# An Exploratory Model to Investigate the Dynamics of the World Energy System

*A Biophysical Economics Perspective*

**M.Sc. Thesis**

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## Abstract

Energy is inherent part of our current life. No one can imagine living without it. It has changed the lifestyle of people and it will continue to do so in future. About 80% of current global total primary energy supply belongs to non-renewable resources. It is also expected that non-renewable resources dominate in total primary energy supply in next decades. The world is moving towards scarcity in non-renewable energy resources. Most studies about the world energy-economy system use standard economic theories. These theories do not include limitations of natural resources and the environment.

Biophysical economics theory considers the relation between economy and natural resources. It has been used as the basis of various energy-economy models. However, those models have a global view on this system. They do not sufficiently provide insights into the properties and international trading behaviors of energy suppliers and consumers. So, they do not provide insight on the effects of these interactions on the emergent behavior of the global energy system. Biophysical economics has high potential for providing insights into the world energy system. However, the current biophysical models are not capable of representing the world energy system considering trade and other interactions among regions.

Considering this problem the main research question in this thesis is stated as follow:

> ***What can be learnt from biophysical economics theory when it is used for the modeling of the world energy system considering energy trade?***

In order to answer this question, the objective of this research is set to develop a model for exploring the behaviors of the world energy system with multiple interacting regions. The theory of complex adaptive systems (CAS) is used to enable biophysical economics theory to consider trade and other interactions among regions. In order to model and analyze the world energy system from both biophysical economics and CAS perspective, agent-based modeling is identified as the most appropriate paradigm.

This thesis provides an analysis of the world energy system from both technical and actor perspectives. The technical analysis aims at describing the main characteristics of and activities in the world energy system. It also identifies the main uncertainties within this system. Actor analysis aims at providing a regional decomposition for the world energy system. To achieve this goal, a number of current regional decompositions are identified. One of those is selected on the basis of a number of criteria. This research uses the 11-region decomposition of (IIASA, 2012b)

To develop the objective model, a two-step approach is used. In the first step, the aggregated world energy model is developed without considering energy trade. In the second step, the multi-region world energy model is developed considering energy trade. The aggregated world energy model is the implementation of the most recent biophysical economics model in the literature, GEMBA by (M. A. J. Dale, 2010), in NetLogo. The multi-region model inherits all characteristics of the first model. However, it considers each world region as a world and facilitates the energy trade among them. The models are evaluated by comparison with historical data and literature.

The multi-region model shows that the energy trade can be modeled and explored using the biophysical economics perspective. Since it includes energy price as a parameter, it also shows that energy trade can be an interface between biophysical economics and standard economics as well.

In addition, exploratory experiments show that size of energy trade for regions is low in comparison to their total production/consumption. Moreover, they show that the size of total energy trade will peak and decline. It is because energy trade mostly belongs to non-renewable energy and the production of non-renewables will peak and decline in the future.  In addition, it shows that lower energy trade can increase the share of production of energy.

**Key Words:** Biophysical economics, Agent-based modeling, world energy system, world regions, exploratory modeling

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# 1 Introduction

Energy is an inherent part of human life. No one can imagine living without it. Different types of energy are being used all over the world for warming, lighting, transportation, manufacturing, and other purposes. Without energy, even the basic needs of human beings cannot be provided completely.

People deserve to have a life at a reasonable quality level and energy is essential for such a life. No one has more right than the others. So, from ethical point of view, everyone has right to have access to sufficient and affordable energy. But, it is doubtful whether the current energy system in the world can provide such energy for people.

Currently, substantial part of global energy demand is supplied from the fossil fuels. Many infrastructures and industries have been developed on the basis of these fuels all over the world. On the other hand, reserves of fossil fuels are diminishing. Many scientists believe that production rate of conventional oil is reaching its peak. At the same time, the world's population is increasing and energy-hungry modern lifestyle is getting popular. Therefore, the global demand for the energy is expected to increase. Any gap between energy supply and demand can influence the availability and accessibility of the energy. So, it seems that conventional non-renewable sources of energy cannot supply the world's demand in future.

Helping future generations to enjoy energy at sufficient quantity and affordable price is the motivation of this research. In order to achieve such goals, deliberate policies should be developed and adopted. Development of policies requires appropriate images about the functioning of systems. This research aims at design and development of a model which may provide one of these images.

## 1.1 Research Problem

### 1.1.1 State of the World Energy System

Energy is one of the essential factors of human life. People use energy to cook their foods, to warm up or cool down their houses, to move their vehicles, etc. Energy is "the go of things" (Maxwell, 1950) and no work can be done without it.

The level of energy production and consumption has changed during years. The level of energy consumption is different from one country to another. In general, it has changed the lifestyle of people and it will continue to do so in future. People use machines to get their jobs done instead of using their body or animals like before. It is because the work which can be done by a machine and a little fuel is equal to the work which can be done by many human beings at the same time. For example, the refined product from one barrel of oil can produce as much work as one can get from 12 people all working for a year. Surprisingly, the average production cost for that barrel of oil is about 1 dollar in a country like Iraq (Gelpke, McCormack, & Caduff, 2006). The energy system has evolved significantly all over the world during the last century. It also has shaped the life of human beings.

Currently, the main sources of energy in the world are fossil fuels. In 2010, coal, oil and natural gas formed 81.1% of world total primary energy supply (TPES). Figure 1 illustrates the mix of TPES of the world from 1971 until 2010.

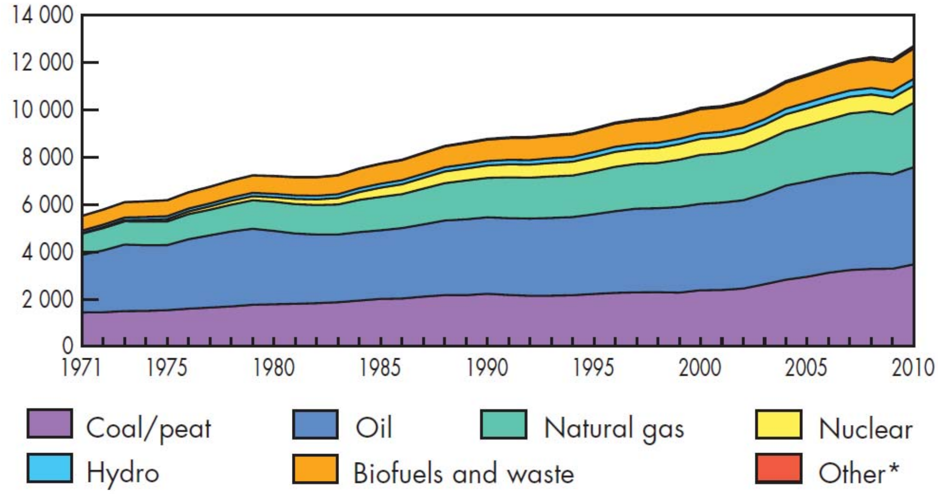


Figure 1 Total Primary Energy Supply in Mtoe - Picture from (IEA, 2012a)

Figure 1 can have two messages: The first message is high share of fossil fuels in the world energy portfolio. The second fact is the strictly increasing volume of total energy production and consumption in the world. Oil and other fossil fuels play very important roles in current world energy system. But, there are some concerns about the capability of fossil fuels for supplying the world in the future. These concerns can be called "End of easy oil".

### 1.1.2 End of Easy Oil

The concerns about "end of easy oil" started when the concept of peak in production of oil was introduced. In 1956, Hubbert fitted bell-shaped curves to cumulative production and discoveries to forecast oil production in United States. He predicted that oil production would peak in 1970 in US (Hubbert, 1956). Time showed that his estimate was very accurate (Nashawi, Malallah, & Al-Bisharah, 2010b). The so-called Hubbert curve caused some concerns about the rate of oil production in other places. It also caused concerns about production rate of other fossil fuels resources.

Many estimates can be found in the literature for the peak time for oil production. For example, Nashawi, Malallah, and Al-Bisharah (2010a) predicted that world crude oil production would peak in 2014 using a Multi-cyclic Hubbert model. In addition, Maggio and Cacciola (2012) developed multi-Hubbert variants to forecast the peak for oil, natural gas and coal. They forecasted that oil, natural gas, and coal would peak in 2015, 2035, and 2050, respectively.

The peak in production of fossil fuels can cause energy scarcity in the future. Limitation of energy resources is the main reason behind this scarcity. Current economic theories however, do not show the impacts of these limitations in production activities within economies. It is because these theories were developed at the time in which there was no perception about scarcity of one of the critical factors of production, energy (C. A. S. Hall & Klitgaard, 2012).

Figure 2 illustrates the relationship between the economic theories and the oil situation of the world. This figure suggests that most economic theories are developed at the time in which there was perception about energy abundance. But, what types of theories are suitable for economic analyses when there is no abundance of energy? Biophysical economics can be an answer to this question.

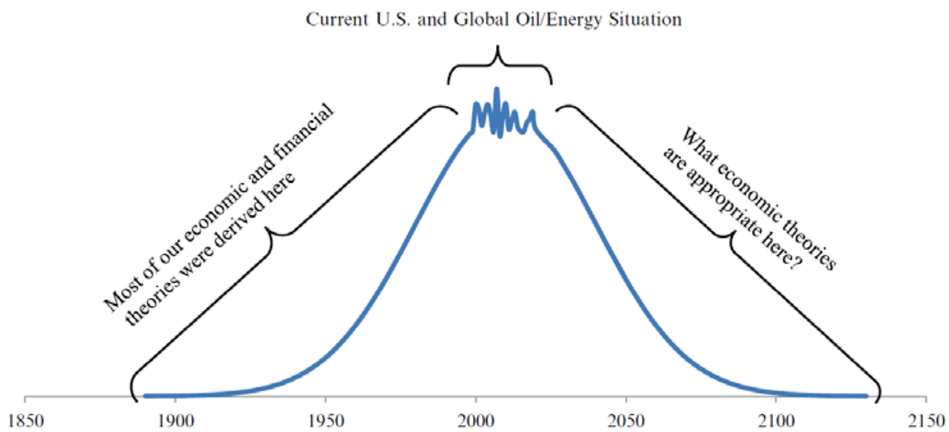


**Figure 2 Conceptual view of relation of economic concepts and the Hubbert curve for global oil use – Picture from (C. A. S. Hall & Klitgaard, 2012)**

### 1.1.3 Biophysical Economics

The standard economic approach, which is currently taught in all economic schools, considers the economy as a closed loop system. In standard economics theories, the economy system contains households and firms. There is a flow of goods and services from firms to households and a counter flow of production factors from households to firms. Laws of thermodynamics necessitate low-entropy resources for production of goods and services within the economy. However, this closed-loop model is incomplete because it does not consider the throughput of low-entropy natural resources (Daly, 1985). Moreover, dominating concepts in the standard economics are money and financial flows. Money is vital for dealing with human-to-human interactions. However, it cannot deal with human-to-nature interactions (M. Slesser, King, & Crane, 1997).

C. A. S. Hall and Klitgaard (2012) in the book *Energy and the Wealth of Nations: Understanding the Biophysical Economy* reviewed the main economic schools of thought[1] and their limitations for analysis of world economy with scarcity in natural resources. They suggested the use of biophysical economics in the energy and economic analyses. "Biophysical economics is a system of economic analysis that is based on the biological and physical properties, structures and processes of real economic systems as its conceptual base and fundamental model" ((C. Hall & Klitgaard, 2006), quoted from (Odum, 1971)). In fact, the difference between biophysical economics and standard economics is the use of thermodynamics and ecological principles. This highlights the role of natural resources and the environment in economic processes (Cleveland, 1987).

Although natural resources have not been considered widely in economics, high energy prices in recent years, the decline in production of some oil fields and the limited results of oil exploration in recent

[1] Mercantilism, Classical political economics, Neoclassical economics, and Keynesian economics

years show the importance of the role of natural resources in economics. Therefore, biophysical economics can be considered as a relevant backbone to deal with these problems.

To better understand the world energy system, biophysical economics has been used in a number of energy supply models. In his classification of the global energy supply models, M. Dale (2010) classified models into three categories: "deterministic models with growth curves", "energy-economy optimization models", and "physical resource accounting models". The renowned example of models in the first category is the Hubbert curve. The famous examples of the energy-economy optimization models are MESSAGE (Schrattenholzer, 1981), MARKAL (Hamilton et al., 1992) and, WEM (IEA, 2012b).

Also, famous examples of the third category are WORLD3 (D. H. Meadows, 1972), ECCO (Malcolm Slesser, 1992), and Dynamic Energy (J. T. Baines & Peet, 1983). WROLD3, ECCO, and Dynamic Energy model are system dynamics model which use biophysical perspective. Recently, M. Dale, Krumdieck, and Bodger (2012) developed a system dynamics model (GEMBA) for analysis of the global energy system from biophysical economic perspective. GEMBA simulates the energy yield of different energy sources from 1800 until 2200.

Although these models provide valuable insights into the world energy system, there is one thing in common among all resource accounting models. Their level of abstraction and aggregation is the "world". These models cannot show the (geographical) distribution of energy production (or consumption) across the world. Instead, they provide aggregated information for the whole world. The geographical diversity of the world energy system can influence its behaviors. Some regions own large reserves of fossil fuels and flow of renewable resources whereas they consume little energy. On the other hand, some regions consume too much energy whereas they do not have sufficient energy endowments. Consequently, energy trade has emerged among regions and countries. One of the drawbacks of the current models is that they do not consider energy trade and other types of interaction among countries.

Following the stated arguments, the research problem can be stated as follows:

> Biophysical economics can be a useful theory to analyze the world energy system which is why it is used as the basis of various biophysical models. However, the current models are all process oriented and only have a global view on this system. They do not sufficiently provide insights into the properties and trading behaviors of energy suppliers and consumers. Consequently, they don't provide insight about the effects of these interactions on the emergent behaviors of the global energy system.

## 1.2 Research Questions

Considering the stated problem, the main research question can be formulated as follow:

> **What can be learnt from biophysical economics theory when it is used for the modeling of the world energy system considering energy trade?**

In order to answer this question, the following sub-questions need to be answered:

1. To what extent can biophysical economics theory be used to develop models for exploring trade in the global energy system?
2. What are the main characteristics and activities in the world energy system from biophysical economics perspective?
3. How can the world energy system be decomposed into different trading regions?
4. What are the requirements to design a model to explore the world energy system considering energy trade?

## 1.3 Research Objective

Considering the stated research problem and the research questions, the objective of this research can be stated as follows:

> To develop a model using the biophysical economics theory in order to explore the behaviors of the world energy system with multiple interacting regions

## 1.4 Research Approach

As it is stated in the research objective, this research aims at including interactions and trade among different world regions in biophysical economics analysis. In such analysis, the holistic behavior of the world energy system depends not only on the behavior of each country or region, but also on the interactions and trade among them.

All regions produce and consume energy. But, there is considerable diversity among world regions regarding the energy production capabilities, and energy requirements. There is no central control or governance over energy sector of the world. Nonetheless, the aforementioned disparities among regions have caused the emergence of global energy trade and other types of interactions among them. These characteristics of the world energy system can classify it as a complex adaptive system.

J. H. Holland defines complex adaptive systems as:

> "… a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents." (Waldorp, 1992)

Currently, the global energy system can be considered as a dynamic network of many regions, institutions and actors. Actors and regions can produce and consume energy. If they have surplus of energy production, they can export it to regions or actor who require that energy. The behaviors of the whole global energy system emerge from the interactions among all the agents. Being a complex adaptive system (CAS), the world energy system owns the common characteristics of CASs. Dynamics and instability are some examples of such characteristics (Van Der Lei, Bekebrede, & Nikolic, 2010). Therefore, in addition to biophysical economics theory, the theory of CAS can add insights into analysis and modeling of the world energy system.

Van Der Lei et al. (2010) proposed a three level conceptual framework for analyzing complex system. These levels are agent level, network level, and environment. Figure 3 illustrates the three level frameworks for the analysis and modeling of complex adaptive systems.

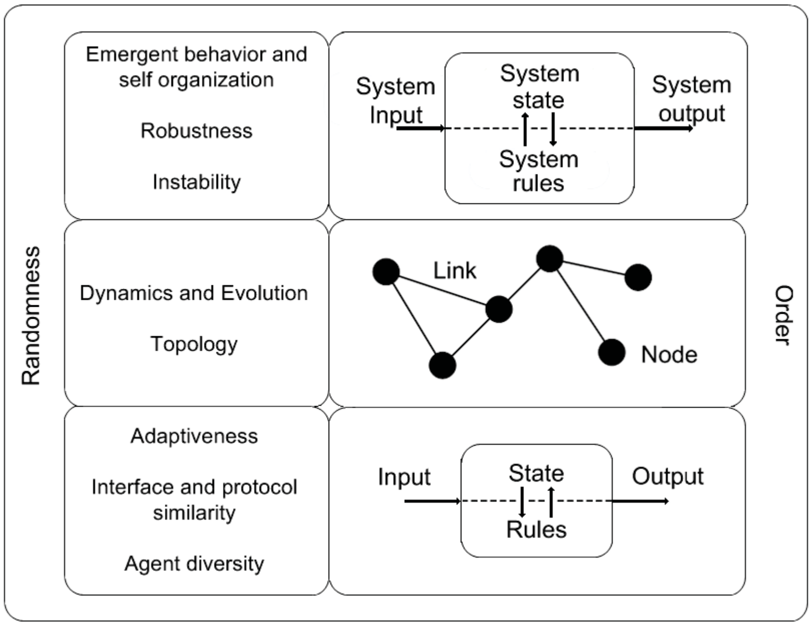


**Figure 3 Conceptual Framework for Complex Adaptive Systems – Picture from (Van Der Lei et al., 2010)**

To strengthen the biophysical economics analysis of the world energy system, the perspective of complex adaptive system will be considered in this research. A suitable approach for modeling and analysis of complex adaptive system is agent-based modeling.

The agent-based modeling approach models "things" and their interactions (van Dam, Nikolic, & Lukszo, 2013). "Agent-based models are essentially decentralized. Compared to system dynamics or discrete Event models, there is no such place in agent-based models where the global system behavior would be defined. Instead, the modeler defines behavior at individual level, and the global behavior emerges as a result of many individuals, each following its own behavior rules, living together in some environment and communicating with each other and with the environment" (Borshchev & Filippov, 2004).

In this approach, for each main actor (or maybe physical entity) of the system, a computer program (agent) is developed. Agents have their own states and behaviors. They can make decisions autonomously. They can also communicate and interact with each other for making decisions. Agent-based models can produce the characteristics of complex adaptive system which are mentioned in Figure 3.

In general, agent-based modeling has the following advantages over other modeling paradigms such as system dynamics modeling (Borshchev & Filippov, 2004):

- Ability to capture more complex structures and dynamics.
- Ability to build models in the absence of the knowledge about the global interdependencies

- Higher maintainability (model refinements normally result in very local, not global changes)

Because of these advantages and capabilities, agent-based modeling will be considered as the main modeling approach in this research. Details of modeling paradigms such as system dynamics, agent-based modeling and their comparison will be provided in Chapter 2.

### 1.4.1 Research Process

In order to develop an agent-based model and answer the research questions, a number of phases should be completed. The research process in this research can be divided into five main phases. Each phase consists of a number of steps in the research. The main research phases in this research are:

- Theoretical Perspective
- System Analysis
- Model Development
- Experimentation
- Exploration and conclusion

The research process is depicted in Figure 4.

#### *Theoretical perspective*

The objective of Phase 1 is elaborating on the theories which are used in this research. In this phase, the theoretical perspectives of the research are delineated. Combination of "biophysical economics" theory and "complex adaptive systems" theory constitute the theoretical foundations of this research. So, literature review on these two theories is the dominating part of this phase. For each theory, the relevant tools and techniques will be explained and introduced. So, literature review on, and comparison between relevant modeling paradigms is one of the important steps in this phase.

#### *System Analysis*

In phase 2, the research questions *"What are the main characteristics and activities in the world energy system from biophysical economics perspective?"* and *"How can the world energy system be decomposed into different trading regions?"* will be answered. In this phase, different characteristics of the world energy system as a socio-technical system will be analyzed. Socio-technical system can be seen from "System" (also called technical) and "Actor" perspectives (de Bruijn & Herder, 2009). For both analyses, literature review is the dominating method.

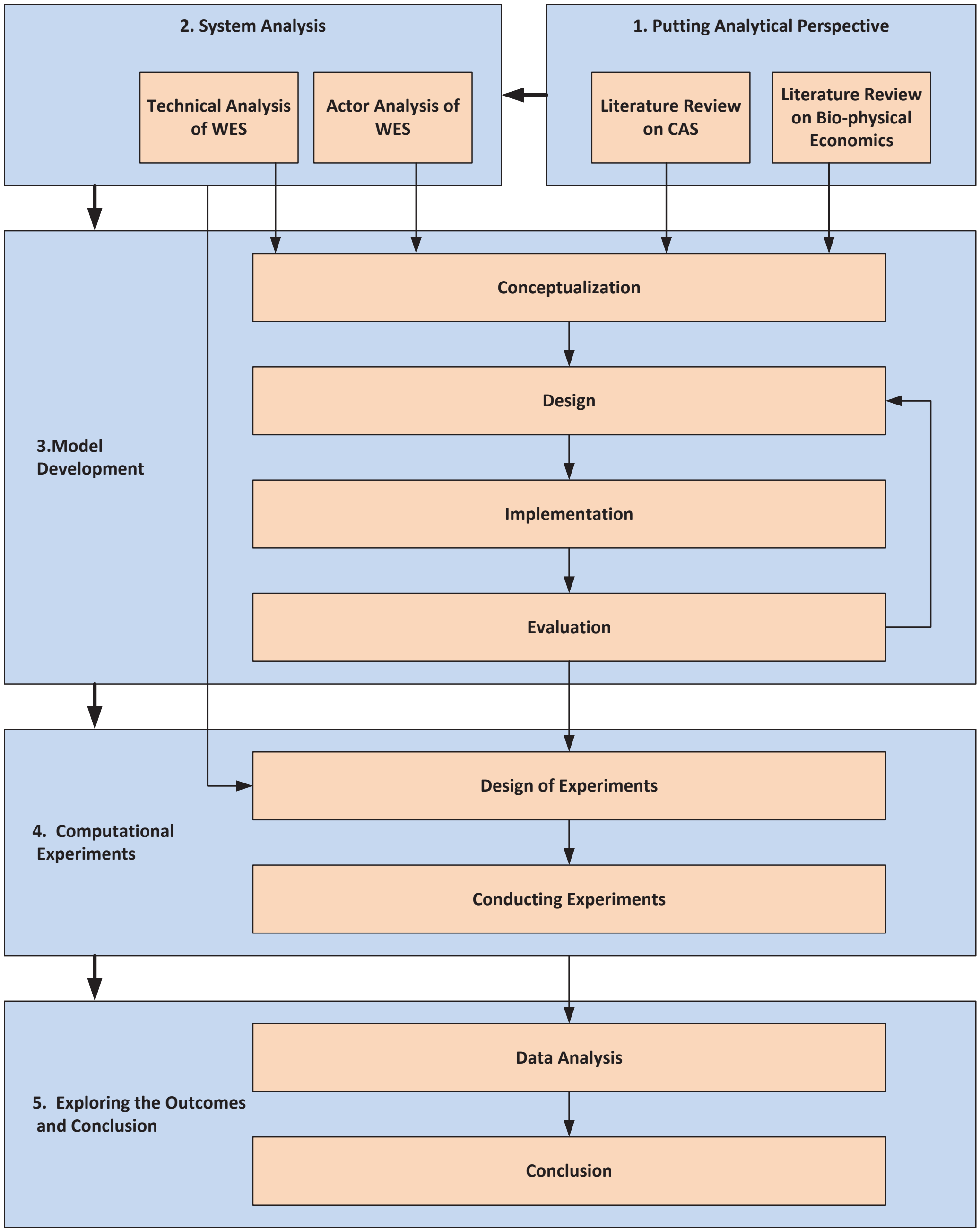


Figure 4 Research Methodology

In order to model the world energy system with considering diverse regions, this phase provides two types of decomposition for the system: Technical decomposition and actor (regional) decomposition.

The general technical decomposition of world energy system is extracted from Global Energy Assessment (GEA, 2012). Also, biophysical model of the economy is extracted from the PhD thesis by M. Dale (2010). In Chapter 4, the reason for selecting this model will be explained. Moreover, the actor network of the world energy system is defined by selecting an existing regional decomposition proposed by IIASA, IEA and BP.

The outputs of this phase are technical and regional decomposition of the world energy system and the data on ultimately recoverable resources of non-renewables and technical potential of renewables.

### *Model Development*

In this phase, the research question *"What are the requirements to design a model to explore the world energy system with considering energy trade?"* will be answered. The objective of this research is exploratory modeling of the world energy system. Exploratory modeling and Analysis (EMA) is a method for researching complex and uncertain systems using computational models (Steve Bankes, 1993). The method is founded on the fact that there is no model fully explaining all behavior of a system correctly and uses uncertainty exploration for making sure that all possibilities are taken into account when researching a particular problem (S Bankes, Walker, & Kwakkel, 2010).

Phase 3 aims at developing such a model. In order to develop such a model, 4 steps are followed. These steps are:

- Conceptualization
- Design
- Implementation
- Evaluation

The implementation step is done in NetLogo software. NetLogo provides the possibility for both agent-based modeling and system dynamics modeling. Being user-friendly and comprehensive documentation were main reasons for selecting this software.  In addition, NetLogo can easily be controlled in Java which gives possibility for the use of algorithms for calibration of the model.

The initial concept of global energy modeling from biophysical perspective is obtained from GEMBA model by M. Dale (2010). So, all the steps in Phase 3 are followed twice. First, they are followed for redevelopment of GEMBA model. Then, they are followed for development of a multi-region model.

### *Computational Experiments*

Phase 4 consists of two main steps: "Design of experiments" and "Experimentation".  Design of experiments in exploratory modeling is done by considering different ranges for uncertain variables. The uncertain variables are obtained from Phase 2. They are also obtained from definition of trade EROI function in Phase 3. The aim of Phase 4 is studying the emerging pattern in the behavior of system under different ranges of uncertainties.

### *Exploring outcomes and conclusion*

Phase 5 aims at recognizing informative patterns in results of the model. The information will be used for answering the main research question. It consists of two main steps: exploring outcomes and drawing conclusions. For the exploration of outcomes, data analysis is the dominating method. For data analysis, R Studio is used. The reasons for using R studio are: 1) capability to handle large volumes of data, 2) being open source software, and 3) comprehensive online documentation.

## 1.5 Outline of Thesis

This chapter has introduced the research problem, research questions, and the research approach. The rest of this report is structured as follows:

Chapter 2 elaborates on the first phase of the research process, the theoretical perspectives. First, the biophysical economics theory will be explained. The standard economics and its limitations will be elaborated on and the biophysical view of world economics will be presented. In addition, since this research aims at incorporating energy trade into analysis, the concept of energy trade in biophysical economics will be introduced and explained. Next, the theory of complex adaptive systems (CAS) will be explained. First, the characteristics of CAS will be introduced and its relevant examples in the energy systems will be explained. Then, the relevant modeling approaches for this research will be introduced and compared.

Chapter 3 elaborates on the second phase of the research approach4, the analysis of the world energy system. This chapter answers two questions "*What are the main characteristics and activities in the world energy system from biophysical economics perspective?*" and "*How can the world energy system be decomposed into different trading regions?*" First, the technical analysis will be provided. The world energy system will be defined, and its main characteristics and uncertainties will be elaborated on. Next, the actors of the world energy system will be introduced and a regional decomposition will be suggested for the modeling process.

In this research, two models will be developed. Chapter 4 elaborates on third, fourth and a part of fifth phases in the research methodology for the first model. The development process, experimentation process, and the data analysis for the aggregated world energy model will be provided in this chapter.

Chapter 5 elaborates on third, fourth and the first part of the fifth phases of the research approach for the second model of the research. The Multi-Region World Energy Model is the main model in this research. It will be developed on the basis of aggregated world energy model. The development, experimentation and data analysis for the multi-region model will be presented in chapter 5.

Finally, in Chapter 6, the research process and the main outcomes will be reviewed and the main conclusions will be drawn. In this chapter a number of features in this research will be reflected on and suggestions for future work will be presented.