SFU Sustainable Energy Engineering

SEE 310 Course Pack

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Introduction

Introduction

Energy impacts all aspects of our lives. From travel to/from work, cooking and preserving food to visiting family and friends, modern life depends on energy in a myriad of ways. Unfortunately, our use of energy, although it comes with significant advantages for overall human well-being, also has significant impacts on the environment, climate and often also on human health. Of the 17 Sustainable Development Goals (SDGs), goal 7, Affordable and Clean Energy, has been shown to have a strongly reinforcing impact on 12 of the goals, with only minor negative counter interactions (McCollum et al., 2018). If we can develop systems to supply affordable and clean energy this can contribute significantly towards solving many of the other sustainability challenges identified in the SDGs.

Figure 1 - Source: United Nations. "Sustainable Development Goals." 2015. https://sustainabledevelopment.un.org/sdgs. Accessed May 17th, 2020.

Unfortunately, designing clean and affordable energy systems is not a simple task. The interactions between the energy system, climate, human activities and the environment are often complex and difficult to understand, and weather and climate impacts on the energy system are both variable and uncertain... Engineers therefore use energy system models of various types to make decisions on the best ways to supply energy to meet humanity's needs. These models help engineers design systems that balance the positive and negative impacts of the energy system.

There are many different classes, philosophies and structures of energy systems. They span the spatial range from models of buildings and even parts of buildings all the way to models that encompass the entire globe. Some models have temporal resolution of milliseconds to study the very short-term impacts of power flows with variable renewable energy while others study systems on multi-year time scales to study long term changes and impact.

In SEE 310 we will study four different types of models that cover a wide range of energy engineering decisions. These are energy-economy models, which provide some measure of the economic response of different system decisions, capacity expansion models, which determine the optimal development pathway for a given energy system within a given set of constraints, power system models, which model the short-term operation of the system, and building system models, which allow engineers to evaluate different building upgrades and modifications from an energy use and impact perspective.

References
McCollum, D. L., Echeverri, L. G., Busch, S., Pachauri, S., Parkinson, S., Rogelj, J., Krey, V., Minx, J. C., Nilsson, M., Stevance, A.-S., & Riahi, K. (2018). Connecting the sustainable development goals by their energy inter-linkages. *Environmental Research Letters*, *13*(3), 033006. https://doi.org/10.1088/1748-9326/aaafe3

Reading: Neshat et al. 2014
(http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1021-447X2014000400010)

Reading Questions

Define the following terms:
- Top-down
- Bottom-up
- Economic equilibrium
- Optimization
- Endogenization
- At the end of section 3.1 Neshat et al. state "It can be concluded that most of the standard (computer based) models are perhaps not suitable for developing countries applications…" Do you agree with this statement? Why or why not?
- What does energy system modelling look like with and without sustainability and equity? What are the engineering implications of considering sustainability and equity in system design?

Further Reading (Optional)

Wikipedia (https://en.wikipedia.org/wiki/Energy_modeling)

Subramanian et al. 2018 (https://www.mdpi.com/2227-9717/6/12/238/htm)

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> international licence. It contains links to:
> - *Energy Models: Methods and Characteristics* by Neshat et al., licensed CC
>   BY-4.0
> - *Energy Modeling* by Wikipedia, licensed CC BY-SA 3.0
> - *Modeling and Simulation of Energy Systems: A Review* by Subramanian et al.,
>   licensed CC BY-4.0

Optimization Models

Introduction

For many engineering applications and for company and government decision making, one wants to choose the 'optimal' solution. This may be the cheapest system to meet the given demands for a power utility, the highest profit production mix for a manufacturing plant, or the best route to get from your home to school using transit, a bike or a car. Each of these problems fits within the broad scope of optimization modelling - how to find the optimal (maximum or minimum) solution to the given challenge within the given set of constraints.

Although there are many specific optimization techniques applied to many different problems in industry, for energy systems modelling optimization models generally fall into two categories: capacity expansion models and power system models. Capacity expansion models are used to determine an optimal system mix to meet the energy demands for a given system over a long period of time while power system models are used to model the shorter-term dynamics of the system. Due to the structure of these problems different solution mechanisms are needed.

Capacity expansion models are generally formulated to be linear, and therefore linear programming (LP) techniques are used to solve these types of problems. Power system models, on the other hand, often incorporate non-linear factors including unit commitment (if a generator is operating in a given time period) which requires mixed integer programming (MIP) algorithms.

This course pack will reference some examples of how linear programming and mixed integer programming work conceptually. After this a brief introduction is provided that shows how capacity expansion models use linear programming techniques and how mixed integer programming is applied to power systems models.

Optimization

The basic structure of an optimization problem consists of an objective function and a number of constraint functions:

        maximize/minimize: objective function

        subject to: mathematical constraints

For example, we might want to maximize the profit from building electric vehicles but have constraints on the size of the market (maximum number of vehicles we can sell), the number and type of vehicles we can produce with our factory as well as constraints on material inputs.

If both the objective function and the constraints are linear (see definition for linear programming below) then the problem can be solved using linear programming techniques. If the problem has non-linear elements then other techniques such as mixed integer programming are required.

Linear Programming

An optimization problem is linear if the objective can be written as a linear combination of the decision variables and each constraint is similarly linear:

$$max/min : c_1 x_1 + c_2 x_2 + \cdots + c_n x_n$$
$$subject\ to : a_{11} x_1 + a_{12} x_2 + \cdots + a_{1n} x_n <= b_1$$
$$...$$
$$subject\ to : a_{m1} x_1 + a_{m2} x_2 + \cdots + a_{mn} x_n <= b_m$$

For many engineering problems, including long term capacity expansion planning models (with some assumptions) this is a reasonable approximation and works very well. An additional constraint is often that the decision variables (x_n) are non-zero but this is not a strict requirement.

To solve a linear programming problem of the form shown above there are a number of algorithms available but the simplex algorithm is probably the widest used. An example of graphically solving linear programming problems is provided in the following link: https://courses.lumenlearning.com/sanjacinto-finitemath1/chapter/reading-meeting-demands-with-linear-programming/.

You can read an overview of the simplex algorithm on wikipedia: https://en.wikipedia.org/wiki/Simplex_algorithm.

Mixed Integer Programming

For some problems it is not possible to write the objective or some of the constraints in a linear fashion. There are many examples of different non-linear optimization problems and each has different algorithms for solving them - see https://en.wikipedia.org/wiki/Mathematical_optimization for examples of the major sub-fields of optimization. It should be noted that some non-linear solution algorithms are very difficult to solve and research into solving (or proving that a given solution is near optimal) for these types of problems is active and ongoing.

For power system modelling a major sub-class of optimization problems involves the 'unit commitment' problem - given start-up times, minimum stable operating parameters and associated costs for the generators in a system, which units should be 'on' at any given time. This type of problem is fundamentally a mixed integer program as the 'on' or 'off' state of the generator is a binary integer constraint - a generator cannot be in a partially 'on' state.

The solution algorithm(s) for solving a MIP are beyond the scope of this course pack, but there are many examples of how to solve MIP problems online and the integer programming page of wikipedia includes many examples: https://en.wikipedia.org/wiki/Integer_programming. See

also https://developers.google.com/optimization/mip/integer_opt#python_7 which has some examples of how MIP problems can be solved using python. We will discuss some of the challenges inherent in MIP as applied to unit commitment problems under power system models below.

The major challenge with MIP problems is the potentially long solve times. Worst case solve times for a problem with n binary variables is 2^n (though there are algorithms that reduce this significantly, solution times are still exponentially challenging). As such, adding just one binary variable to the problem doubles the solve time. With multiple binary variables the solve time increases drastically and many problems are therefore intractable.

Capacity Expansion Modelling

Capacity expansion models are generally formulated as linear programs to allow for long term perspectives on the energy system and the cost optimal build out plan given constraints such as available resources, limits on GHG emissions, etc. The major assumptions inherent in capacity expansion models include the assumption that all users will optimize their decisions, that there are no economic feedbacks and that it is possible to build a small fraction of a power plant need to be considered and one needs to determine if the model is appropriate for the given structure. For many situations (centralized planning organizations) these assumptions are acceptable for the specific questions the planner wishes to use the model to evaluate.

An example of building a capacity expansion type of model in the OSeMOSYS Open Source Energy Modelling System is available at https://osemosys.readthedocs.io/en/latest/manual/Create%20a%20model%20in%20OSeMOSYS.html#mapping-the-res-of-atlantis. Another article describing the structure and application of the MARKAL optimization model is available at: https://www.sciencedirect.com/science/article/pii/S2300396015300562.

To make capacity expansion models solvable in a reasonable time many assumptions/modelling decisions are required. These include:
- Temporal aggregation - most capacity expansion modelling applications split the year into a handful or tens of timeslices. This impacts the ability of these types of models to adequately model the impacts of short duration events and the impact of variable renewable energy sources.
- Technological aggregation - often all power plants of a given type are aggregated into a 'typical' plant of that time. This reduces the ability of the model to take into account cost variations in plant technologies and variations in capital costs for building plants in different locations.
- Spatial aggregation - countries or regions are often modeled as 'copper plate' with power in one area instantly and freely available in another area without transmission losses or costs, with only inter-regional or inter-country transmission considered.

Each of these assumptions have inherent trade-offs. Including high temporal, technological and spatial resolution is possible but every increase in resolution increases the solve time. The modeller needs to carefully consider the trade-offs and decide on the resolution required to answer the specific questions they wish to answer.

Power System Models

As noted briefly above, power system models are used to evaluate the operation of a given power system. Due to the mixed integer programming required for power system questions such as unit commitment they are usually applied to relatively short time frame questions but, since unit commitment is a short term temporal challenge, they often have high (10 minute/1 hour) temporal resolution.

The PyPSA power system model (https://arxiv.org/pdf/1707.09913.pdf) is a good example of a power system model and PyPSA has some excellent examples online of the model and how it works (https://www.pypsa.org/examples/).

The major challenge with mixed integer power system models is keeping the number of time periods low enough to allow for a reasonable solve time while at the same time having both the temporal resolution and model period to answer the specific questions being investigated.

Building Energy Models

R-Value Calculations

In the context of building and construction,[4] the **R-value** is a measure of how well a two-dimensional barrier, such as a layer of insulation, a window or a complete wall or ceiling, resists the conductive[5] flow of heat. R-value is the temperature difference per unit of heat flux needed to sustain one unit of heat flux between the warmer surface and colder surface of a barrier under steady-state conditions.

The *R-value* is the building industry term[4] for thermal resistance "per unit area."[6] It is sometimes denoted **RSI-value** if the SI (metric) units are used.[7] An R-value can be given for a material (e.g. for polyethylene foam), or for an assembly of materials (e.g. a wall or a window). In the case of materials, it is often expressed in terms of R-value per unit length (e.g. per inch or metre of thickness). R-values are additive for layers of materials, and the higher the R-value the better the performance.

The **U-factor** or **U-value** is the overall heat transfer coefficient that describes how well a building element conducts heat or the rate of transfer of heat (in watts) through one square metre of a structure divided by the difference in temperature across the structure.[8] The elements are commonly assemblies of many layers of components such as those that make up walls/floors/roofs etc. It measures the rate of heat transfer through a building element over a given area under standardised conditions. The usual standard is at a temperature difference of 24 °C (43 °F), at 50% humidity with no wind[9] (a smaller *U-factor* is better at reducing heat transfer). It is expressed in watts per meter squared kelvin ($W/m^2 \cdot K$). This means that the higher the U-value the worse the thermal performance of the building envelope. A low U-value usually indicates high levels of insulation. They are useful as it is a way of predicting the composite behavior of an entire building element rather than relying on the properties of individual materials.

R-Value Exercises

Building Materials and their R-Values

Material	R-Value (ft^2 °Fh / BTU)
Plain glass, 1/8 inch	0.03
Stone per inch	0.08
Common Brick per inch	0.20
Asphalt Roof Shingles	0.44
1/2 inch Gypsum Board (Drywall or plasterboard)	0.45
Wood Siding, 1/2 inch	0.81
Plywood, 3/4 inch	0.94
Insulating sheathing, 3/4 inch	2.06
Fiberglass, per inch (battens)	3.50
Polystyrene per inch	5.00
Polyurethane Board per inch	6.25
Cinder Block (12 inches)	1.89

Question 1:
Find the composite R-value for the wall shown in the figure below.
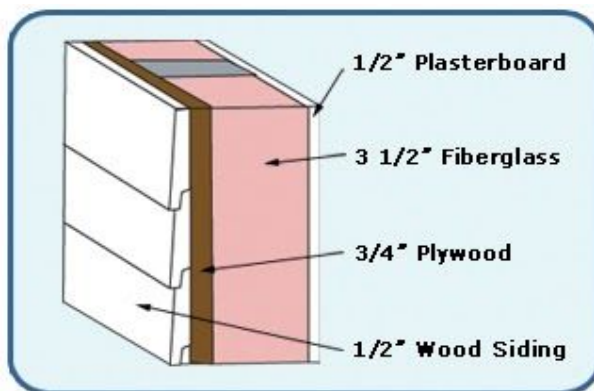
Question 2:
A ceiling is insulated with 0.75" plywood, 2" of polystyrene board, and a 3" layer of fiberglass. What is the R-Value for the ceiling?

For the following questions use the R-values found here (the chart above may also be used):
https://en.wikipedia.org/wiki/R-value_(insulation)#Example_values

Question 3
A wood frame wall has the following characteristics:
- It is built around 100 mm softwood studs (D).
- The cavity between the studs is filled with fiberglass batts insulation (C).
- The inside is finished with 9 mm gypsum board (E).
- The outside is finished with 11 mm wood panels (B) covered by 11 mm hardwood siding (A).
- The insulated cavity constitutes 75% of the heat transmission area. The studs, plates, and sills constitute 21%. The headers constitute 4% and can be treated as studs.
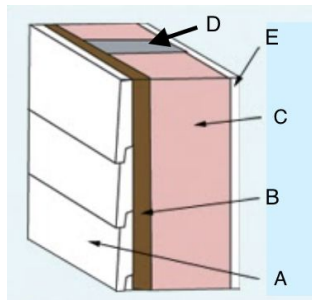
What is the overall thermal resistance (R-value) and the overall heat transfer coefficient (the U-factor). The inside and outside surfaces also need to be considered in this calculation. All assumptions made in your calculations must be noted.

What is the rate of heat loss through the walls of a house with a perimeter of 50 m and wall height of 2.5 m. The winter design temperature is -2°C and indoor design temperature is 22°C. Assume 20% of the wall area is occupied by glazing.

$$\text{Heat Loss: } \Delta Q = U * A * (T_{in} - T_{out})$$

Question 4
As an upgrade for the wall in question 3, a 20 mm thick rigid foam insulation is added between the wood panels and hardwood siding. Find the new overall R-value and, once that has been established, the percent increase in the R-value of the wall.

Question 5
A masonry wall has the following characteristics:
- The wall is built around 8 inch thick concrete blocks made from aerated concrete.
- The outside is finished with 3.5 inch brick.
- There is a .5 inch layer of cementitious foam between the bricks and concrete blocks.
- The inside is finished with .5 inch gypsum board

- Between the concrete and gypsum board there is .75 inch vertical furring (R = 4.5 h*ft^2*°F/Btu) constituting 20% of the heat transmission area and .75 inch thick air space constituting 80% of the heat transmission area. The internal surface of the gypsum board is reflective, making the R-value for this air space 2.0 h*ft^2*°F/Btu.

What is the overall unit thermal resistance (the R-value) and overall heat transfer coefficient (the U-factor) for this wall? Assume provided R-values are normalized to a 1-inch thickness.

Heat Sensing Technology for Energy Efficiency

Infrared images can be used to identify areas of large heat loss in buildings. After detection, insulation can be added to make the building more energy efficient. *Image from the US National Park Service.*
Usage Rights

eQUEST

For this lab, we will be navigating our way through eQUEST, an open source building energy modelling system. First we will walk through a tutorial in order to get familiar with the software, then there will be an activity to practice using the software yourself.

eQUEST and its documentation is available here: http://www.doe2.com/equest/

Tutorial

eQUEST has three 'modes': Schematic Design Wizard, Design Development Wizard, and Detailed Data Interface. We will start in the Schematic Design Wizard, in which you need to provide the least inputs in order to simulate a building. This mode creates a building that you can modify or leave in the basic form it provides. The Design Development Wizard requires more detailed inputs and allows you more control over the building design. The Detailed Data Interface requires very detailed data inputs, allowing you to have even more control and make refinements as needed.

1. Open eQUEST, create a new project via the Wizard, and select Schematic Design Wizard to get started. Name this project in a memorable and useful way for when you refer back to it, including your own name.

2. In the Schematic Design Wizard, you can see what specifications the software has provided already for the building, and customize these as you go.

   Tip: It's best to work in a linear way through eQUEST, since each change you make might affect the next step, and if you go back and change something then work you have already done in one of the later steps may no longer be relevant and disappear.

3. The first selection you will make is the Building Type. The wizard will then create a basic design of that building, based on typical requirements/specifications for that type of building.

4. There is the option to both step through the wizard screens by clicking next each time, or using the drop down menu to select which screen to jump to (located in the bottom left). Spend some time looking through the wizard screens to see what modifications can be made to the building settings. Examples of some other modifications that can be made are:

      a. Location. An important aspect of setting the location is the weather data used to simulate the building energy performance. If User Selected is chosen, you can upload a weather data file. Otherwise, data is provided for the selected region.

      b. Area of the building and number of floors.

      c. Main HVAC system for the building.

      d. Building footprint. Shape, dimensions, and orientation of the building.

      e. Building envelope and interior construction.

      f. Doors, windows, and skylights.

Tip: Default settings will be in green, and anything customized will turn to red. By right-clicking on a red setting, you have the option to 'restore default'. Once you are done modifying settings, click Finish to allow eQuest to create the building you specified.

5. When you are ready choose finish to exit the wizard.

6. Now in the main eQUEST window, you can see the building you've designed.

Tip: You can return to the Schematic Design Wizard by finding the Schematic Design Wizard icon along the top of the main eQUEST window (Toolbar).

7. Across the top of the screen (Project Navigation Bar) there is Project and Site, Building Shell, Internal Loads, Water-Side HVAC, Air-Side HVAC, and Utility and Economics. Click through some of these, including looking at some of the spreadsheets for these sections (depending on which modifications were made, some or all of the spreadsheets may not contain additional information).

8. In Building Shell go to 3-D Geometry.

Tip: You can control-click-hold and drag to change the view of the building, and control-right click-scroll to zoom in and out.

9. On the left, there is the option to look at your Actions or the Component Tree. Select the Component Tree. This shows all the components of your project design.

Tip: If you double click on any of these, another window will open up where you can modify the settings of this component.

10. When you are in Actions, there are several options including Energy Efficiency Measure Wizard, Simulate Building Performance, and Review Simulation Results View. Selecting Simulate Building Performance will create the simulation of the building's energy use. Select Simulate, then save your project when prompted. Once the simulation is done running, select View Summary Results/Reports. Once the simulation is run you can view the building's energy use and navigate through the different reports on the left hand side

in Results/Reports view. Spend some time looking through what information is provided in these reports. Once you are done, click "Return to building description mode".

11. Now go to the Energy Efficiency Measure Wizard under Actions to compare the energy use of your baseline (the building as you've designed it so far) to the same design except with an energy efficiency measure chosen in this wizard. Select the Measure Category, then Measure Type. Now, where it says EEM Run Name you may change the name of this run. Select EEM Run Details and input what energy measure you are implementing in order to compare the impact to the baseline. To add another EEM measure, click on Create Run. Select another Measure Category, Measure Type, and apply the measure to baseline. After you are done creating the EEM Runs, select Finish. Now when you select Simulate Building Performance, eQUEST will show you which EEM runs it will simulate, including the baseline. Make sure that all the runs you want to simulate and compare are selected.

12. Back in the Results/Reports view, changing to Reports and selecting the Comparison Report for Monthly Total Energy Consumption will show you, side by side, the energy use for the baseline and EEM runs that were simulated. Spend some time looking through what information is provided in these reports.

   Tip: Save often. If the software freezes the best course of action is to restart eQUEST, so make sure to always save your progress.

For more detailed information on eQUEST, see the following tutorials available online:

1. YouTube Mastering the Basics, a much more detailed walk through of the eQUEST interface and capabilities:
   https://www.youtube.com/playlist?list=PLp4AMb3KSG2bdTvVV8BbBAgRj6ncOhp9R

2. A comprehensive written tutorial for eQUEST:
   http://doe2.com/download/equest/eQ-v3-64_Introductory-Tutorial.pdf

eQUEST Activity

For this activity you will use eQUEST to evaluate energy efficiency measures for a building and write up a short report detailing the efficiency measure and the impact on energy use and GHG emissions.

1. Create a building in eQUEST that will be the baseline for your report. The efficiency measures or other changes you put in place will be compared to the energy use in this building for their effectiveness. For your baseline, you should choose one of the building

types and then leave all other options as the eQUEST default to ensure a simple and solid baseline for your analysis.

2. Change aspects of a building with the same core features as your baseline. Choose at least two from the following options to include in your report:
   a. Any of the options in the Energy Efficiency Wizard
   b. Energy efficiency gains of a window, insulation, and/or wall siding upgrade.
   c. Two or more locations with different climates. Consider how this changes the heating/cooling needs for the building.
   d. If there is another energy efficiency measure you would like to test and include in your report, discuss it with the TA to confirm it is appropriate for this exercise.

3. In your report, include comparisons of energy usage and a discussion on the impacts this has. Include only the relevant results from eQUEST into your report in the form of images or charts with captions.

Energy-Economy Models

Energy-Economy Models

Energy-Economy models are used to evaluate the economic impacts of different policy decisions. They generally fall into three broad categories: Input-output, Computable General Equilibrium and Partial Equilibrium models. In all cases, the general objective is to get an idea of how the broad economy will react to different policy objectives, government interventions and/or industry investments.

Computable General Equilibrium (CGE) models represent the entire economy in a single model structure where every transaction and activity in the model results in a rebalancing of the supply and demand curves for every commodity in the model. So, if a carbon tax is applied in the economy economic theory dictates that there should be a decrease in the demand for fuels that emit carbon. A CGE model will balance the supply and demand curves for such fuels (including the downstream supplies and demands) to determine the new economic equilibrium. The adjustments of the supply and demand curves are based on 'elasticities' which represent the willingness of consumers to adjust their spending based on price signals. For commodities with high elasticity consumers are willing to shift their spending with price signals, but for some commodities (such as electricity) price signals have little impact on consumer behaviour and therefore are considered inelastic. Initial calibration is usually based on the same social accounts matrix used for Input-Output models and elasticities are estimated based on empirical data. For more details on CGE models see the overview description from the Scottish government:
https://www.gov.scot/binaries/content/documents/govscot/publications/factsheet/2016/01/cge-modelling-introduction/documents/computable-general-equilibrium-cge-modelling-sgs-cge-model-pdf/computable-general-equilibrium-cge-modelling-sgs-cge-model-pdf/govscot%3Adocument/Computable%2BGeneral%2BEquilibrium%2B%2528CGE%2529%2Bmodelling%2Band%2BSG%2527s%2BCGE%2Bmodel.pdf

Partial equilibrium models, in contrast, focus on a subset of the economy and balance the supply and demand within these subsets assuming 'Ceteris Paribus' (that all other sectors do not change). They therefore generally require less computational power but, by definition, do not allow for economy wide shifts between unrepresented sectors to occur. They allow for investigation of the impacts of a given policy or investment on a given sector without having to solve the challenge of what happens everywhere in the rest of the economy. An example of a partial equilibrium model used for many energy analysis is the Global Change Assessment Model (GCAM): http://www.globalchange.umd.edu/gcam/.

Input-Output models use a transaction table that represents the consumption and production of commodities amongst different sectors of the economy. Statistical agencies in most developed countries (and increasingly in most developing ones) spend significant effort gathering the data to represent the economy in a 'social accounts matrix' which shows where inputs to production

for a given sector come from and where outputs from each sector go. Using this Input-Output table one can estimate the production increase required in all other sectors for each unit increase in a given sector. Although the Input-Output model is very easy to compute (since all parts are linear), and this works well for small shifts in the economy, the linearity assumption inherent in I-O models limits their application to relatively small shifts. For more details of the method behind I-O modelling see section 4 of this paper:
https://www.mdpi.com/2227-9717/6/12/238/htm.

Reading Questions:

Define the following terms:
- CGE
- I-O
- Partial Equilibrium
- Social Accounts Matrix
- List some strengths and weaknesses of CGE, Partial Equilibrium and I-O models.

Further Reading:
https://en.wikibooks.org/wiki/Linear_Algebra/Topic:_Input-Output_Analysis
https://en.wikipedia.org/wiki/Input%E2%80%93output_model

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- Computable General Equilibrium modelling: introduction from the Scottish Government, used under an Open Government Licence
- Global Change Assessment Model by The Joint Global Change Research Institute, licensed ECL-2.0
- Modelling and Simulation of Energy Systems: A Review by Subramanian et al., licensed CC BY-4.0
- Linear Algebra/Topic: Input-Output Analysis from Wikibooks, licensed CC BY-SA-3.0
- Input-output model from Wikipedia, licensed CC BY-SA-3.0