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Addressing the challenge of modelling energy storage in a whole energy system

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Future energy targets are driving the deployment of renewable technologies

London Array – the world's largest offshore wind farm

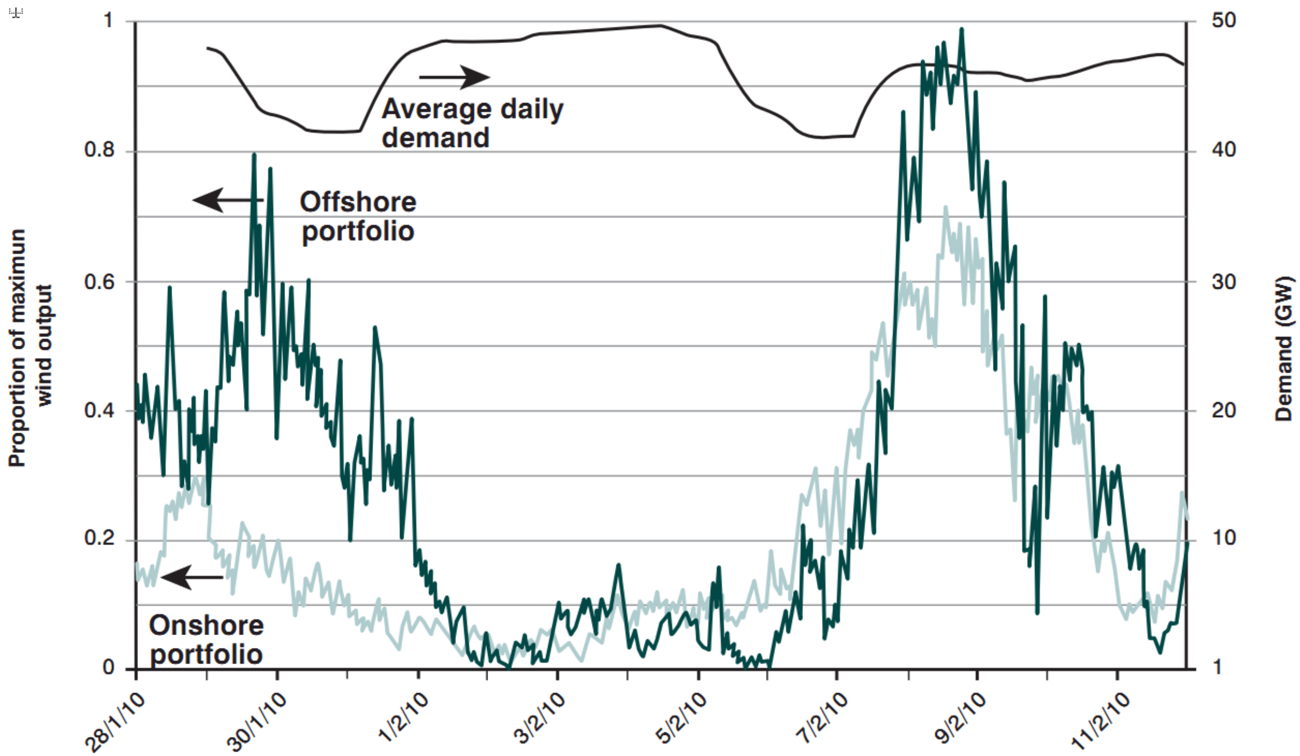
A solar farm

Aquamarine Power's Oyster Wave Energy

Photo credits: http://www.londonarray.com/media-centre/image-library/offshore/
http://www.solarselections.co.uk/blog/wp-content/uploads/2012/09/ROC-solar-farm.jpg
The future role for energy storage in the UK, Energy Research Partnership, 2011

The intermittency challenge

Source: The future role for energy storage in the UK, Energy Research Partnership, 2011



- Renewable energy is generated when it's not needed
- Large dip in generation during high demand
- Peaking generators, e.g. gas turbines, used to balance supply and demand are expensive and produce GHG emissions

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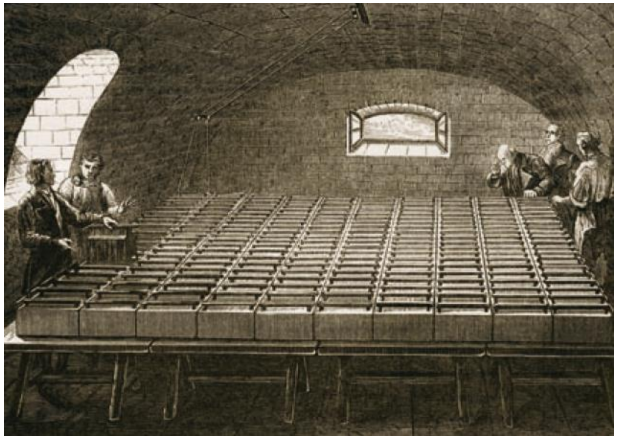
Energy storage solution

Photo credit: The future role for energy storage in the UK, Energy Research Partnership, 2011

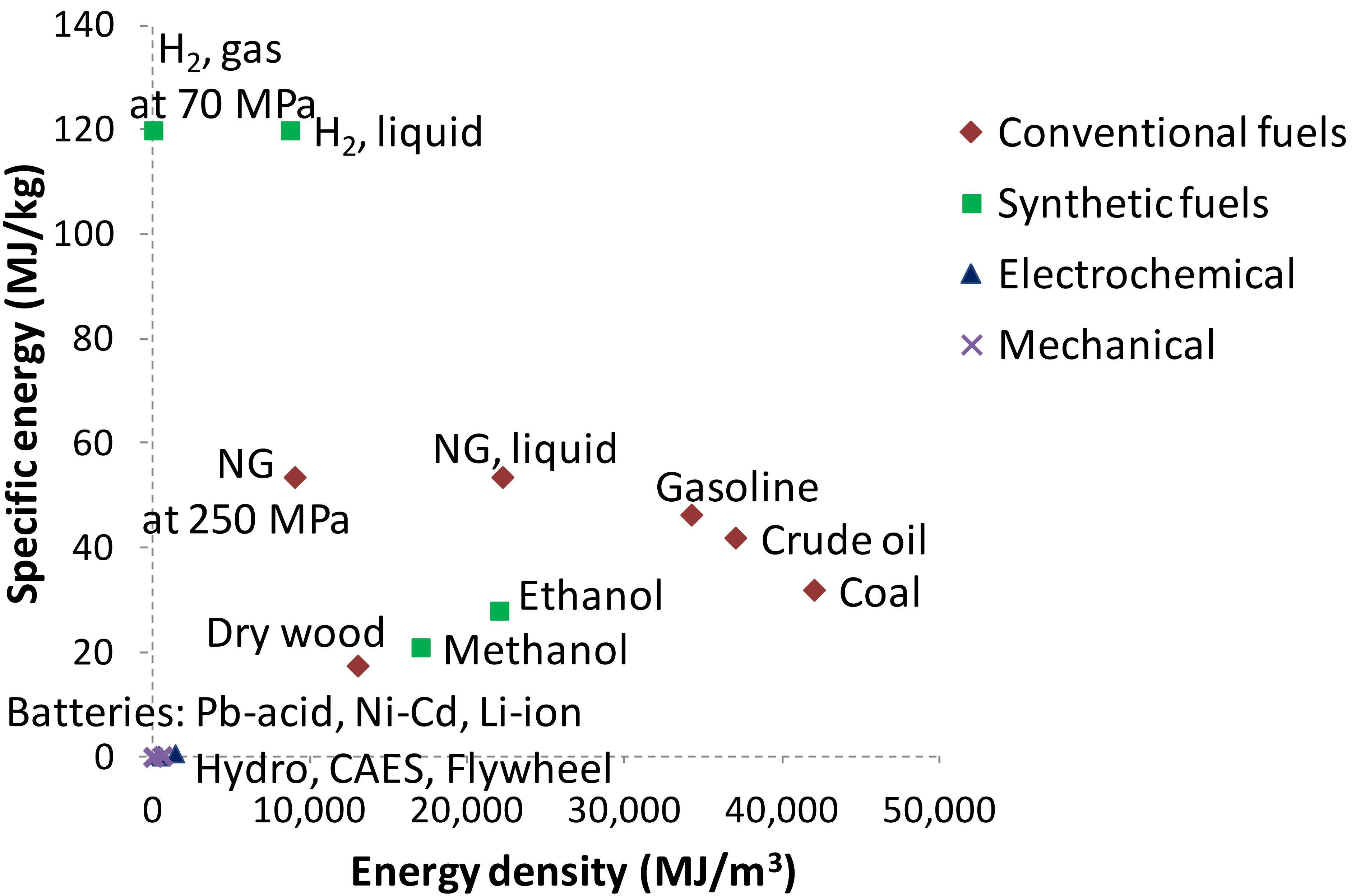


Royal Institution Battery 1807

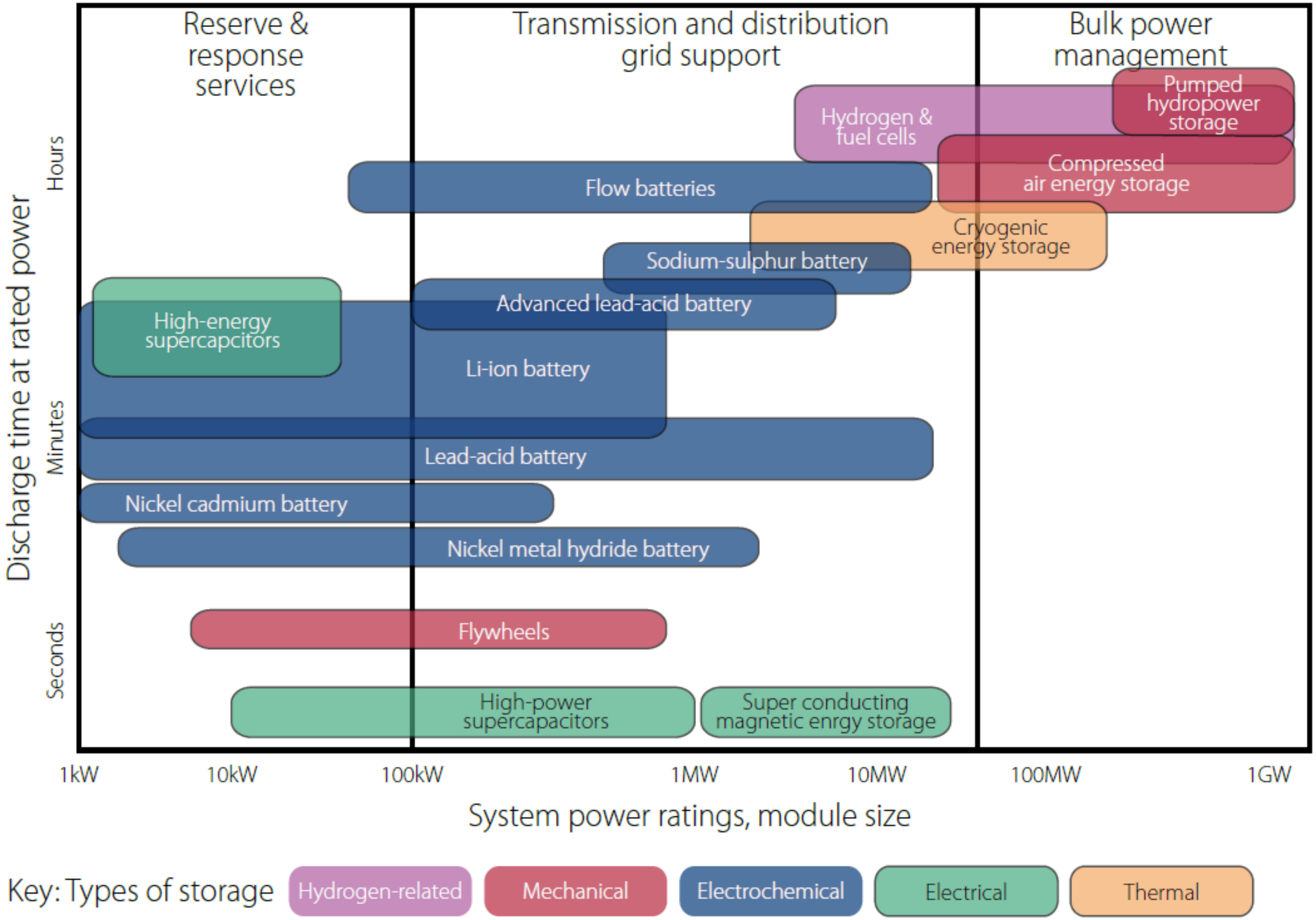
Llyn Stwlan reservoir

Hot water storage tank in the basement of a smart house

- Enables “wrong-time” energy generation from intermittent renewables
- Reduces need for peaking generators
- Improves energy use efficiency



Reference: Wikipedia



Source: Williams, R. Is liquid air the missing link in energy storage. Focus April 2013.

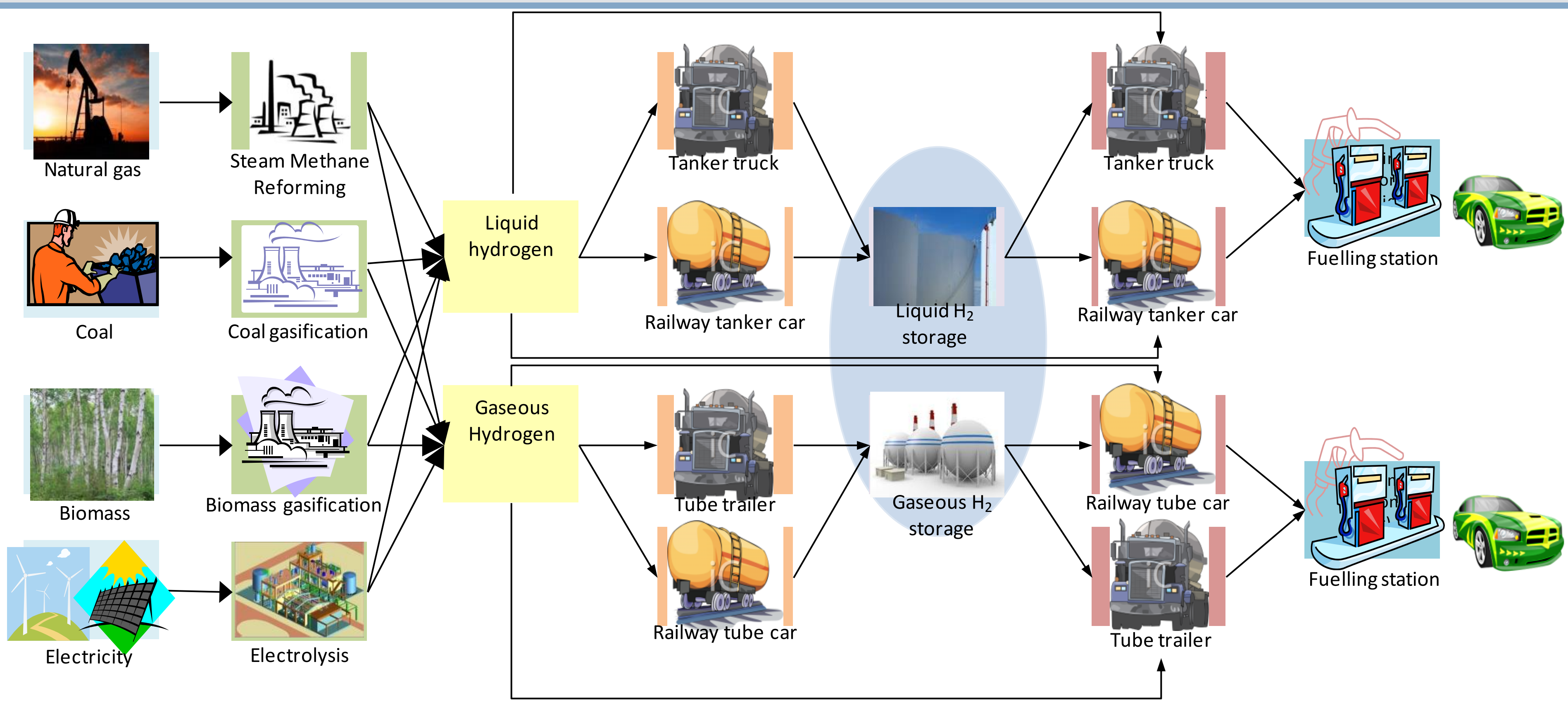
Modelling challenge: the dynamics of storage technologies occur over short time scales (<hourly), very different from the time interval in energy system planning models (>yearly)

Tractability is an issue!

Challenges

- We need a dynamic energy system model with a very wide range of time scales
  - Planning: years or decades
  - Seasonal: variations in demands and availability
  - Hourly (or shorter):
    - Dynamics of storage technologies
    - Variations in demands, intermittency of renewable resources
- Still need to model spatial aspects
  - Demands and availability depend on location
  - Determine location/size of technologies and storage facilities
    - Requires integer variables
  - Transport of resources (centralised vs. distributed)
- Very large scale model

Hydrogen Supply Chain (HSC) model



Spatial element: Great Britain represented by 34 108×108 km2 square cells
Temporal element: 2015-2044 divided into 5 6-year periods
Last upgrade: made it a dynamic model with time intervals of 4 seasons in a year and 4 6-hr periods in a day

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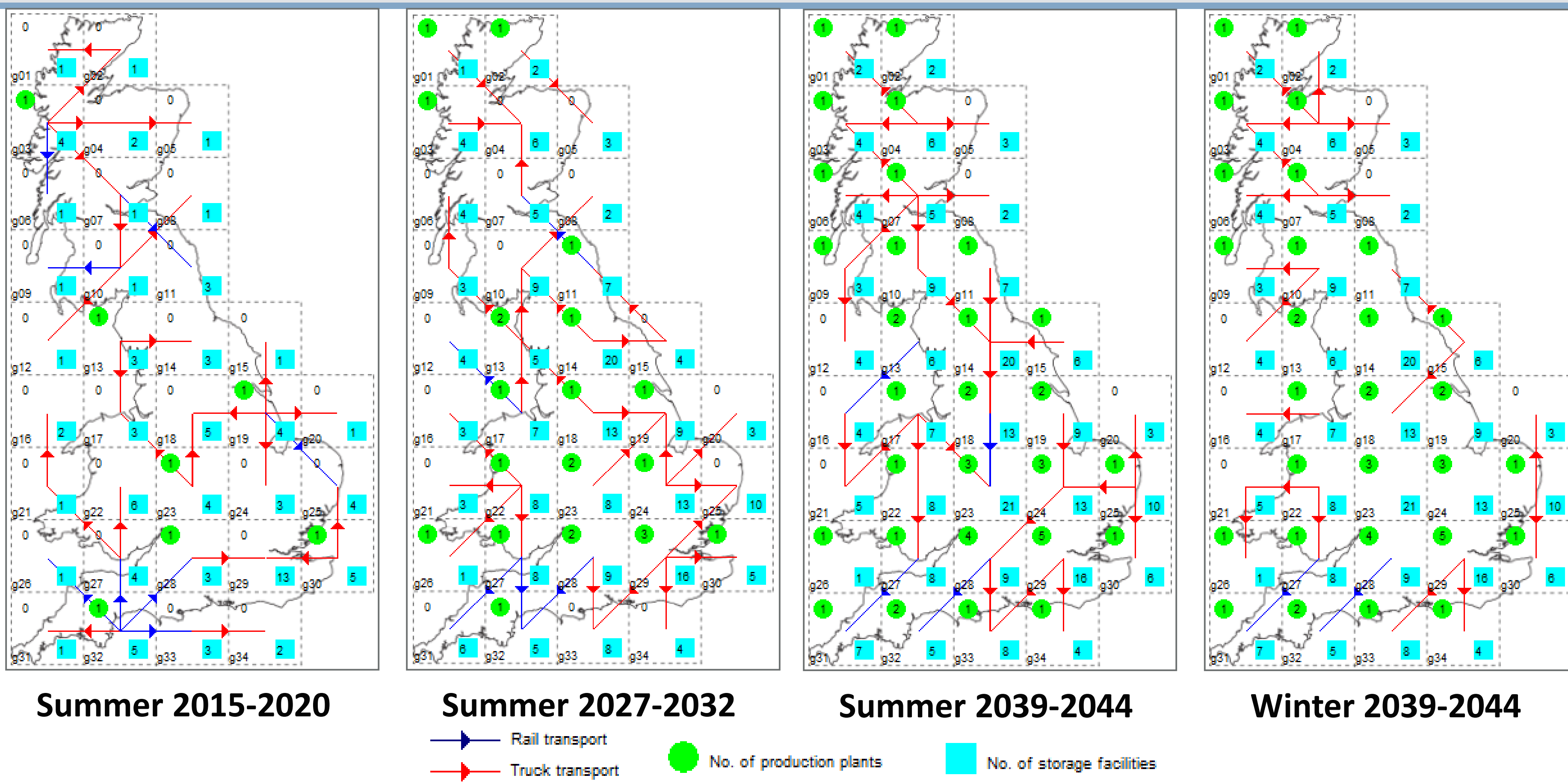
Example case study

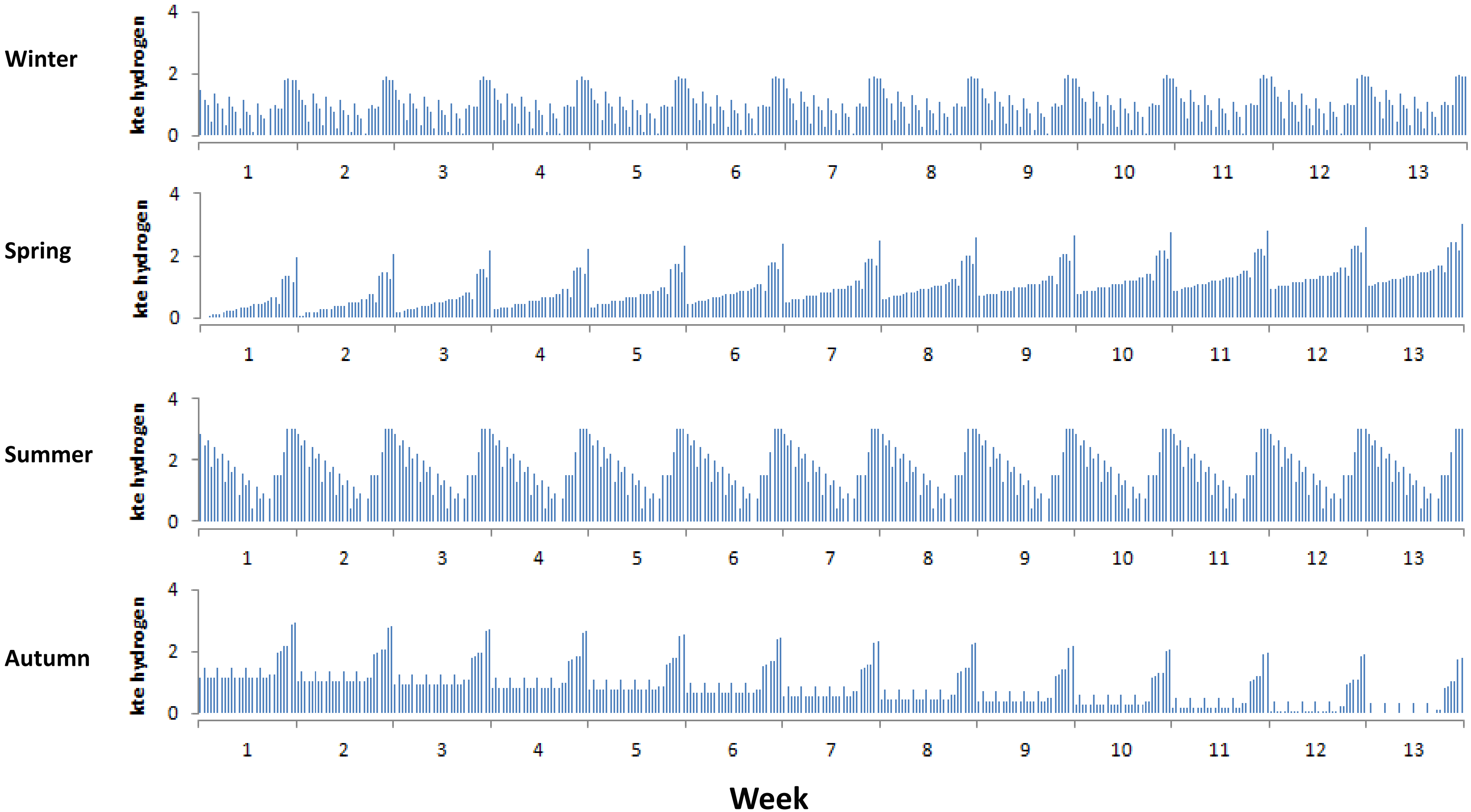


No. of variables > 1M, No. of constraints > 0.5M, Integers = 15k

Took ~3 days to solve full MIP!

Inventory profile for a whole year

London and the South East (cell 29) in 2039-2044



Limitations of the HSC model

- Multi-echelon model
  - Pathways inflexible
  - Distribution within cells too complex
    - Too many binary variables
    - Big M formulation
- Too large to be extended
  - Adding a pipeline transport mode resulted in intractable problems
  - Difficult to add new technologies and resources
  - Still not enough time intervals

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Back to basics:
A very simple MILP model with storage

Resource balance: $I_{rch} + U_{rch} + \sum_{p} \alpha_{rp} P_{pch} + \sum_{c'} \left(Q_{rc'ch} - Q_{rcc'h} \right) - D_{rch} = S_{rch} - S_{rc,h-1} \quad \forall r,c,h$

Production capacity constraint: $P_{pch} \leq NP_{pc} p_{p}^{\max} \quad \forall p,c,h$

Resource availability constraint: $U_{rch} \leq u_{rch}^{\max} \quad \forall r,c,h$

Storage capacity constraint: $S_{rch} \leq s_{rc}^{\max} \quad \forall r,c,h$

Objective function definition

A *simple* model is intractable for the time horizon needed for a planning model!

$|r|$ = 3 $|p|$ = 4 $|c|$ = 14 No. of integer variables = 56

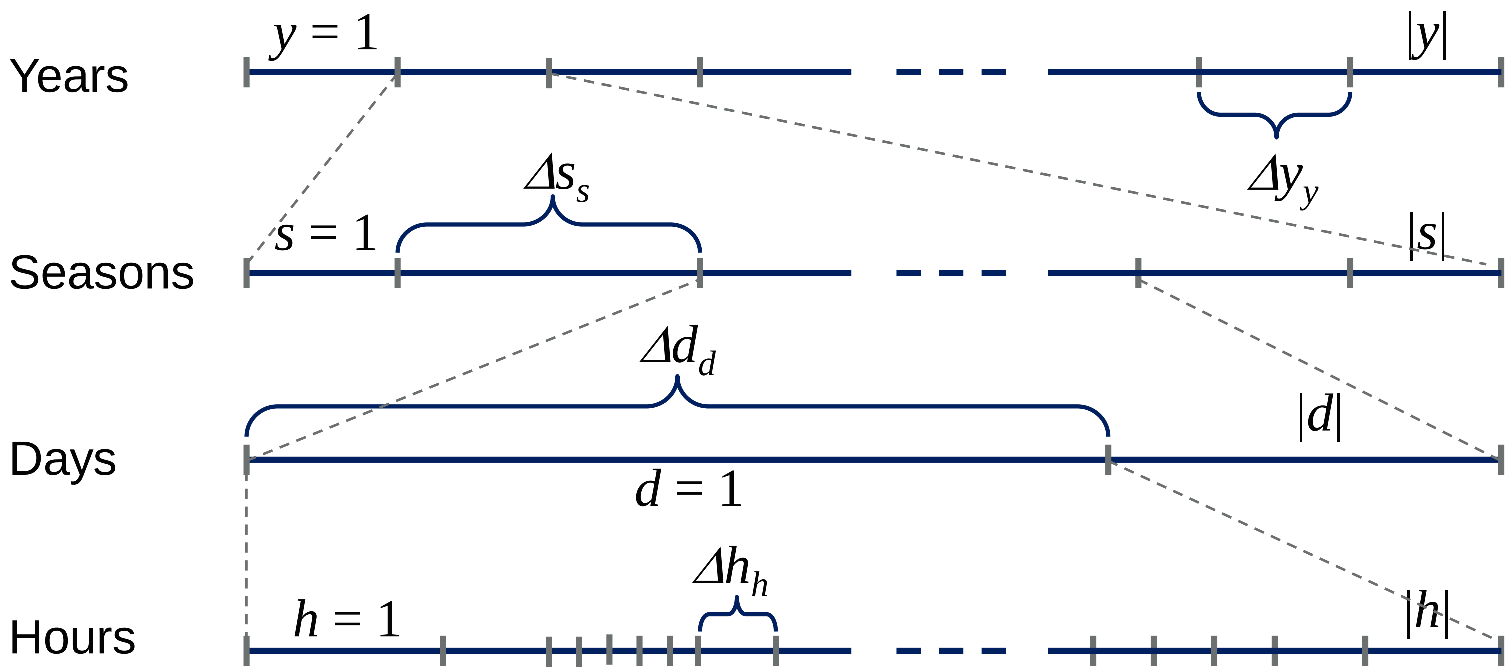
h - contiguous hourly interval

$\lvert h \rvert$	No. of variables	No. of constraints	Solution time (s)
24	6,139	3,703	7
168	42,427	25,879	744
720	181,531	110,887	22,248
2,160	544,411	332,647	>155,520
8,760	2,207,611	1,349,047	??!

STeMES

- **S**patio **Te**mporal **M**odel for **E**nergy **S**ystems
- RTN representation of energy pathways
  - same framework as the BVCM and TURN model in SynCity toolkit
- MILP formulation
- Efficient representation of time
- Detailed storage formulation
- Transport losses modelled in detail

Hierarchical non-uniform time discretisation

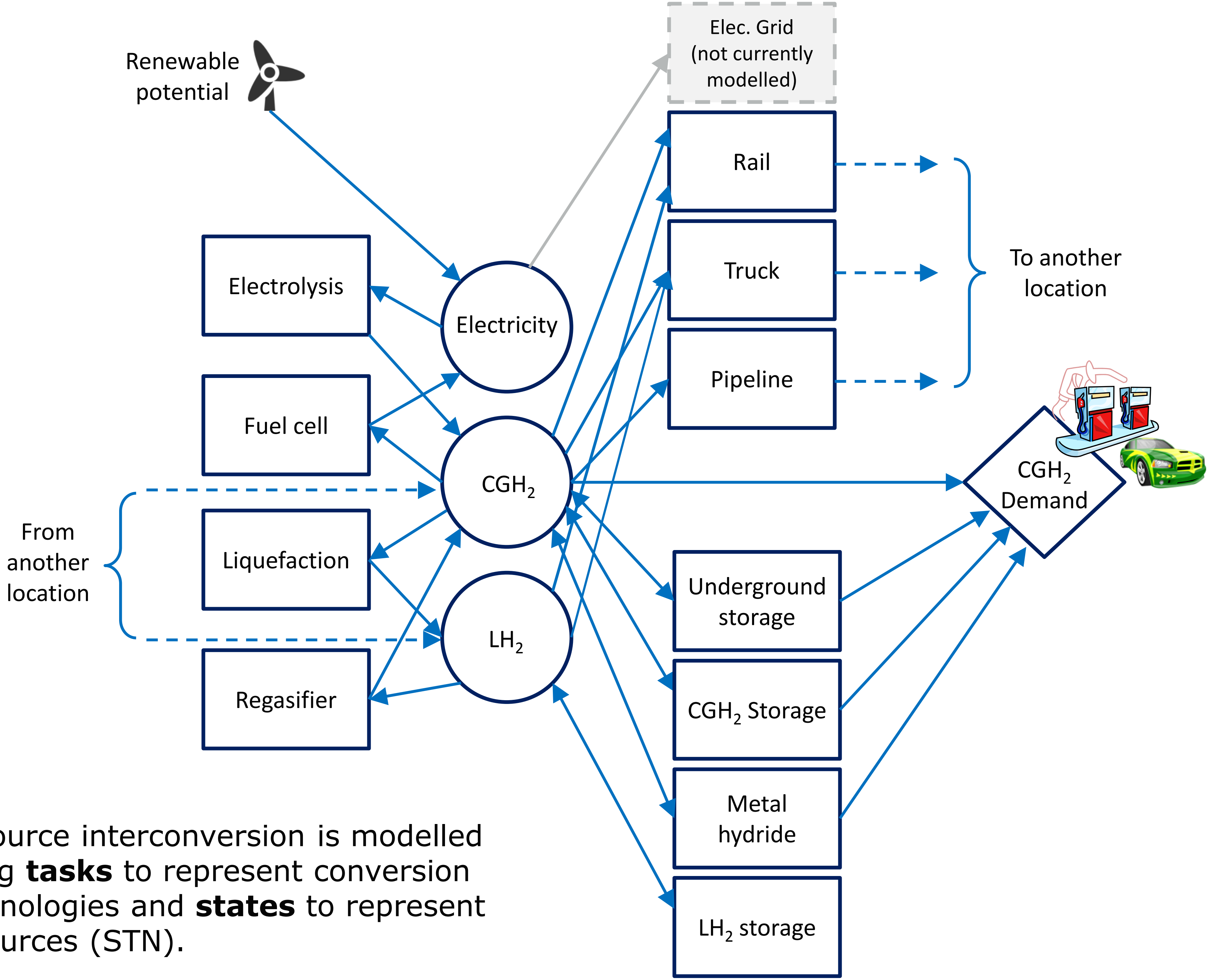


Total number of time intervals $T = |y| \times |s| \times |d| \times |h|$

e.g. for one year, $T = 1 \times 4 \times 2 \times 24 = 192 << 8760$

Without storage – very easy!

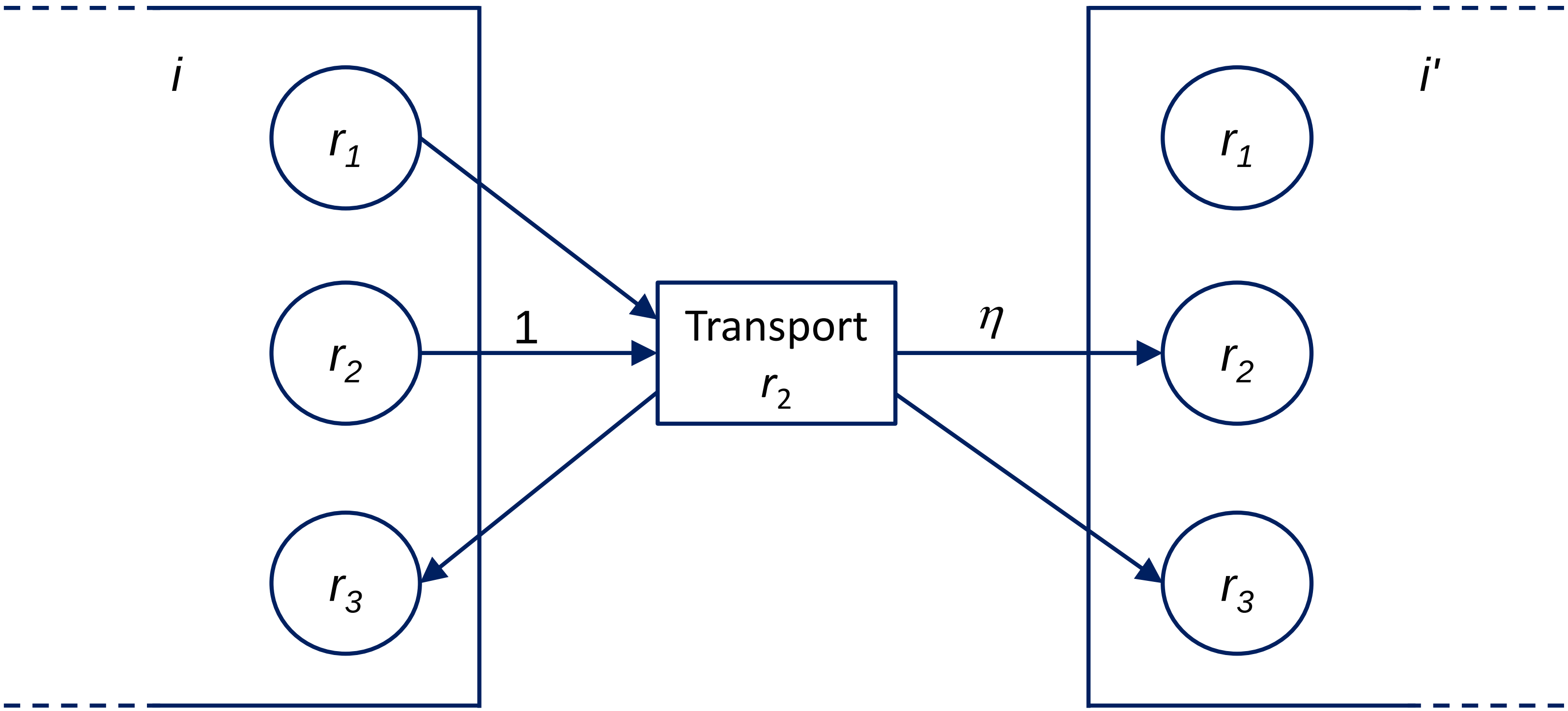
With storage – extra variables for initial inventories; extra constraints to link inventories within and between time levels



Resource interconversion is modelled using **tasks** to represent conversion technologies and **states** to represent resources (STN).

Transport

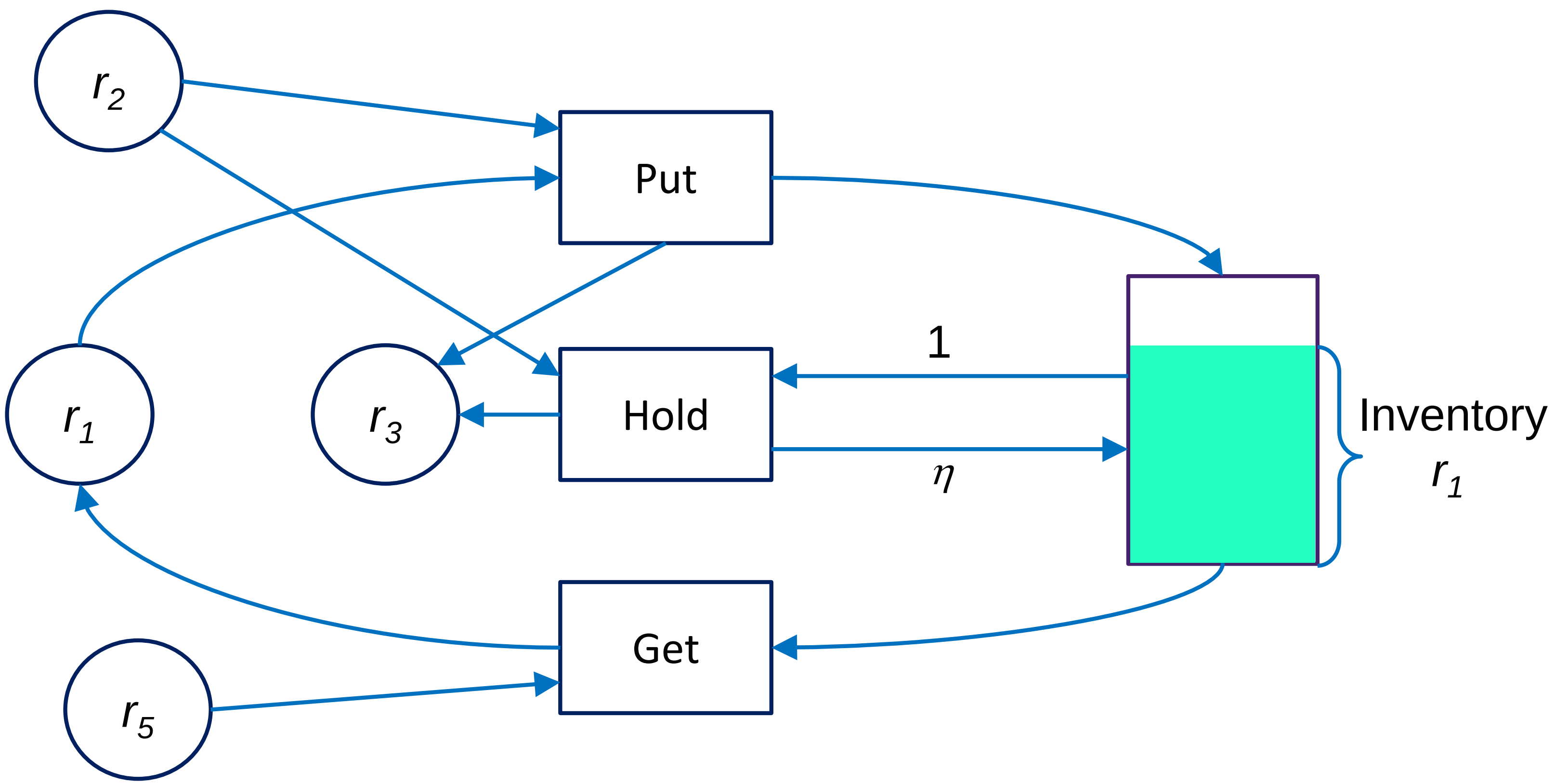
Transport task – used to model connections between cells



Resource r_2 is transported from cell *i* to cell *i'*, which requires r_1 from cell *i* and results in waste r_3 being generated in both cells

Storage

An example set of **storage tasks** to store resource r_1.



The "put" task transfers r_1 from the cell to the store, requiring some r_2 and producing some wastes r_3 (e.g. CO_2). The "hold" task maintains r_1 in storage, which also requires some r_2 but at less than 100% efficiency, the losses being converted to r_3. Finally, the "get" task retrieves r_1 from storage and delivers it to the cell, requiring some r_5.

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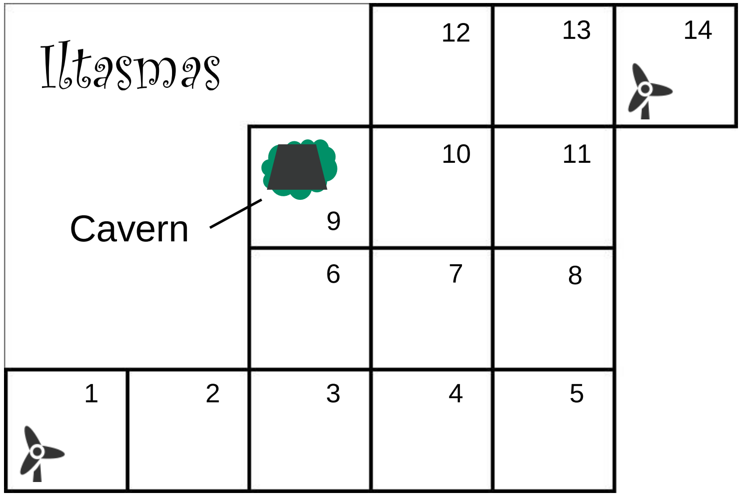
STeMES prototype

- Developed and tested for a hypothetical island of 14 50×50km cells
- Wind generation installed at two locations
- Choice of storage technologies
  - Salt cavern available for use as hydrogen storage facility
  - Other H_2 storage technologies: gaseous (tank), liquid, metal hydride

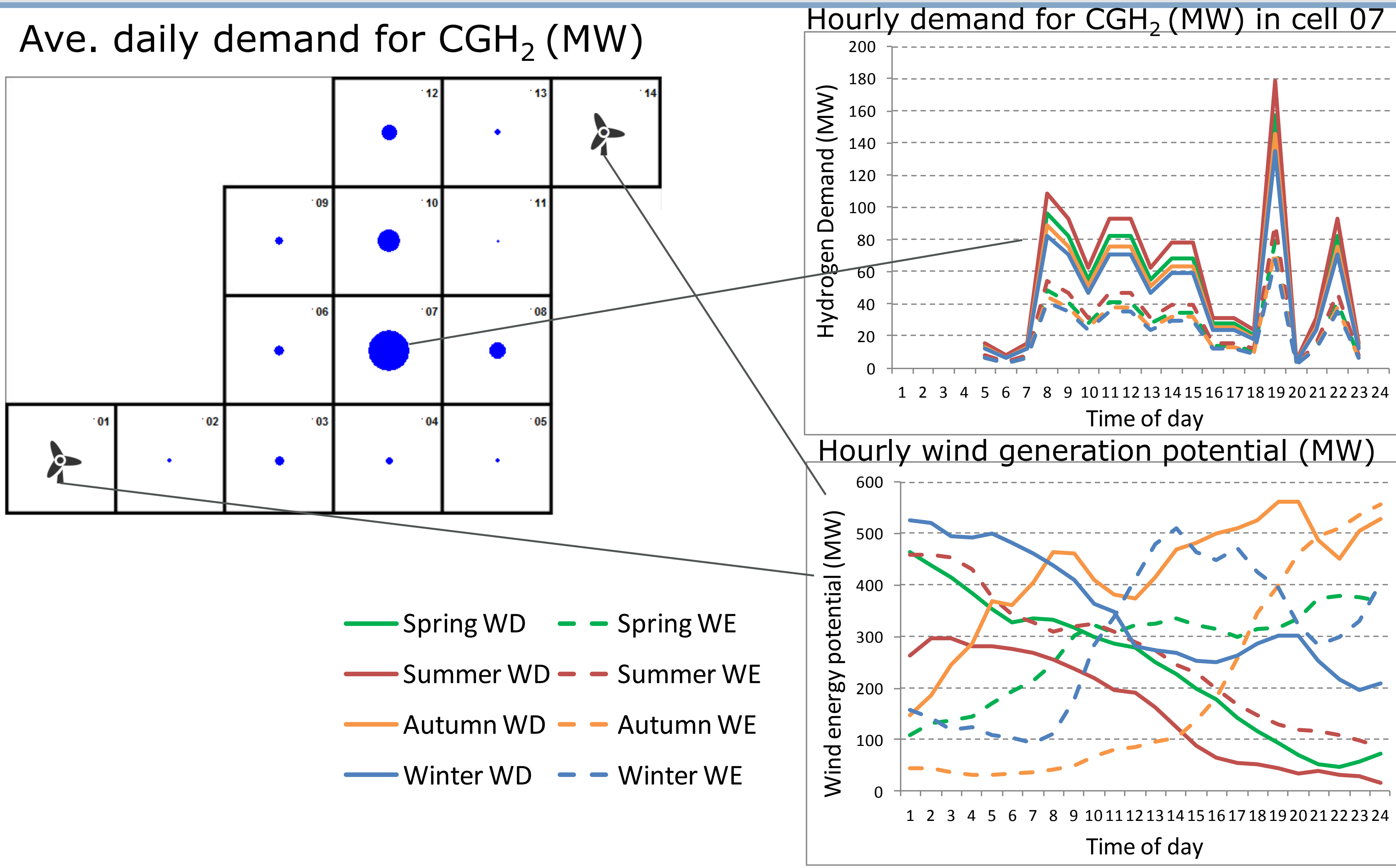
- Target: transport demand to be met by hydrogen (CGH_2)

- Objective: Minimum cost

- Decisions
  - Location and size/number of hydrogen production and storage facilities
  - Operation of production facilities
  - Operation of storage facilities
    - when to charge and discharge
  - Transportation of hydrogen

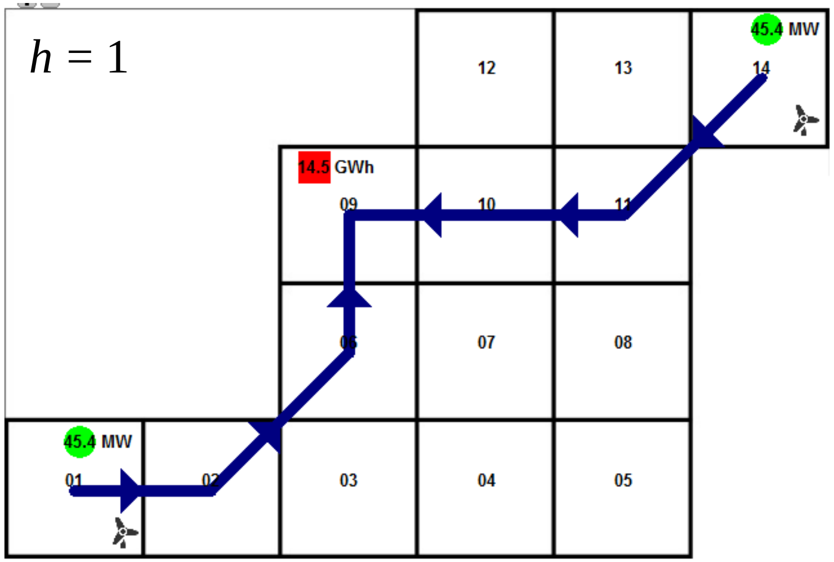


Spatio-temporal input data



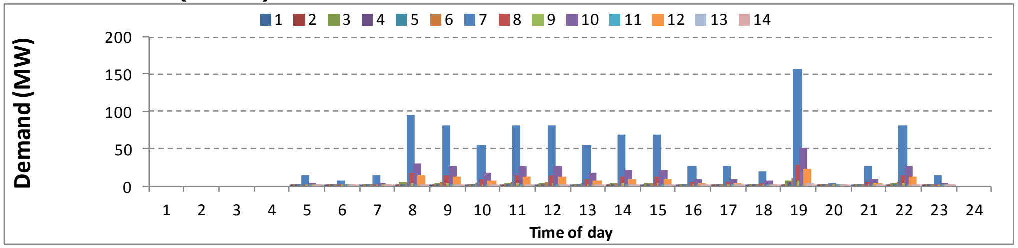
Results $|y|=1, |s|=4, |d|=2, |h|=24$

Snapshot of the network during weekday (d=1) in spring (s=1)

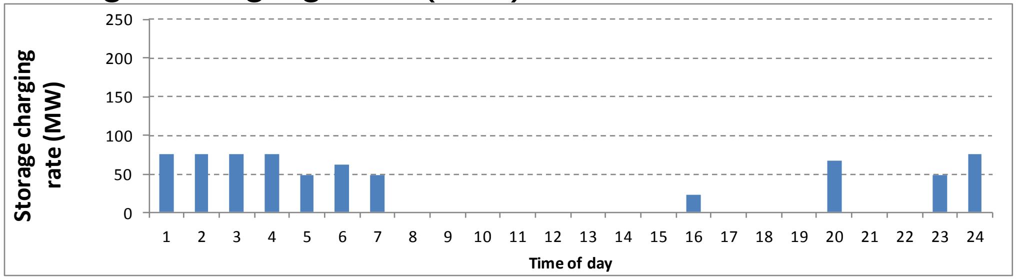


- Hourly transport of CGH2 by pipeline
- Installed electrolyser capacity (3 small units)
- Installed underground storage capacity

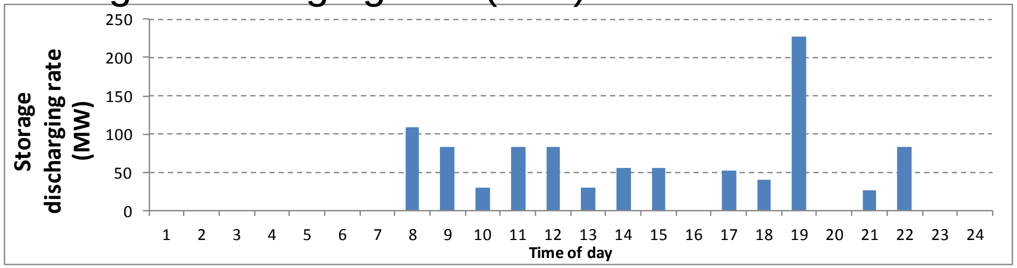
Demand (MW)



Storage charging rate (MW)



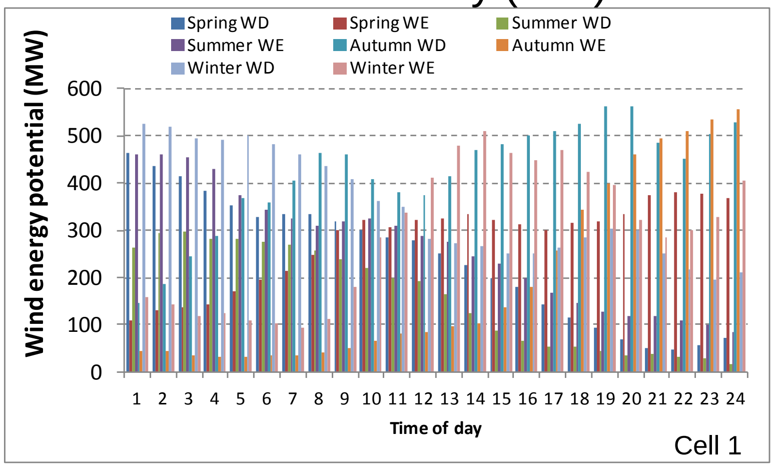
Storage discharging rate (MW)



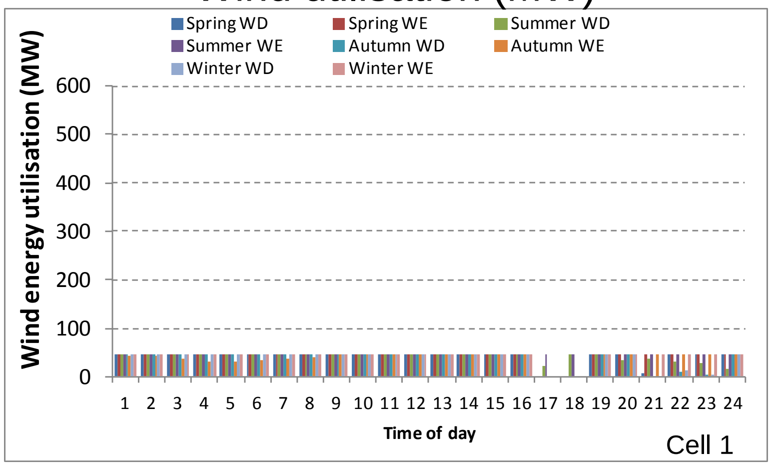
Resource Utilisation

- Without storage, the scenario is infeasible
- BUT with storage, only a fraction of the available wind energy is needed!

Wind availability (MW)

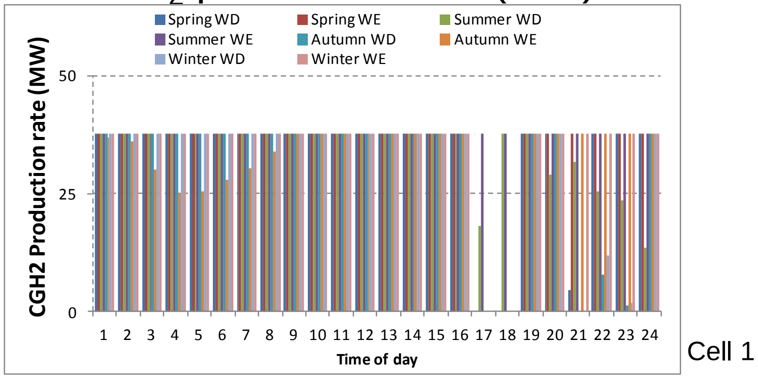


Wind utilisation (MW)



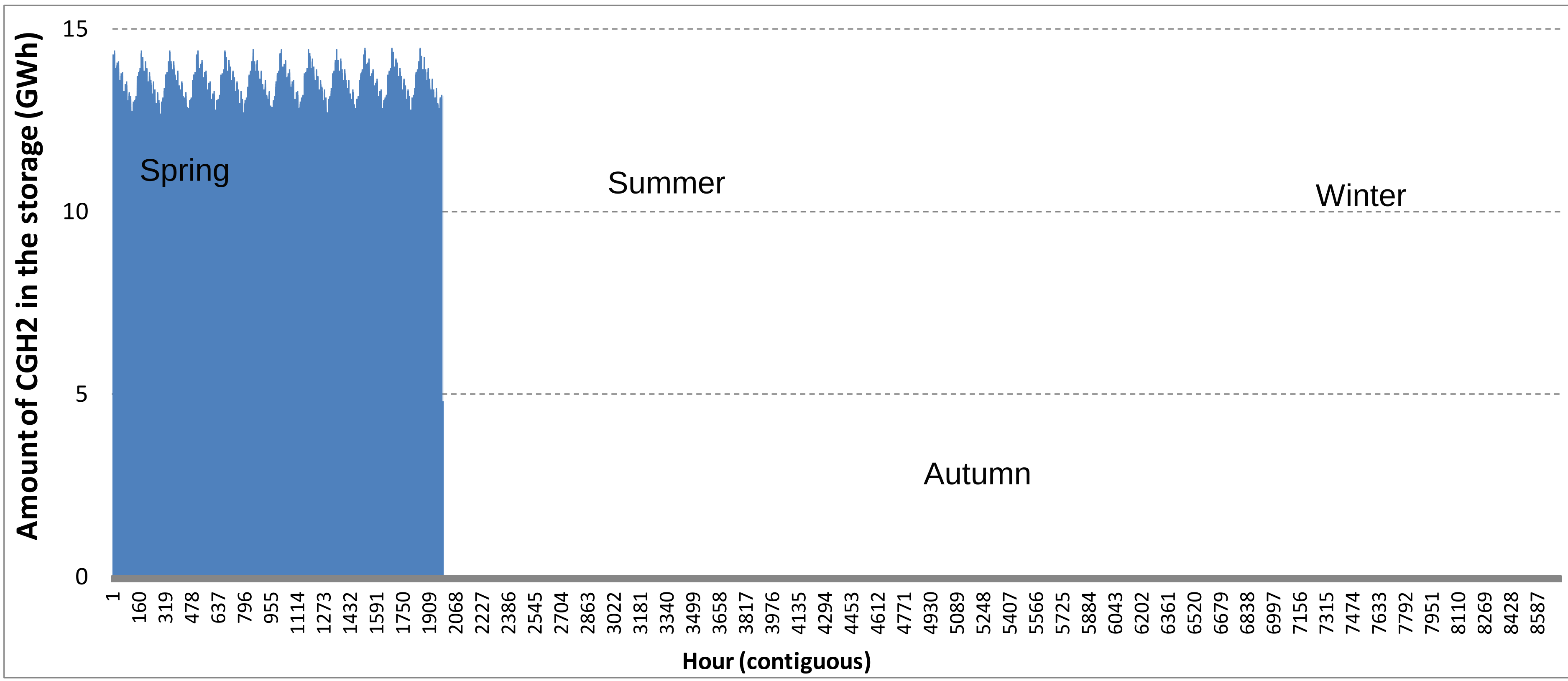
- The rate of operation of electrolyser is effectively constant

CGH_2 production rate (MW)



Results $|y| = 1$, $|s| = 4$, $|d| = 2$, $|h| = 24$

Hourly inventory of CGH_2 in the storage for a whole year

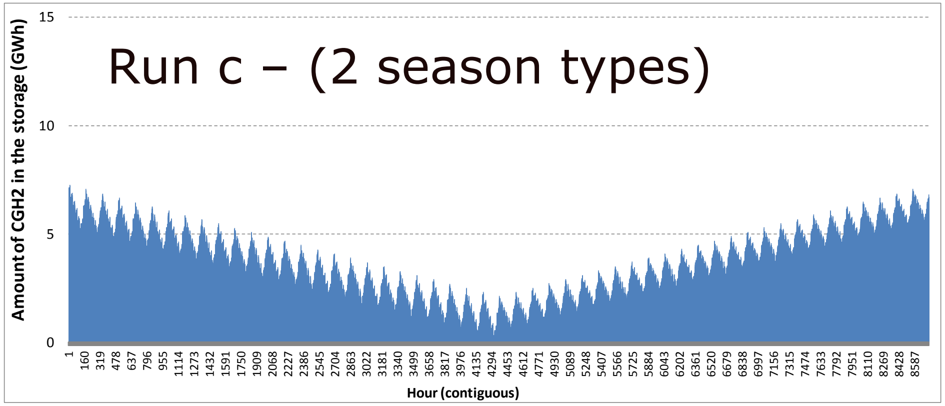


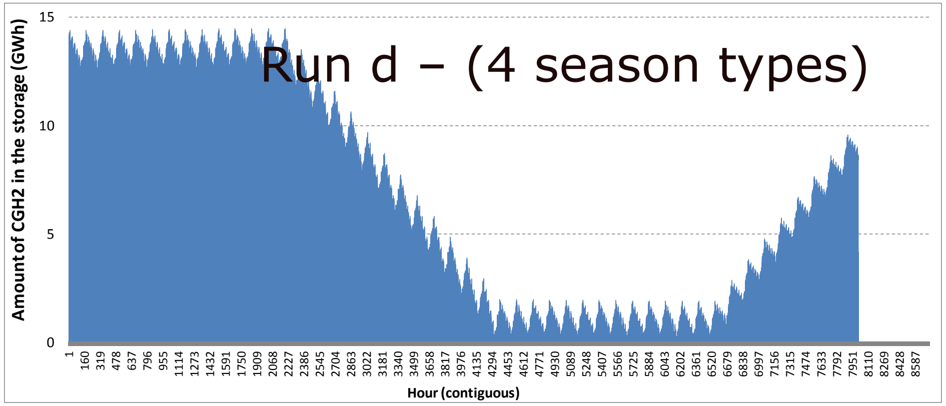
Benchmarking

No. of integers = 336, relative tolerance = 0.1%

Run ID	|y|	|s|	|d|	|h|	No. of variables	No. of constraints	Solution time (s)
a	1	1	1	24	32,823	98,631	7
b	1	1	2	24	64,959	196,911	272
c	1	2	2	24	129,399	393,639	2,543
d	1	4	2	24	258,279	787,095	69,480

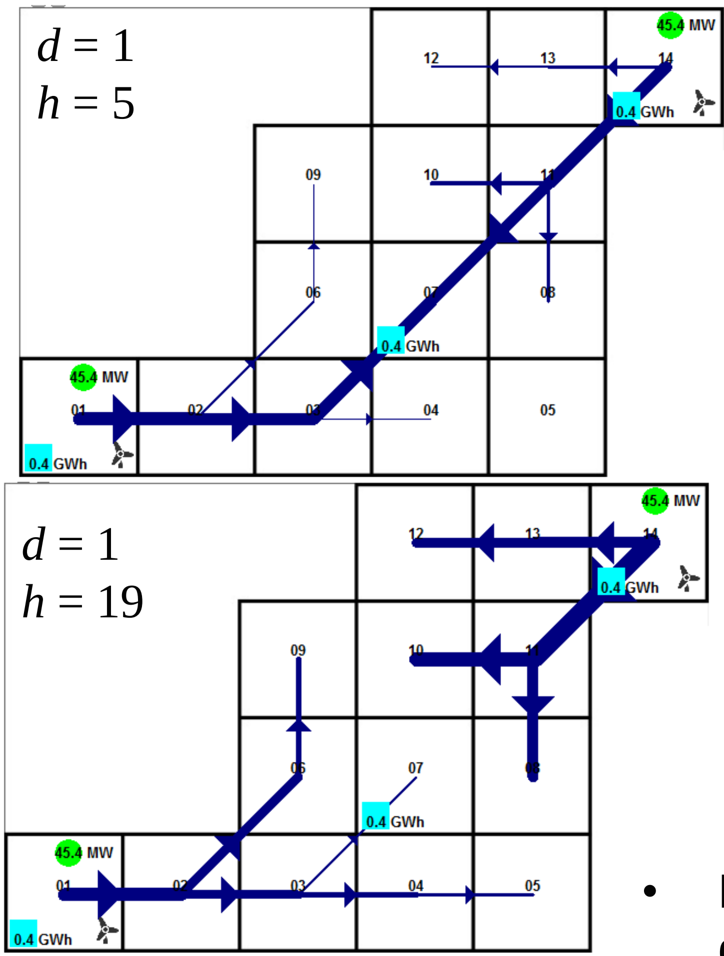
- All runs determined 45.4 MW of electrolysis capacity installed in cells 1 and 14, H_2 transport by pipeline and underground storage.
- However, the runs with fewer time intervals underestimated the storage capacity.





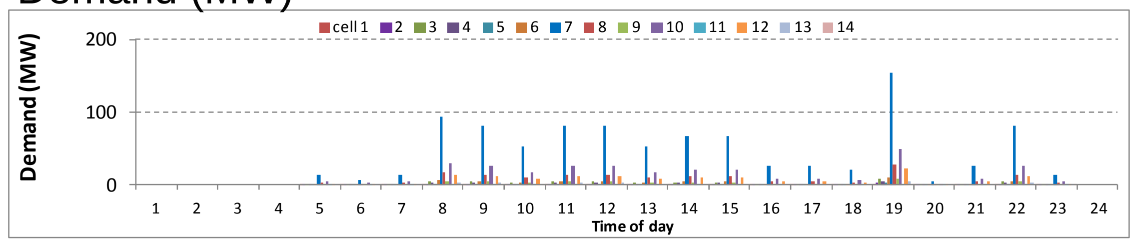
If underground storage is not an option

$|y|= 1, |s|= 1, |d|= 2, |h|= 24$

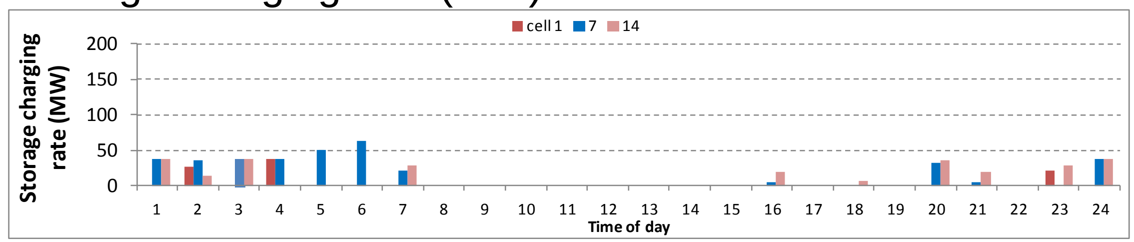


- ➔ Hourly transport of CGH_2 by pipeline
- ● Installed electrolyser capacity (3 small units)
- ■ Installed CGH_2S capacity (1 small unit each)

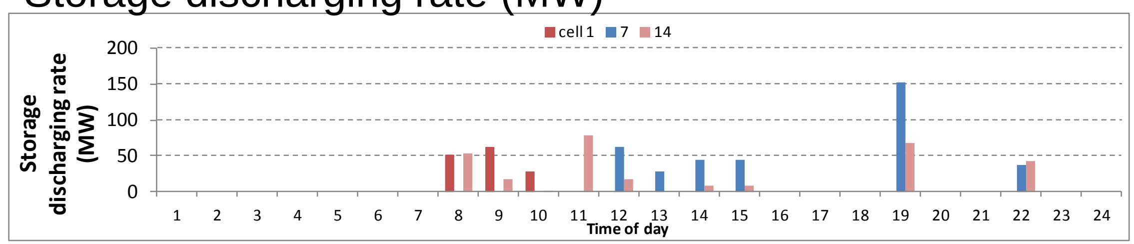
Demand (MW)



Storage charging rate (MW)



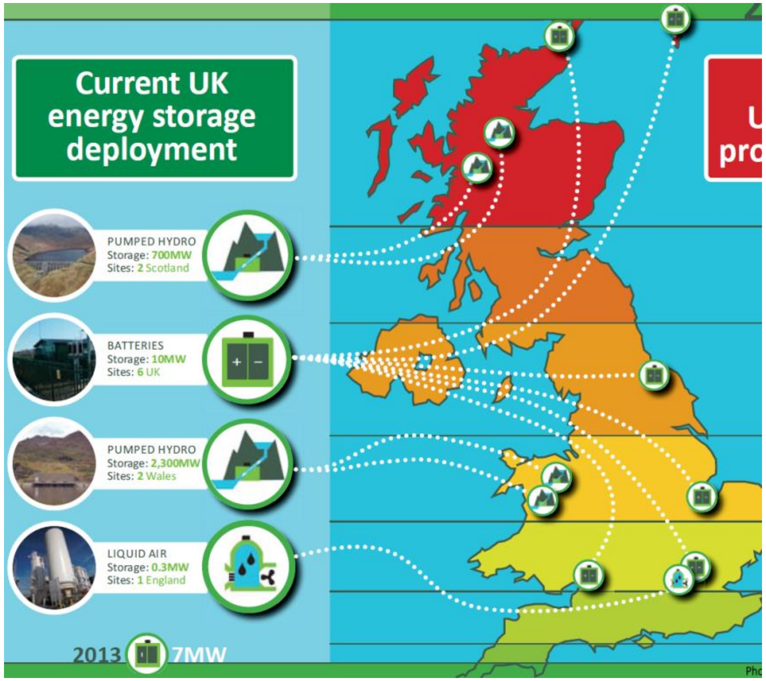
Storage discharging rate (MW)



- Network is more distributed with small compressed gaseous H_2 storage technologies installed in cells where generation are located and cell the with highest demand.

Next steps

- Real case studies (e.g. UK scenarios)
- Add more resources and technologies
- Exploit the full potential of the non-uniform hierarchical discretisation method
  - E.g. Use fewer *non-uniform* hourly intervals
- Additional decomposition methods
  - Benders decomposition did not work
  - Test in-house approaches



Source: The Electricity Storage Network. Development of electricity in the national interest. May 2014

Conclusions

- Storage is a key-enabling technology for meeting the energy demands using renewable resources
  - Without storage the example problem is infeasible
  - With storage, only a small fraction of available primary resource is used and the generation technology operates effectively at a constant rate
- To model storage accurately, hourly or shorter intervals are needed
  - In the example, four seasons are also needed
- Model tractability is a big challenge
  - Even the simplest model cannot handle a whole year at an hourly level
  - Hierarchical time decomposition allows a whole year (and longer planning horizon) to be considered by exploiting periodicity in the data