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**title: Mini-Lecture 2.1 -- MUSE (ModUlar energy system Simulation Environment)**

keywords:

- MUSE

- Agent-based model

- Energy planning

authors:

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# Short description

In this mini-lecture we will give an introduction into the energy systems model, MUSE (ModUlar energy system Simulation Environment). We will cover the differences between MUSE and intertemporal optimisation models. We will also address the advantages and disadvantages of using MUSE.

# Learning objectives

- Learn the difference between MUSE and intertemporal optimisation models

- Explore the pros and cons of using the energy systems model MUSE

# Introduction to MUSE

We will first classify MUSE as per the classifications defined in the previous lecture. MUSE falls into the following categories:

- Long-term

- Global, national and local

- Bottom-up

- Simulation model

Therefore, MUSE is mainly designed to understand how long-term energy markets may evolve on both a national and global scale. MUSE explicitly models technoeconomic data on various technologies and therefore is a bottom-up model. Finally, MUSE is a simulation model, and can model various competing objectives to display what could happen under certain scenarios.

## What are MUSE's unique features?

MUSE is a generalisable agent-based modelling environment that simulates energy transitions from the point of view of the investor and consumer agents [@Sachs2019a]. This means that users can define their own agents based upon their needs and data. In addition, each of these agents can have different objectives. For instance, a proportion of the population may have higher disposable incomes, which allows them to spend more on heating and cooling rather than requiring cost minimisation. Another proportion may prefer to spend less on heating and cooling while still having high disposable incomes. This features differs from the optimisation-based approaches which can, for instance, minimise costs or maximise welfare from a central perspective.

Another aspect that differs from optimisation models is the ability to model imperfect information and limited foresight. Optimisation models require full knowledge of the system at the beginning of the simulation. For example, such a model needs to know what the demand will be in 2050 at the beginning of the simulation in 2020. MUSE does not give this information to the investing agents at the beginning of the simulation, and therefore they must makes their investments under uncertainty. This adds a level of realism to MUSE and is a unique feature of agent-based models when compared to intertemporal optimisation models.

## Benefits and disadvantages of MUSE

MUSE comes with a number of advantages and disadvantages when compared to other models. The benefits include, as discussed, the ability to model heterogeneous and diverse agents as well as to model limited foresight and imperfect information. Another one of the benefits of MUSE is its flexibility in designing a case study. Users can model anything from a single region to the global scale with trade occurring between regions. In addition, MUSE is able to model a single sector (such as the transport sector) to a whole energy systems approach. This flexibility allows for many different applications to be devised for interesting research and applications.

However, this flexibility and simulation approach comes with a number of disadvantages when compared to other models. The first disadvantage is the complexity of the model. While building a case study is similar to the process for other models, the inner workings of MUSE can be complicated. This is due to its simulation-based method which relies on rule-based behaviours, as opposed to optimisation. Another disadvantage is that the computation time of MUSE can increase with the complexity of the case study. Therefore, it becomes important to make decisions based on the sectors, timeslicing and other characteristics that are modelled. For instance, it may not be feasible to model every single sector in an energy system, and instead the model should be limited to a subset of relevant sectors.

# Summary

In this mini-lecture we were introduced to the energy systems model, MUSE. We learnt of its unique features, such as heterogeneous agent behaviour, limited foresight and imperfect information. We also discovered the advantages and disadvantages of MUSE. For example, its flexible nature, which allows many different types of case-studies, can also make the model increasingly complex.

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**title: Mini-Lecture 2.2 -- How MUSE works**

keywords:

- Service demands

- Technologies

- Market clearing algorithm

authors:

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# Short description

In this mini-lecture we will give you an overview of how MUSE works. This will include the different sectors that make up MUSE, including primary supply sectors, conversion sectors and demand sectors. We will discover how these sectors are interlinked through a market clearing algorithm, which ultimately decides the prices of energy commodities and the final energy system, according to MUSE.

# Learning objectives

- Identify the key components which make up MUSE

- Understand the fundamental underpinning of how MUSE works

# MUSE Visualisation

MUSE is made up of various components which interact to give a projected energy system as an output. Figure 2.2.1 displays these major components. The key sections of MUSE include:

- Primary supply sectors

- Conversion sectors

- Demand sectors

- Climate model (in the current model this is simplified by the use of a carbon budget.)

- Market clearing algorithm (MCA)

![](assets/Fig\_2.2.1.png){width=100%}

\*\*Figure 2.2.1:\*\* Different components which make up MUSE.

MUSE works by iterating between the sectors shown in Figure 2.2.1 to ensure that energy demands are met by the technologies chosen by the agents. Next, we will detail the calculations made by MUSE throughout the simulation.

- The service demand is calculated. For example, how much electricity, gas and oil demand is there for the energy services of cooking, building space heating and lighting in the residential sector? It must be noted that this is only known after the energy service demand sector is solved and the technologies invested in are decided.

- A demand sector is solved. That is, agents choose end-use technologies to serve the demands in the sector. For example, they compare electric stoves to gas stoves to meet the energy service demand of cooking. They then choose between these technologies based upon their:

- Search space (which technologies are they willing to consider?)

- Their objectives (which metrics do they consider important?)

- Their decision rules (how do they choose to combine their metrics if they have multiple?)

- The decisions made by the agents in the demand sectors then lead to a certain level of demand for energy commodities, such as electricity, gas and oil, as a whole. This demand is then passed to the MCA.

The MCA then sends these demands to the sectors that supply these energy commodities (primary supply or conversion sectors).

- The supply and conversion sectors are solved: agents in these sectors use the same approach (i.e., search space, objectives, decision rules) to decide which technologies to invest in to serve the energy commodity demand. For example, agents in the power sector may decide to invest in solar photovoltaics, wind turbines and gas power plants to service the electricity demand.

- As a result of these decisions in the supply and conversion sectors, a price for each energy commodity is formed. This price is formed based on the levelised cost of energy of the marginal technology, that is, the technology which produces the most expensive unit of an energy commodity. This price is then passed to the MCA.

- The MCA then sends these prices back to the demand sectors, which are solved again as above.

- This process repeats itself until commodity supply and demand converges for each energy commodity for each region. Once these converge, the model has found a partial equilibrium in the energy system, and it moves forward to the next time period.

# Summary

This mini-lecture provided key information to understand the underlying mechanics of MUSE. We learnt how MUSE is made up of different sectors, which are linked by a market clearing algorithm to simulate how prices are calculated. This mechanism closely models the real-life global electricity market.

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**title: Mini-Lecture 2.3 -- Benefits of an Agent-Based Approach**

**keywords:**

- Imperfect foresight

- Limited information

- Agent-based modelling

authors:

- Alexander J. M. Kell

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Mini-lecture 2.3 provides an overview of the benefits of using an agent-based modelling and simulation when applied to energy systems analysis. We will learn how we can more closely model real-life by relaxing some of the assumptions necessary in other energy systems models.

# Learning objectives

- Understand the concept of limited foresight

- Understand the concept of imperfect information

# Introduction

As previously discussed, different modelling approaches have different advantages and disadvantages. One of the main differences that MUSE has, which it is able to model through its agent-based simulation approach, is its ability to model both limited foresight and imperfect information. These are significant relaxations when compared to optimisation-based models. In this mini-lecture we will explore these concepts in more detail and discover how these relate to MUSE and energy systems specifically.

## Imperfect information

Imperfect information is an economic term which is the opposite of perfect information. With perfect information in a market, all consumers and producers have perfect and instantaneous knowledge of all market prices, their own utility and cost functions. However, in real-world energy markets, this is not the case. Some information is hidden or unknown, such as other player's cost functions.

With some models it is necessary to make this assumption of perfect information. For example the bids of all the agents in the market are known at all times. This is a significant assumption and can influence the final outcome of the model. By using the agent-based simulation methodology, we can avoid making this assumption and allow information to be hidden between agents, as happens in decentralised energy markets.

## Limited foresight

Limited foresight specifies how players within a game understand how the future may evolve. In the real-world, prediction and forecasting are difficult problems to solve, particularly within the uncertainty of energy markets. This become even more challenging when trying to make long-term predictions.

Within MUSE long-term predictions must be made by investor agents. For example, if a company wanted to invest in a power plant, they would need to predict the amount of money they can sell their electricity for over the lifetime of the power plant, or in other words the market price for electricity. In some cases power plants operate for 30 years or more and so electricity prices 30 years into the future are required!

MUSE makes a simplified assumption about the future prices expected by investors: they know what the price will be in the next five years. However, they assume a flat forward extension of the prices from this period. Or in other words, the energy prices over the entire lifetime of the plant are the same as the known price in the next five years. However, this assumption that the investors make will more than likely not be correct, leading to errors in their predictions, just like in the real world.

In contrast to perfect foresight, where variables such as prices, demand and technology costs in all the future time periods are known from the beginning of the simulation, using the limited foresight period, agents make investments under expectations of the market, which may be wrong.

Figure 2.3.1, below, details how MUSE runs. Firstly, the initial capacity, price trajectory and demand trajectory are known and set by the user. These variables are exogenous to the model, which is to say that they are fixed and imposed on the model. These are used to initialise the MCA convergence algorithm. The MCA convergence algorithm finds a suitable set of investments which equilibrate supply and demand. Once equilibrium has been reached, the technologies are decided and the commodity prices are set. These commodity prices reflect the technology marginal costs, or the costs required to generate or create 1 unit of commodity, excluding capital costs. The investments balance asset retirements and the increase in demand, ensuring that supply meets demand.

This whole process repeats itself at every timestep (t) until the specified number of milestone years have run.

![](assets/Fig\_2.3.1.png){width=100%}

\*\*Figure 2.3.1:\*\* MUSE iteration process

# Summary

This mini-lecture provided an introduction to the terms limited foresight and imperfect information. We learnt how these assumptions have been integrated into the MUSE model and what this means for the modelling process. In the next mini-lecture we will explore the key components that make up MUSE.

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**title: Mini-Lecture 2.4 -- Key MUSE components**

keywords:

- Service demand

- Agent-based modelling

- Market clearing algorithm

authors:

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In this mini-lecture we will explore the key components which make up MUSE. These key components include the service demand, technologies, agents and sectors. We will now explore what these components do and how they interact.

# Learning objectives

- Understand what the key components of MUSE are

- Understand what these terms mean in the context of MUSE

- Understand how these components interact within MUSE

## Service Demand

The energy service demand is a user input which defines the demand that an end-use sector has. An example of this is the service demand commodity of heat or cooling that the residential sector requires. End-use, in this case, refers to the energy which is utilised at the very final stage, after both extraction and conversion.

The estimate of the energy service demand is the first step. This estimate can be an exogenous input derived from the user, or correlations of GDP and population which reflect the socio-economic development of a region or country.

## Technologies

Users are able to define any technology they wish for each of the energy sectors. Examples include power generators such as coal power plants, buses in the transport sector or lighting in the residential sector.

Each of the technologies are placed in their regions of interest, such as the USA or India. They are then defined by the following, but not limited to, technoeconomic variables:

- Capital costs

- Fixed costs

- Maximum capacity limit

- Maximum capacity growth

- Lifetime of the technology

- Utilisation factor

- Interest rate

Technologies, and their parameters, are defined in a specific file called the Technodata file.

## Sectors

Sectors typically group areas of economic activity together, such as the residential sector, which might include all energy consuming activities of households. Possible examples of sectors are:

- Gas sector

- Power sector

- Residential sector

- Industrial sector

Each of these sectors contain their respective technologies which consume energy commodities. For example, the residential sector may consume electricity, gas or oil for a variety of different energy demands such as lighting, cooking and heating.

Each of the technologies, which consume a commodity, also output a different commodity or service. For example, a gas boiler consumes gas, but outputs heat and hot water.

## Agents

Agents represent the investment decision makers in an energy system, for example consumers or companies. They invest in technologies that meet service demands, like heating, or produce other needed energy commodities, like electricity. These agents can be heterogenous, meaning that their investment priorities have the ability to differ.

As an example, a generation company could compare potential power generators based on their levelised cost of electricity, their net present value, by minimising the total capital cost, a mixture of these and/or any user-defined approach. This approach more closely matches the behaviour of real-life agents in the energy market, where companies, or people, have different priorities and constraints.

## Market Clearing Algorithm

The market clearing algorithm (MCA) is the central component between the different supplies and demands of the energy system in question. The MCA iterates between the demand and supply of each of these sectors. Its role is to govern the endogenous price of commodities over the course of a simulation. In other words, it calculates the prices based on the supply and demand of the various technologies and regions.

For a hypothetical example, the price of electricity is set in a first iteration to $70/MWh. However, at this price, the majority of residential agents prefer to heat their homes using gas. As a result of this, residential agents consume less electricity and more gas. This reduction in demand reduces the electricity price to $50/MWh in the second iteration. However, at this lower electricity price, some agents decide to invest in electric heating as opposed to gas. Eventually, the price converges on $60/MWh, where supply and demand for both electricity and gas are equal.

This is the principle of the MCA. It finds an equilibrium by iterating through each of the different sectors until an overall equilibrium is reached for each of the commodities. It is possible to run the MCA in a carbon budget mode, as well as an exogenous mode. The carbon budget mode ensures that an endogenous carbon price is calculated to limit the emissions of the energy system to be below a user-defined value. Whereas, the exogenous mode allows the carbon price to be set by the user.

# Summary

In this mini-lecture we have explored the different components which make up MUSE. We have explored the:

- Service Demand

- Technologies

- Sectors

- Agents

- Market Clearing Algorithm

All of these components interact, for example the agents in a particular sector invest in technologies to meet a certain service demand. Finally, the market clearing algorithm brings these different components together to find an ultimate price on all the different factors of the particular case study.