STeMES - Model Functionality Overview

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This document provides an overview of the functionality of the model STeMES, which stands for Spatio Temporal Model of Energy Systems.

STeMES is a generic optimisation model of energy systems comprising technologies for generation/conversion, transport and storage and transport infrastructures. The model determines the optimal network structure (e.g. location, size and interconnection between technologies) and its operation considering simultaneously the short-term dynamics and a long-term planning horizon.

The energy pathways are modelled using a Resource-Technology Network (RTN) representation, thus the model is data-driven, which means that extending the model to include additional resources and technologies is simply a matter of changing the data without the need to modify the model formulation. STeMES can be applied to any region of interest, e.g. a city or a country, which can be represented by a number of cells. A long-term planning horizon (e.g. decadal or yearly) with short time intervals (e.g. hourly) can be considered. STeMES uses a non-uniform hierarchical time discretisation approach to represent time efficiently and a decomposition method which breaks down the large optimisation problem into 3 subproblems which are then solved iteratively until the objective function is no longer improved. Therefore, high-fidelity solutions can be obtained witihin an acceptable time.

STeMES is a mixed-integer linear programming model implemented in AIMMS 3.12 and solved using CPLEX 12.6.

1 Key elements of STeMES

STeMES has the following five key elements:

1. Space

   The region of interest is divided into a number of cells. Each cell, which may be of any shape and size, represents a geographical location and is characterised by its centroid and area. The cells may have different dynamic demands for various resources. Also, some resources may be available in certain cells in varying quantities. Each cell may enclosed different technologies for converting and storing resources. It may also have infrastructure connections with other cells for transport of resources and external connections for import and export of resources. System properties that may vary across space are resource demands and availability, land cover, built environment etc.

2. Time

   The time element needs to capture the long-term strategic decisions as well as short-term operational issues. A multi-time scale concept was used in modelling: decadal and yearly intervals for investment decisions; seasonal intervals to capture seasonal variations; daily intervals to capture, for example, the difference between weekdays and weekend; and hourly and shorter intervals for system balancing. An obvious example of a system property that varies with time is the resource demand: it can vary within a day due to peak and off-peak times; it is likely to be different in weekdays or weekend, or in different seasons; and it can be expected to increase year on year because, for example, of population growth. Resource prices and technology costs can also change with time. Also, some resources may only be available in certain times.

3. Resources

   Resources refer to any material or energy vector considered in the energy system model. A resource can be consumed or produced by a technology, transported from one cell to another cell, imported from outside the region under study (e.g. abroad) to certain locations and stored when seasonality is considered. Resources include: raw materials or primary energy resources such as sunlight, wind or biomass; intermediates, which are produced by one technology and then consumed by a different technology, e.g. syngas, pyrolysis oil; end-use vectors such as electricity, heat and transport fuels (hydrogen and bio-methane are also widely regarded as final vectors); by-products, which are valuable materials that are generated in the process of producing the end-use vectors; and wastes, e.g. CO_2 and waste heat.

4. Technologies

   Technologies convert one set of resources into another set of resources. For example, a gas turbine takes natural gas and converts it into electricity, heat and CO_2.

   A flexible multi-vector model, such as STeMES, allows a technology to convert different input resources into the same output resource (e.g. a boiler can use either natural gas or hydrogen to generate heat). Similarly, an input resource can be transformed into different output resources via different technologies (e.g. hydrogen can be converted into electricity using fuel cells or heat using a boiler). Indeed, a particular resource can be an input to a technology and at the same time an output from a different technology (e.g. an end-vector, bio-methane, produced from anaerobic digestion of wastes, can be used as an input to a gas turbine to produce another end-vectors, electricity and heat). This way, the optimisation can choose the most effective conversion pathway, as well as compare the value of the different energy vectors, for a given objective. Materials (or energy) is lost in the process of transforming an input resource to an output resource, therefore each conversion is associated with an efficiency.

   A technology may be available at different scales of capacity which vary from household scale (e.g. a boiler) to industrial scale (e.g. a combined cycle gas turbine in a power station). The cost and efficiency of a technology may improve over time as more understanding about a technology is gained.

   The multi-vector energy system model can be viewed as a resource-technology network formed by all of the interconnections between resources and technologies.

5. Transport infrastructures

   Infrastructure connects different spatial cells and is used to move resource from one location to another location. Examples are road and railways used to transport solid and liquid resources, electricity and natural gas grids, district heating networks, pipelines for e.g. hydrogen, CO_2 and syngas. An infrastructure either exists already or may need to be built.

2 Problem description

STeMES has been developed to answer variations of the following problem:

Given:

- A spatial description of the region under study represented by a number of cells. Each cell is characterised by the coordinates of its centroid, which are used to calculate the distance between each cell, and its land area.
- A set of resources, with each resource having the following properties (for each cell and for every hour):
  - Demand
  - Availability
  - Unit cost and GHG emissions associated with its purchase, e.g. from the grid

  - Information on storage:
    * e.g. If a resource can be stored in a particular storage technology located in a particular cell
  - Etc.

- A set of production technologies that convert primary energy resources to final energy vectors, via any number of intermediates. Each technology is characterised by its:
  - Minimum and maximum capacity
  - Efficiency (in terms of converting an input resource to an output resource)
  - Capital, operating and maintenance costs
  - Maximum number that can be built each year for the whole region (also referred to as build rate)
  - If a plant can be built in a particular cell
  - Etc.

- A set of storage technologies, each characterised by
  - Efficiencies associated with putting, holding and withdrawing a resource
  - Minimum and maximum holding capacity
  - Minimum and maximum charge and discharge rate
  - Unit capital impact (i.e. cost and GHG emissions)
  - Unit operating impact associated with putting, holding and withdrawing a resource
  - Etc.

- A set of transport technologies, each defined by its
  - Minimum and maximum capacity
  - Efficiency in transporting a resource (which can be dependent or independent of the distance travelled)
  - Unit cost and GHG emissions associated with transporting a resource (which can be dependent or independent of the distance travelled)
  - Etc.

Determine:

- The number and location and size of production and storage technologies and transport infrastructures invested in every year
- How to operate each production plant (in each cell at every hour)?
  - Production/consumption rate of each resource
  - Utilisation rate of each technology
- How to operate each storage technology (in each cell at every hour)?
  - Inventory level of each resource in each storage technology
  - Rate at which a resource is added, held and withdrawn from each storage technology
- How to transport each resource between cells at every hour?
  - Rate and mode of transport

Subject to:

- Meeting the hourly energy demand for each resource in each cell
- Maximum resource availability (local and abroad)
- Maximum capacity of technologies (including production, storage and transport

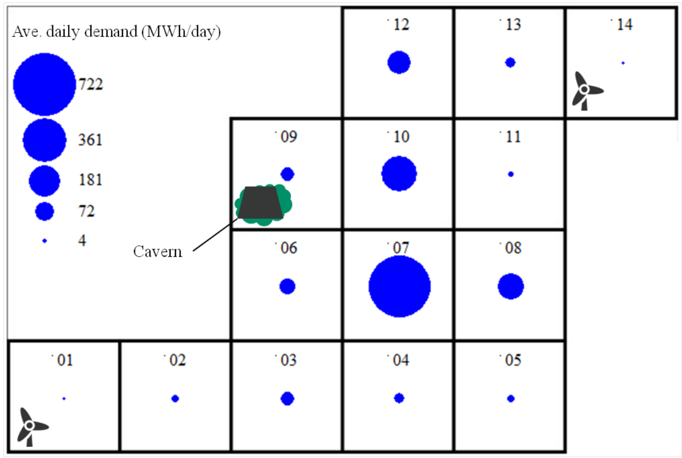
In order to:

- Minimise total cost and/or GHG emissions (or any performance criterion)

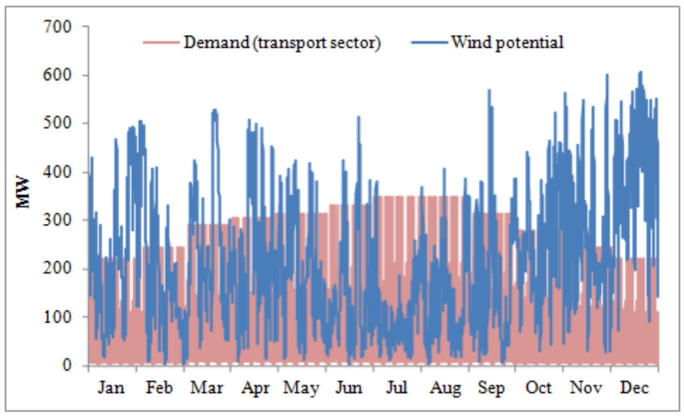
3 Illustrative example: design of a hydrogen network

The example considers a geographical region, shown in Figure 1(a), that represents an island using 14 50 km$\times$50 km squares. There is a plan to replace all fossil fuel powered cars with fuel cell cars running on hydrogen. There are two wind farms, located in the north-east and south-west coasts of the island, which can be used to generate electricity that is then converted to hydrogen by electrolysis. The blue circles in the figure indicate the average daily demand for hydrogen for transport in each cell; it also shows the location (cell 9) of a salt cavern that may be used for hydrogen storage. The aim is to design a hydrogen infrastructure network comprising technologies for resource interconversion, storage and transport utilising the intermittent wind capacity to meet the temporally- and spatially-distributed transport demand. Figure 1(b) shows the hourly transport demand along with the wind potential for a reprsentative year. The transport demand has daily variations, being lower at weekends, as well as an overall seasonal variation, peaking in the summer. The wind potential is much more variable, sometimes higher and sometimes lower than the transport demand. In contrast to the transport fuel demand, the wind potential peaks during the winter months and is lowest during the summer. Both of these features suggest that storage could play a role in ensuring the demands are always satisfied.

The aim is to design a hydrogen infrastructure network comprising technologies for resource interconversion, storage and transport utilising the intermittent wind capacity to meet the temporally- and spatially-distributed transport demand. The generated hydrogen can be transported to different cells and stored in either liquid or gaseous form. The choice of storage technologies include compressed gaseous storage (e.g. pressurised tanks), liquid storage (e.g. cryogenic vessels), metal hydride and underground storage (there is a salt cavern in cell 9 that is suitable for this purpose). The problem involves determining the network components, their number, size and location, their interconnections (through transport infrastructures), and their hourly operation over an entire year so as to minimise the total system cost.



(a)



(b)

Figure 1: Example network design problem in which the spatially- and temporally- distributed transport demand of an island is to be met by intermittent wind capacity: (a) geographical region under study discretised into 14 cells showing the distribution of transport demand over different locations in the island; (b) representative data for transport energy demand and wind energy potential

The possible energy pathways are represented using Resource Technology Network such as in Figure 2.

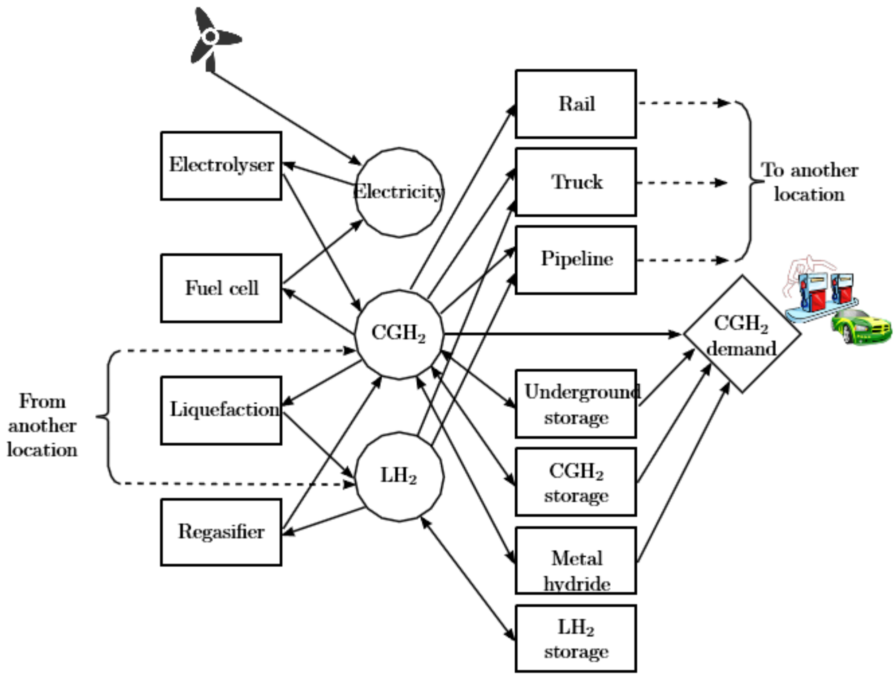


Figure 2: RTN representation of the problem.

3.1 Example results

Figure 3 shows the resulting network structure, i.e. the number, location and size of hydrogen production and storage facilities and the type of transport infrastructure established between cells.

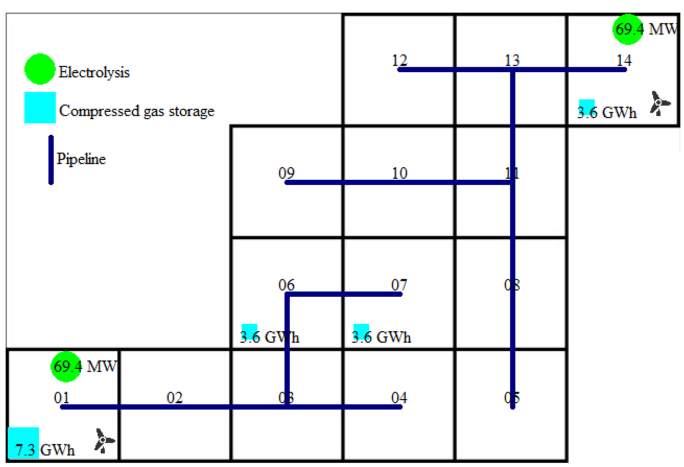
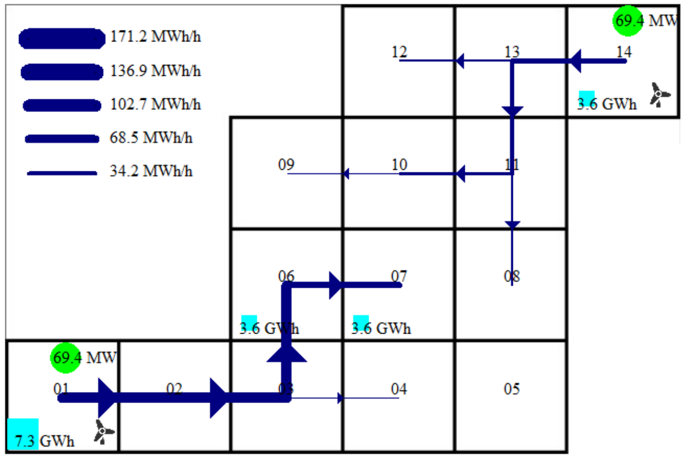
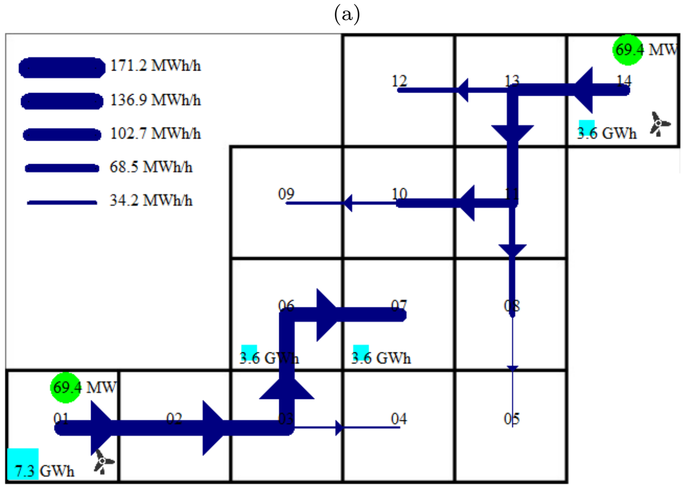


Figure 3: Optimal network structure: electrolysers are installed in the same cells as wind turbines; compressed gas storage units are located in the same cells as hydrogen-generating technologies and near the cells with highest demand; and pipeline networks are established to transport hydrogen between cells.

Figure 4 shows different snapshots of the transport operation at different times during a weekday in summer. Storage plays an important role in meeting the demands especially during peak times.



(a)



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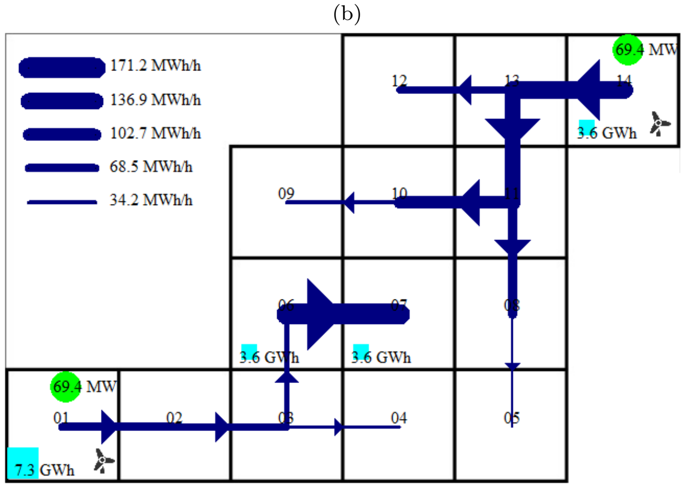
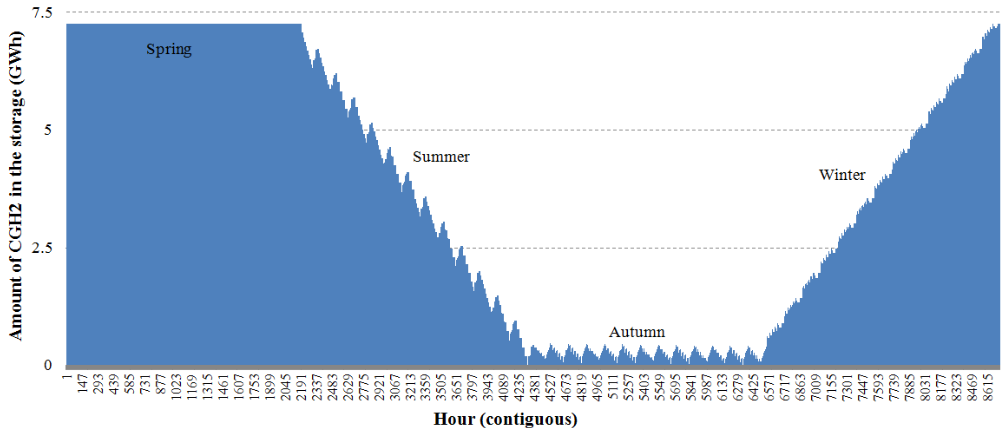


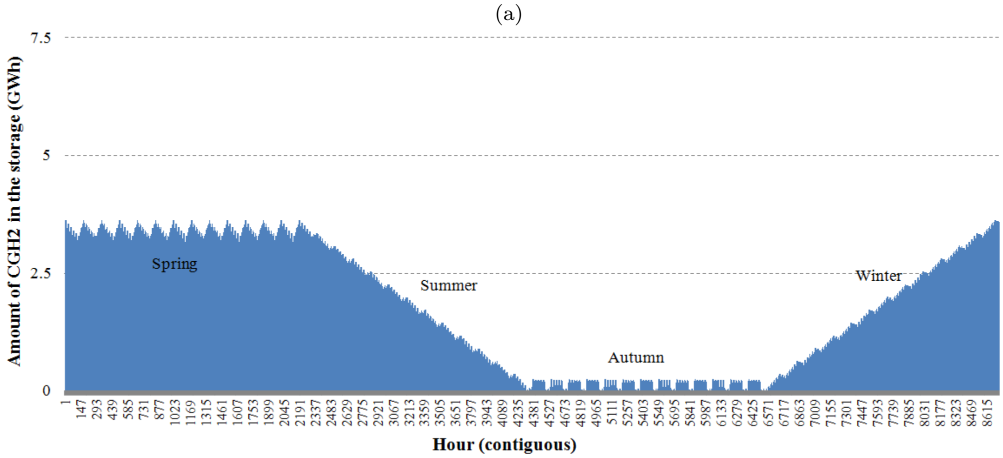
(c)

Figure 4: Snapshots of transport operation at different times of a weekday in summer: (a) 7:00; (b) 12:00; and (c) 19:00.

Figure 5 shows the whole-year inventory of hydrogen in storage at different locations in the island.



(a)



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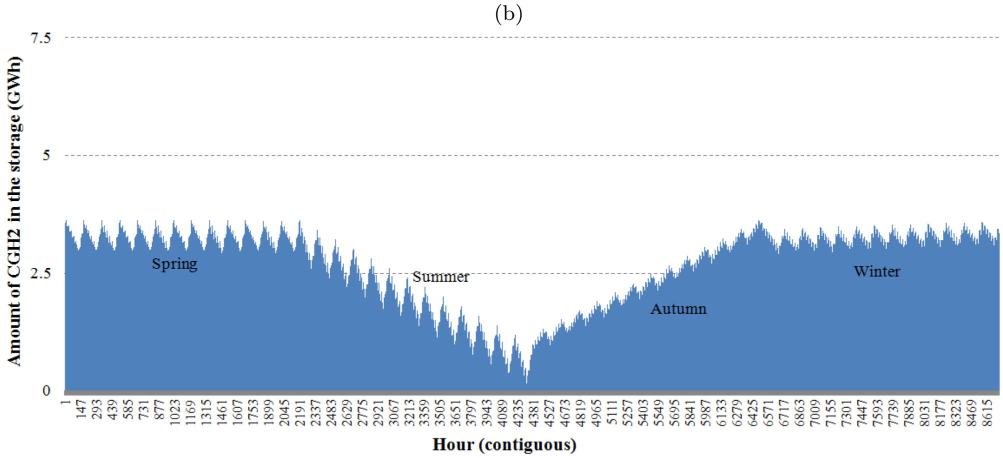

(c)

Figure 5: Compressed hydrogen gas inventory for a whole year in the storage located at different locations in the island: (a) cell 1; (b) cell 7; and (c) cell 14.

4 More information on STeMES

- The full mathematical model is discussed in detail in a journal article in preparation for submission in early December 2014.

  S. Samsatli and N. Samsatli. A generic spatio-temporal energy system model (STeMES) with a detailed account of transport and storage.

5 Other examples of spatio-temporal models developed by our group

- Biomass Value Chain Model (ETI-BVCM)

  S. Samsatli, N.J. Samsatli, N. Shah. BVCM: A comprehensive and flexible toolkit for whole-system biomass value chain analysis and optimisation – mathematical formulation. Applied Energy (under review).

- TURN model for urban energy systems

  N. Samsatli, M. Jennings, Optimization and systems integration, in: J. Keirstead, N. Shah (Eds.), Urban Energy Systems: An Integrated Approach, Routledge, 2011, Ch. 9, pp. 157–184.

- Hydrogen supply chain model

  A. Almansoori, N. Shah, Design and operation of a future hydrogen supply chain: Multi-period model, International Journal of Hydrogen Energy 34 (19) (2009) 7883 – 7897.