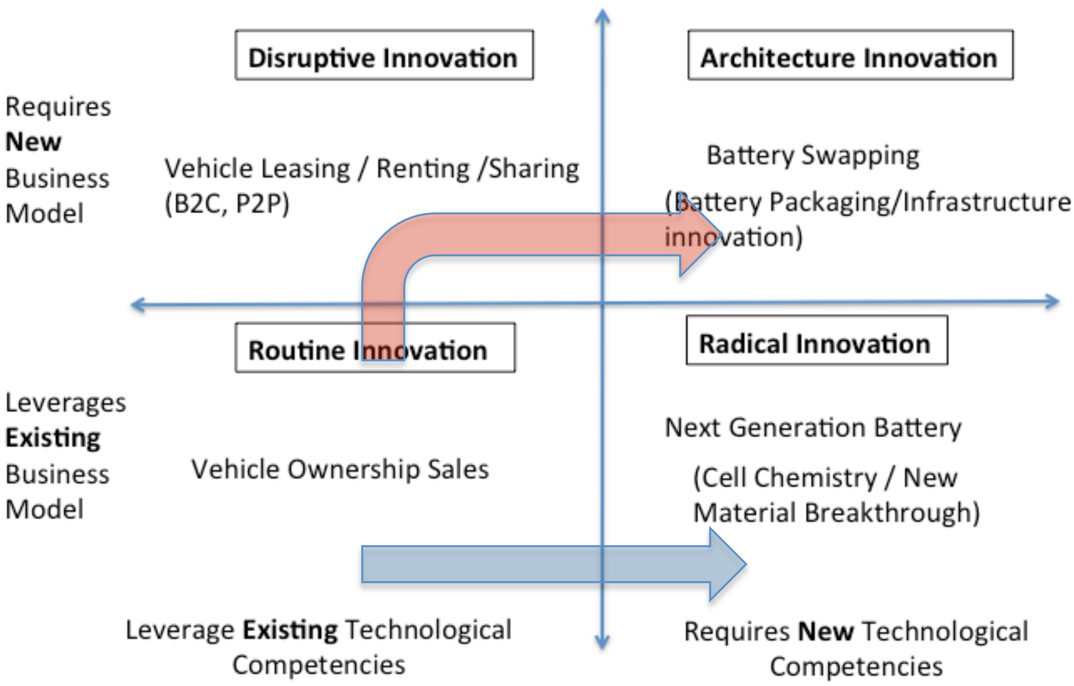

Figure 2: Directions of innovation strategies in electric mobility

1.4.3 Overcoming the obstacles in the research

EV system has only begun to take off since 2010 and only represent <1% of the global vehicle stock based on the report of Global EV Outlook 2015 by International Energy Agency and Electric Vehicle Initiative. **Lack of past data** is the first obstacle. To overcome this problem, this research does not attempt to model past behavior instead it aims to compare the system behavior in different context based on a set of assumptions. The numbers not to serve as a prediction but the behavior is the outcome of the model that we want to study.

Second obstacle would be **model nonlinear behavior** without involving too much mathematics. Human tends to scale things by multiplication. Often linear prediction tends to underestimate the opportunity as well as the problem. Systems approach is then being employed in this research due to thinking principle of "seeing the forest instead of seeing the trees", "the whole is more than the sum of parts" and "taking account of the delay and feedback to avoid unintended consequences. Applying the methodologies in systems approach is what makes this research unique compared to conventional studies.

Finally, systems methodology like any other method has its own Achilles' heel that is dealing with sudden disruption or low probability "black swan" event. For this reason, the model simulation is designed to be highly adjustable as the assumptions are modified. From early stage, the model is designed to **accommodate many uncertainties** then simulate with Monte Carlo sensitivity test, as we knew any optimization attempt would be futile due to lack of data and certainties. Instead the evaluation is done on the resilience of an EV business model; focus on less studied battery swapping in the context vehicle leasing/sharing model.

1.4.4 Breakthrough of this research

The research originality is determined by what the breakthrough has been done after overcoming the obstacles during the process of research studies. This research is organized by a set of system theory into a practical example of business system evaluation for electric vehicle. A model is developed for simulation to evaluate the viability of battery swapping in vehicle leasing business model. User could change the assumption based on the social environment and technological advancement. The breakthrough is **a model of evaluating the resilience of a business system through simulating the dynamics of operation and finance of a business system**. The model can also be generalized for simulating business model of a resourced based system to embrace the sharing economy.

1.5 Thesis Structure

This thesis is organized into 6 chapters as follows:

Chapter 1 is the introduction of the research in which serve as the essence describing what this research is all about. This chapter covers brief background of EV and its research field. The purpose of research describes the "Why" and "What" to study. The research strategy is described on how to position this research to add value in the knowledge field and finally how to find the originality.

Chapter 2 explains the target application in detail. The subject of study here is the case study of electric vehicle business model and what a business model innovation is. 8 business models will be studied to learn about its innovation point, failure lesson and the system behavior to form the dynamic hypothesis for the next step which is model formulation.

Chapter 3 presents a step-by-step model formulation based on various systems theory and methodologies. This chapter explains the visualization of a business system, selection of variables in a boundary, describing system behavior based on its archetypes, building structure to study its behavior using system dynamics methodology.

Chapter 4 contains the ways to testing a model, verifying a model and analyzing the result. The simulation are mainly done on Vensim DSS software but could be viewed in the free Vensim Personal Learning Edition (PLE). Model testing is done is verify to model for determining its usefulness. Further testing is done to study the system behavior based on structure change and parametric change. The final testing is the shock test to examine its resilience over the external influences.

Chapter 5 integrates the developed models in Chapter 3 and apply to a designing an EV business system using battery swap in vehicle ownership model. This chapter serves as practical example for user who wants to use the model of this research based on their environment. The chapter closed the loop of the research from visualization of a system, breaking down to parts for analysis and integrating the model to a system design of a practical example.

Chapter 6 concludes all the sub-conclusions of each chapter and review the learning points after every simulation has done. Limitation and future work would be stated in this chapter for future researchers to continue the work by enriching the model or extending the model in other application.

Table 1: Thesis Structure

Chapter # and Title	What it is about?	Key words
1. Introduction	How to position this research? What is the value of this study?	Purpose, Originality, Literature Review
2. EV Business Model Innovation	What has been done? What can be learnt?	Case Studies, Business Model Innovation
3. Business Dynamics Evaluation Framework and its Methodologies	Framing problem statement. How to study a problem? How to solve a problem?	Systems Approach, System Engineering, System Dynamics, Boundary
4. Model Testing and Result	Testing the model Analyze the result	Verification, Simulation, Sensitivity Test, Scenario Analysis
5. Model Use for System Design	Integrate the model into a solution for new system design	Integration, System Design
6. Discussion and Conclusion	What we have learnt?	Limitation, Future work

Chapter 2: Electric Vehicle Business Model Innovation

2.1 Case Study of 8 Electric Vehicle Business Models

2.1.1 Category of EV System based on Business and Operation Type

Table 2: Categories of EV Business Model in Case Studies

Company/Scheme Name	Vehicle and Battery Ownership	Vehicle-Battery Rent/Lease/Share	Battery Charging	Battery Swapping
Tesla Motors Company	O	X	O	X
Autolib Blue Car		O	O	
Gogoro Smart Scooter	O			O
BYD and Wanxiang Electric Bus		O	X	O
Eclimo Scooter Fleet Rental		O	O	
Greenway Delivery Fleet		O	X	O
Better Place Inc.	X	O	X	O
Okinawa EV Rental		O	O	

O—Main Operation; X—Developing / Secondary Operation

2.1.2 Case Studies and Parameters Data Gathering:

Case Study 1: Tesla Motors Company

Tesla Motors started to produce mass production Model S for USD 76,000 on average in 2012. The sales of vehicle are growing at second order polynomial so far as illustrated by the chart below.

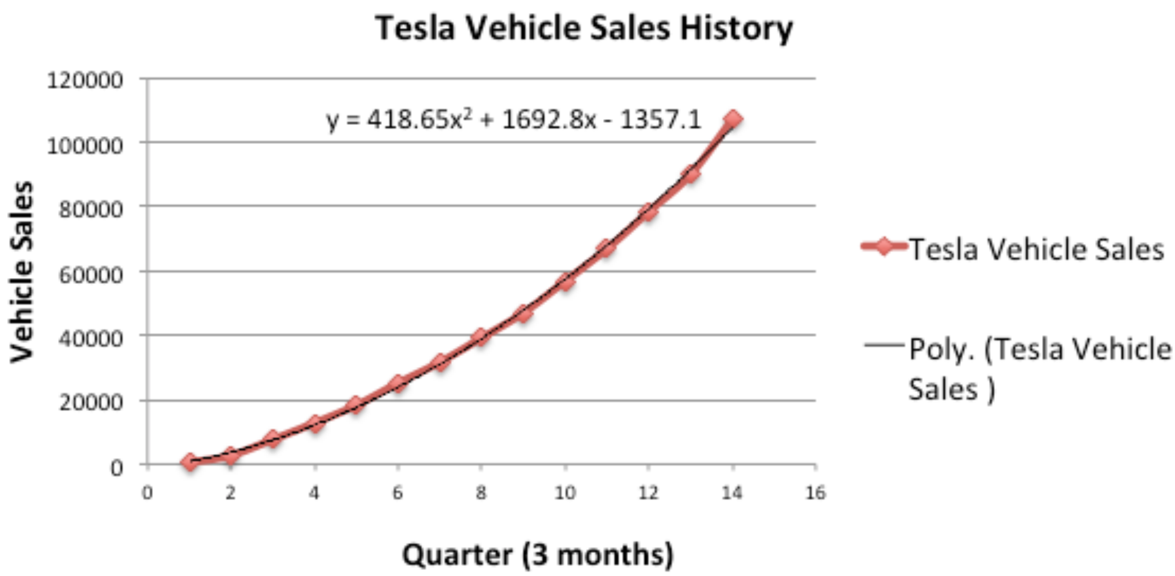

Figure 3: Tesla Motors EV Sales Records (Data Source: SEC Filings)

Tesla Supercharging Network is also one the most important asset for the growth of EVs in worldwide. The figure below shows the growth of supercharging stations in the network worldwide.

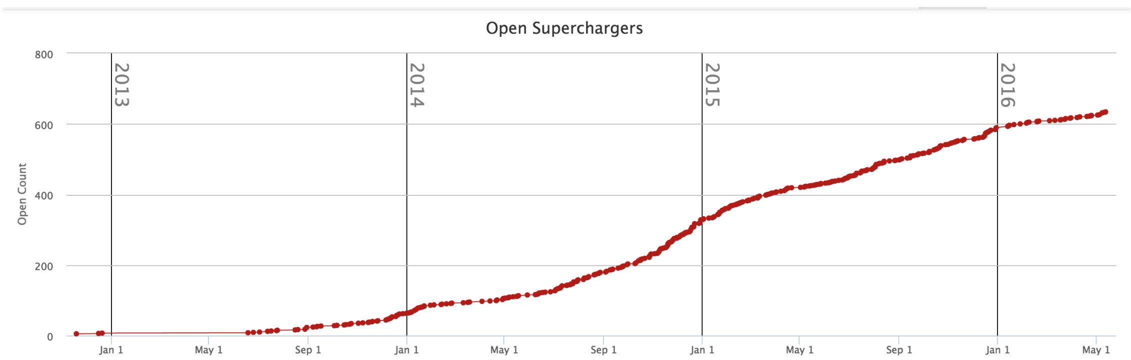

Figure 4: Number of Supercharging Station Count Worldwide (Source: http://supercharge.info/)

Tesla Motors main business model is vehicle ownership sales. The company believes plug in charging suits the most for their EV owners as they think that the cars have enough mileage (>300 miles) for a day and assumes that most Tesla owners will do overnight charging to top up the battery and occasionally use the supercharging network once awhile for long distances driving. Tesla Motors developed a battery swap prototype in 2013 and showed case in a Tesla event to the public. Tesla CEO Elon Musk said that it takes twice less the time (90 seconds) to refuel the car of the same class. Even though Tesla has developed the battery swap capability but might not roll out battery swap service in near future unless there is a demand for the service for a cost instead of free fast charging. However, with the growing popularity of EV, the charging stations will soon faces the limitation of the service capacity capability.

Case Study 2: Paris Autolib Car Sharing Scheme

Autolib scheme is a model of urban car sharing system pioneered by the city of Paris. In order to reduce the traffic congestion, the city of Paris wants to promote car-sharing service called the Autolib following the success of their Velib bike-sharing program. Bollore Industry Group will operate the system with their electric vehicles named the Blue Car. The goal is to create of car sharing system that has more than 3000 cars in 1000 kiosk in the city and suburb for Parisians to travel on short, zero emission trip. The program has now achieved 4000-5000 rental times a week. Unlike traditional car renting service, Autolib subscribers could drive the cars and park at the station differs from the original pick up station. The electric cars are charged by pole charging when it is parked and not used. Each parked space has to come with a charging station making the infrastructure more expensive when it scales. This project is an example of Private-Public partnership. To what extend this system is viable considering the amount of subsidize received and the delay of cash flow in car sharing service, the dynamics of operation and financial has to be modeled for evaluation so that the similar system could be extend to another city.

Case Study 3: Gogoro Smart Scooters

2015 in Taipei, a new brand of electric scooters has emerged in the market with a beautifully designed scooter chassis made of aluminum alloy and flashy customizable display panel, which is very appealing to young riders in the market. The supporting infrastructure of Gogoro is the battery swap stations where riders could drop off at any of the station and replace their batteries with new ones by their own hand within 20 seconds. The mobility energy storage network is the bigger concept of the company beyond their beautiful scooters. Till date, they have sold more than 4000 scooters and built more than 120 kiosks that could store about 20 batteries enough for 10 scooters to swap for their new battery at once.

Case Study 4: Chinese BYD and Wanxiang Electric Bus

One of the best selling Electric Bus is BYD electric bus. The bus battery pack capacity is equivalent to 4 Tesla Model S batteries (4 x 90kWh = 360kWh). Malaysia has imported these BYD buses for implementing the EV Roadmap.

Wanxiang Electric Bus formed a joint venture with the State Grid Corporation of China to implement city wide electric power charging and battery-swapping infrastructure for their electric bus. They tested their pilot project during the Shanghai Expo in 2010. There is a specific pilot project for battery swap electric bus conducted in QingDao city, China in which the city buses are replaced with electric buses. The initial result of the pilot project has proven feasible for the bus company and the State Grid to maintain viable partnership for providing electric mobility to the citizens on daily basis [12].

Case Study 5: Eclimo Electric Scooters in Malaysia

A small company in Penang is producing their own brand of electric scooter with latest Li-ion batteries and in wheel motors. However, the high initial price of scooter make it very hard to sell to general public considering the fuel price in Malaysia is relatively low due to the Malaysia is an oil producing country. The company is then changed their business model to leasing the scooters to KFC fast food chain to support their delivery fleet. Eclimo is now focusing on scooter deliver fleet to generate revenue to the company and at the same time spreading awareness of electric mobility to the public through different usages of electric scooter like police patrol and city touring.

Case Study 6: Greenway Delivery Truck in Slovakia

Greenway in Slovakia is one of the pioneers in providing battery swap electric delivery truck in central Europe. The company focuses on Delivery Company as their main customer by reducing their operation cost on fuel. Since the delivery truck are making the same fixed route daily, Greenway was able to place the battery swap station in a strategic location for long distance journey of the delivery truck. The truck drivers are trained to swap the batteries by themselves using forklift, thus the cost of the station is lower compared to an automatic one.

Case Study 7: Better Place Inc.

One of the most famous battery swapping EV business system is none other than Better Place Inc, an Israeli startup in California in which raised more than 875 million USD in 2007. The company aims to become the operator of electric mobility by providing battery swap subscription service to the customers. The cost of vehicle without the battery would cost the same or lower than the gasoline car could reduced the barrier of customer adoption while the company owns the battery and is responsible for maintaining the battery performance. Customers who subscribe to their service would drive to the station for swapping new battery to get full charge. The operation concept was being implemented in many countries such as US, Japan, Australia, Israel and Denmark. However all operation comes to a halt in 2013 when the company declared bankruptcy and liquidated. It was said that the battery swap idea is not practical for personal vehicles as people only anxious about the charging time and range but in reality do not drive that much of miles in a day while an overnight charging or fast charging would suffice. Thus, some of the founding team members of Better Place pivot the battery swap idea to Electric Bus in China[13].

Case Study 8: Okinawa EV Rental

Car Rental Companies like ORIX, Nippon Rent-A-Car and Nissan Rent-A-Car are also experimenting Electric Vehicle Rental in tourist hotspots like Okinawa, Japan. A study published by Cambridge Service Alliance Group is done on this particular project.

The project is to provide cleaner transport to the tourists and residents of Okinawa Island. The business model is rent the EV for tourists use for the first 3 years, after that the car is sold as second hand to the resident to own. The project experienced some obstacles due to low incentive for rental company to promote EV, second hand value perceived by the customer is 1.5 million yen which is lower than the expected 2 million yen [14].

2.1.3 Observed Facts and Hypothesis on Business System Behavior

Table 3: Facts and Hypothesis of Business System Model

System Model	Facts	Hypothesis
Vehicle Ownership (Tesla, Gogoro, Eclimo)	A high capital is required to build a very compelling vehicle for customer to own. Otherwise, EV finds it very hard to gain traction to be sold as it has perceived risk in technology.	The adoption curve will be either takes off very slowly and flat down or rise exponentially but flatten out due to the limit to growth.
Vehicle Access (Autolib, Wanxiang, Greenway, Better Place, Okinawa)	Vehicle access model required certain scale of infrastructure in place in advanced. Various partnership needed. Cashflow will be delayed over the time of lease.	Adoption of subscribers will increase faster but also will fade of fast once perceived value is lower than expectation. The growth is more dynamic.
Battery Charging (Tesla, Okinawa, Eclimo)	Charging to 80% will take 30mins at least, Frequent user are reluctant to adopt this system. Super charging is popular if it remains free and wide coverage.	The delay of recharging will be more significant when vehicle-station ratio is higher. At bigger scale, the system will face capacity limit.
Battery Swapping (Better Place, Autolib, Wanxiang, Gogoro)	Upfront cost of Swap station is higher than normal charging. Suitable for commercial purpose or smaller vehicle. Criticized for proprietary system.	The growth of system is proportionate with the coverage of station. Battery-station ratio is a more significant metric.

2.2 Business Model and Technology Competency Innovation

The term “Business model” has no unified definition but there are a few good definitions for it. A business model is description of how a company creates, delivers and captures values[15]. A viable business model must provide a value to the customers higher than the price they willing to pay. The price must be higher than the cost of providing it so the business owner could capture the difference.

A business could create new value to the customers if they pursue innovation in both business model and technology competency. An article written in Harvard Business Review in June 2015 proposed an innovation landscape map on how company can create an innovation strategy. They can make a choice on how to focus on technology innovation; how to focus on business model innovation. The matrix above shows how innovation strategy could be decided by matching existing technical capabilities or business model[16].

To commercialization of EV system requires innovation from both business model and technology aspects. An innovation landscape of a 2x2 matrix for developing innovation strategy has proposed to categorize innovation into 4 groups namely Routine Innovation, Radical Innovation, Disruptive Innovation and Architecture Innovation[16]. This frame has been used as a retrospective way to categorize various type of innovation in different industries such as next generation car, ride-sharing, digital camera and jet engine. The matrix is then been used in this research specifically for electric mobility system in this research to categorized the type of innovation strategy for different business model with a specific focus on commercial purpose, battery swap EV system.

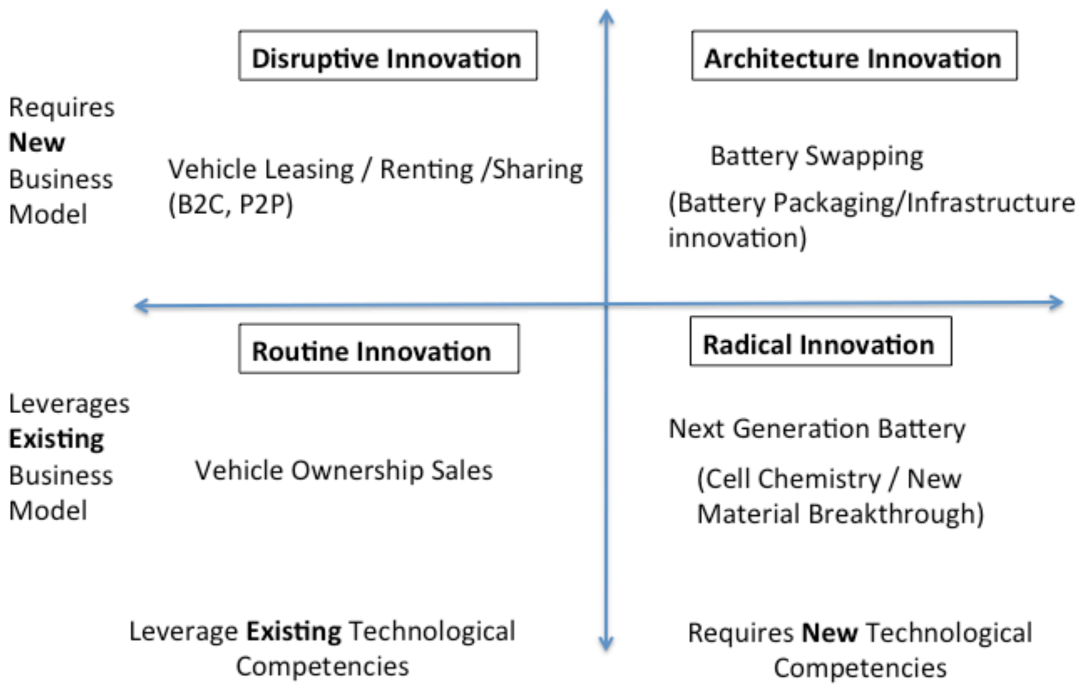

Figure 5: Adopted Pisano Model on Innovation Strategy for EV Business Model

Most of the incumbents and entrepreneurial firms start of in lower left quadrant and then pursue routine innovation to improve the product. Incumbents have legacy of product development in which lock them into existing business model and technological competencies. Entrepreneurial firms like Tesla will seek to move to radical innovation by building Gigafactories to drive down the cost radically. Autolib Blue Car starts of in upper left quadrant to create car-sharing system in partnership with city municipals like Paris and leverage its existing battery system. Gogoro in Taipei pursues partial architecture innovation with their battery swap energy network and also their open initiative to spread mobility energy network. Even though, they selling scooters ownership but customers are required to sign up electric mileage monthly subscription. Greenway Inc. and Better Place Inc. pursue architecture innovation with vehicle lease and battery swap model but Greenway is focus on commercial delivery truck to build the foundation of infrastructure while Better Place take all out strategy from personal car to company car to taxi with aggressive expansion of operation in many counties. As result the aggressive strategy back fires with off the roof cost of operation. Okinawa EV Rental service took a very conservative approach to test the EV adoption by car renting model. The apparent advantage is merely operational cost saving which customers do not feel the exception value of renting EV resulting the perceived value of used EV is (1.5 million yen) lower than the expected price (2 million yen) for the business to be viable. Eclimo in Malaysia promote their E-scooters in KFC delivery, police patrol fleet in the effort to spread the green branding. The business model could be disruptive if delivery fleet starting to embrace EV and set up charging station for future EV customers to dine in the restaurants.

Another study identifies 4 business model archetypes: Luxury specific purpose, Luxury multi purpose, Economic specific purpose and Economy multipurpose, then these archetypes are described in 3 components which are Value Proposition, Value Network and Revenue & Cost Model. The study also include the path dependency and the evolution of the archetypes from both incumbent and entrepreneurial firms and concludes that their business model will converge in the direction of economy multi-purpose vehicles[17]. That conclusion enhances the logical direction of this research to focus on sales of vehicle, battery lease with battery-swapping options in which is currently under studied. However, vehicle ownership sales could be a contemporary model for the auto-companies; vehicle access subscription like Uber, Lyft service is experiencing mass growth and this model should not be ignored in our research.

Chapter 3: Business Dynamics Evaluation Framework and Applied Methodologies

3.1 Overview of Business Dynamics Evaluation Framework

The business dynamics evaluation framework is based on how the system operates and evaluates its viability in financial terms. The operation model consists of vehicle, battery and infrastructure. The interfaces between these subsystems are illustrated as below:

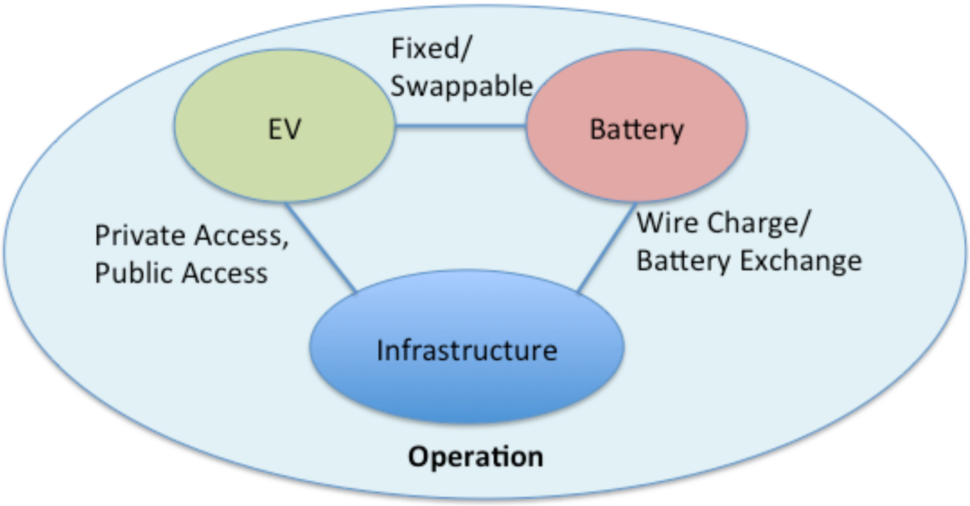

Figure 6: Operation Model between Vehicle, Battery and Infrastructure

Beyond operation model in which describes the physical interfaces of EV subsystems, the financial model describes the ownership or the transaction interfaces of these subsystems to customers, company or collaborators. The interfaces of operation model with financial model are illustrated as below:

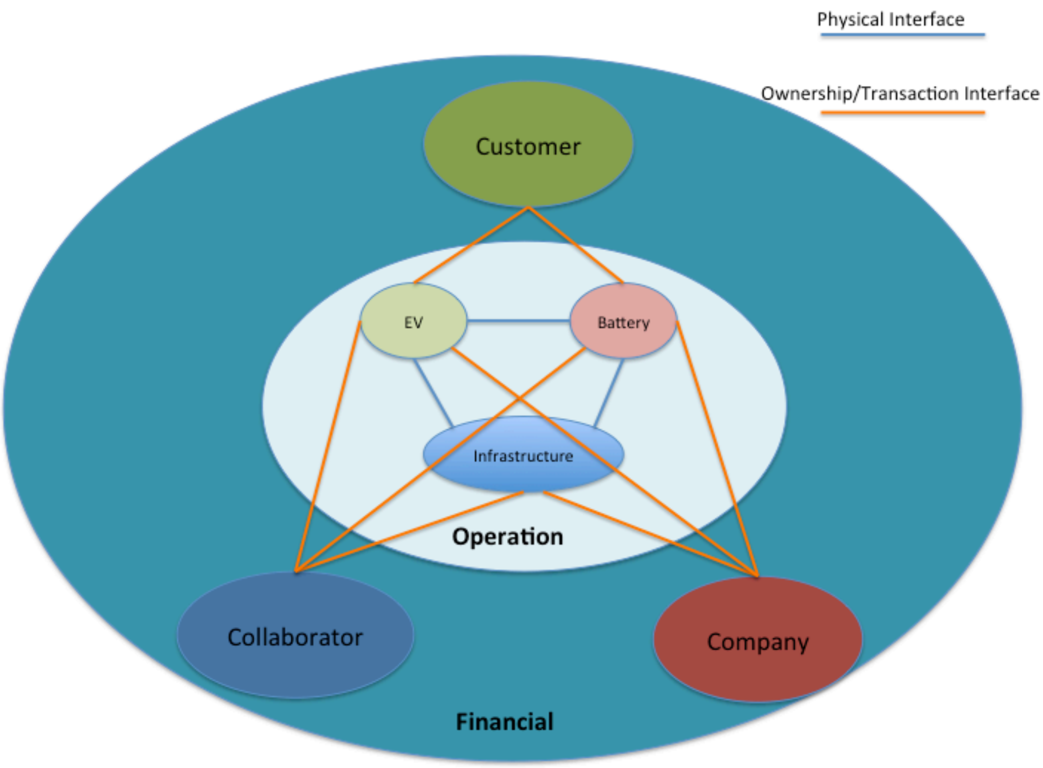

Figure 7: Interfaces between subsystems in Financial Model and subsystems in Operational Model

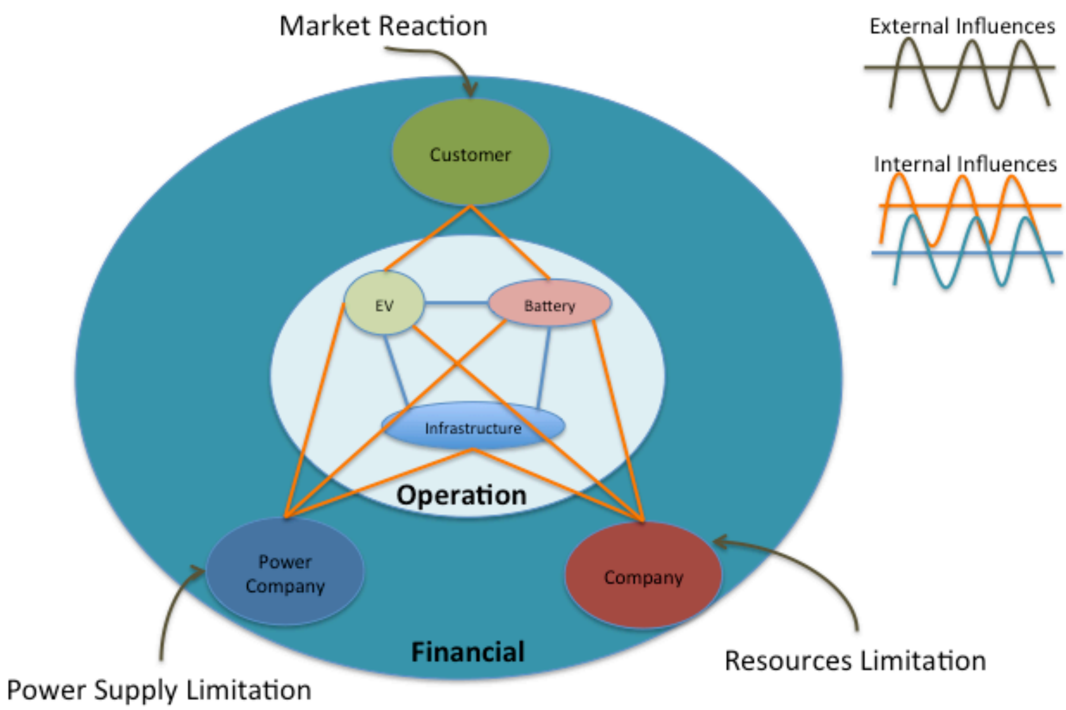

Figure 8: External and internal influences that affect the system model

The final diagram is an overview of the evaluation framework of this research. It serves as the foundation for the next step that is building model structure and testing its behavior.

3.2 Development of the Evaluation Framework by Systems Approach

Systems approach is generally defined as "a holistic multidisciplinary methodology for analyzing, evaluating and optimizing a complex system understanding how elements are interacting with each other within a whole system" [18]. Systems approaches embodied in Systems Thinking in which promotes optimizing the whole by improving the relationship among the parts and focus on key coordinated changes sustained over time to produce large system change[19]. The systems approaches that are been implemented in this research: System Engineering to define the model boundaries, System Archetypes to generate hypothesis for system behavior, System Dynamics to build and test the model.

3.2.1 Defining scope of model using System Engineering Principles

By doing System Engineering, the scope of the system is be defined and model is formulated within the boundary. One should understand and acknowledge that there are 7 interrelated systems for consideration: Intervention System (S2) that is to be engineered to solve a problem in Context System (S1) with the help of the Realization System (S3). The Intervention System becomes the Deployed System (S4) once the Intervention System is installed due to difference from original intent and work with Collaborating System (S5) to perform the functions. Sustainment System (S6) provides the services to keep Deployed System operational and could be challenged by Competing System (S7) in which might be solving the same original problem[20].

This research applying the similar viewpoint of identifying the 7 systems in the process of model formulation and the 7 samurai diagram is as follows:

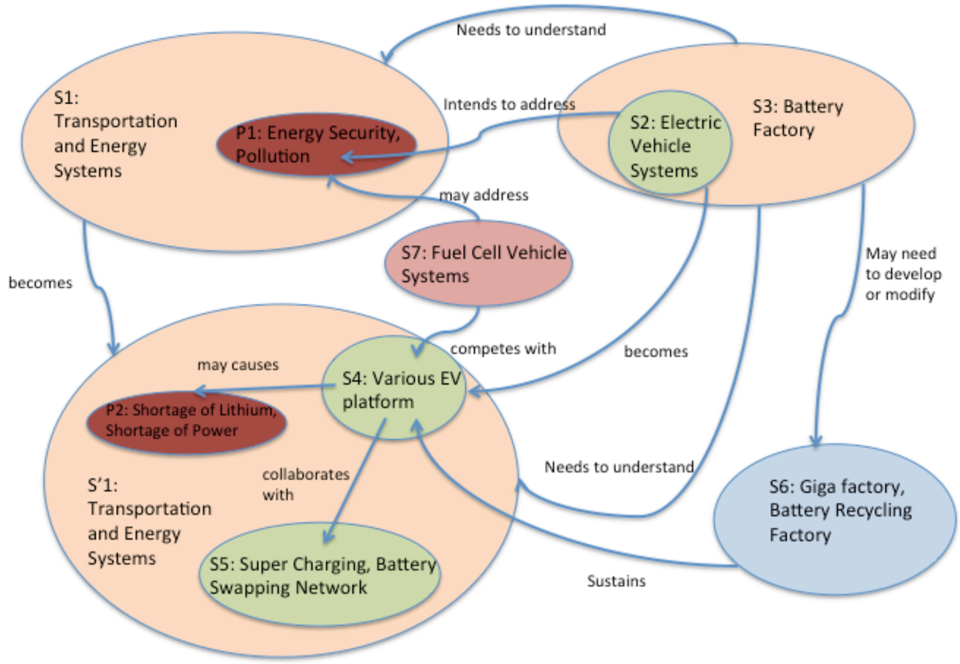

Figure 9: Visualization of EV System by 7 Samurai Diagram

Electric vehicle (EV) system designed is the intervention system to address energy security and air pollution problem in the context of transportation and energy systems. To realize the production of electric vehicles, battery factories should be developed to produce enough battery for the vehicles. After the introduction of EV systems, it comes in many sizes such as electric buses, electric trucks, electric passenger cars, electric scooters etc. and different charging platform such as plug in fast charging, battery swapping or even wireless charging. Thus, the collaborating infrastructure has to adapt to the platform of vehicle such as the deployment of super charging network and battery swap station. The introduction of EV also could solve the problem in the old context system but might also face new problem in the modified context system such as power supply limitation and battery material shortage. To sustain the EVs, battery factories have to upscale like the Gigafactories built by Tesla Motors, battery-recycling factories need to be in place to recycle the batteries for reuse of it material. Finally, fuel cell vehicle that is the competing system in which might solve the same initial problem show be taken into consideration in visualizing the whole EV system.

After drawing the 7 samurai diagram, the boundary of the system is drawn for clarification of model scope. To illustrate the variables within the model boundary clearly, the variables are grouped into different categories of how the variable will be modeled in a bull's eye diagram as follows:

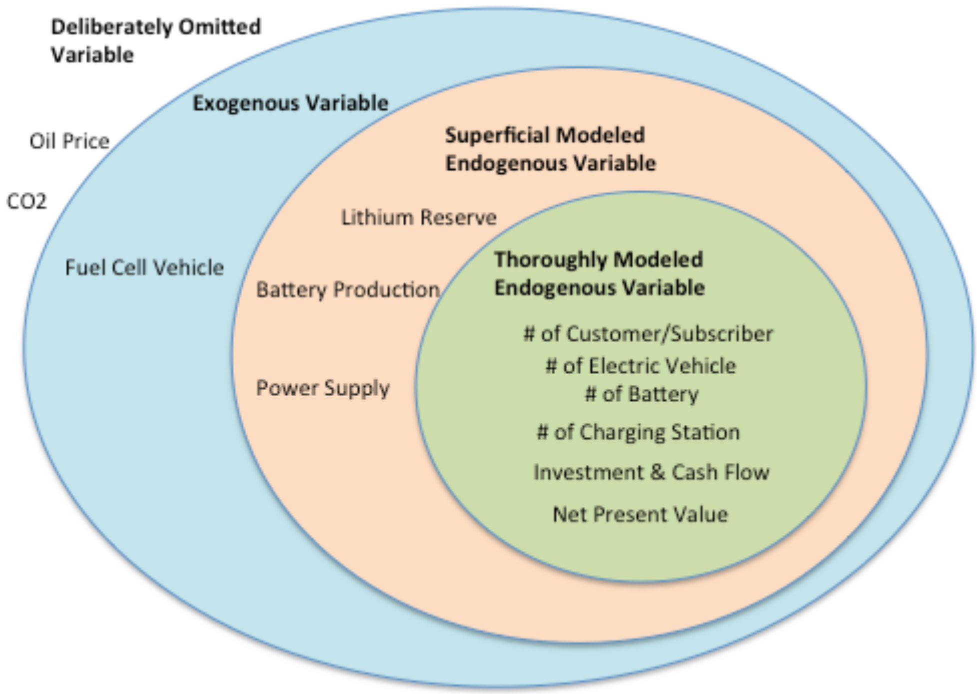

Figure 10: Model Boundary in Bull's Eye Diagram: EV System

Thoroughly Modeled Variables are the main variables considered in the model. It should have detailed delay and feedback to simulate its behavior completely. Superficial Modeled Endogenous Variables are the variables involved in the feedback or the limiting factors to the Thoroughly Modeled Variables. Exogenous Variable may be model as shocks to the systems. Both Superficial Modeled Endogenous Variables and Exogenous Variables would present in scenario analysis. Finally, the Deliberately Omitted Variables will not be considered in this model due to the irrelevant of importance and out of scope/interest. The main principle of modeling is to solve a problem and not a model a system.

3.3 Model Building using System Dynamics in Vensim Software

3.3.1 System Dynamics Introduction and Its Principles

"The field of system dynamics created by Jay Forrester in MIT in 1950, designed to help facilitate learning of structure and dynamics of complex systems in which high leverage policies can be designed for sustained improvement and catalyze successful implementation and change". System dynamics are most effective when:

- It is used not to model a system but to solve problem.
- Used to capture time delays, feedbacks, and interactions that unaccounted by most people in a broad model boundary.
- The model is an open box rather than a black box that is used to facilitate learning and policy design.
- The model is open reviewed by relevant stakeholders' critics and modelers to challenge the model with data and test assumption [21].

Referring the principle of system dynamics, this model purpose is described in

To-By-Using Framework:

To: Solve the problem of evaluating EV business viability based on different business model and operation.

By: Capturing the time delay of physical structure lead-time, investment perceived delay, interaction of between physical stocks and flows.

Using: Causal Loop Diagram (CLD) to visualize causal relationship and Stock and Flow Diagram (SFD) to model the delay, feedback of accumulated stock and its flow of the system in which may produce non-linear behavior result. The diagrams were created in Vensim DSS software.

3.3.2 Process of Model Formulation

The textbook of Business Dynamics provides a recommended process of the formulation of model[22]:

3.3.2.1 Problem Articulation:

Problem Definition: How to evaluate EV Business Viability under vehicle ownership and leasing model? Which, Plug In Charging or Battery Swap Operation is more stable under internal delay, external shock?

Key Variables: Refer to Figure 10.

Time Horizon: 100 Business Cycle Quarters (25 years)

3.3.2.2 Formulation of Dynamic Hypothesis:

Initial Hypothesis Generation: Commercialization of EV requires simultaneously development of infrastructure and a strong adoption of customers to support the viability of the business.

Endogenous Forces: The viability of EV system will depend on how well to system can accommodate the growth of system while maintaining healthy cash flow to assure the interest of partner to continue invest in the systems.

Exogenous Forces: Viability of EV system should be able to withstand the shocks (market reaction, power supply, material resources), internal delay of to react to the shocks.

3.3.2.3 Mapping:

Model Boundary Bull's Eye Diagram: Refer to Figure 10.

Causal Loop Diagram: 2 System Archetypes

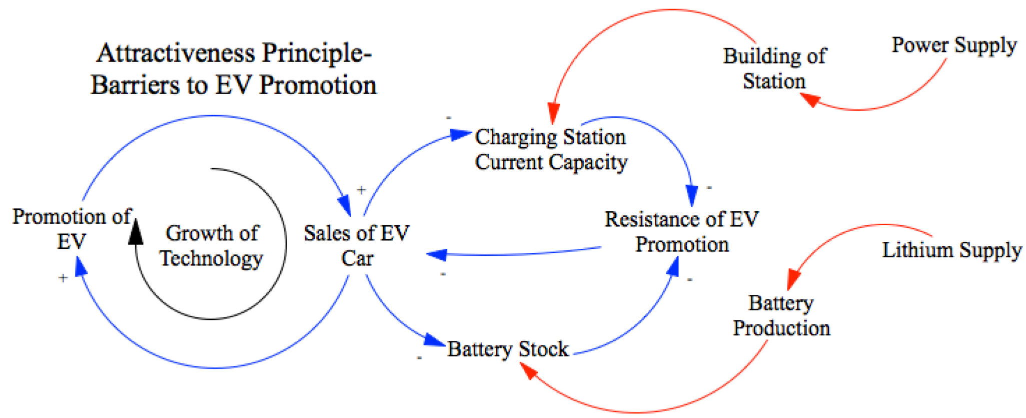

Figure 11: CLD identifies Attractiveness Principle to the promotion of EV

One of the system archetypes was identified (Attractiveness Principles) associated with barriers to EV promotion due to the resources limitation and power supply of supporting system such as battery production and charging station. If EV were to be sold as a vehicle ownership, the system will be experiences commodity limitation and charging station dependence.

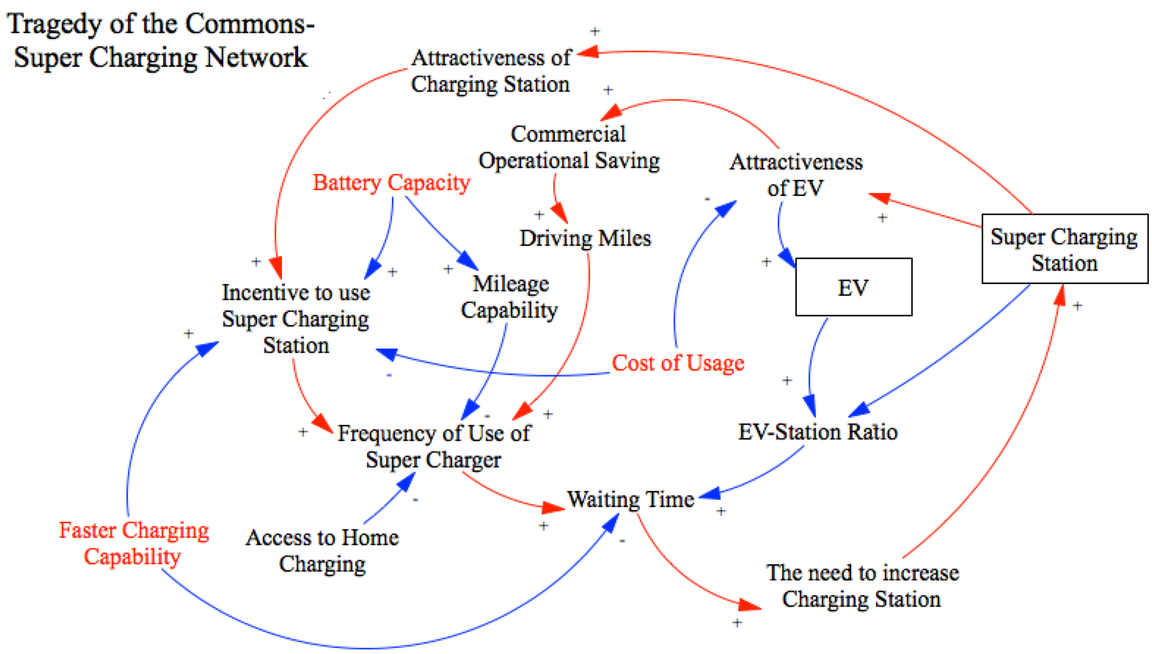

Figure 12: CLD identifies Tragedy of the Commons on over dependencies of charging network

The growth of infrastructure indeed will promote the growth of EV however as the network grows, the vehicles will be very much dependent on the charging network and the attempts to reduce frequency of use on vehicle design such as improved fast charging capability and battery capacity will further enhance the incentive to use the charging station. Suitable cost of usage has to implement to limit the over use of the network while not to reduce the attractive of EV. The CLD is drawn based on the observation on Tesla Motors case on the hidden/potential problem of service capacity expected after the launch of mass production Model 3.

Stock and Flow Diagram:

The figure below shows the SFD on plug in charging and battery swap model modeled by the change of interaction.

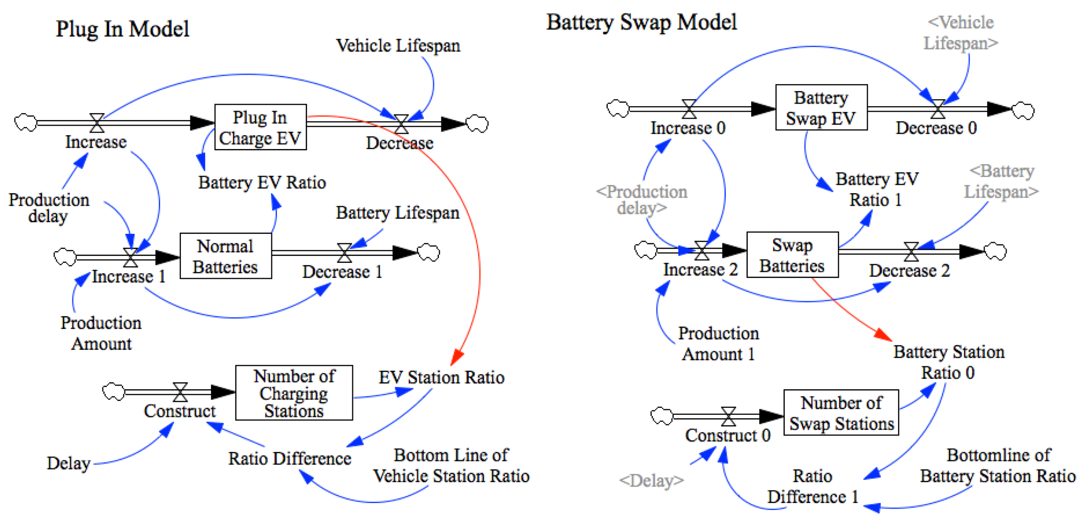

Figure 13: SFD on Plug In and Battery Swap Model Service Capacity

A simplified model is done on 3 common stocks (EV, Battery and Infrastructure) in both Plug In and Battery Swap model. EV and Battery Stock are modeled on pipeline delay as the first produce will first experience the decrease of lifespan. The rate of EV production increases the rate of production of Battery. The ratio between two stocks such as **EV-Station** in Plug In Model drives construction of infrastructure, while in battery swap model, that ratio is **Battery-Station ratio** instead. The construction of infrastructure means it service capacity is increase to accommodate more EV and hence increase the stock of EV as feedback. The main difference is highlighted in red arrow as shown in figure above.

A detailed look into the battery swapping system is modeled quickly by stock and flow diagram. The advantage of battery swapping lies on the ability for the charging station to maintain stable charging input despite changing output due to demand. By having a battery stock as buffer, the station can maintain minimum charging capability by the grid, combined with renewables energy sources like solar or wind. Figure below shows the energy flow and storage in a battery swap station.

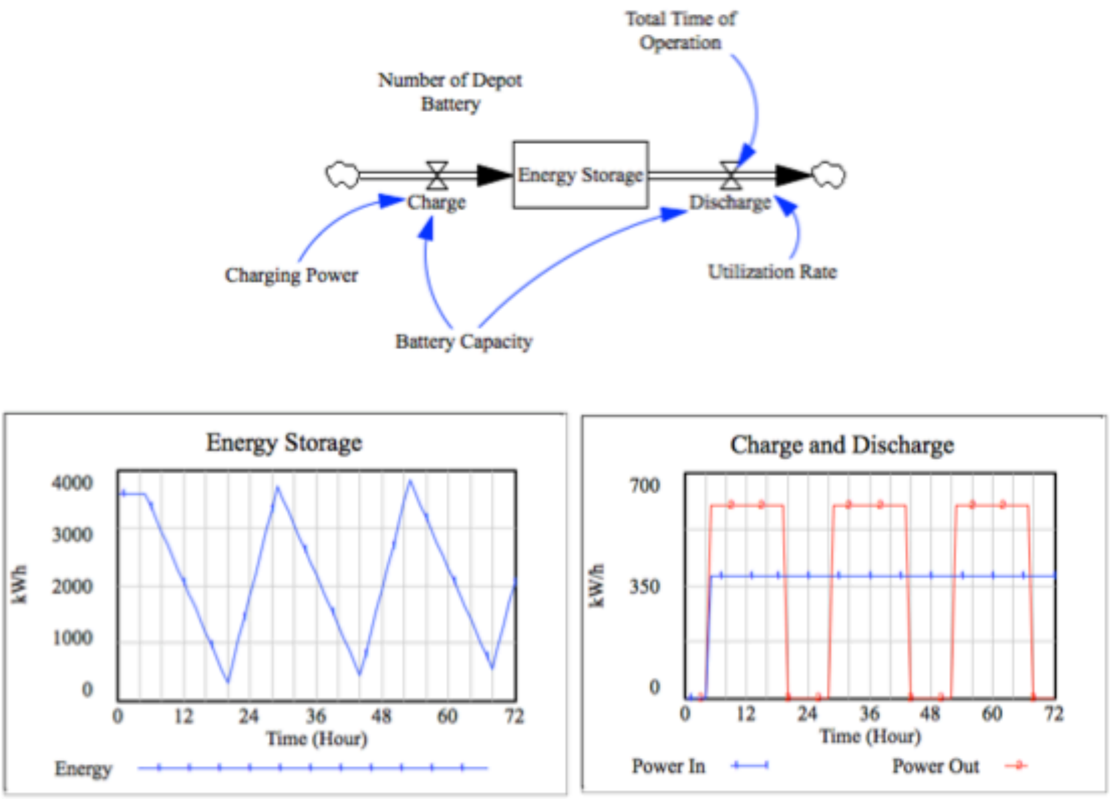

Figure 14: Energy Flow and Storage

Based on figure above, the station charging capability is be maintained at 400kW and the battery at depot takes in 400kwh of energy every hour otherwise, system has to upgrade to 600-700kW charging capability to accommodate the change of demand.

Every change could possibly affect the station capability for plug in model; meanwhile battery swap system has more way to accommodate demand change. Referring the equation below:

$$Utilization\ Rate\ \leq \frac{Charging\ Power\ (kW) * \#\ of\ station}{Battery\ Capacity\ (kWh)} + \frac{Depot\ Battery\ Buffer}{Total\ Operation\ Hours\ per\ Day}$$

Equation 1: Formula for the relationship of utilization rate and system charging rate.

The charging station needs to maintain the right side of the equation bigger than the utilization rate. As utilization rate increase due to system growth or temporarily demand spike, the system has to be either increase charging power or increase number of station. Battery swap system will have an addition way to keep the system stable by adding mode depot battery as buffer. By increasing charging power and number of depot battery, the change of energy storage is shown as in figure below. Charging Power should be increased for fixed demand increase while number of depot battery should be increased for fluctuation demand.

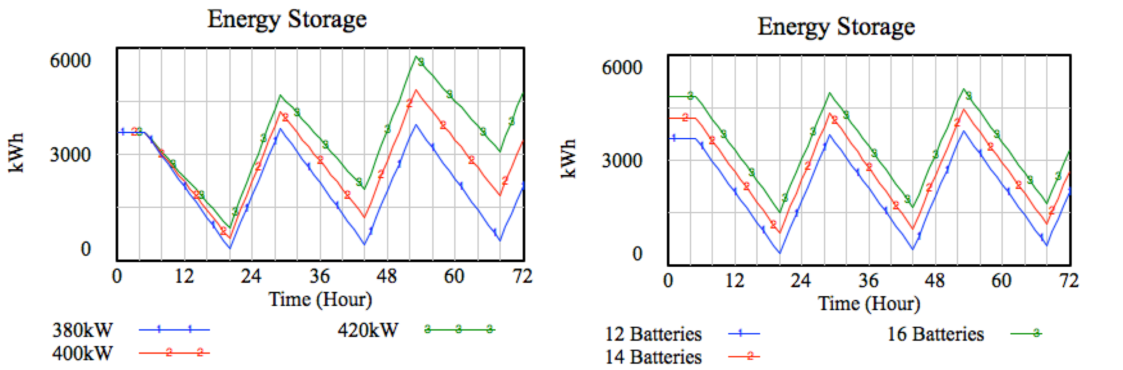

Figure 15: Energy Storage change by increase in charging power capability (left) and number of depot batteries (right).

Compared to the operation models in figure below, the vehicle ownership and leasing models have structural difference hence; these models will behave differently which is observed from its cash flow.

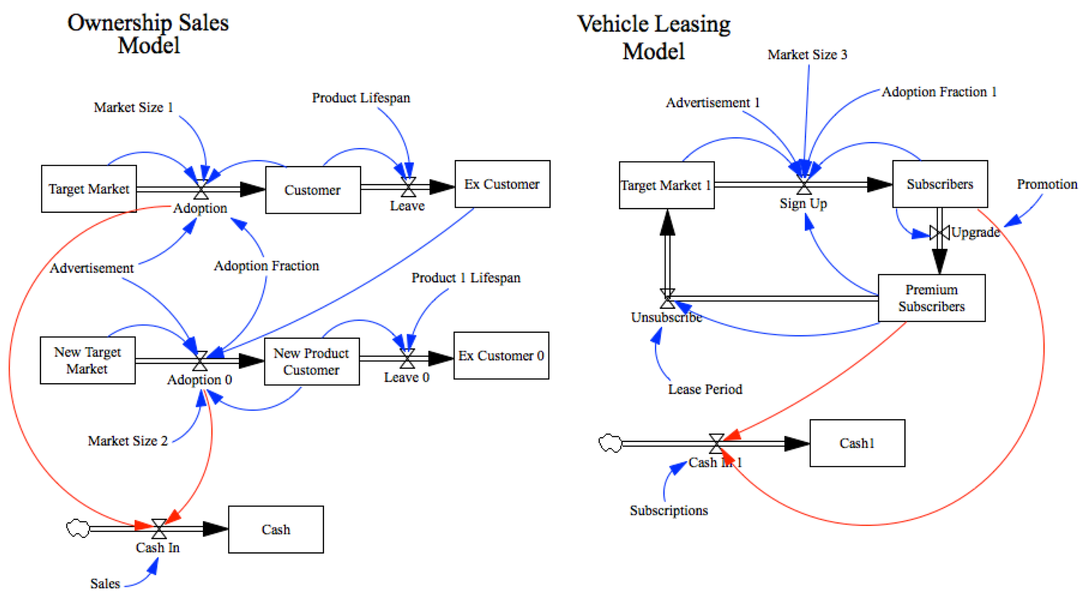

Figure 16: SFD on Vehicle Ownership Sales and Leasing Model

The incumbents in automotive industries typically implement the vehicle ownership model. The customers adopt flows from target market and undergo adoption curve (normally S shape growth) under the influences of advertisement and word of mouth effect. The adoption curve formula is as follows:

$$Adoption = Target\ Market * Advertisement * \frac{Customer}{Market\ Size} * Adoption\ Fraction$$

Equation 2: Formula for passenger adoption curve

Equation 2 is modified after Susceptible-Infectious-Recover Population (SIR) Model for disease outbreak. The population that will get infected by disease is non-linear due to the rate of infection people increases with the number of infected population. The disease “infection” is similar to a “customer adoption” of a new technology or service. The non-linear behavior models the “word of mouth” effect. “Advertisement” in Equation 2 is contact rate of the target market expose to knowing service. “Adoption Fraction” is the coefficient of the target market people willing to adopt the service.

The customers will flow to ex-customers over the lifespan of vehicle. These ex-customers are assumed to become the driver of next product which will target to a bigger market as the brand becomes more received and new target market are assumed to flow at the same adoption curve again.

Meanwhile vehicle-leasing model will have a closed loop flow as subscriber sign up for the access instead of ownership. It is expected that the adoption fraction will be higher than ownership sales as the risk is lower but the flow out rate back to potential customers is higher due to the shorter time of lease period compared to vehicle lifespan.

The red arrows on both diagrams show that main revenue streams in both models in which in vehicle ownership model, company makes money on the **flow of customer**, while in vehicle leasing model, company gain revenue on the **stock of subscribers**.

Evaluation of business viability could be done in financial model. In this simplified model, 3 approaches have been utilized: Income Statement Approach, Balance Sheet Approach and Cash Flow Approach.

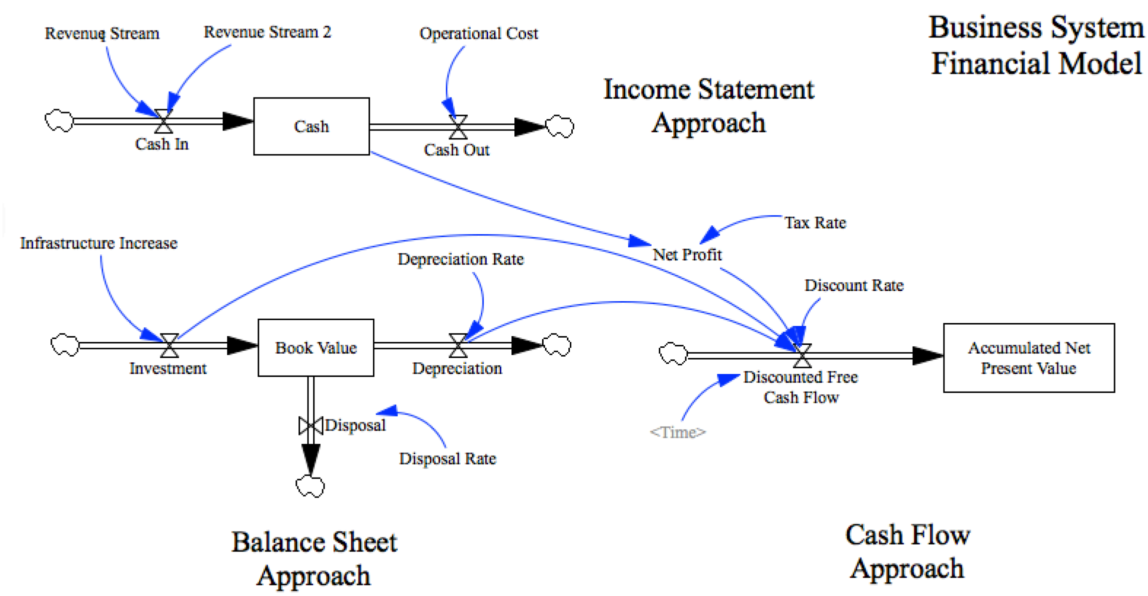

Figure 17: Financial Model for a business system

Income statement approach models the cash flow in and out driven by revenue streams and operational costs. The accumulated stock is the gross profit. Cash flow will show the profitability of the operation.

Balance sheet approach takes account of the investment capital for asset building e.g. infrastructure, fleet of vehicle cost and battery cost as asset of the company minus the depreciation and disposal value of the asset. In this model, book value is calculated to generate variables (investment and depreciation) for calculating Free Cash Flow for compound Net Present Value.

Cash flow approach measured the discounted free cash flow (FCF) to calculate Net Present Value (NPV). It is used as a metric to measure whether this system is worth investing by bringing forward the future value to present time. FCF is the sum of After Tax Profit and Depreciation of asset minus Investment. It is an important indicator to see if the company still be able to generate real cash to enhance shareholder value after operation and capital expenditure. The formula of FCF and Discounted FCF are as follows:

$$Free\ Cash\ Flow\ (FCF) = (Revenue - Expenses) * (1 - Tax\ Rate) + Depreciation - Investment$$

$$Discounted\ FCF = \frac{Free\ Cash\ Flow}{(1 + Discount\ Rate)^{Time}}$$

Equation 3: Formula for discounted free cash flow calculation

Chapter 4: Model Testing and Result

4.1 Verification: Robustness Test and Dimension Check

Dimension Check is done by go through the formula and check the unit dimensions. Robustness Test is done by reality check on based on test input such as "IF Ratio Difference = 0, THEN Construction of Station = 0", " IF Construction of Station = 0, THEN Increase of EV = 0". The system should stop growing

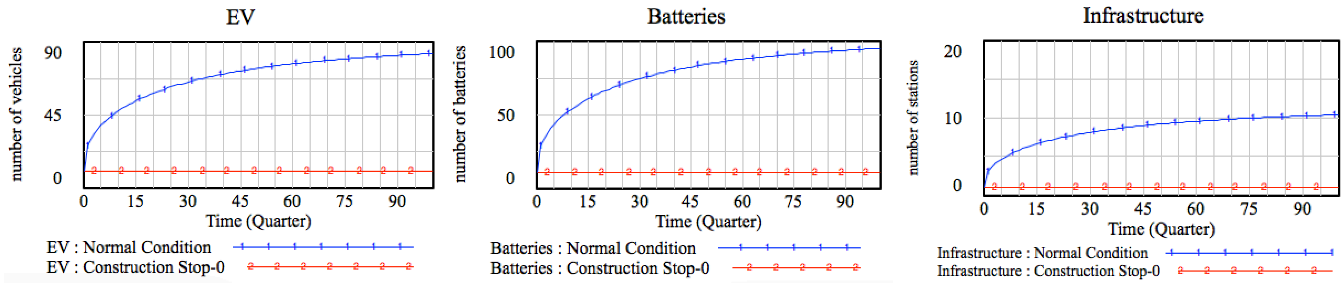

Figure 18: Examples of Model Robustness Check

4.2 Model Testing by Monte Carlo Simulation

Both plug in and battery swap model as shown in Figure 16 are set in Equilibrium Initialization (system is stable on its own) as shown below:

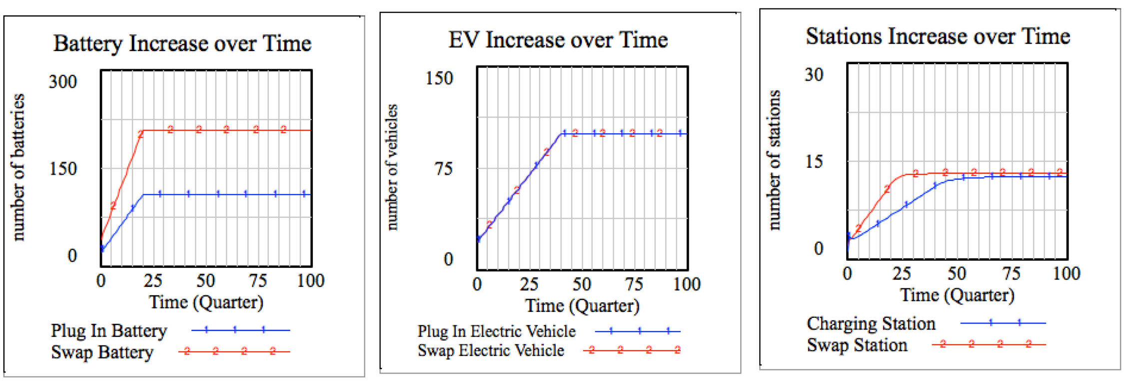

Figure 19: System capacity behavior over time (blue for Plug In; red for Battery Swap)

Table 4: Parameter Inputs to Model in Figure 13

Variables	Plug In	Battery Swap	Unit
Vehicle Lifespan	40	40	Quarter
Battery Lifespan	20	20	Quarter
Battery Production Amount	1.2	2	# of Battery
Bottom Line of Vehicle-Station ratio	8	-	Dimensionless
Bottom Line of Battery-Station ratio	-	16	Dimensionless

Based on the results on the initial condition as listed in Table 4 of both plug-in and battery swap, the system capacity of battery swap system reaches stable state earlier than the plug in model due to a buffer stock of battery between EV and station. Both models show the same vehicle-station ratio (referring the center and right graph in figure 18). The amount of battery is for battery swap is twice as much as required compared to plug in model due to stock battery is needed to be charged at depot.

Graphs in Figure 18 show normal condition of a system growth. However, some of the parameter could be different than our assumption e.g. vehicle lifespan, battery lifespan and station construction delay.

To understand how the more than 1 parameters change could affect the system, Monte Carlo sensitivity could be performed to do that. In this simulation, parameters are put under Random Uniform (min, max) function in which chooses the variable value within the minimum and maximum limit set by the user randomly under uniform probability [23]. The result of system behavior is shown as below under different uncertainty of 50%, 75%, 95% and 100% region. Number of simulation is set as 1000.

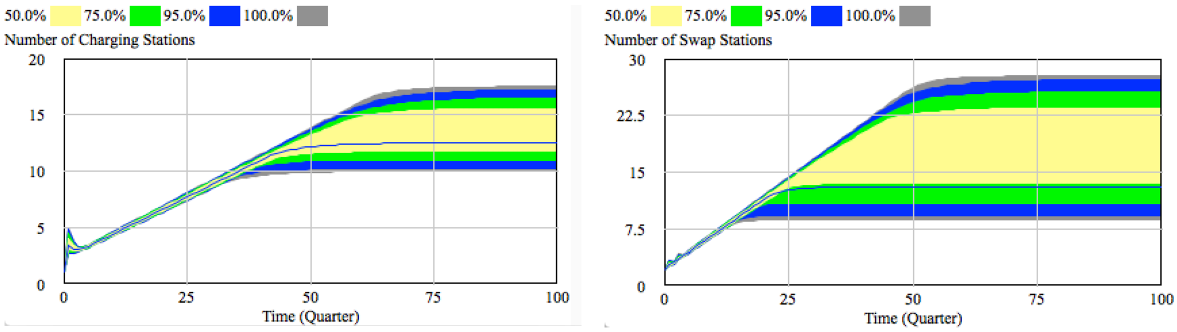

Figure 20: A Monte Carlo simulation on behavior of number of station increase in reaction to vehicle and battery lifespan uncertainties. (left: Plug In model, right: Battery Swap Model)

As the structure of operation for both models is very similar, the behaviors are about the same but a slight difference on uncertainty region. The wider range of 50% uncertainty region in which means the system is more predictable against uncertainties. 100% uncertainty region covers the boundary of system behavior.

Model testing of comparing vehicle ownership model and vehicle leasing model are more interesting as the behavior is expected to be very different due to the different structure of the model. The accumulated cash flow projection of both vehicle ownership sales and leasing models are shown as below.

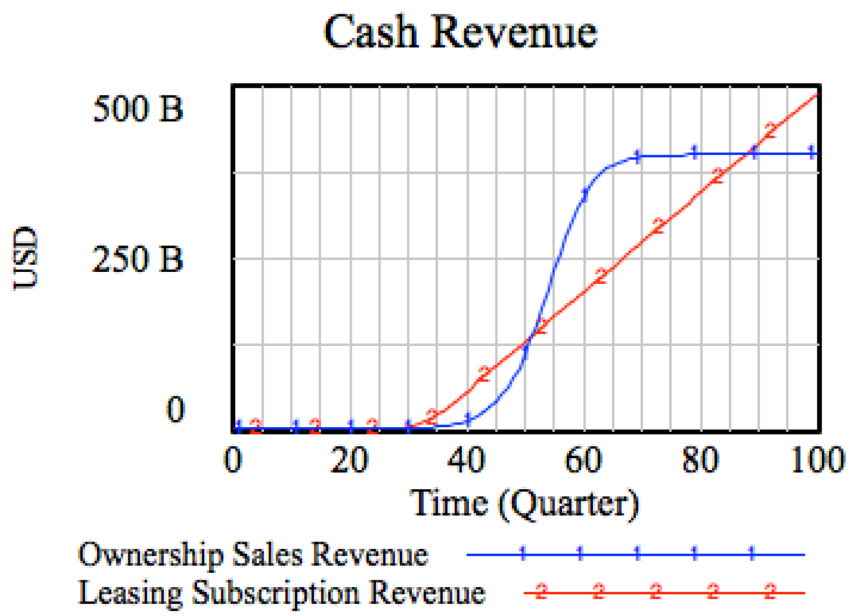

Figure 21: The accumulated cash for both ownership model (blue) and leasing model (red)

Table 5: Parameter Input for Model in Figure 16 and Equation 2

Variables	Ownership	Leasing	Unit
Target Market	2	10	Million People
New Target Market	8	-	Million People
Advertisement	3	3	Dimensionless
Adoption Fraction	0.1	0.2	Dimensionless
Promotion	-	0.5	Dimensionless
Product Lifespan	40	-	Quarter
Lease Period	-	4	Quarter
Sales	40000	-	USD
Subscription	-	1000	USD/Quarter

The cash flow is explained as the stated hypothesis in Table 3. Vehicle ownership model experience lower adoption fraction thus, the cash flow is slower but at high magnitude as vehicle sales price is way higher than lease price. Ownership model experiences the S shape adoption curve every time customers follow the adoption curve on one product. On the other hand leasing model cash flow take off faster at linear rate as leasing is lower risk for subscriber. Existing subscribers continue replenish the potential market. Vehicle leasing company continues making money on the stock of subscribers.

Chapter 5: Model Use for System Design

5.1 Application Background

The model presented in the previous sections is used for designing a new system for mobility systems and energy storage system [24]. In this application, the background is a battery swappable highway electric bus in Malaysia.

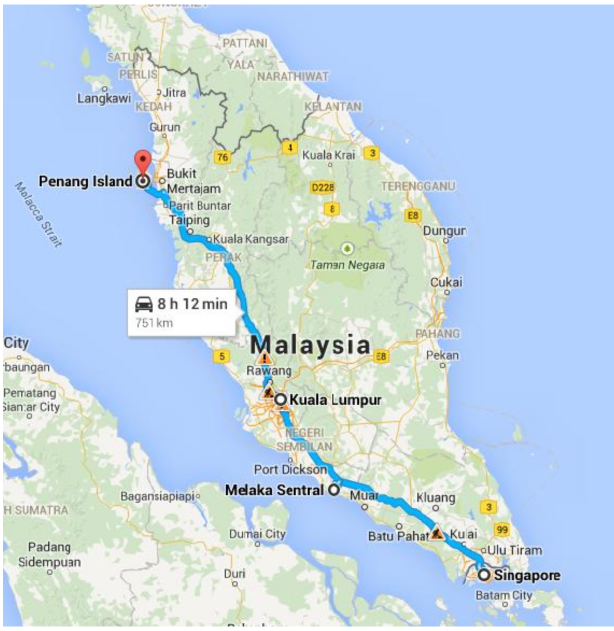

Figure 22: Map view of Express Bus Route in NSE, Malaysia (Source: Google Map)

Value Proposition:

Current electric buses are mainly designed to cycle the city due to their range limitation and long charging time. With battery swapping, the potential of electric bus can be unleashed to serve long distance highway bus which captures more revenue on longer distance with cheaper operating cost of electric power. Battery Swap model also opens another opportunity for swap stations along the highway to implement renewable energy power generation by having their depot batteries for energy storage.

5.2 Reference Mode:

Table 6: Baseline Data for System Parameter in 3 Cases: Optimistic, Practical and Conservative

	Case		
Parameters	**Optimistic**	**Practical**	**Conservative**
Number of Passenger	10000	10000	10000
Number of Bus	66.7	83.3	100.0
Number of Battery	133	208	300
Number of Swap Station	33	52	75
Investment (USD)	102933333	152500000	211600000
Quarterly Revenue	4500000	4500000	4500000
Cost	733333	1125000	1600000
Profit	3766667	3375000	2900000
Breakeven (Quarter)	27.3	45.2	73.0

Three Cases are used as model baseline reference. Optimistic Case is based on least amount of investment needed for the system with minimum amount of stock. Practical Case accounts some buffer to the system to be operation while Conservative Case is built upon worse case scenario by having extra 50% of the system capacity to accommodate the same amount of passenger compared to Practical Case. This results the double of the investment needed and 2.5 times longer period for breakeven.

Table 7: Constant Value and Assumptions for Table 6

Constant	Value	Assumptions
Daily Passenger	100-150	Passenger/day
Bus Battery Capacity	360	kwh (BYD bus)
Battery Price	200	USD/kwh
Cost of Battery	72000	USD (Battery Price x Battery Capacity)
Cost of Bus	400000	USD (BYD bus)
Cost of Station	2000000	4x Tesla Supercharger Cost
Battery-Bus Ratio	2-3	1 Bus should have 2-3 batteries
Battery Station Ratio	4	1 Station can accommodate 4 batteries
Revenue	450	USD/quarter (fuel cost replacement)
Bus Operating Cost	1000	USD/quarter
Station Operating Cost	20000	USD/quarter

Table 6 and 7 are the basic reference for quick evaluation of a battery swappable electric bus system to put in Malaysia. The constant values are obtained from price of currently available technology such as BYD Electric Bus specification, Tesla Motors Battery and Super Charging Network. Table 6 shows how quick this system breakeven but it is hard to consider the dynamics of the system such as the delay of the system, different lifespan of stock, time value for money. In this research, a model is developed to show all the relevant details in operations and finance in one picture and the dynamics of the system is simulated extensively based on the change of assumptions.

5.3 Model Boundary:

Table 8: Model Boundary Chart

Endogenous Variables	**Exogenous Variables**	**Excluded Variables**
Number of Passengers	Cost of Electric Bus	CO2 Emission
Average user per bus	Cost of Battery	Oil Price
Number of Bus	Cost of Swap Station	
Average bus per station	Cost of Administration	
Number of Battery	Cost per km	
Standard Battery Charging Time	Revenue per km	
Number of Swap Station	Battery Degradation	
Average Battery per station	Electric Bus Degradation	
Investment	Battery Size	

This table is essential to tell what variables are being considered in the model. Model user could quickly find out what are the parameters they need to access in the model.

5.4 Model Subsystem Diagram

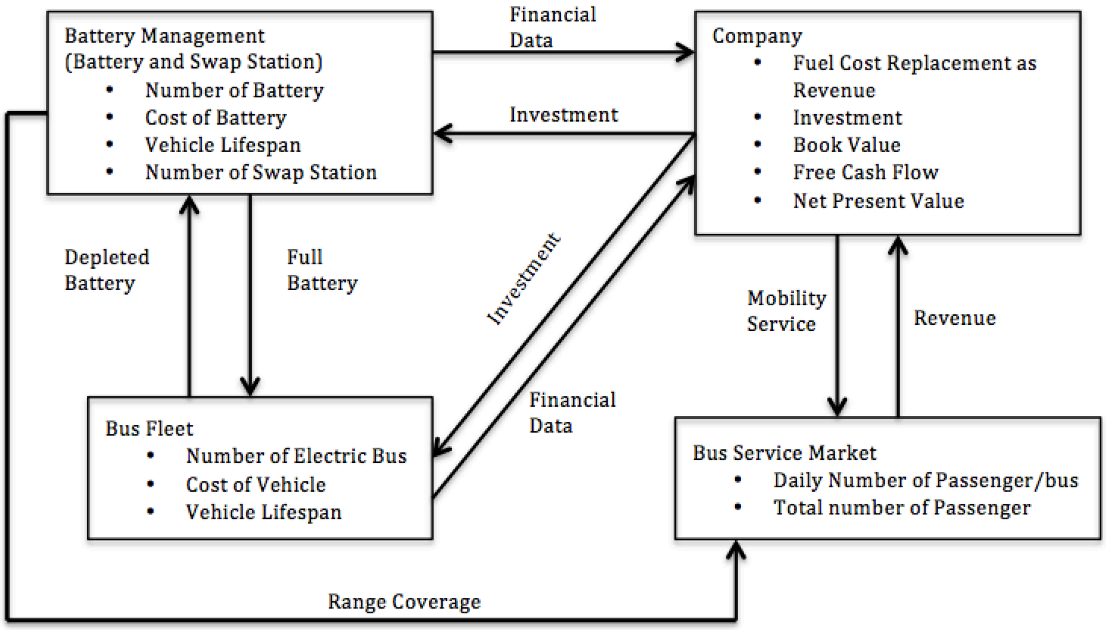

Figure 23: An abstract view of model to be developed.

Subsystem Diagram shows how the subsystem interacts with different segments of the model without needing the proficiency of SFD.

5.5 Model Overview:

In this system there are two models: operation and finance. Operational Model includes the variables of the physical system namely “Electric Vehicle”, “Battery” and “Swap Stations”. Financial Model links the information of physical and its inflow to “Cash”, “Book Value” and “Net Present Value (NPV)”. In this stock and flow diagram, the physical systems with different life spans is modeled as to know how it affects the cash flow, the change of book value and the projected NPV.

5.6 Model Formulation:

An overall model is a combination of passenger adoption model, electric bus battery swap operation model and financial evaluation model as shown in Section 4.

The passenger growth model in figure below shows that passenger moves from target market to non-regular passenger and then convert to regular passenger. The growth model affects the operation in such growth of customer accelerate the rate of bus increase meanwhile the feedback of more station construction also increases the adoption fraction of the customer due to more stops are available in more places.

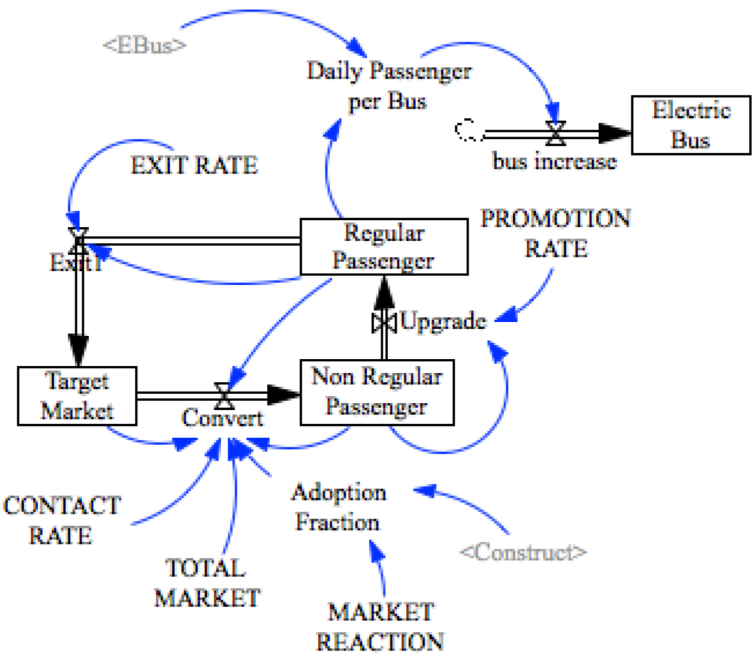

Figure 24: Passenger growth model includes feedback to and from the operation.

The operation model of battery swapping e-bus is shown in figure below is a more sophisticated model than the baseline. All three physical stocks such as buses, batteries and stations have different lifespan, production delay. The baseline is unable capture the dynamics of stock flow in which will affect the scalability of the system for financial evaluation.

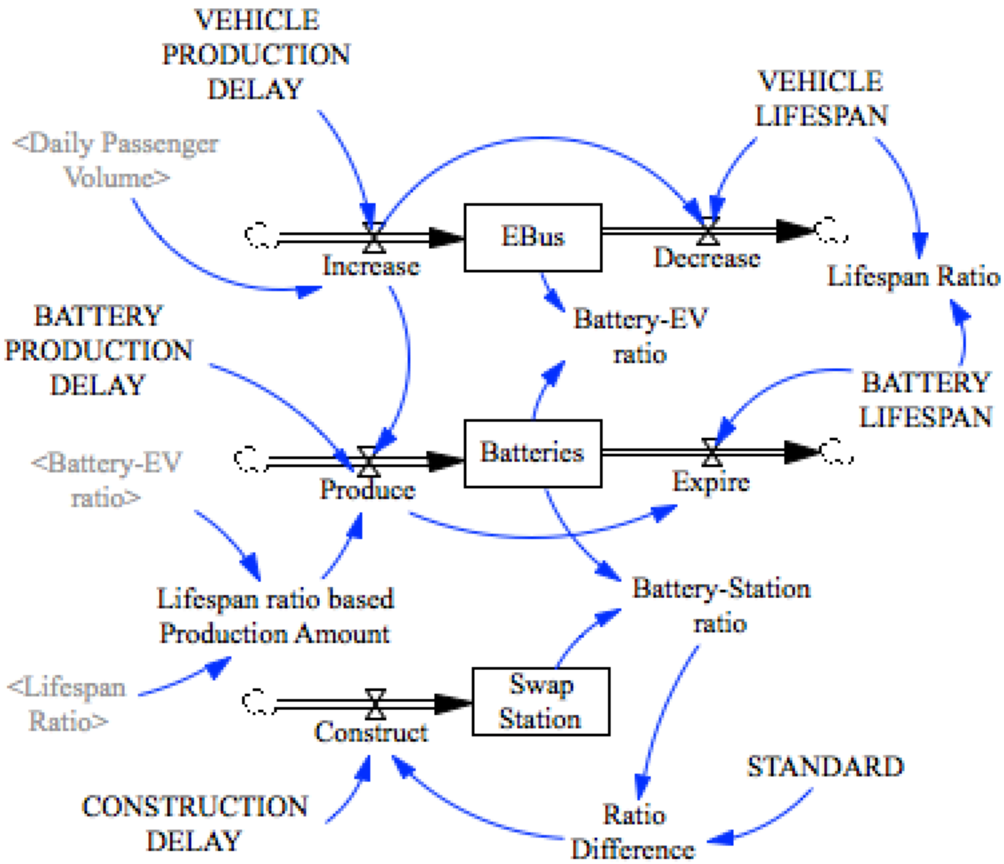

Figure 25: Stock and Flow Diagram of Battery Swapping Electric Bus Operation Model

Financial evaluation is crucial in this model as it capture the perception of people over the asset depreciation and time value of money. Although this accounting is commonly done in business evaluation, this model integrates the operation with financial model in one graphical view showing all the relationships of feedback and delay with other subsystems.

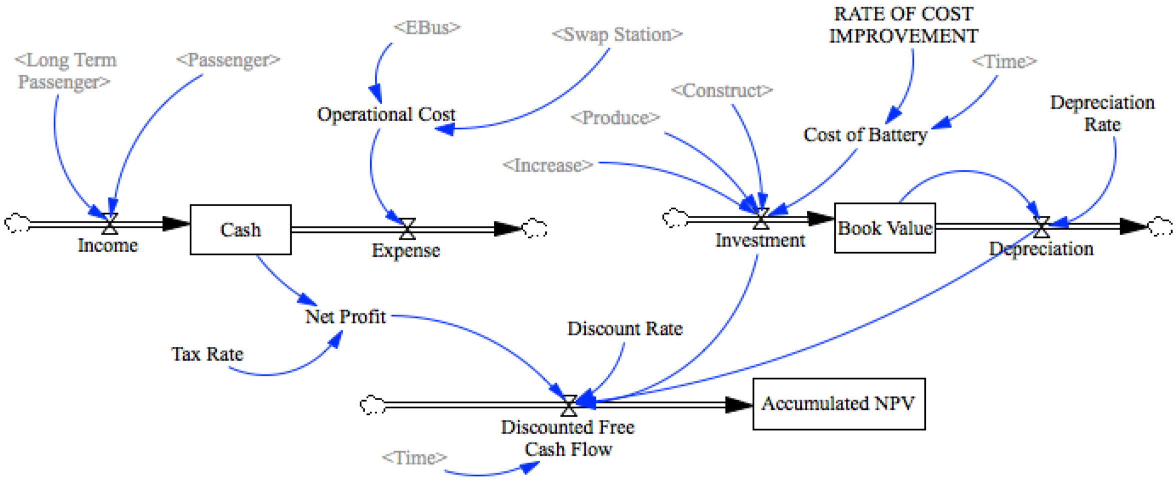

Figure 26: Financial Model for Business Evaluation

5.7 Model Result

This section will show all the important variables visualized in graphical way to explain the outcome of analysis.

5.7.1: System Growth Visualization

The overview of the model and graphs is shown in the appendix. The growth of passenger, physical stock and cash flow is shown in following graphs.

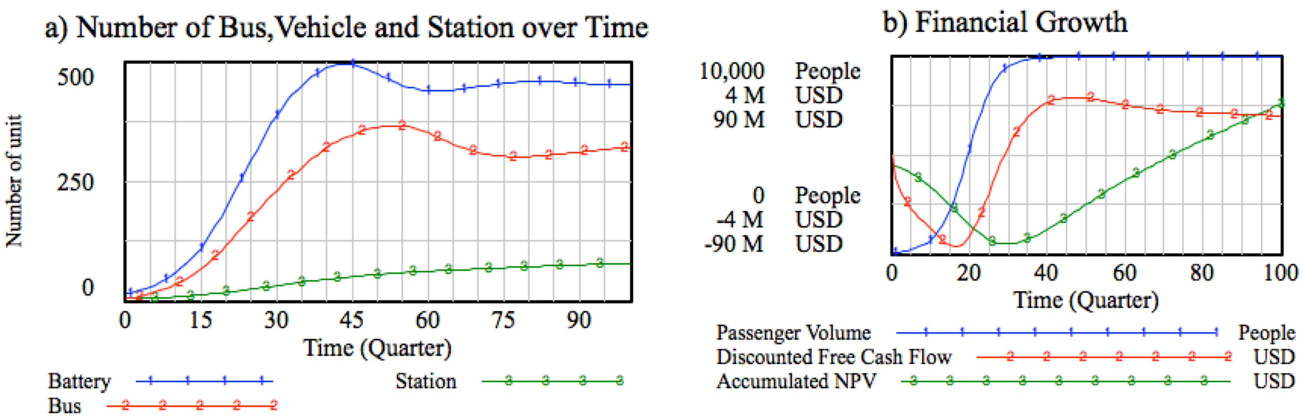

Figure 27: Physical stock (a) and financial growth (b) for a10,000 passengers system capacity

5.7.2: Determine the Critical Scale for Viability

Based on the stock dynamics, the viability of the system is visualized based on a few metrics in operations such as battery-vehicle ratio, battery-station ratio, daily passenger per bus, and metrics in financial model such as discounted free cash flow and net present value.

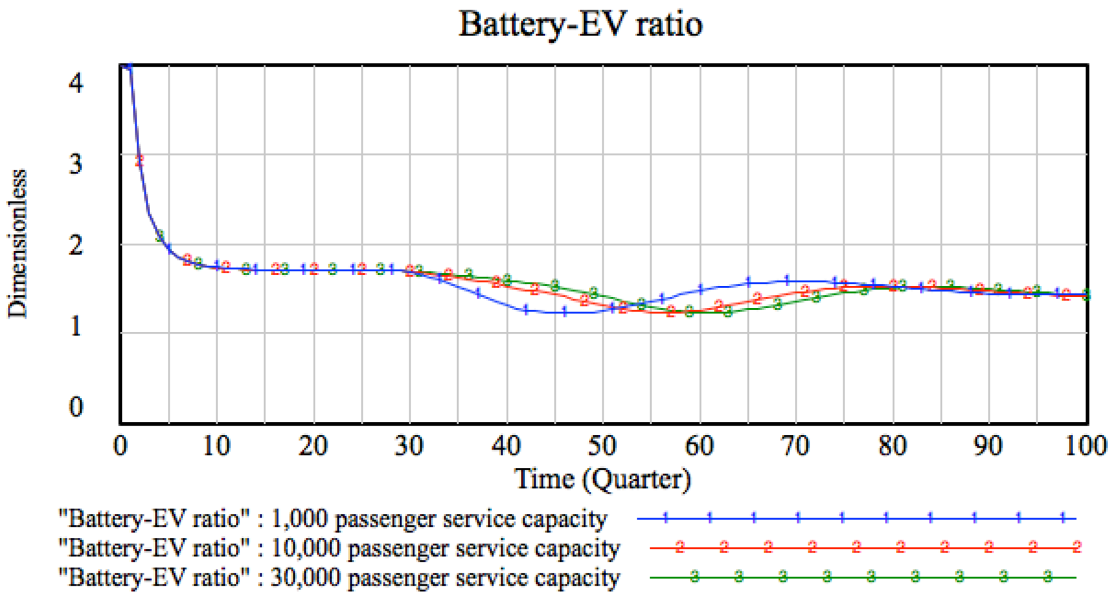

Figure 28: Battery-EV Ratio for different scale of service capacity.

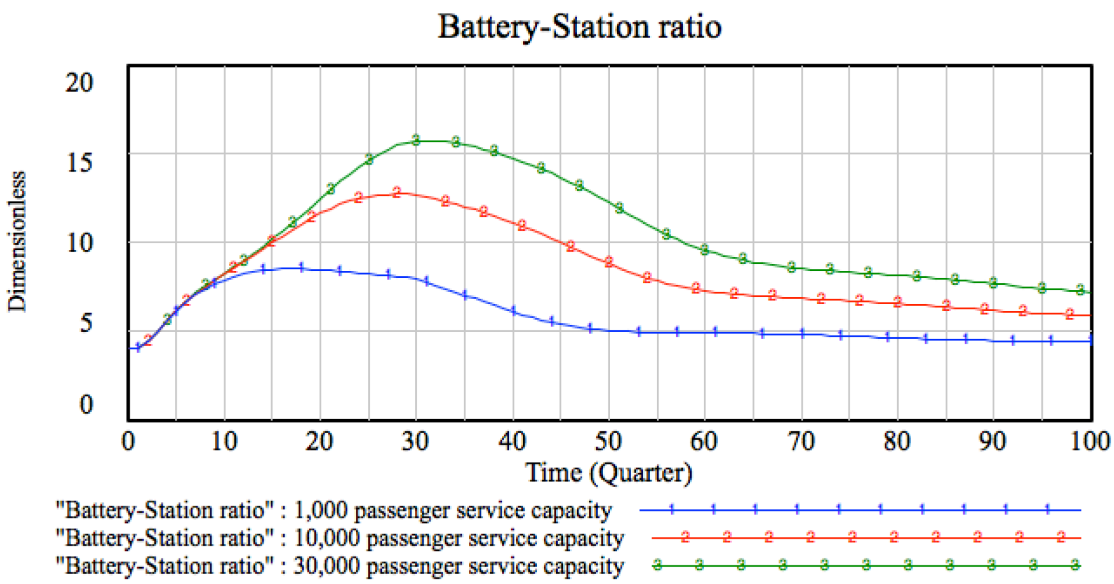

Figure 29: Battery-Station Ratio for different scale of service capacity

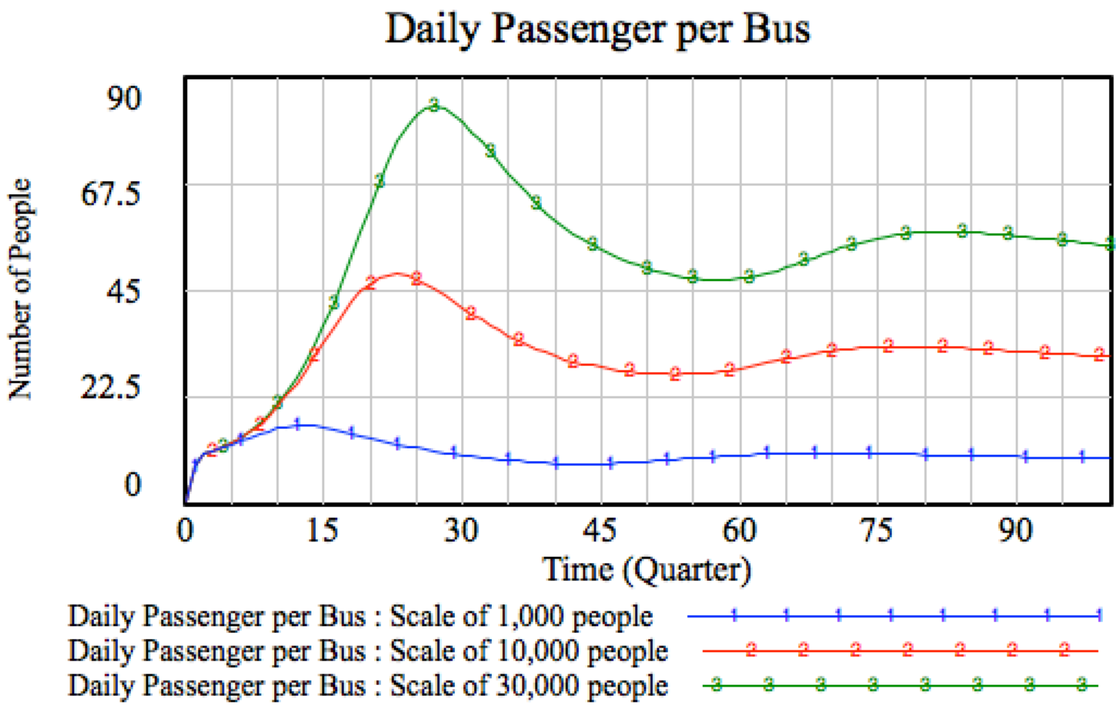

Figure 30: Metrics of Operation for System Scalability

Figure 28 shows the same ratio of battery and vehicle for all 3 scale of service capacity. This is a good indication of each bus has enough share of battery to maintain the operation. Figure 29 shows the ratio of battery and station increases, as the scale of business grows larger provided the charging power is still maintains the same. Figure 30 also shows that the bus operates more frequent as the system grows.

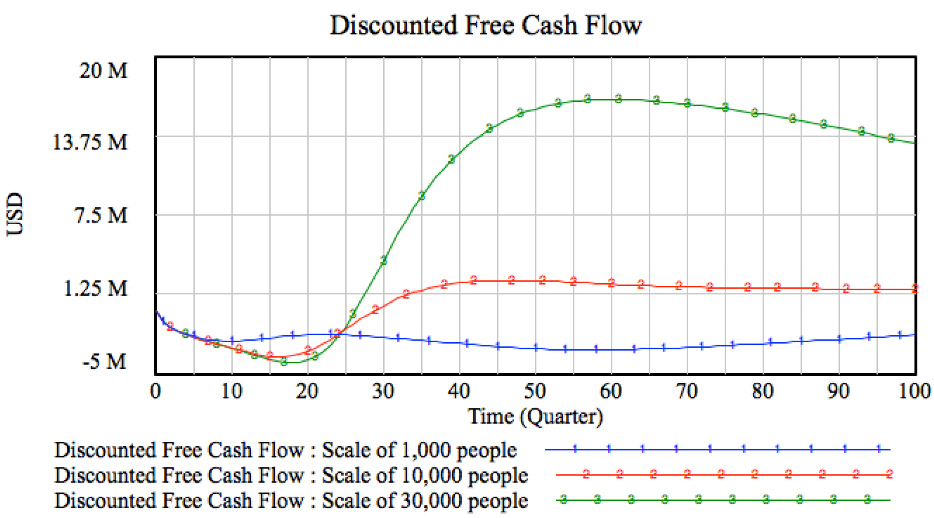

Figure 31: Discounted Free Cash Flow of 3 different scales of system.

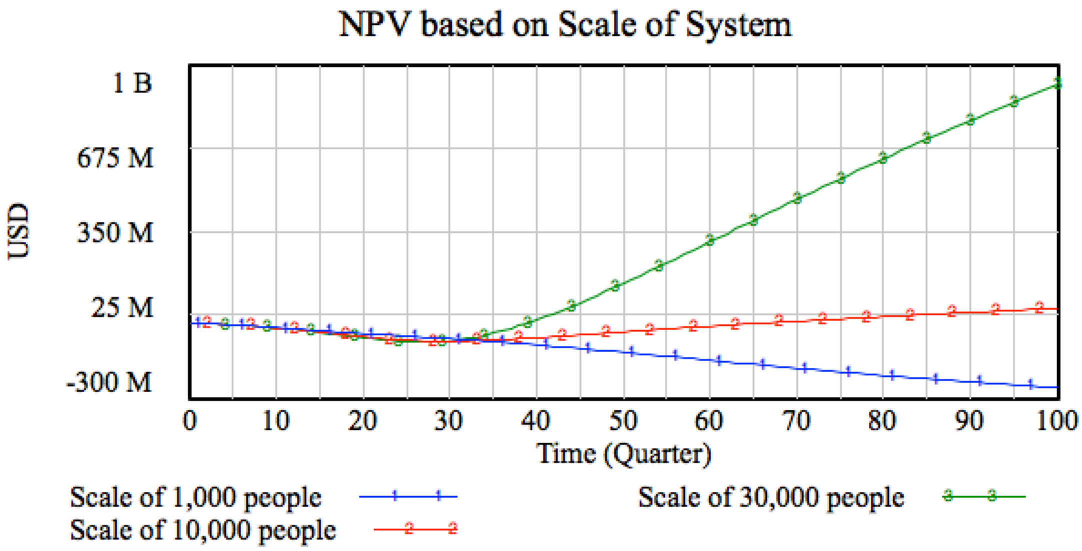

Figure 32: Financial Metric (FCF and NPV) for System Viability based on Scale

Viability of a system is also heavily based on the scale of operation. If operation is big enough to capture more value than the cost of provide that value, the system is said to be viable at larger scale. Likewise if the system is smaller enough for not incurring too much cost as it grows bigger, then the system is said to be viable only as pilot project. Figure above shows the modeled electric bus system with battery swap system is more viable at above 10,000-passenger scale. Thus, that is the critical scale for business viability.

5.7.3: Parameter Uncertainty Check by Monte Carlo Sensitivity Test

Challenging the model assumptions is a form of model validation. Monte Carlo Sensitivity Test is be used to simulate multiple parameter uncertainties. In this test, 3 main uncertainties such as vehicle lifespan, battery lifespan, and battery cost improvement are examined. The results are shown in terms of certainty bound of 50%, 75%, 95% and 100% in Figure 28. Model user can make use of the 50% region and the 100% region. This 50% certainty region means of all the 1000 simulation trials run at different parameter values at random, 50% of the time happened in this region. The bigger the region is, the more control you can anticipate. Other than the 50% certainty region, the 100% region shows the boundary of the system behavior.

Table 9: Input Range of Uncertain Parameters

Uncertain Parameters	Value Range	Unit	Remarks
Rate of Cost Improvement	1-2	% per Quarter	Estimated 8% cost reduction by industry
Market Reaction	0.28-0.35	Dimensionless	Coefficient for Adoption Rate
Vehicle Lifespan	32-48	Quarter	6 years to 12 years (typical vehicle value)
Battery Lifespan	20-32	Quarter	5 years to 8 years (battery warranty)

Table above shows the range of input value for the uncertain parameters. These uncertainties subsequently affect the financial evaluation of the system and the financial results are shown in the graphs below. The yellow region is what the modeluser should concern the most. This 50% certainty region means of all the 1000 simulation run at different parameter values, 50% of the time happened in this region. The bigger of this region, the more accurate the estimation is. Other than the 50% certainty region, the 100% region shows the boundary of the system behavior.

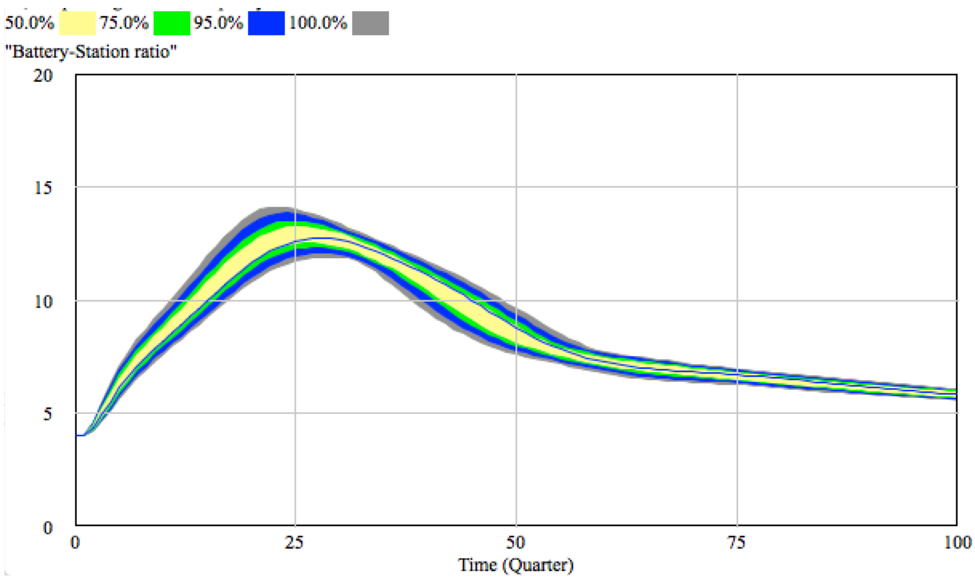

Figure 33: Sensitivity Change of Battery-Station ratio under uncertainties.

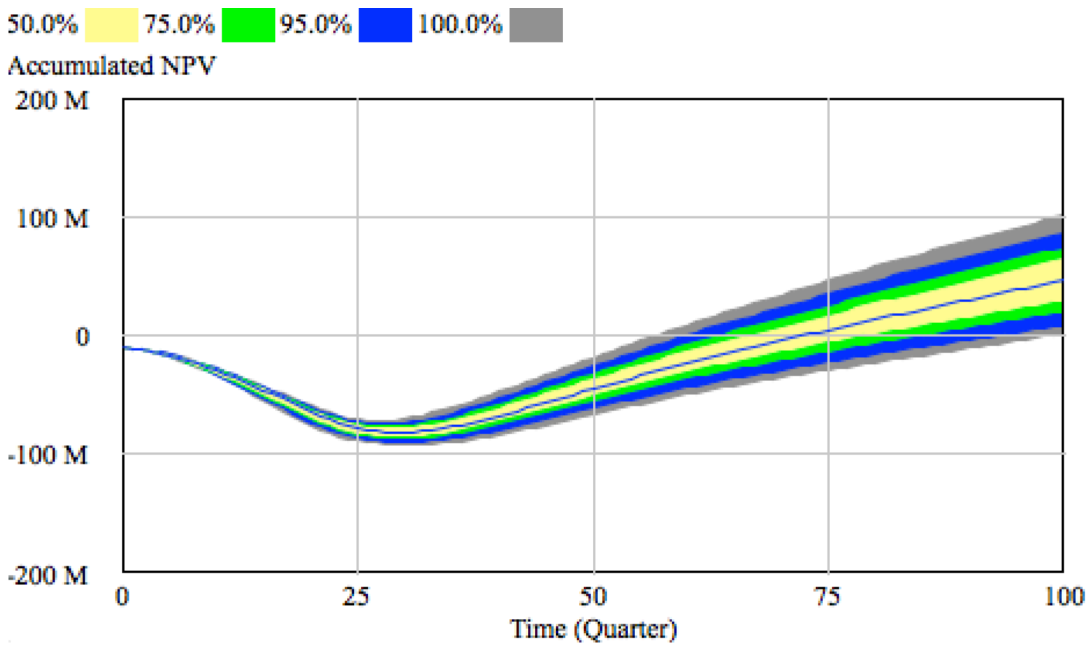

Figure 34: Sensitivity Change of Financial Metric under uncertainties.

Both figures above show insignificant changes due to multiple uncertainties of the system. The 50% certainty regions remains the biggest region, therefore the model user can be more confident in determining the viability of the system is very likely to achieve positive NPV at 65th to 85th quarter.

5.7.4: Model Overview and Variable Explanations

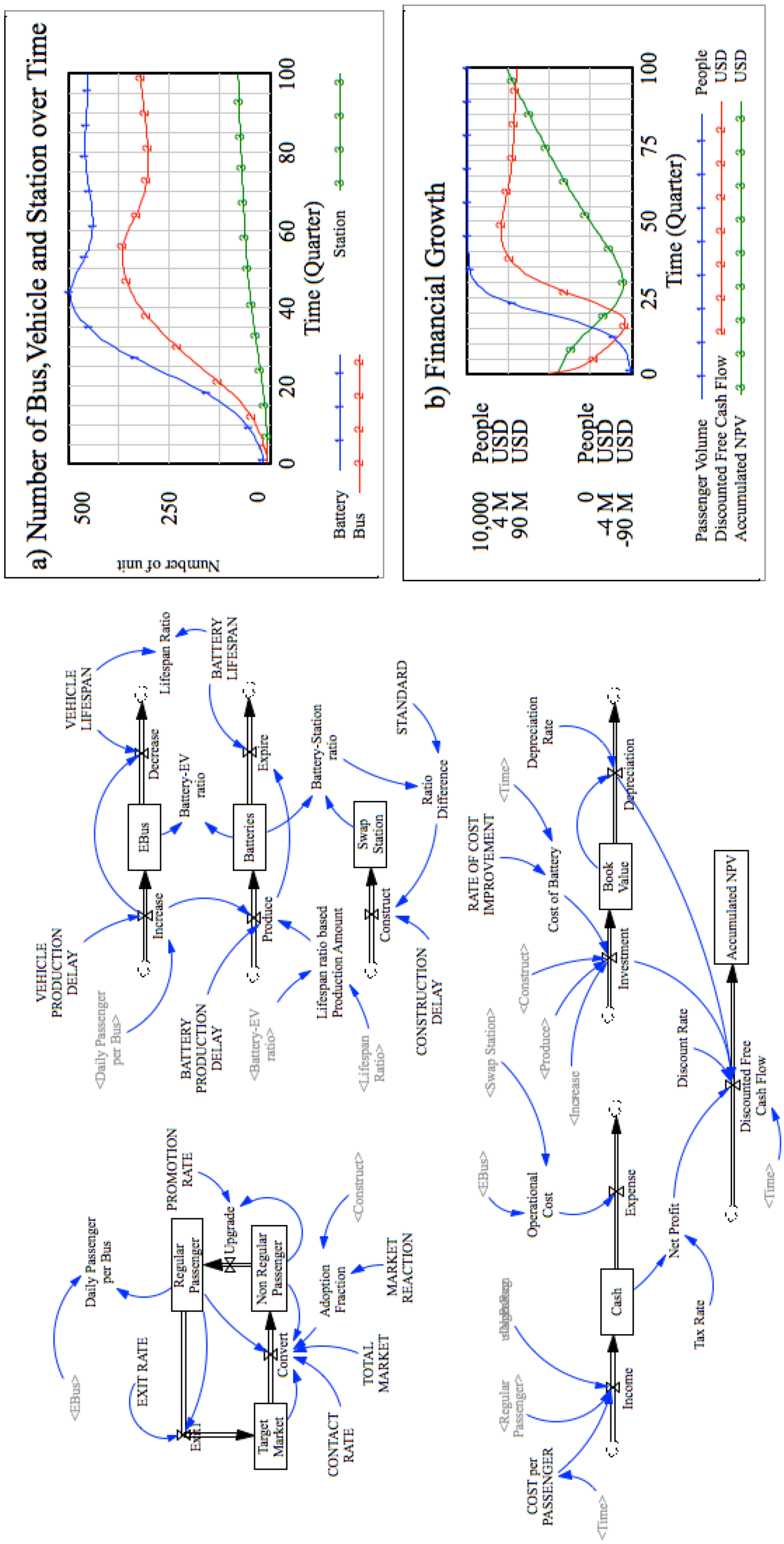

Figure 35: Model Interface

The model overview shows the stock and flow diagram on the left; two overall operation and financial growth graphs on the right. This serves as a quick glance on the dynamic behavior of the business system. The following graphs are the result of each variable in the model. The following will explain the some variables that is not covered in the previous section.

Passenger Growth Model:

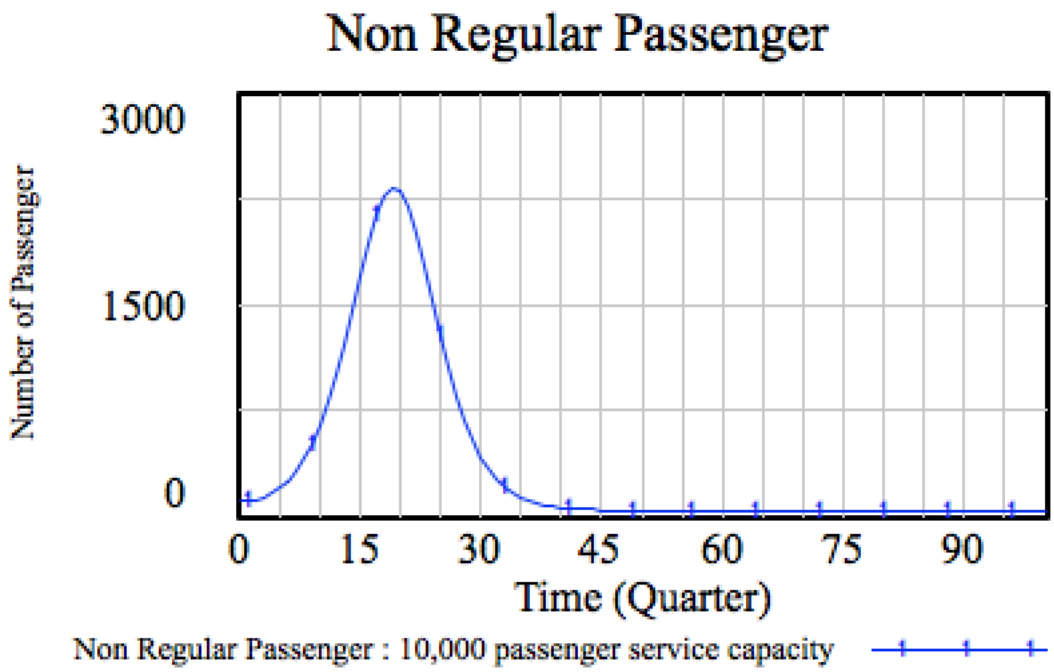

Figure 36: Number of Non-Regular Passenger over time

The non-regular passengers are modeled as influx of new passenger adopting this service. The stock has a temporary peak of at the beginning of adoption before becoming long-term passenger. After awhile the stock will become long-term passenger stock as shown at the figure below.

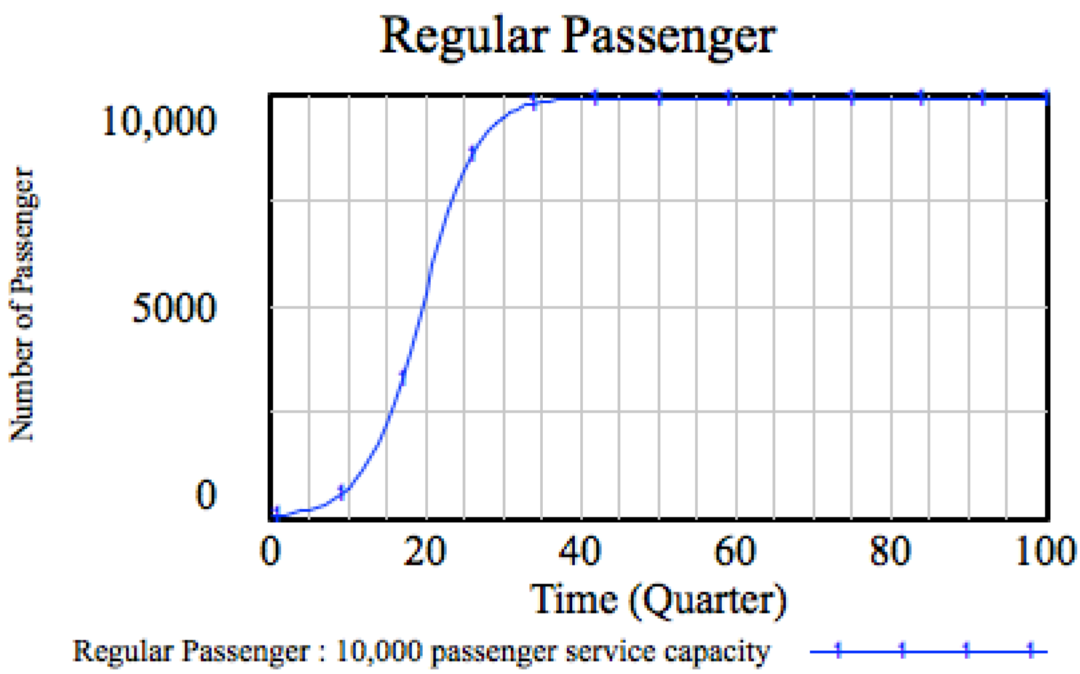

Figure 37: Number of Regular Passenger over time

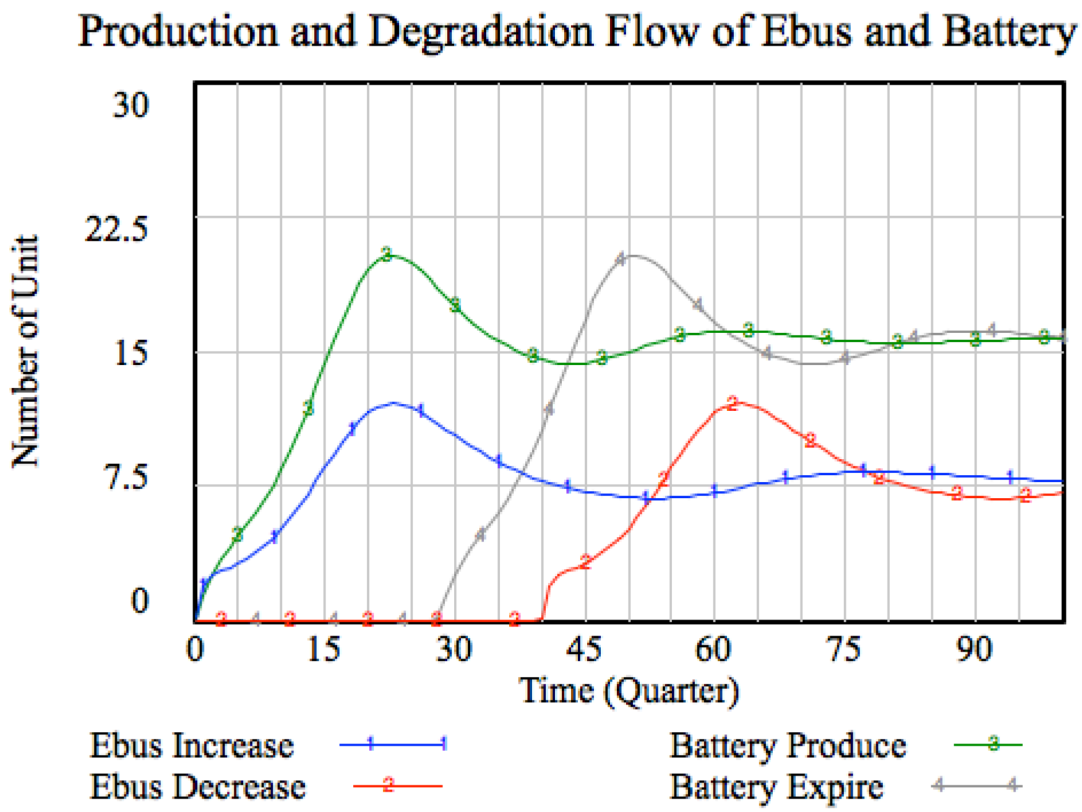

Figure 38: Production and Degradation Flow of Ebus and Battery

All of them are modeled in terms of pipeline delay. The figure above shows the flows of Ebus and Battery are in different period of time due to the difference of the lifespan (28 quarters for battery and 40 quarters for Ebus). The growth of the system is also approaching to a steady state from the observed key metric show at figure below. The Battery-EV ratio stables at 1.4 while Battery-Station ratio plateau at 6.

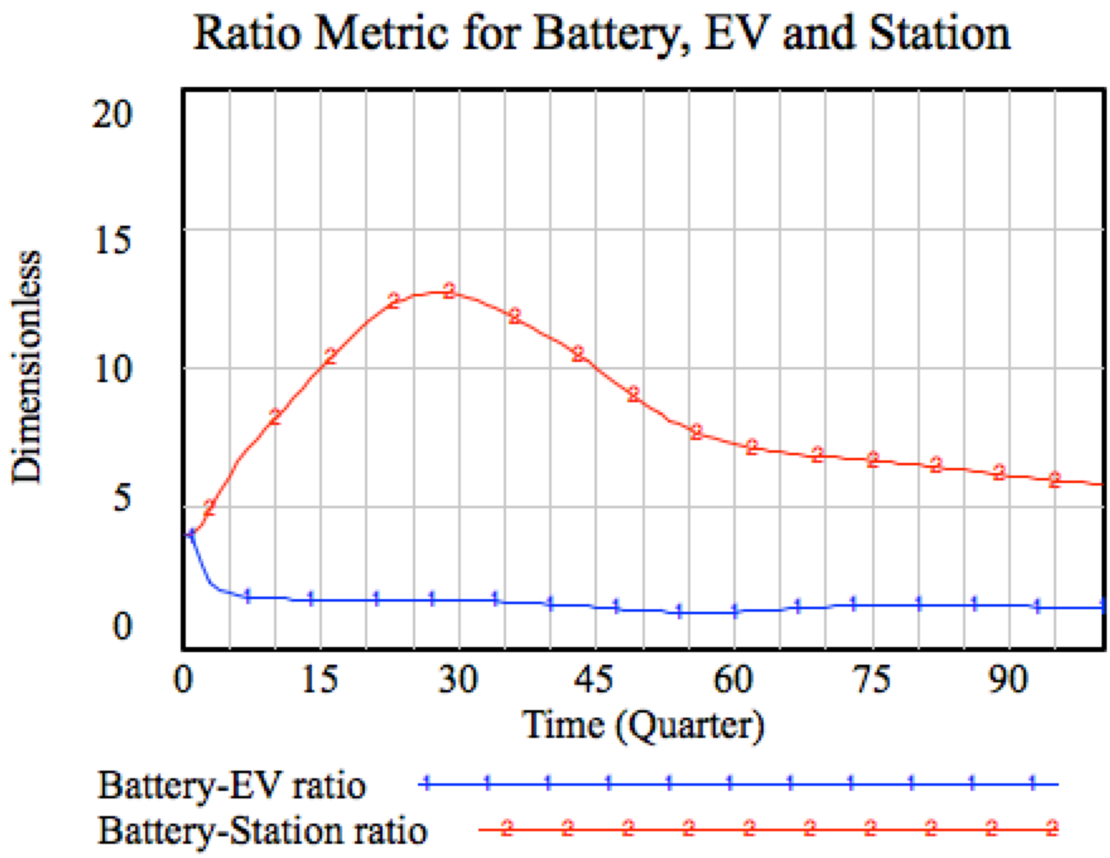

Figure 39: Ratio Metric for Physical Stock

The income statement model is simply integrating the difference of revenue and expense. The stock is the cash profit. The gradient of the profit over time is proportionate with the profit margin that is the difference between revenue and expenses.

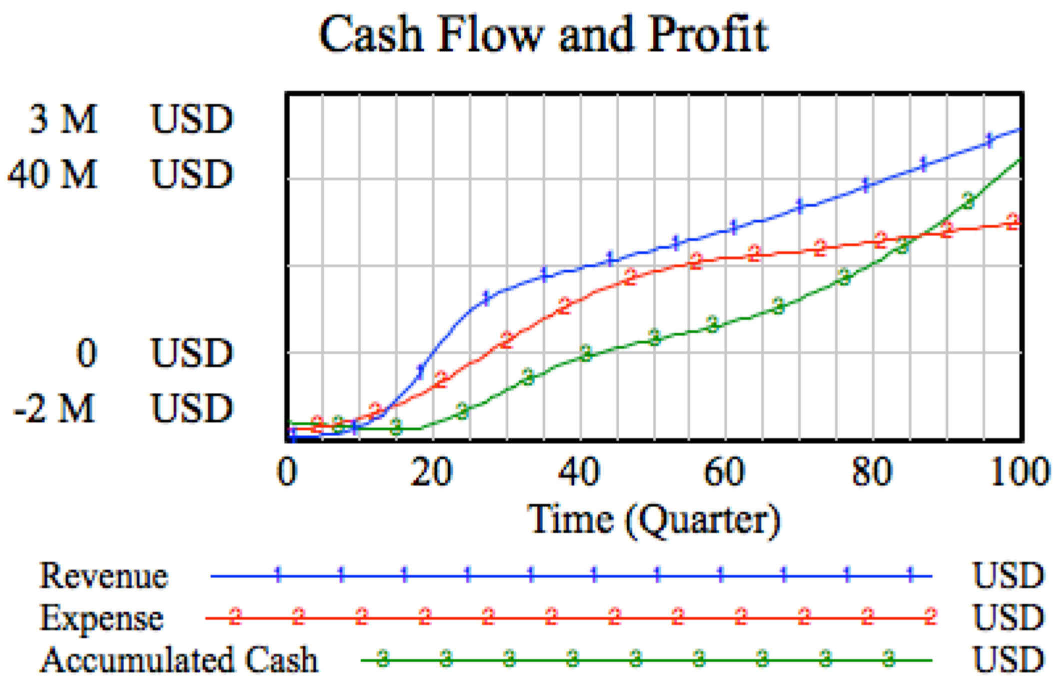

Figure 40: Cash Flow Model

The balance sheet model accounts incoming investment for asset building and outflow of book value as depreciation. Book value as a stock means the value of asset that the company holds at that period of time in which could be liquidated. It does not mean much unless the company declares bankruptcy and is required to sell off its asset for debt payment. However, this balance sheet model is needed for cash flow model for the calculation of Free Cash Flow and Accumulated Net Present Value.

Discount Rate is the key metric here for investors to identify is the business is worth putting money in. For the calculation of free cash flow or net present value, discount rate is an indication of perceived value of future money. 1 USD today means a lot more than 1 USD in 10 years later due to inflation or opportunity cost that the current 1 USD can do e.g. invest in a better business or solve some problem today. The table below shows the compound discount rate for appropriate assessment of business.

Table 10: Compound Interest Rate over 100 quarters

Quarter(th) / Quarterly Interest	1	5	10	20	40	80	100
0.010	1.010	1.051	1.105	1.220	1.489	2.217	2.705
0.015	1.015	1.077	1.161	1.347	1.814	3.291	4.432
0.020	1.020	1.104	1.219	1.486	2.208	4.875	7.245
0.025	1.025	1.131	1.280	1.639	2.685	7.210	11.814
0.030	1.030	1.159	1.344	1.806	3.262	10.641	19.219
0.035	1.035	1.188	1.411	1.990	3.959	15.676	31.191

If a business provides a quarterly interest of 2%, every dollar you invest in this company will give you a return of 1.486 USD (48.6%) in 5 years or 20 quarters. Generally, investor or loan dealer will look at the interest rate of a business can provide. Therefore, in order to evaluate business viability, the key metric is to see the Discounted Free Cash Flow and Accumulated Net Present Value. For a new business, Net Present Value will start from negative due to initial investment to kick start business operation before revenue comes in to cover expenses. Figure below shows a how free cash flow and accumulated net present value behaves throughout 100 business quarters.

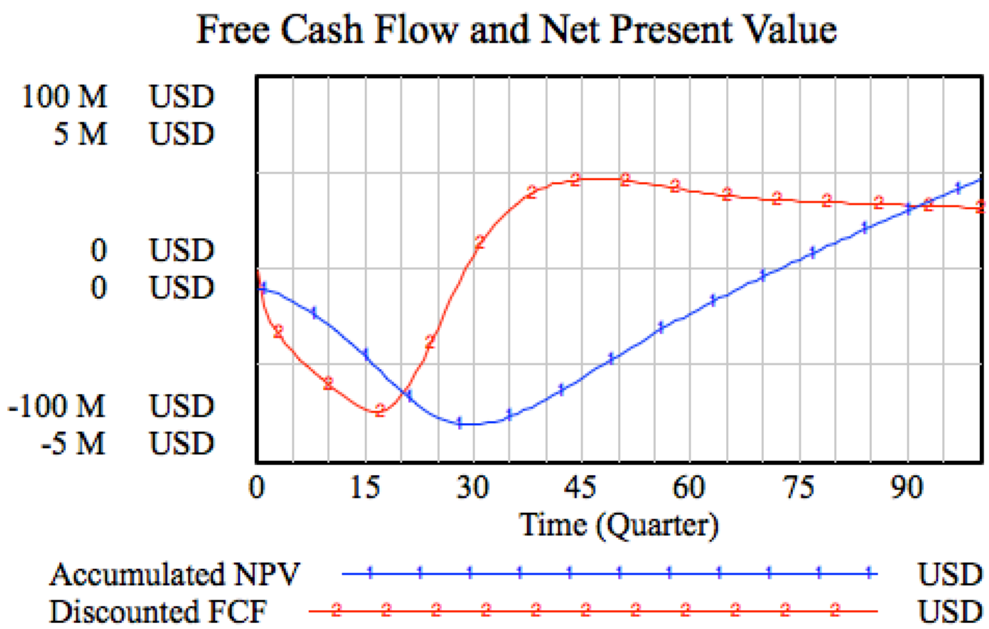

Figure 41: Discounted FCF and Accumulated NPV

This model is based on the cost improvement of battery model as shown in figure below. By assumption of 6-8% cost reduction annually, the battery will be cheaper in the future. The low cost of battery will decrease cost disadvantage to battery swap system in which requires more battery at depot for swapping.

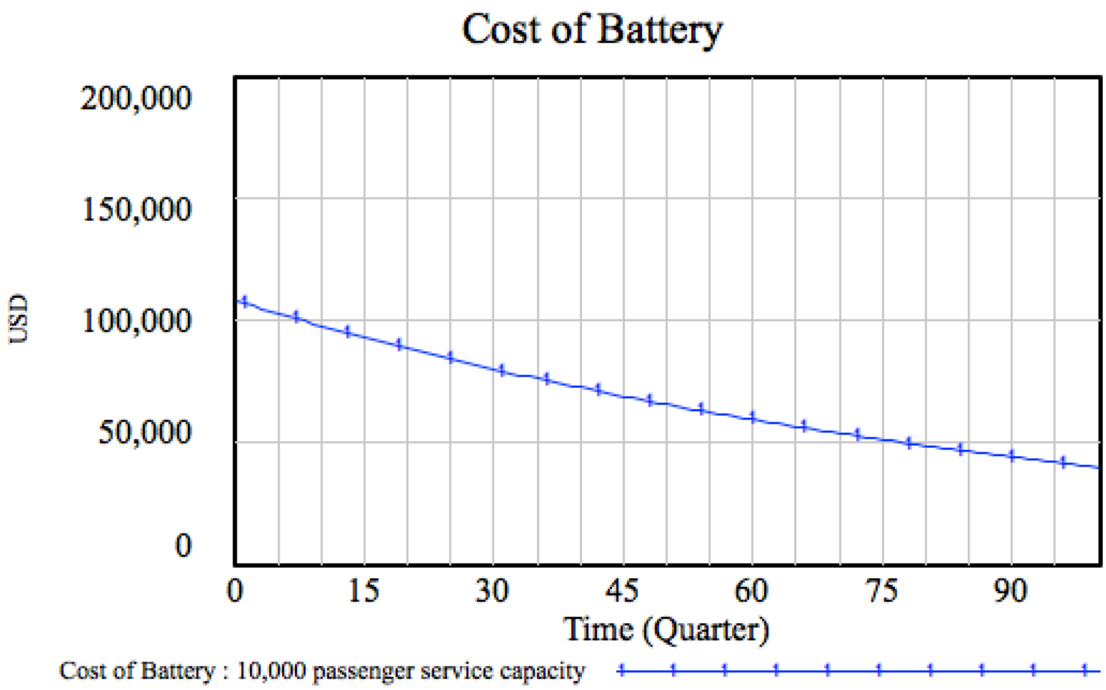

Figure 42: Cost Curve of Bus Battery

The dynamics of model is much more meaningful that the quick reference of the baseline data. By having a model, the business system viability is evaluated with much more fidelity with the inclusion of material delay, perception value with time, feedbacks and non-linearity. The goal of the model is to increase confidence of decision making in making investment and managing business.

5.7.5 What if - Scenario Analysis

There are assumptions or parameters in which could change radically due to unable to predict or it could be happen due to unlikely event like the "black swan" and highly volatile events such as market reaction. If these parameters are contained in the model, a scenario analysis is necessary to be performed to understand how the system will react to those unpredictable influences.

In this model, passenger adoption and battery lifespan are the variables that are unpredictable due to human behavior and disruptive technology breakthrough. A 2x2 matrix is developed to visualize 4 scenarios that could be happened as show in the figure below.

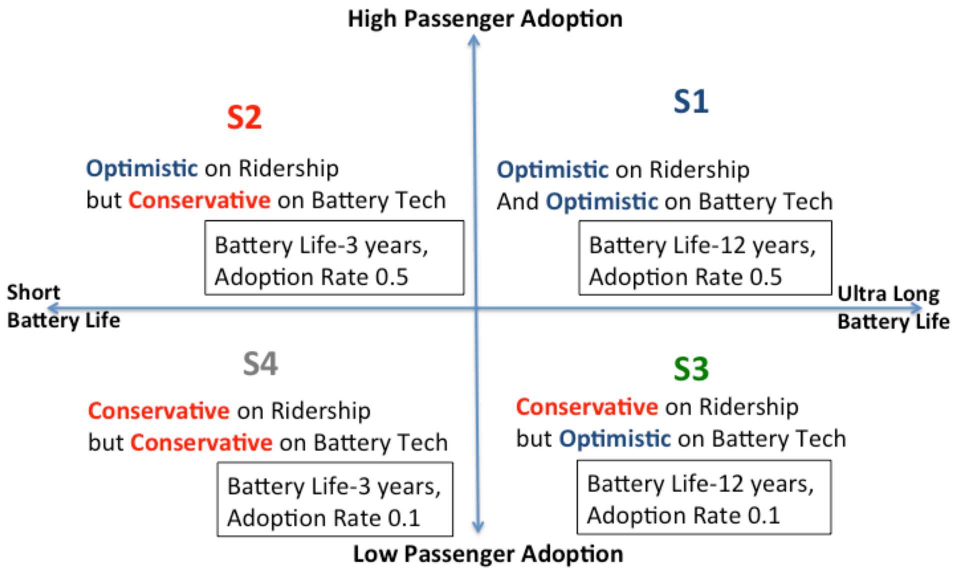

Figure 43: 2x2 Matrix for Scenario Analysis

Based on the conservative and optimistic view on both ridership and battery lifespan breakthrough, the result of scenario analysis is shown in the figure below.

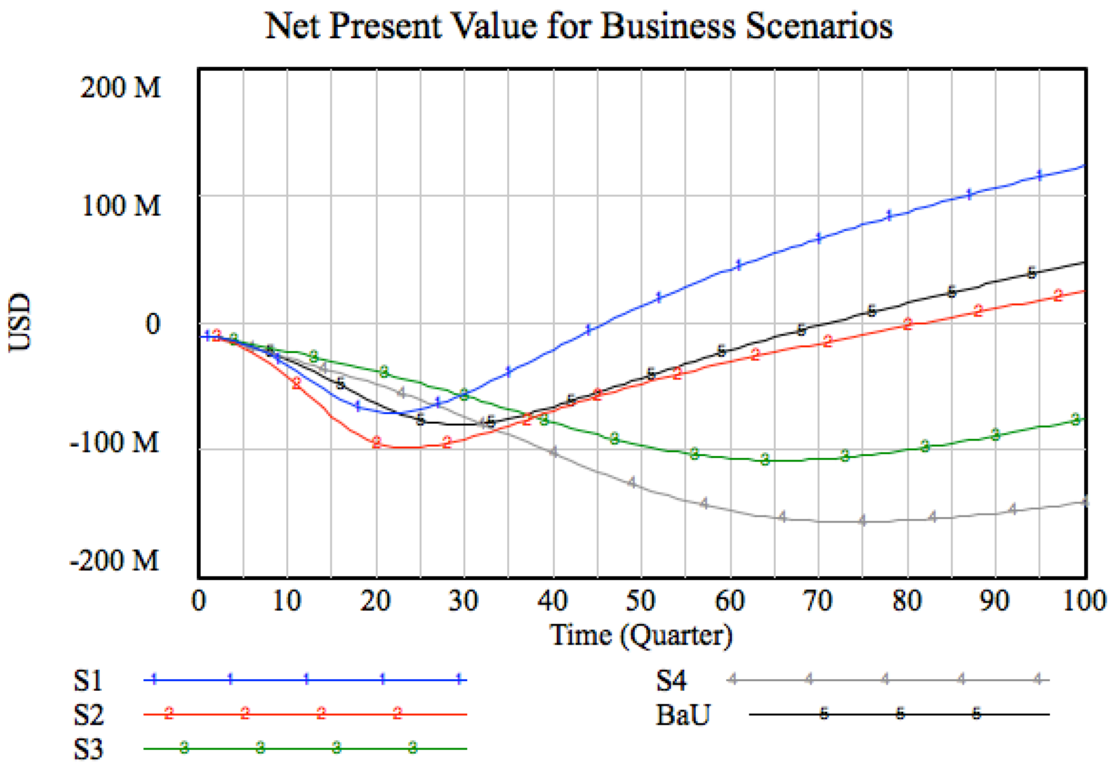

Figure 44: NPV indication for Business Scenarios

The image above shows the viability of the system as indicated by their NPV. Scenario 1 (S1) in which has highest adoption rate and long battery lifespan shows the best NPV as it has the shallow "valley" and highest peak, indicating that the business will be NPV positive at 45th Quarter. High adoption rate allows business to recuperate investment with more revenue over the period of the time. Longer lifespan of battery reduces the need to invest more money to buy new batteries as the old batteries degraded. Scenario 2 (S2) shows a similar curve to S1 but with deeper "valley" and lower "peak" due to more investment is needed for new batteries. Scenario 3 (S3) and scenario 4 (S4) shows the NPV curve will never be positive within 25 years due to low passenger adoption. Business-as-Usual (BaU) shows the NPV curve under normal condition. From this analysis, it is deduced that adoption rate is the high leverage factor for business viability. The technological advancement of battery lifespan accelerates the breakeven period

Chapter 6: Discussions and Conclusions

6.1 List of Discussion Points from Previous Sections

Discussion 1: Battery swapping is needed when utilization rate is higher than the charging time. (Page 41)

Discussion 2: Battery stocks acts like a buffer for fluctuation charging demand. (Page 41)

Discussion 3: Improvement of charging capability of battery is limited by power supply capability but lifespan improvement will help. (Page 41)

Discussion 4: Subscriber adoption is a more important factor than battery lifespan for business viability. (Page 71)

Discussion 5: The electric bus system has a critical mass of 10,000-passenger scale. Therefore pilot project below that scale doest not demonstrate system viability. (Page 70)

Discussion 6: The electric vehicle system has a typical archetype in which to address limitation of power supply and material resources. (Page 38)

Discussion 7: Often solutions for electric vehicle such as battery pack increase, charging capability upgrade only increase the dependency on using free fast charging network unless there is a cost of usage in which will reduce the incentive of use the network extensively. (Page 38)

Discussion 8: Vehicle-Station Ratio and Battery-Station Ratio are the key metrics for Plug in Charging Operation and Battery Swapping Operation respectively. (Page 39)

Discussion 9: Vehicle Ownership leasing model gains revenue from customer flow while vehicle leasing model make money through the stock of subscribers. (Page 41)

6.2 Deduced Conclusions

Conclusion 1: Commercialization purpose EV (Electric Bus System) should lead the electrification of transportation system with battery swap due to its high utilization rate and predictable demand. This type of vehicle is normally cost driven instead of aesthetic driven.

Conclusion 2: Electric Bus System in Malaysia is viable is the scale is > 10,000 people capacity, 15 years to breakeven by fuel cost replacement.

Conclusion 3: Critical Mass and Adoption Rate are the business constraints for battery swapping electric bus system.

6.3 Extended use of the model

This model could be expanded beyond electric vehicle system. Basically it is a generic business evaluation model for more than 3 interdependent subsystems in which have different lifespans and production delay. This financial model can be more complex with the addition of debt, account receivable etc. The most distinguished usefulness of the model is its graphical interface of visualizing the system. It feels like a flight simulator for pilot training. Instead of training to fly a plan, this model simulator trains business owners to manage their business to accordingly. Example of other application used could be futuristic electric airplane, magnetic levitation transportation system etc. in which requires a supporting system (i.e Battery system) and a sustaining system (i.e. Charging Infrastructure).

6.5 Limitation and Future work

The model developed in this research has covered the foundation of model development using systems approach. The system is evaluated at the macro level to prove its viability at the broadest sense. As the author of this research, I am also realized that the very limitation lies on system dynamics methodology itself. The future work of this research can be further polished into agent-based simulation to model the smoothness of the operation of the battery swapping bus system by using queuing theory.

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Appendix 1: Model Equations

BATTERY PRODUCTION DELAY=
1.5
Units: Quarter

Battery-EV ratio=
Batteries/EBus
Units: Dimensionless

Accumulated NPV=
INTEG (Discounted Free Cash Flow,
-(INITIAL NUMBER OF BATTERIES*72000+INITIAL NUMBER OF BUS*400000+INITIAL STATIONS*2e+06))
Units: USD

Remark:
*Cost of Battery=USD 200*360kWh=USD 72,000; Cost of Bus= USD 400,000;*
Cost of Station= USD 2,000,000

Adoption Fraction=
MARKET REACTION+0.01*Construct
Units: Dimensionless

Batteries=
INTEG (Produce-Expire, INITIAL NUMBER OF BATTERIES)
Units: Unit Battery

BATTERY LIFESPAN=
28
Units: Quarter

Battery-Station ratio=
Batteries/Swap Station
Units: Dimensionless

Book Value=
INTEG (Investment-Depreciation,0)
Units: USD

Cash=
INTEG (Income-Expense,0)
Units: USD

Construct=
(Ratio Difference*1)/CONSTRUCTION DELAY
Units: Unit Station

CONSTRUCTION DELAY=
6
Units: Quarter

CONTACT RATE=
1
Units: Dimensionless

Convert=
Target Market*CONTACT RATE*(Passenger+Long Term Passenger)/TOTAL MARKET*Adoption Fraction
Units: People

Cost of Battery=
108000*(1-RATE OF COST IMPROVEMENT)^Time
Units: USD

COST per PASSENGER=
100*(1.01)^Time
Units: USD

Remark:
Cost per Passenger means the fuel cost to spend on each passenger. In this model, the revenue comes from fuel cost replacement.

Daily Passenger per Bus=
Long Term Passenger/EBus
Units: People

Decrease=
DELAY FIXED(Increase, VEHICLE LIFESPAN , 0)
Units: unit Vehicle

Depreciation=
Book Value*Depreciation Rate
Units: USD

Depreciation Rate=
0.05
Units: Number (5% per Quarter)

Discount Rate=
0.03
Units: Number (3% per Quarter)

Discounted Free Cash Flow=
(Net Profit+Depreciation-Investment)/(1+Discount Rate)^Time
Units: USD

EBus= INTEG (
Increase-Decrease,
INITIAL NUMBER OF BUS)
Units: Unit Vehicle

EXIT RATE=
0.001
Units: Dimensionless

Exit1=
Long Term Passenger*EXIT RATE
Units: People

Expense=
Operational Cost
Units: USD

Expire=
DELAY FIXED(Produce , BATTERY LIFESPAN , 0)
Units: unit Battery

Income=
Passenger*(COST per PASSENGER/3)+Long Term Passenger*COST per PASSENGER
Units: USD

Increase=
Daily Passenger Volume/2/VEHICLE PRODUCTION DELAY
Units: unit bus

INITIAL NUMBER OF BATTERIES=
16
Units: unit Battery

INITIAL NUMBER OF BUS=
4
Units: unit Vehicle

INITIAL STATIONS=
4
Units: unit Station

Investment=

Increase*400000+Construct*2e+06+Produce*Cost of Battery
Units: USD

Lifespan Ratio=
VEHICLE LIFESPAN/BATTERY LIFESPAN
Units: Dimensionless

Lifespan ratio based Production Amount=
Lifespan Ratio/Battery-EV ratio*3
Units: Dimensionless

Remark
Battery Production Amount is based on Lifespan ratio between vehicle and battery.

Regular Passenger=
INTEG (Upgrade-Exit1,1)
Units: People

MARKET REACTION=
0.3
Units: Dimensionless

Net Profit=
Cash*(1-Tax Rate)
Units: USD

Operational Cost=
EBus*1000+Swap Station*20000
Units: USD

Non-Regular Passenger=
INTEG (Convert-Upgrade,100)
Units: People

Produce=
Increase*Lifespan ratio based Production Amount/BATTERY PRODUCTION DELAY
Units: Unit Battery

PROMOTION RATE=
0.3
Units: Dimensionless

RATE OF COST IMPROVEMENT=
0.01
Units: Number (1% per Quarter)

Remark:
200 USD/kwH, Battery=360kWh

Ratio Difference=
"Battery-Station ratio"-STANDARD
Units: Dimensionless

STANDARD=
4
Units: Dimensionless

Remark:
Initial Ratio of Battery/Station Ratio Target

Swap Station=
INTEG (Construct,INITIAL STATIONS)
Units: Unit Station

Target Market=
INTEG (Exit1-Convert,TOTAL MARKET)
Units: People

Tax Rate=
0.07
Units: Number (7% per Quarter)

TOTAL MARKET=
9900
Units: People

Upgrade=
Passenger*PROMOTION RATE
Units: People

VEHICLE LIFESPAN=
40
Units: Quarter

VEHICLE PRODUCTION DELAY=
2
Units: Quarter
