A Machine Learning Approach to Determining Viable Energy Future Scenarios

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A Changing UK Energy Sector

- Increased national and international pressures to reduce greenhouse gas emissions

- Possible energy futures vary widely with a complex and diverse mixture of fuels, technologies, build rates and objectives.

- DECC have completed extensive work on a range of energy futures alongside academic consortia such as the Realising Transition Pathways (RTP) consortium

Realising Transition Pathway Consortium

University of Strathclyde Engineering

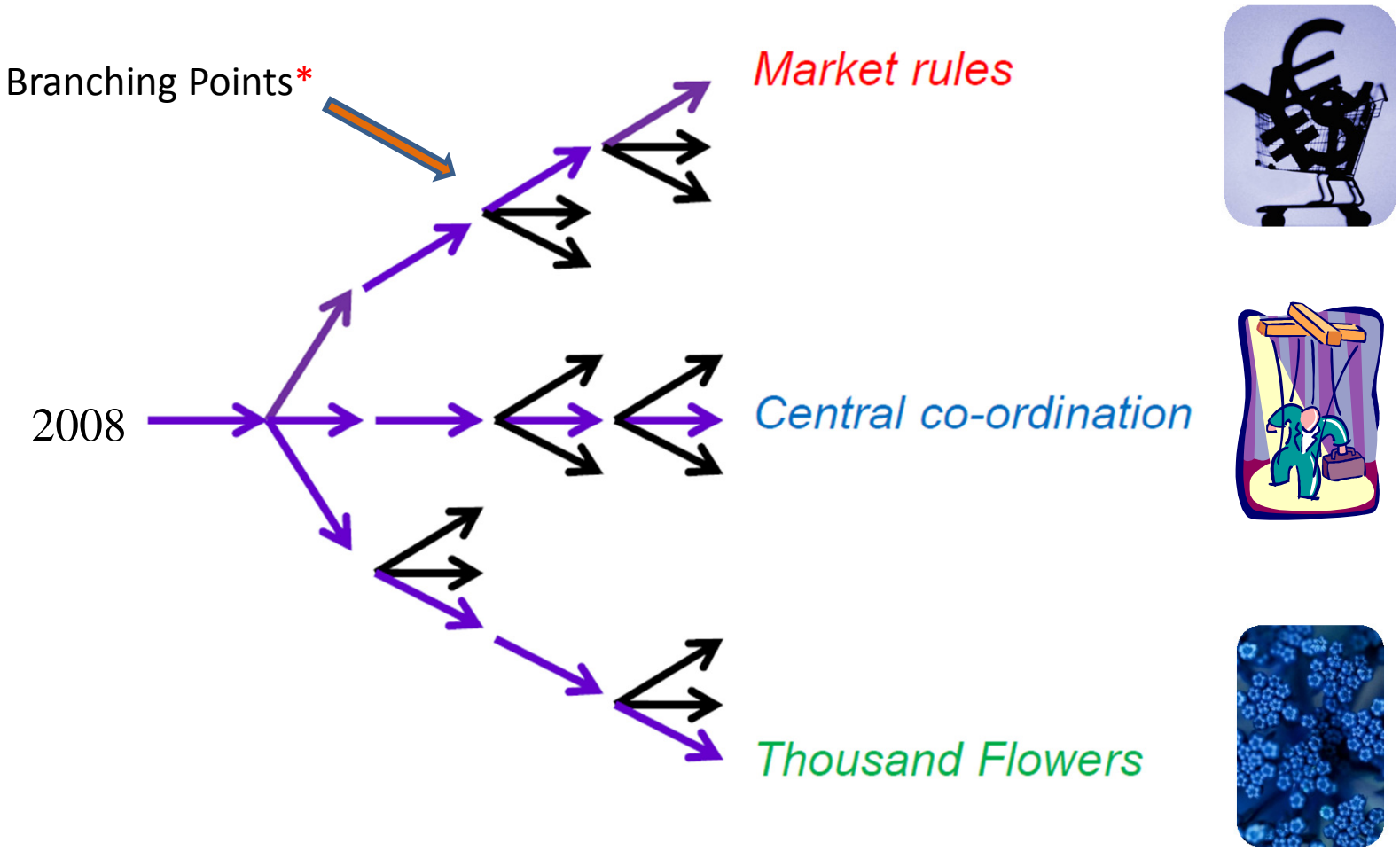
University of Bath | University of Leeds | University of East Anglia | Loughborough University | Cardiff University | UCL | Imperial College London | University of Strathclyde Glasgow | University of Surrey

- Nine academic institutions including engineers, social scientists, historians and transition specialists
- Key aims:
  - Analysing actors' choices and decisions within past, current and prospective dynamic changes in electricity supply and demand systems
  - Undertaking detailed analysis of social, behavioural and technical drivers and implications of demand side responses
  - Undertaking techno-economic system modelling and energy and environmental assessments of the developments in electricity supply

ITL energy

Realising Transition Pathways

The Transition Pathways



* Branching Points: deviations from pathway (s) driven by social/technical/economic drivers

The Transition Pathways

Market Rules a business as usual case where the market is still the main driver

- Energy companies focus on large-scale technologies: nuclear offshore wind and capture-ready coal
- Minimal interference in market arrangements

Central Coordination where the government has stepped in to direct the energy sector toward low carbon options

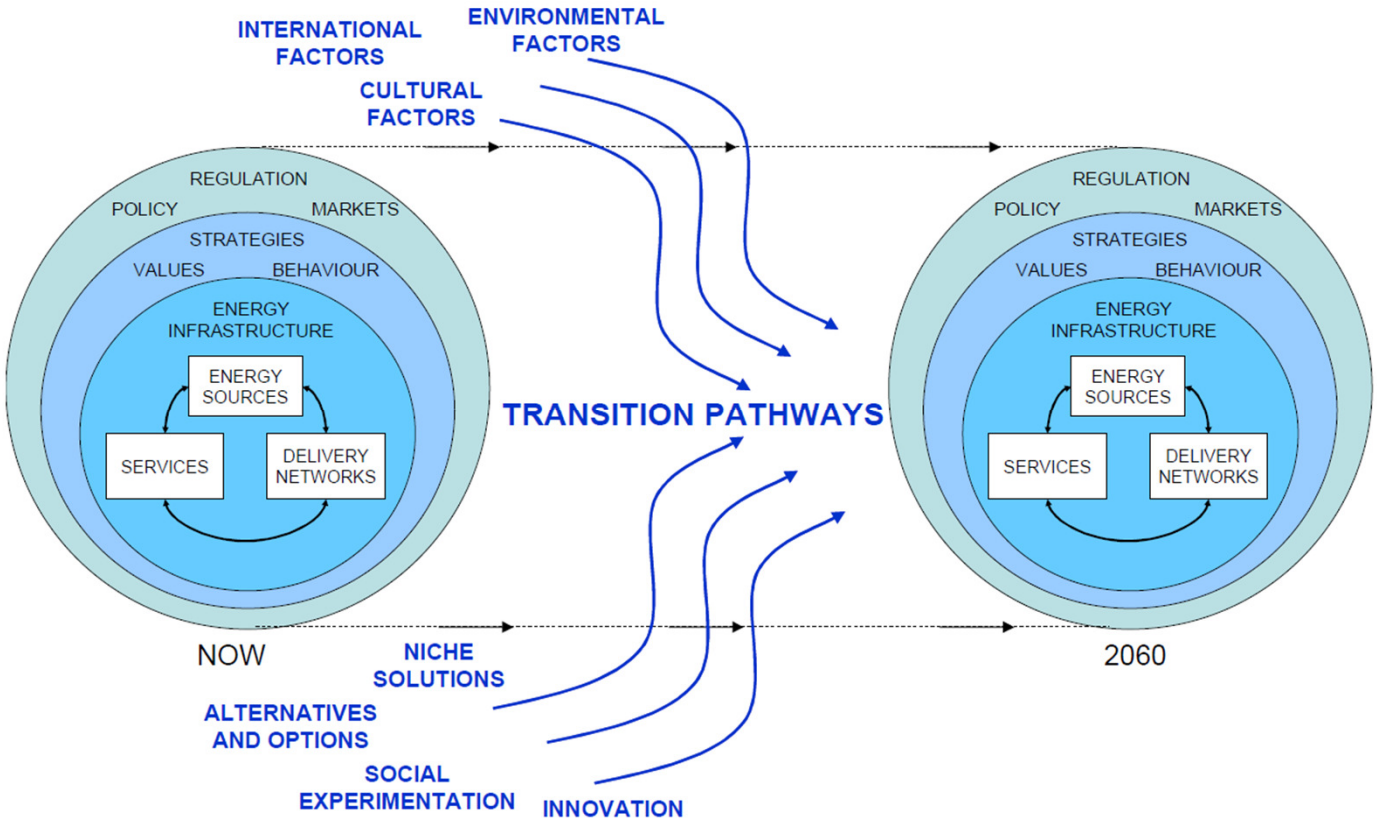
- Greater direct government involvement in governance of energy systems, e.g. issuing tenders for tranches of low-carbon generation
- Focus on centralized generation technologies

Thousand Flowers a pathway which describes a 'bottom up' solution to low carbon generation with large amounts of distributed generation brought in by the people.

- More local, bottom-up diversity of solutions
- Local leadership in decentralized options

Although all three pathways have set transitions studying *branching points* allows us to investigate divergence and generate multiple transitions

The Transition Pathways



Foxon, T J, Hammond, G P and Pearson, P J (2010). Developing transition pathways for a low carbon electricity system in the UK. *Technological Forecasting and Social Change* **77**, pp. 1203-1213,

EXPANSE model

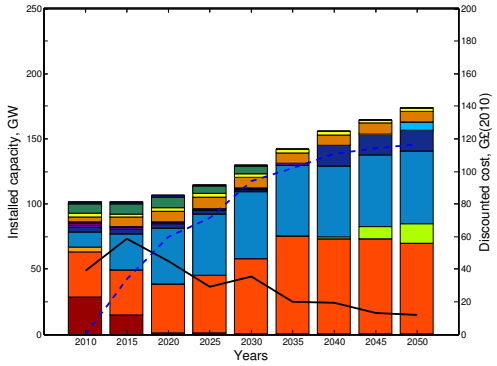
EXploration of **PA**tterns in **N**ear-optimal energy **S**c**E**narios

- Bottom-up, technology rich, cost-optimisation model
- Includes exploration of near-optimal pathways, e.g. that have up to 20% higher total system costs
- Analyses patterns in a large number of pathways
- Selects a smaller set of maximally-different pathways

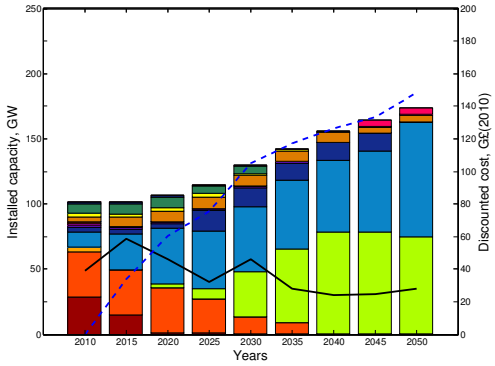
Trutnevyte, E. (2013). EXPANSE methodology for evaluating the economic potential of renewable energy from an energy mix perspective. *Applied Energy* **111,** 593-601.

Maximally-different pathways in terms of technology choices (work in progress)

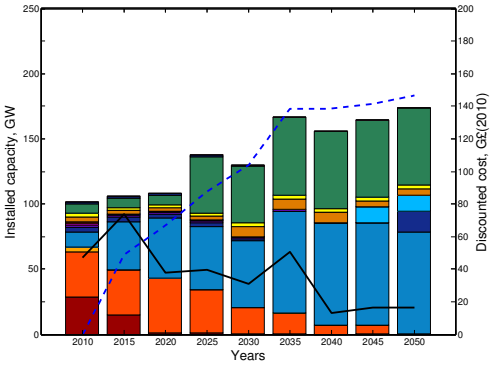
Gas, nuclear, gas CCS, onshore wind



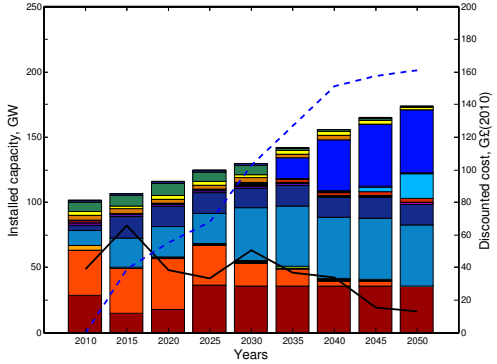
Gas CCS, nuclear, onshore wind



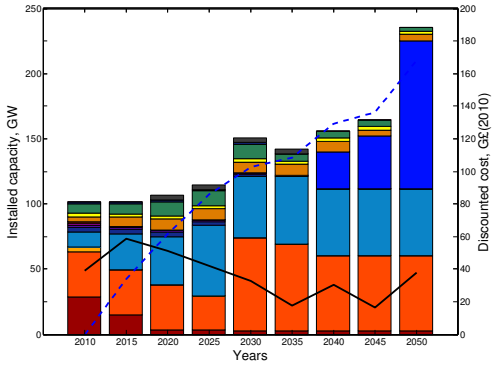
Nuclear, large CHP, wave, onshore wind



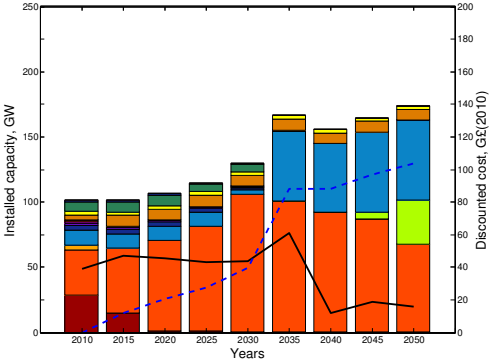
Nuclear, coal, solar, wave, onshore wind

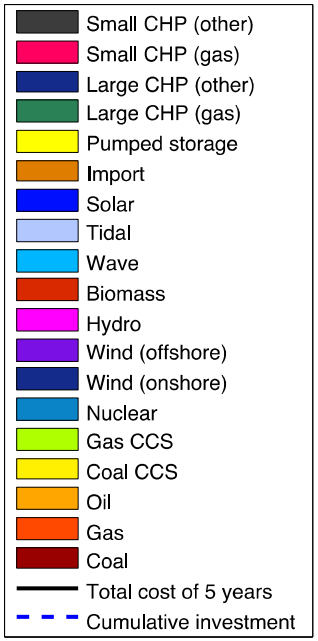


Gas, nuclear, solar



Gas, nuclear, gas CCS





The economic potential of renewable energy sources is established for these generation mixes

Only as good as the data …

- Modelling work from **RTP/EXPANSE** and other approaches like them rely on examination of many possible sets of input data to evaluate the future
- Theses futures are often rationalised *by some functional approach or through the use of expert judgement*
- But good input data itself can be difficult to obtain and sometimes synthesised data sits along with measured, experimental or estimated values

Only as good as the data …

- To accommodate a range of futures, even within a context (e.g. **RTP**), input data is often varied across a range.
- Resulting in a broad range of possible futures and necessitating a robust post-processing stage
  - *But how good are we at specifying this range across several categories?*
  - *Is there a better way to conduct the refinement of solutions?*

EXPANSE Outputs/Inputs for clustering example

A typical run of **EXPANSE** will establish a cost-optimal pathway and from this generate say 1000 near-optimal pathways.

Lots of possible variation here

Near-optimal pathways vary:

- Installed Capacity - GW
- Produced Electricity - TWh/(5 years)
- Across nine 5-year times steps from 2010-2054
- For 19 different generator types

Post-processing step

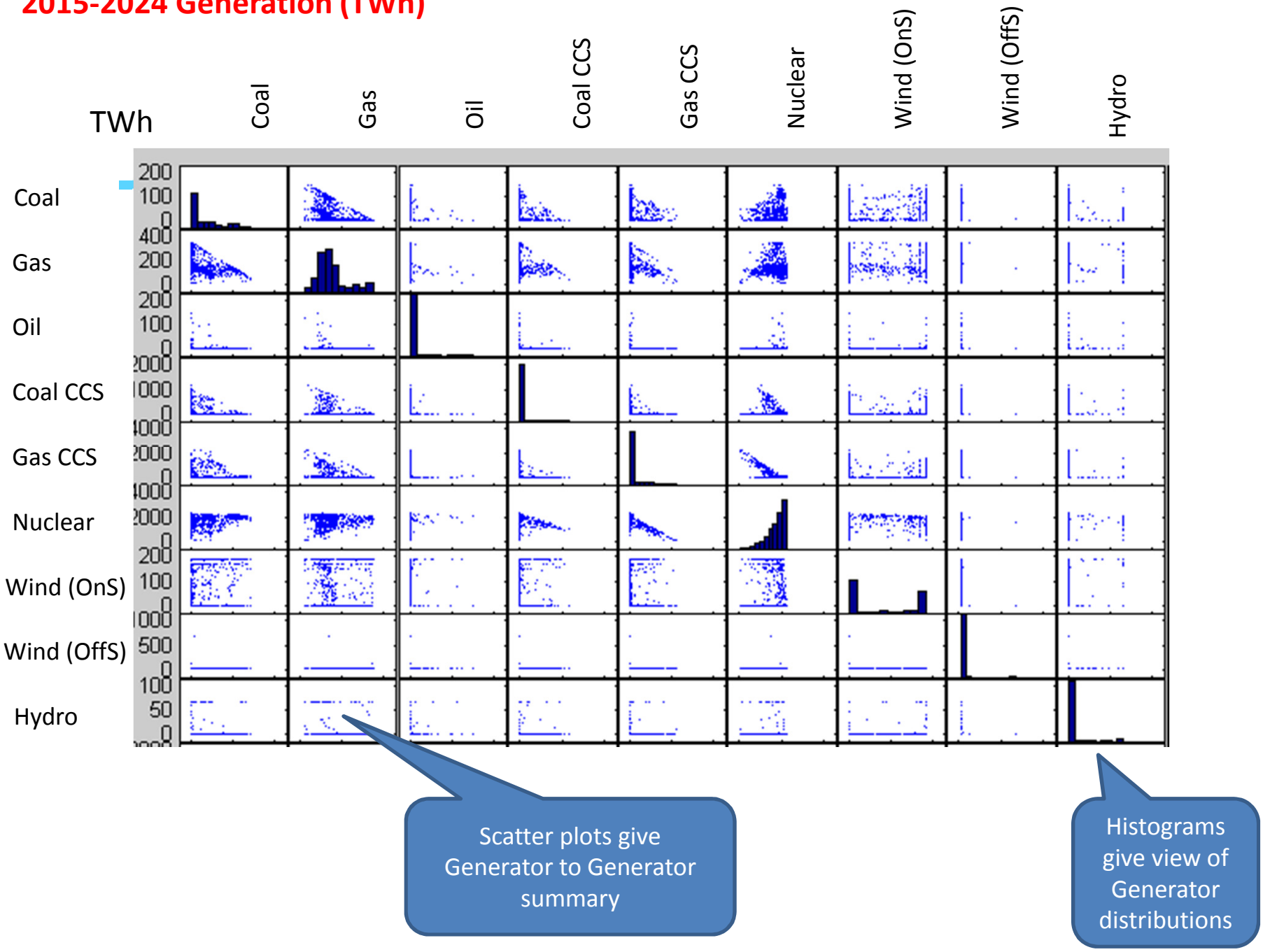
From these the “best” solutions are established

EXPANSE Outputs/Inputs for clustering example

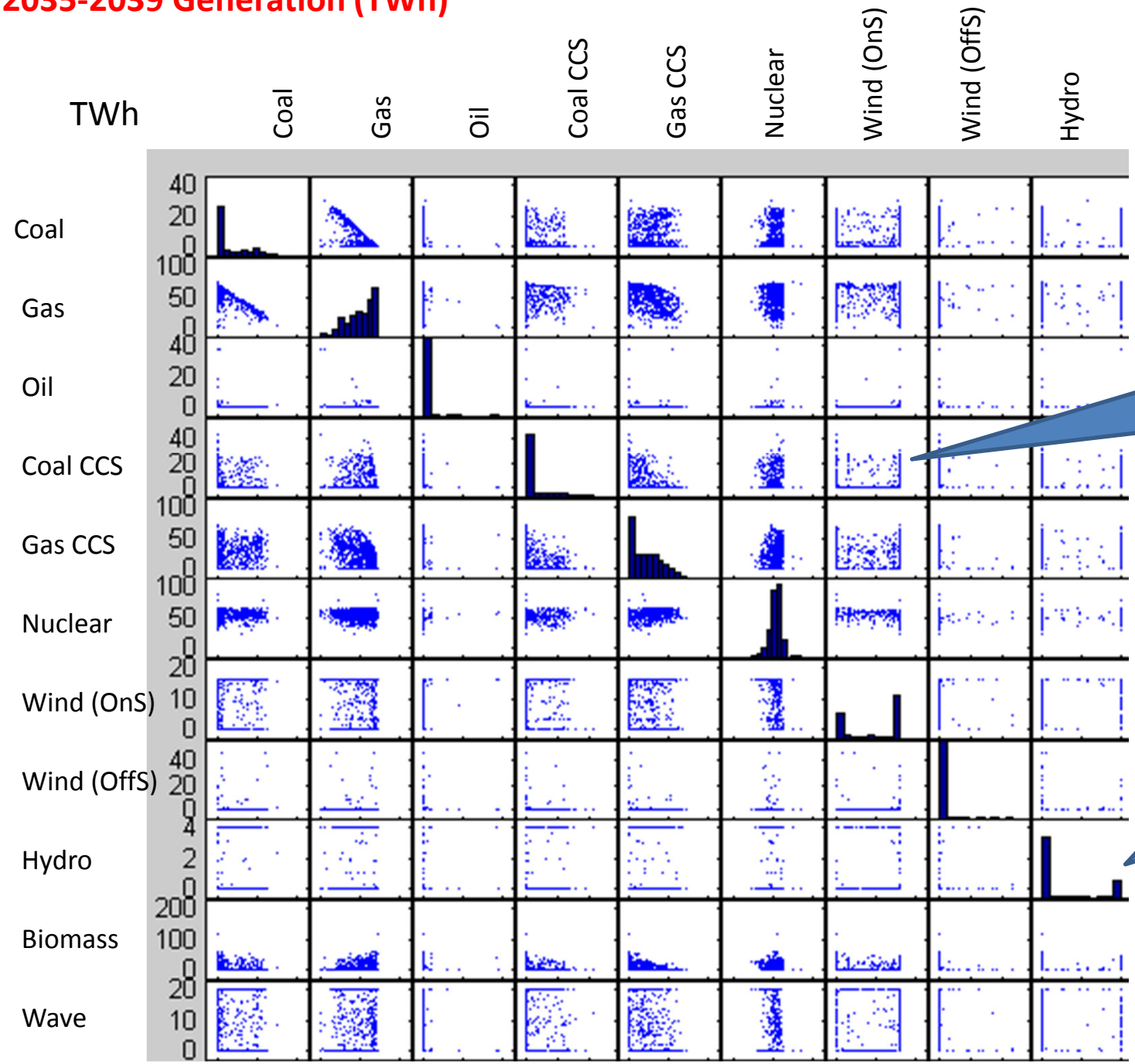
We have looked at a 998 near optimal pathway data set to:

- Understand the relationships imposed
- See how good we are at specifying the range of behaviours
- Consider if there are better ways to rationalise the number of near-optimal pathways

2015-2024 Generation (TWh)



2035-2039 Generation (TWh)



Some interesting relationships are evident

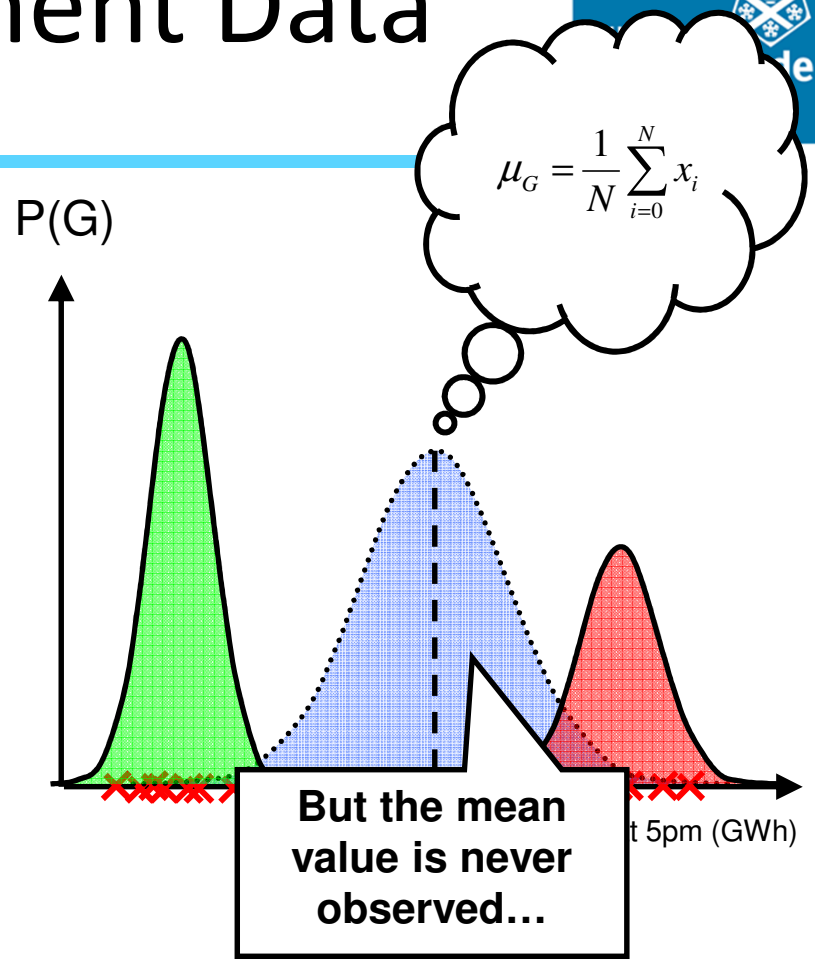
Look at the change in Generation

Visualisation of **EXPANSE** results

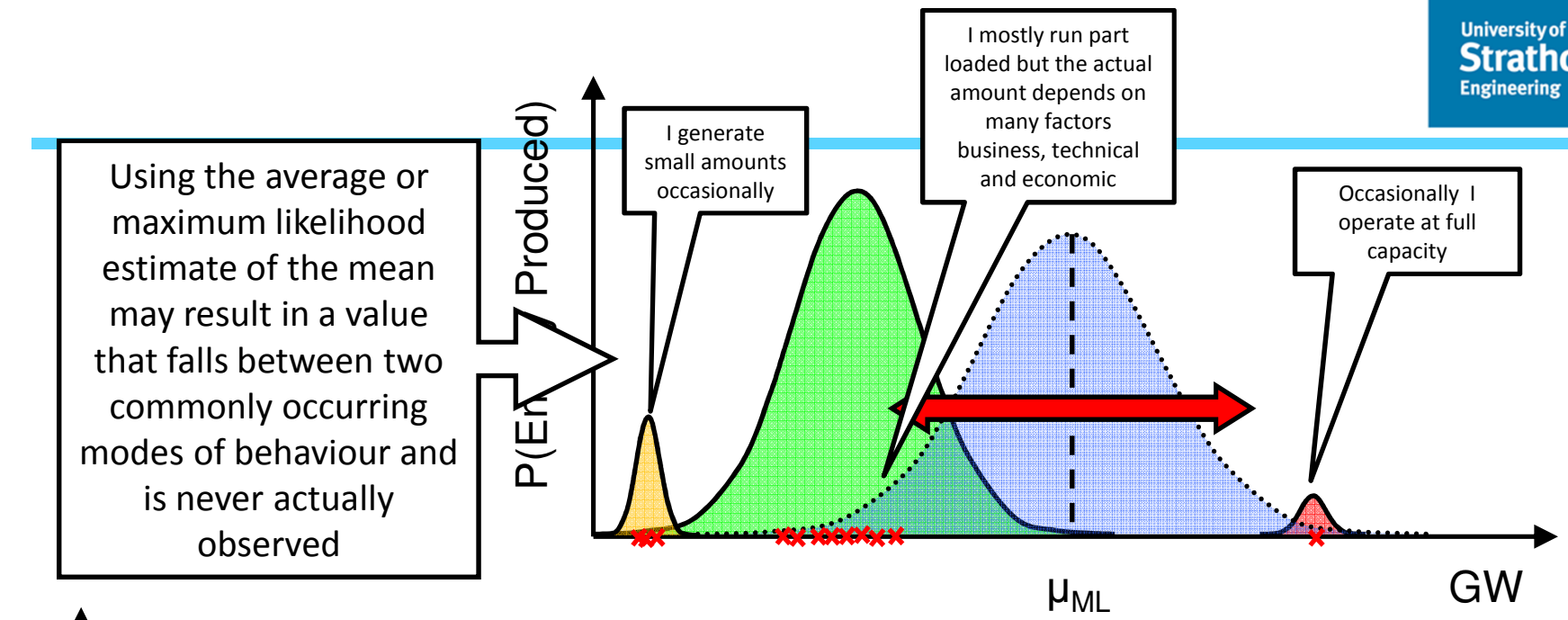
- Visualisation of the data like this lets us see
  - The spread of outputs for each generation technology
  - The pairwise relationships between generation technology outputs
  - Evolution with time
- Its it useful?
  - Are the relationships evident from the data what was intended?
  - Are the consistent with the pathway?

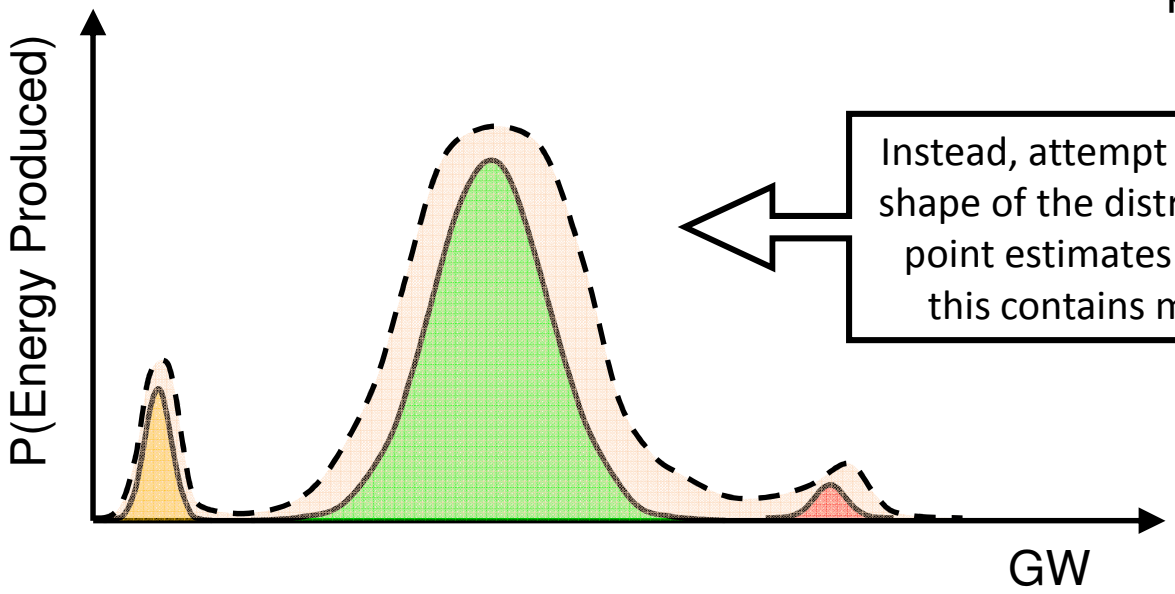
Analysing Measurement Data

- Often, when attempting to analyse measurement data from an experiment, the first thing that comes to mind is to calculate the mean of the data
- The implication of this is that the data is Gaussian distributed with a single peak (mode)
- There are circumstances where this isn't the case…



What can the data tell us?



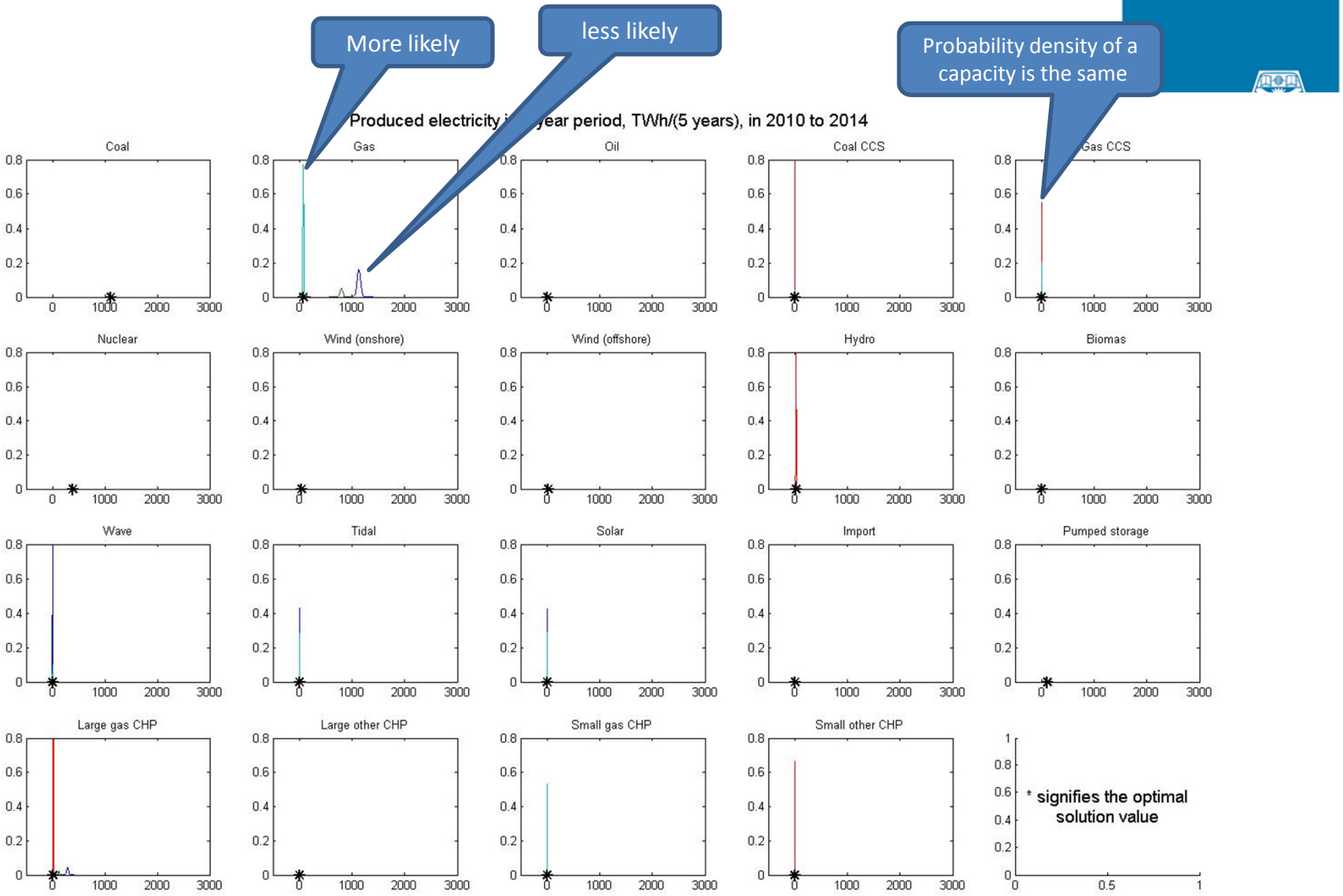


Instead, attempt to approximate the shape of the distribution rather than point estimates of statistics of it – this contains more information

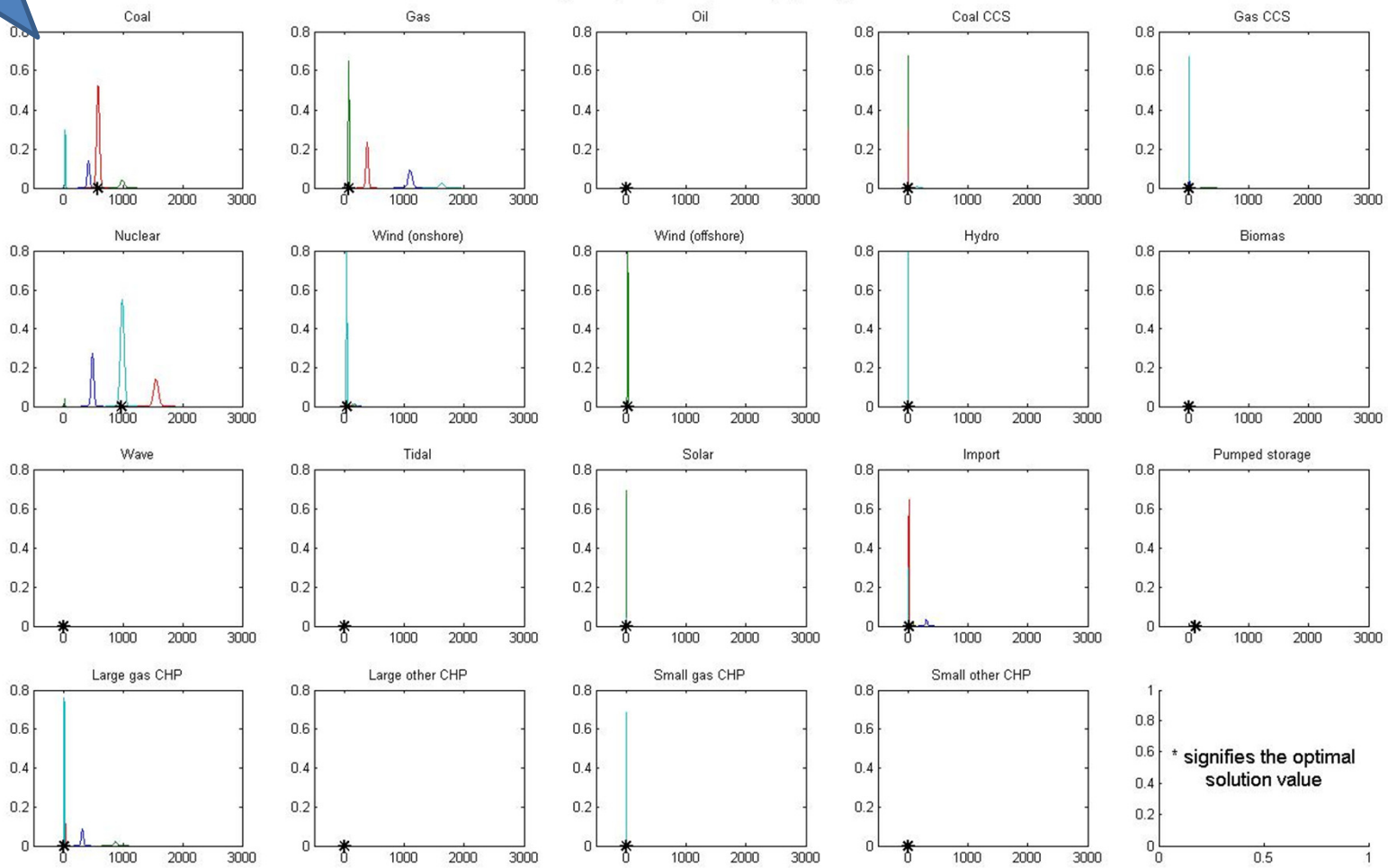
Clustering

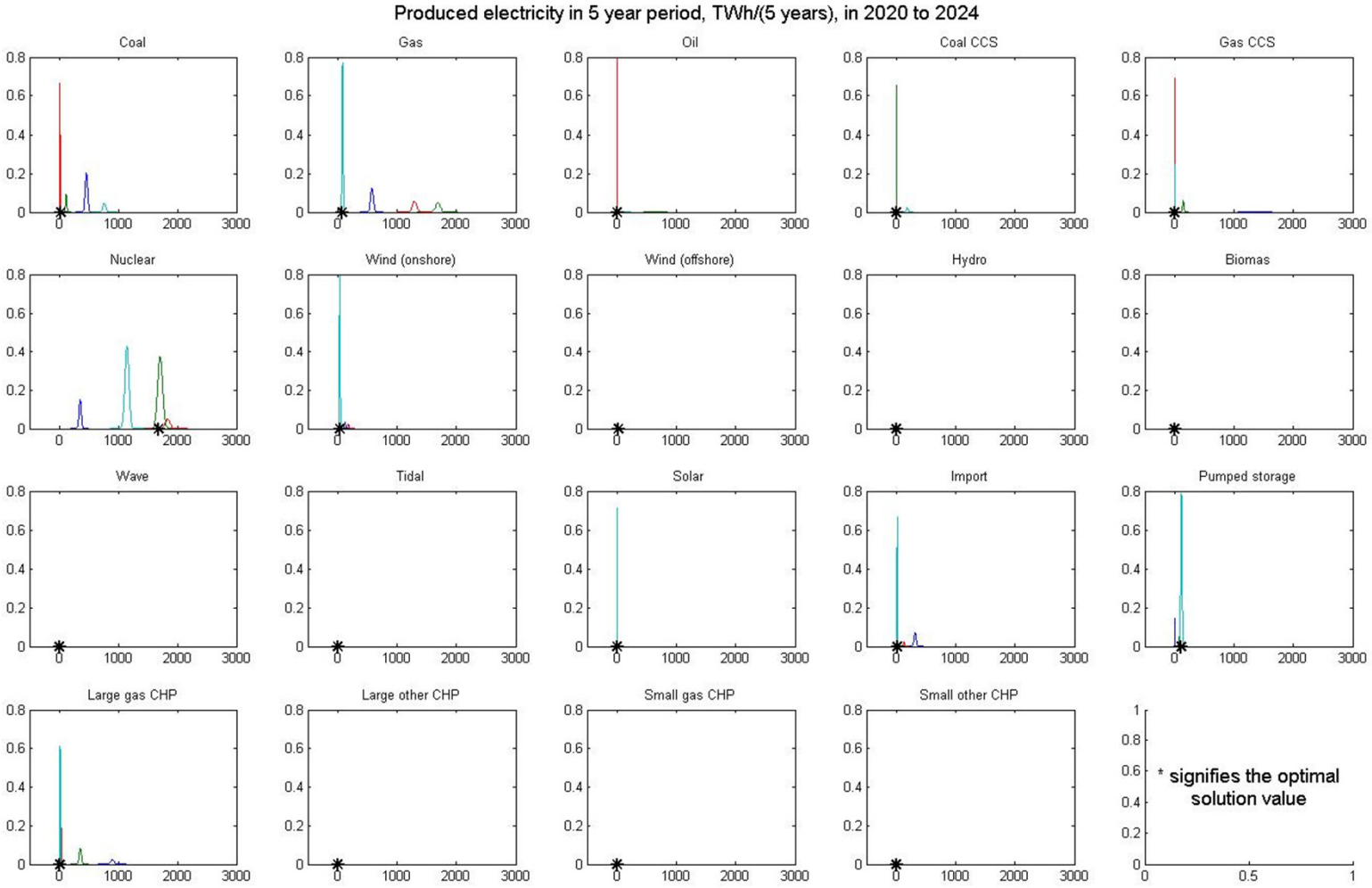
- For each generator type in each time-step a mixture of 4 Gaussians is used to represent the spread of installed capacity and generation
- Clustering allows us to interpret the change in generation and installed capacity along the pathway out to 2054

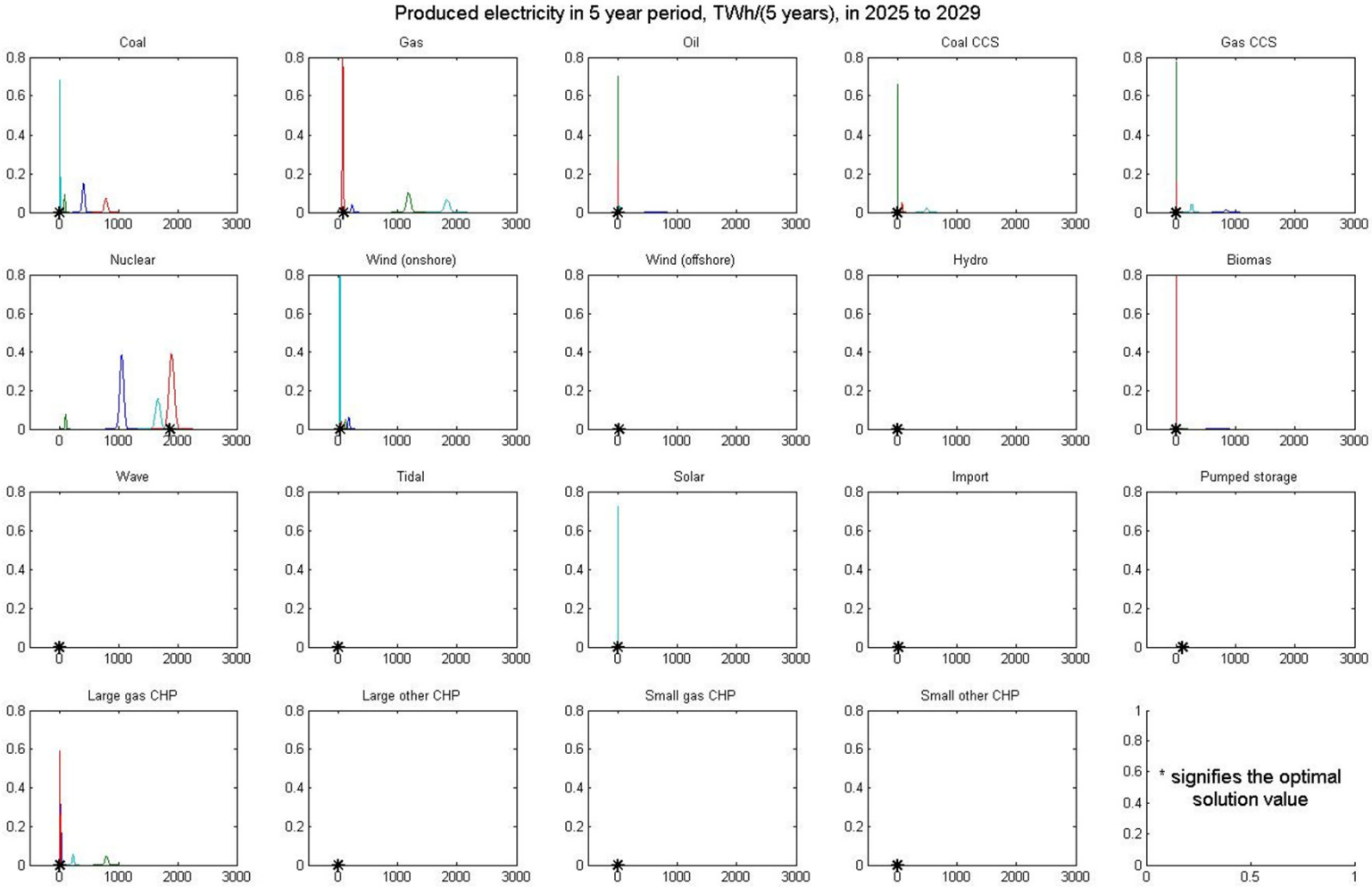
GENERATION

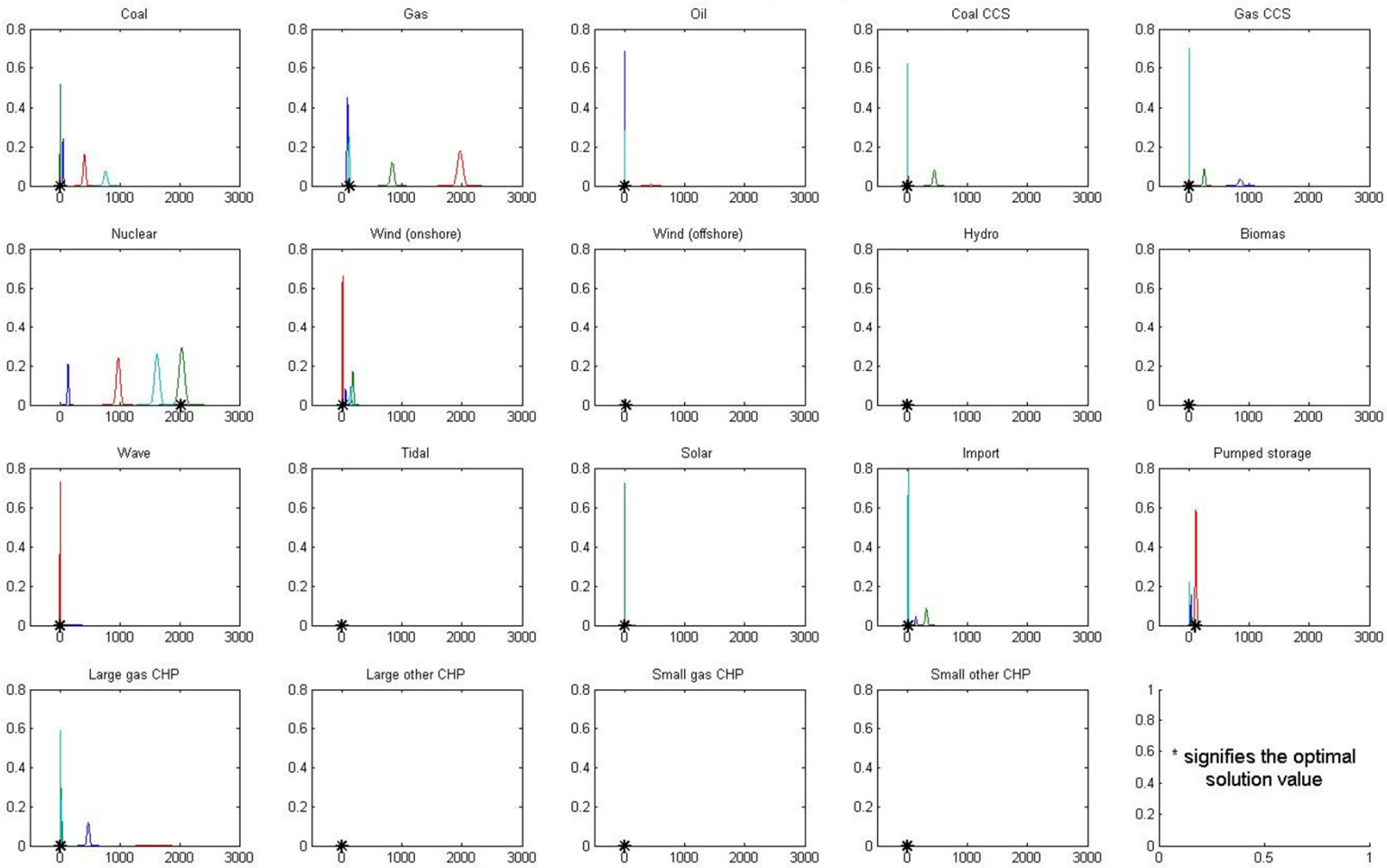

More likely
less likely
Probability density of a capacity is the same
Produced electricity i year period, TWh/(5 years), in 2010 to 2014
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value

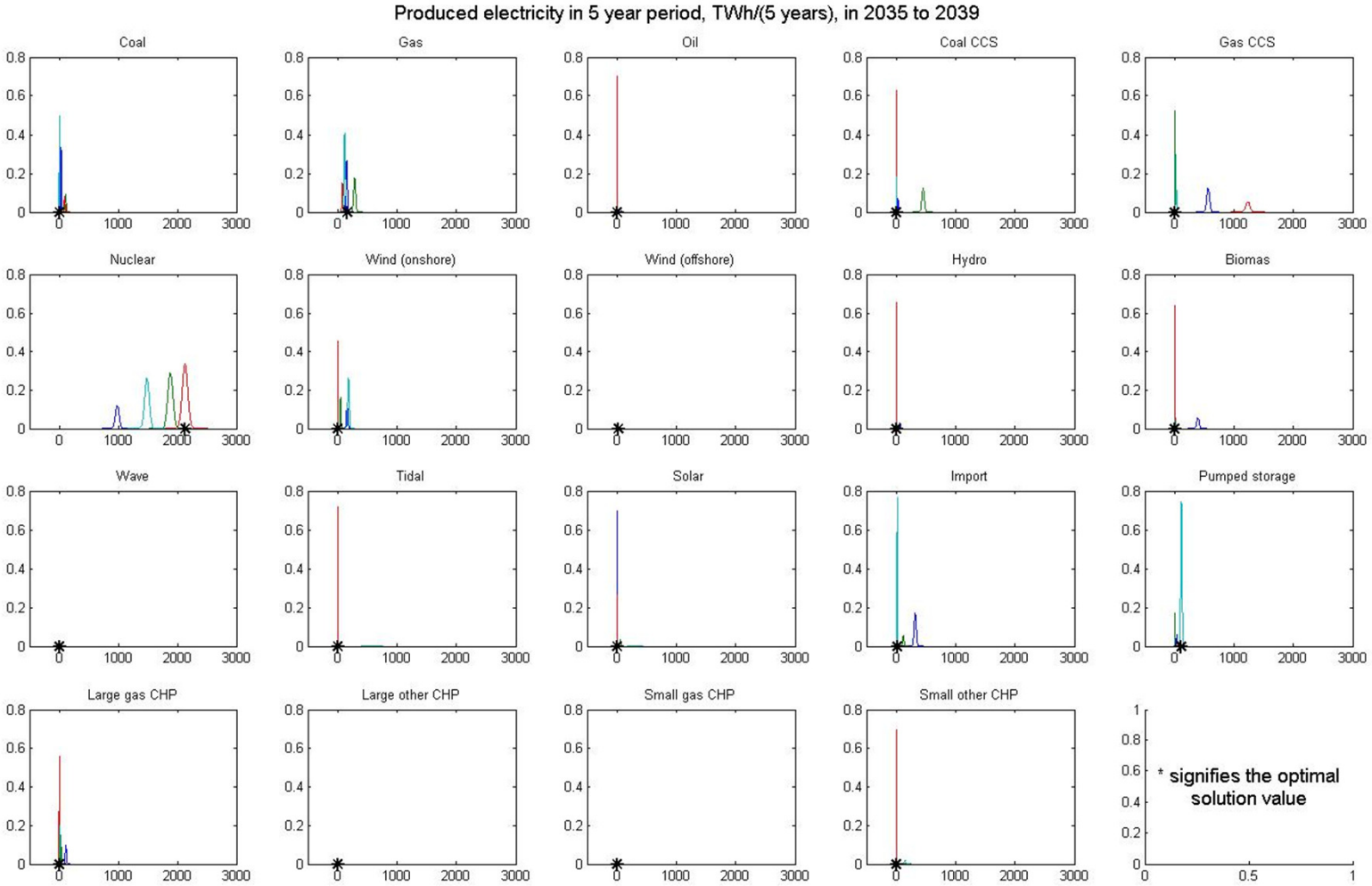
4 different regimes for different scenarios

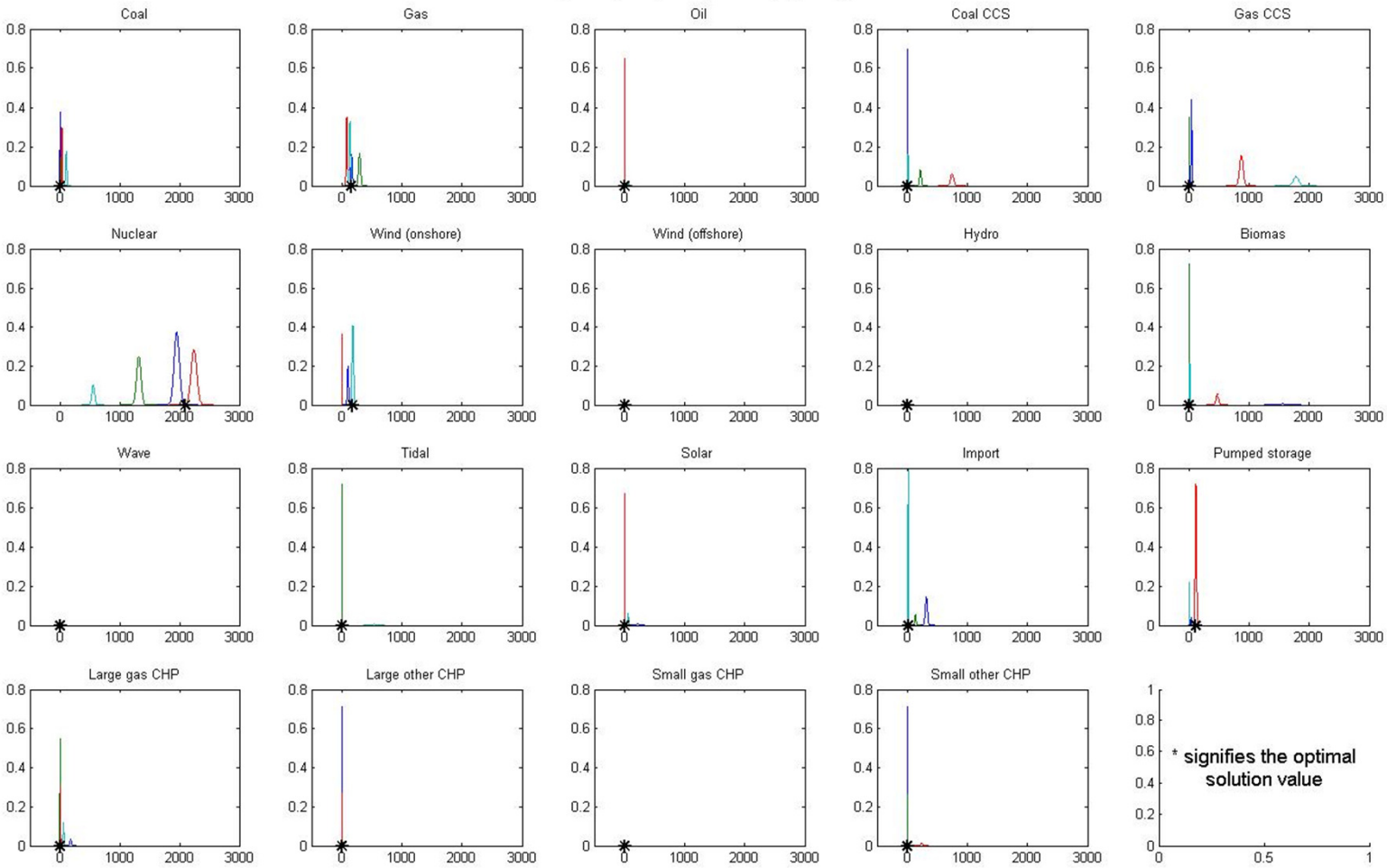


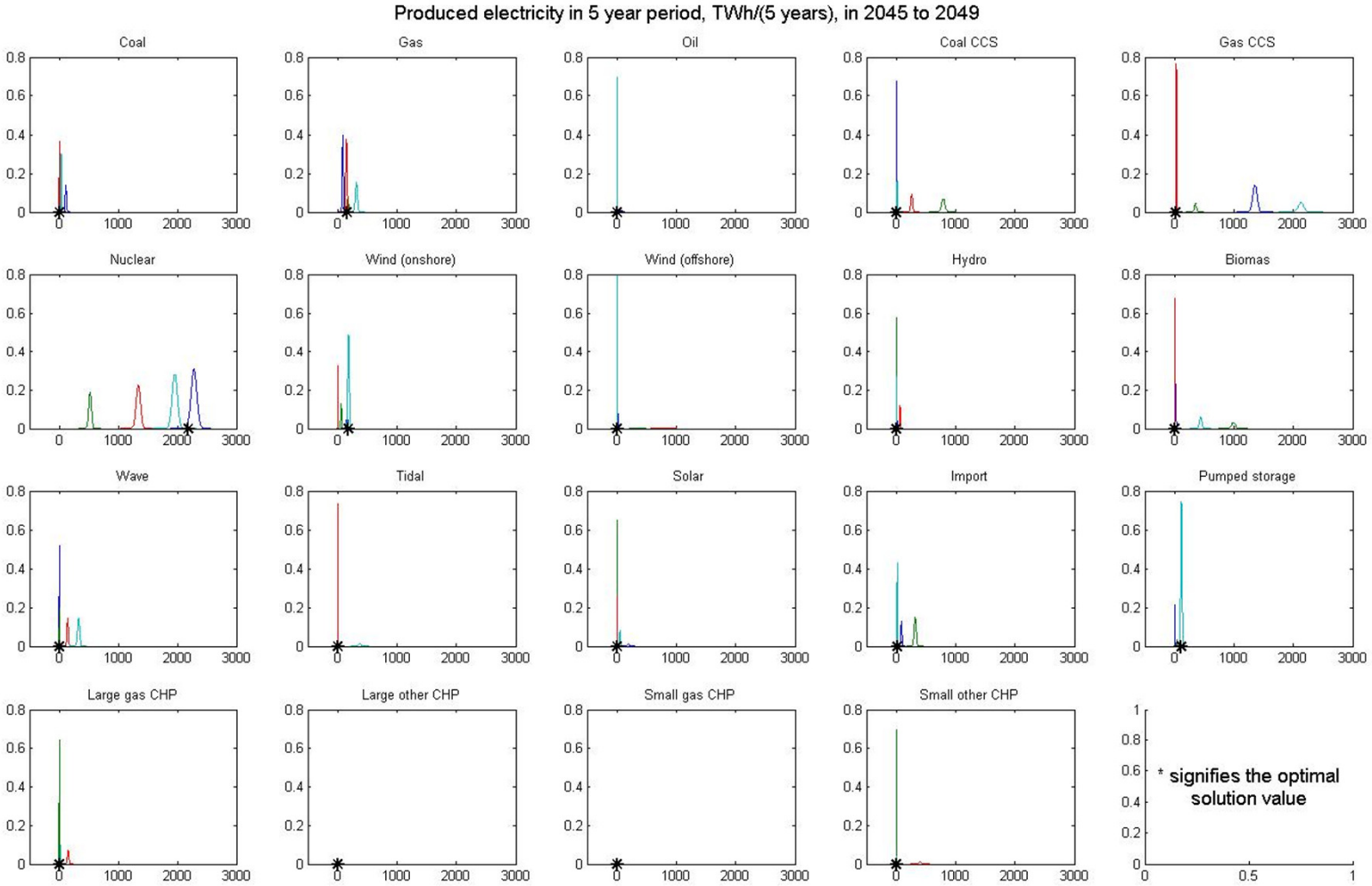

Produced electricity in 5 year period, TWh/(5 years), in 2020 to 2024
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value

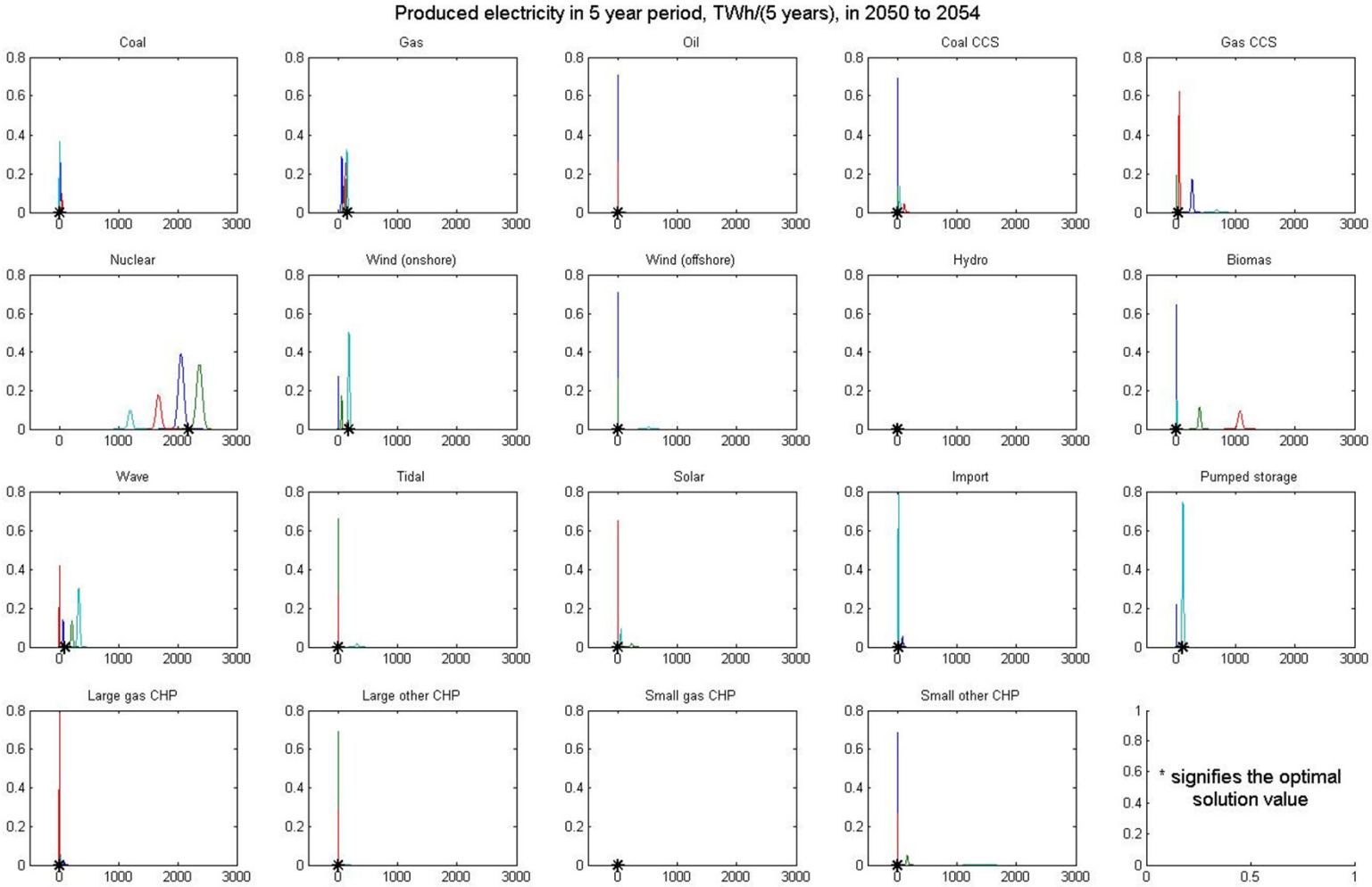

Produced electricity in 5 year period, TWh/(5 years), in 2025 to 2029
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value


Produced electricity in 5 year period, TWh/(5 years), in 2030 to 2034
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value


Produced electricity in 5 year period, TWh/(5 years), in 2035 to 2039
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value


Produced electricity in 5 year period, TWh/(5 years), in 2040 to 2044
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value


Produced electricity in 5 year period, TWh/(5 years), in 2045 to 2049
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value

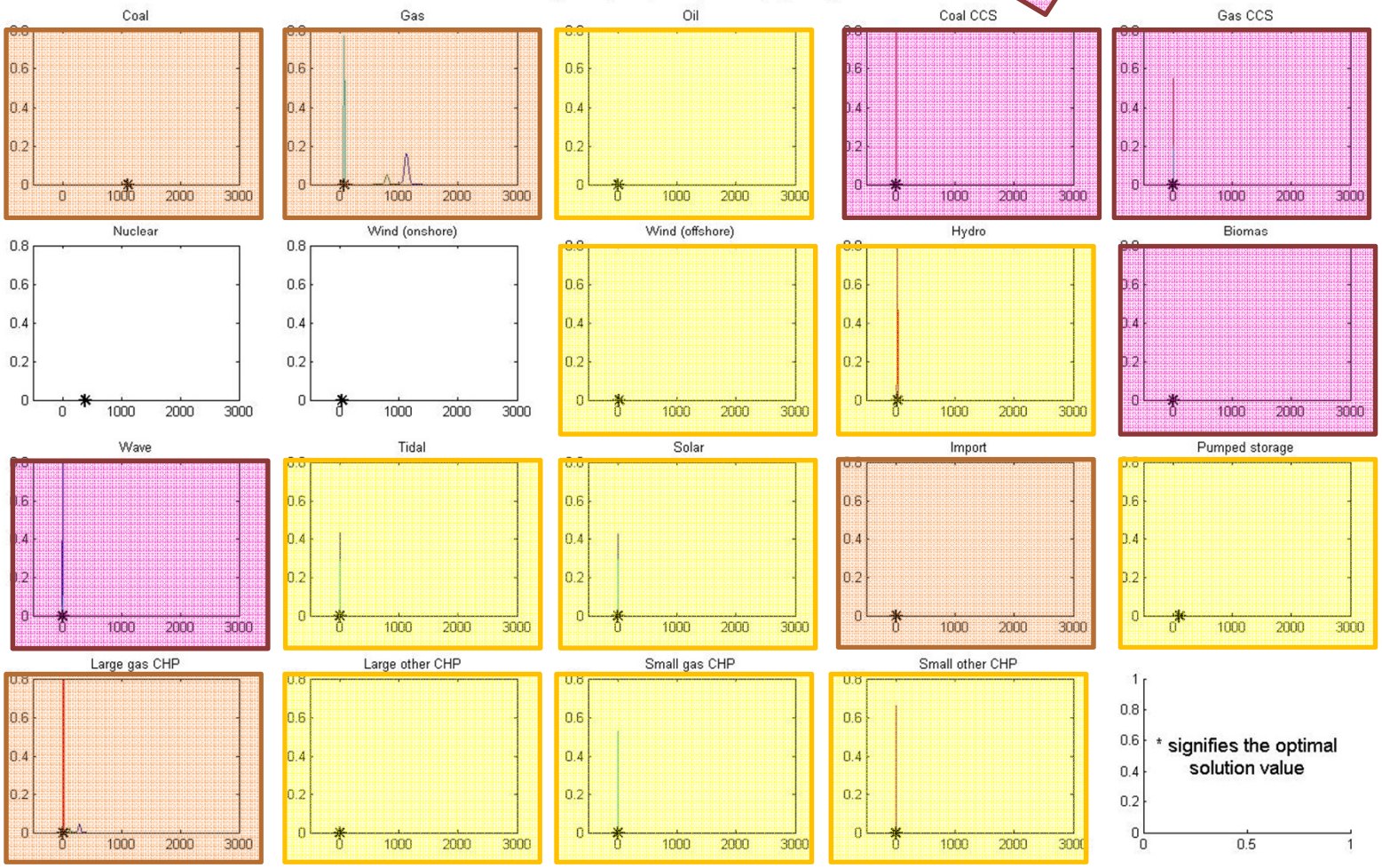

Produced electricity in 5 year period, TWh/(5 years), in 2050 to 2054
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value

Trends in Generation

- Clustering lets us see that there is limited change in the generation level of most generation types
- Real change only from:
  - Nuclear
    - A wide spread of possibilities throughout the transition with a trend for large growth
  - Onshore Wind
    - A smaller change later in the transition with a distinct tight cluster of increase

*But this is fine if this is what was intended for the near optimal pathways; if not need to retune

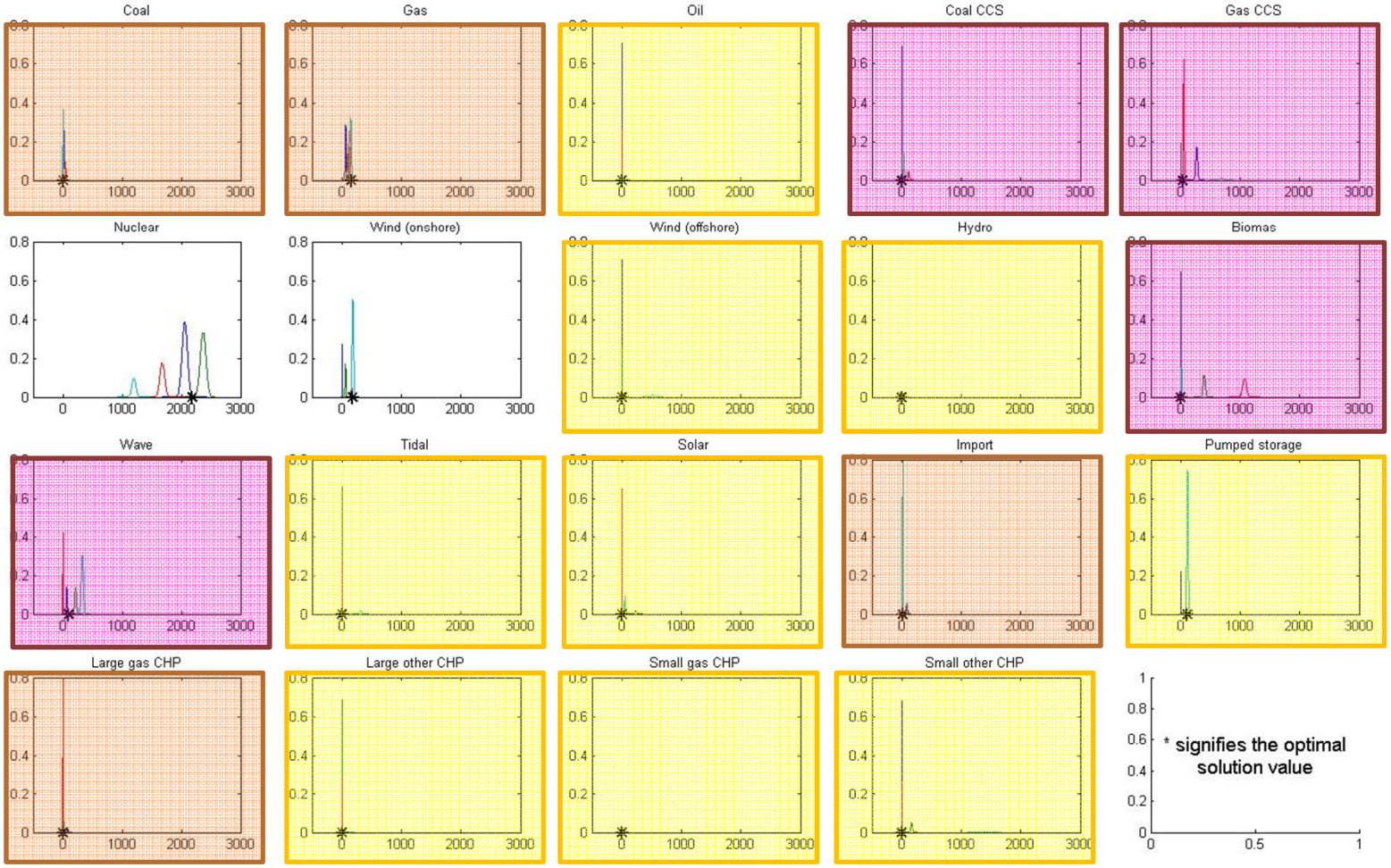
Are small contributors throughout the transition



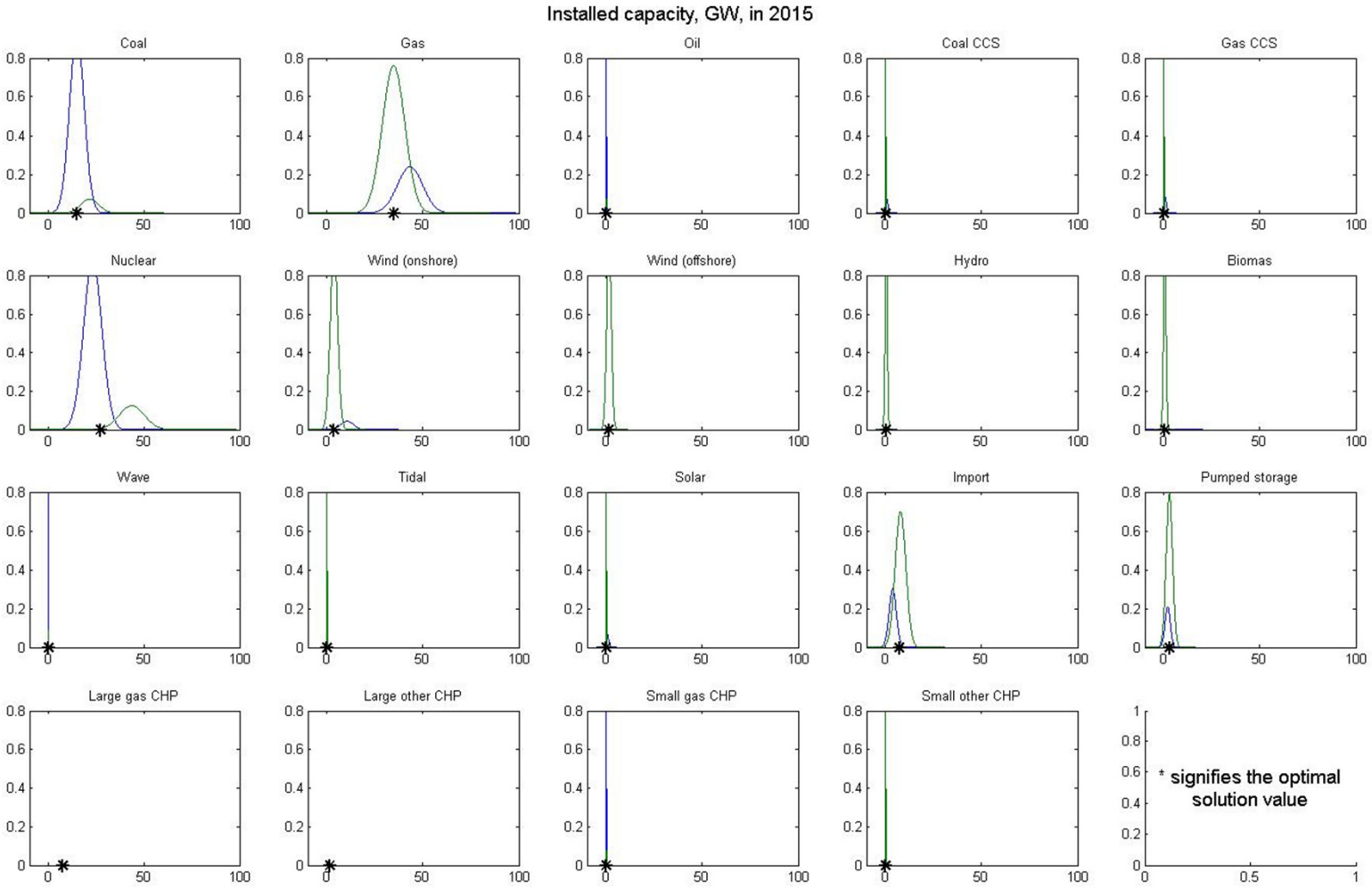
These generators tend to low TWh generation early in the transition (by 2035)

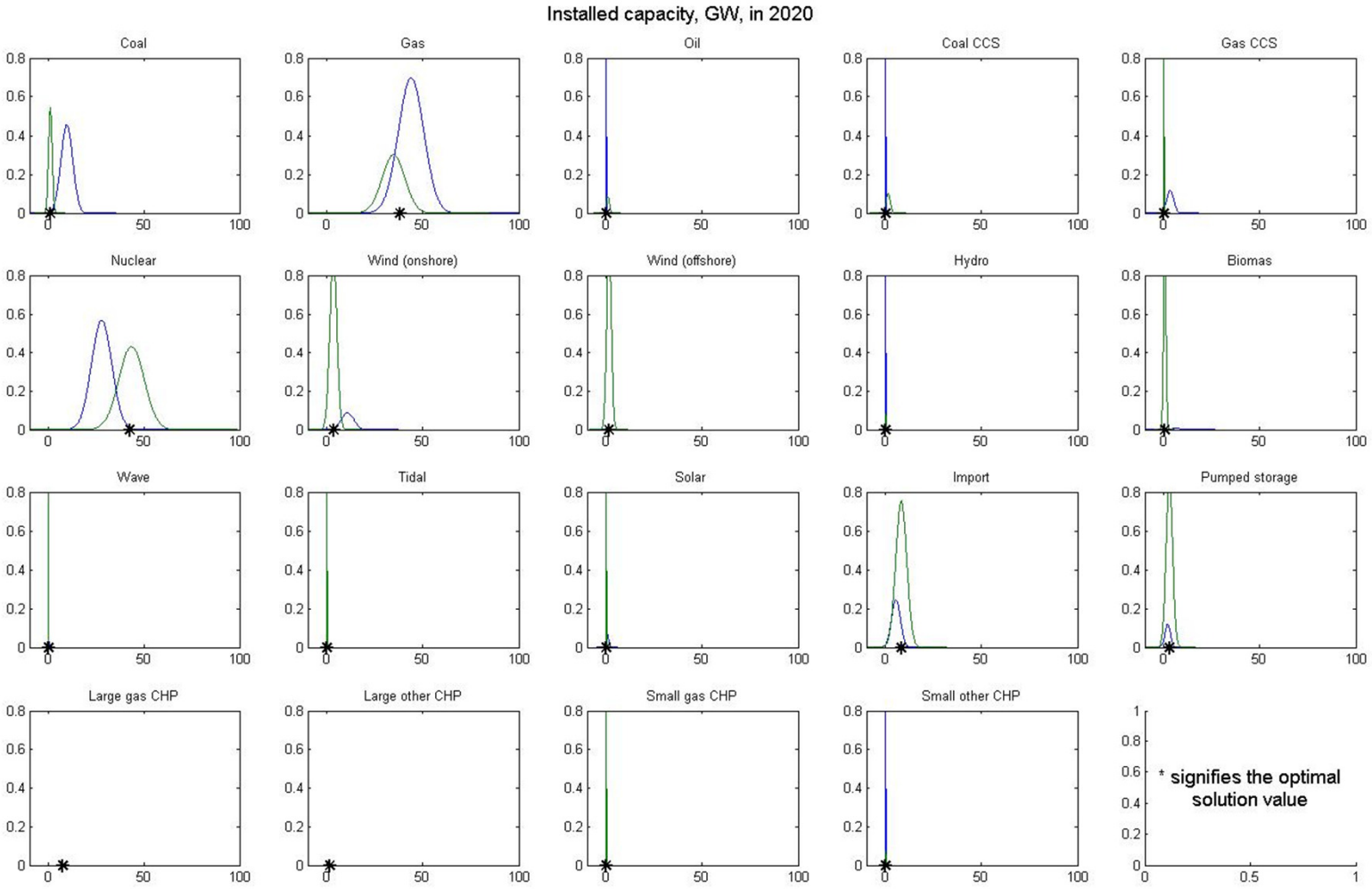
These generators stay at zero TWh throughout the transition

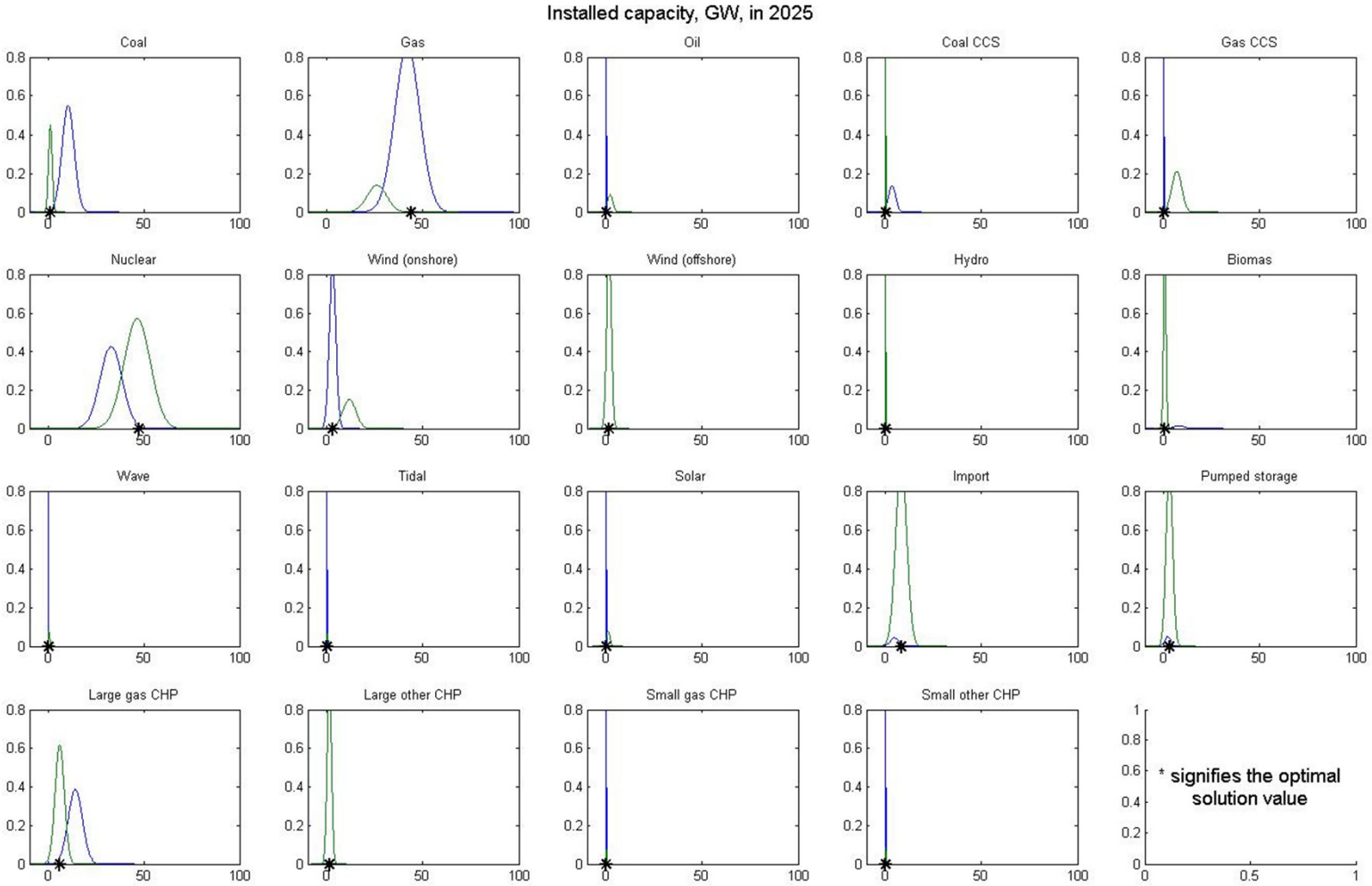
Produced electricity in 5 year period, TWh/(5 years), in 2050 to 2054

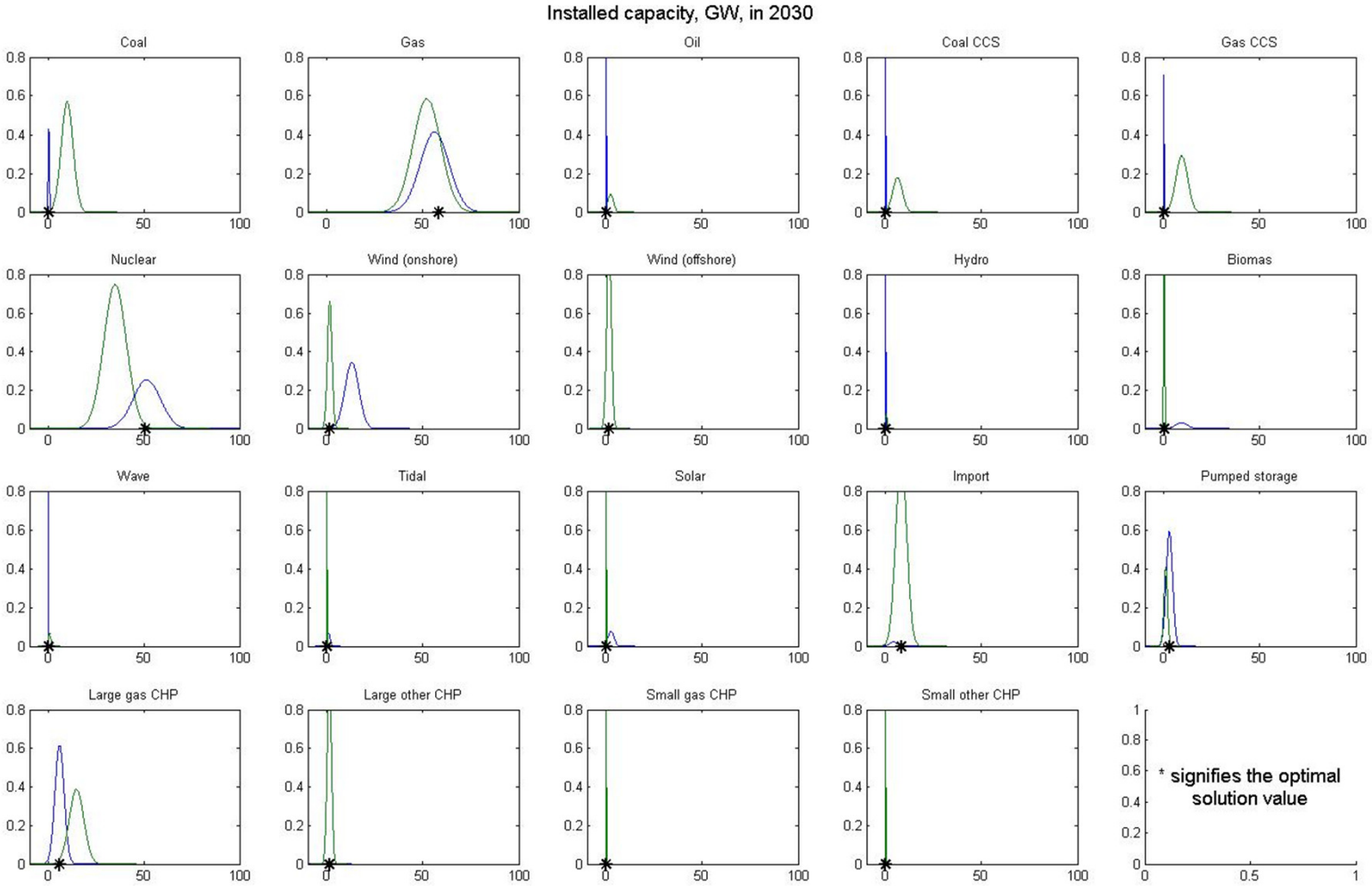


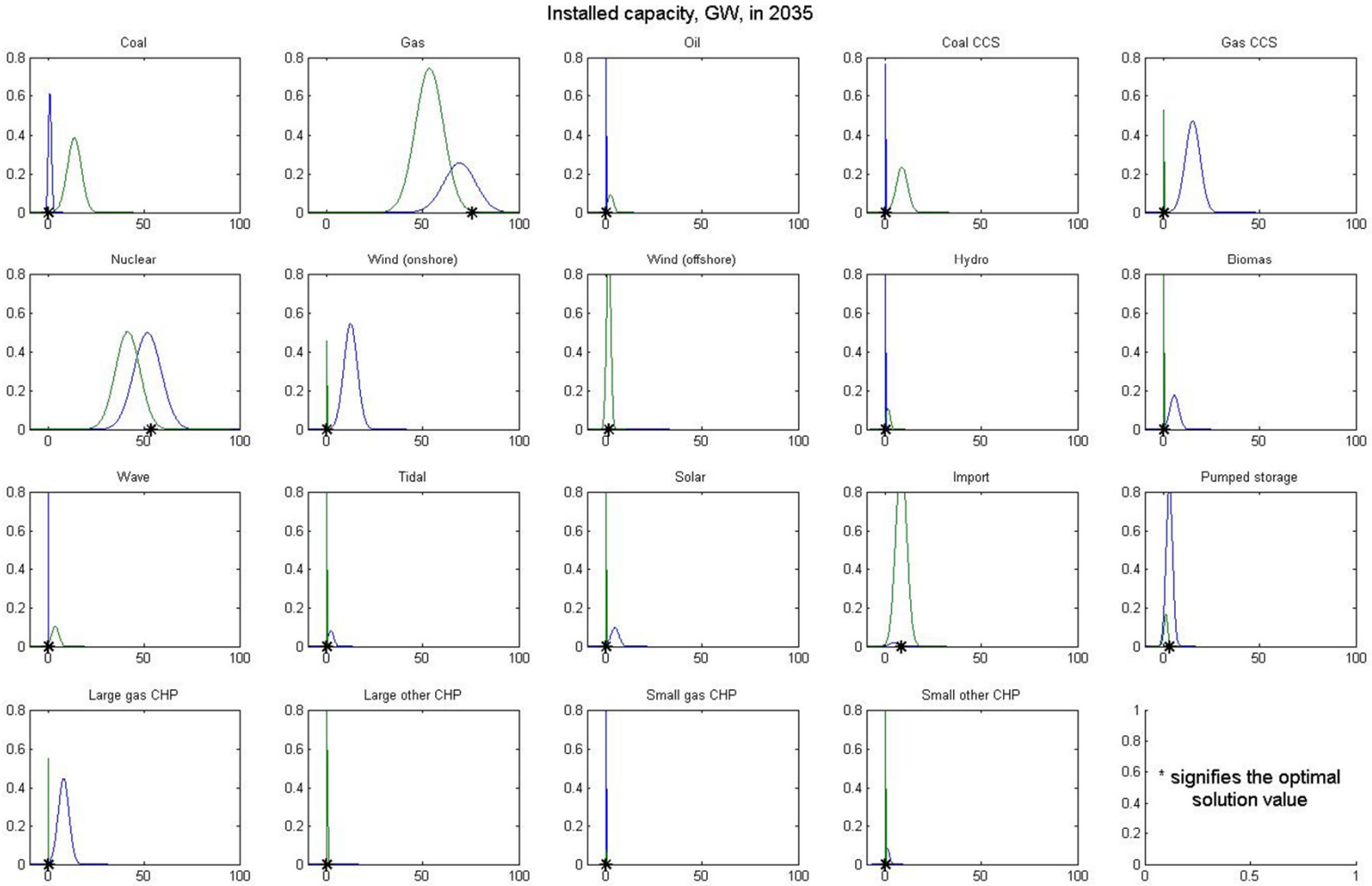
INSTALLED CAPACITY

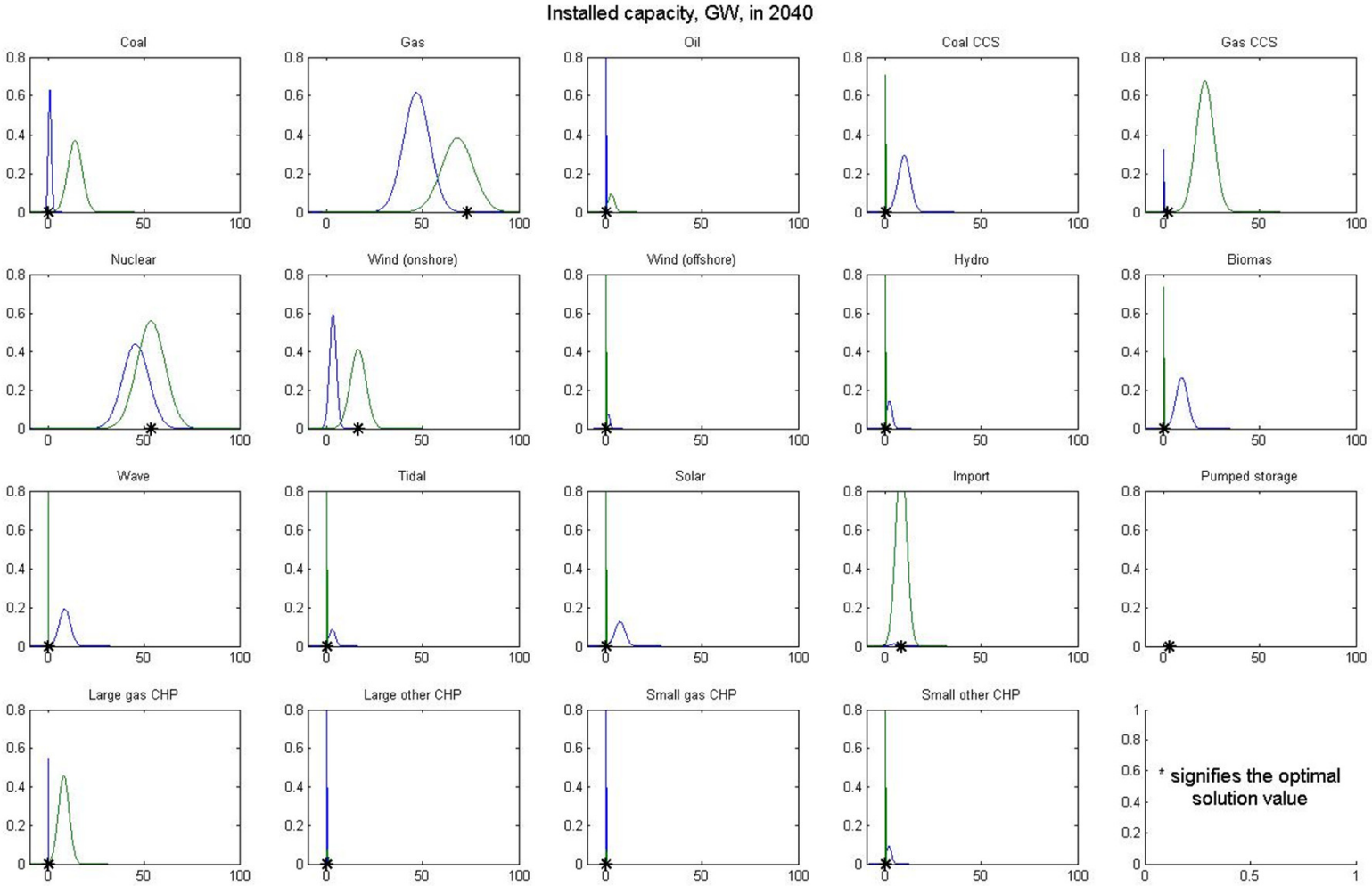

Installed capacity, GW, in 2015
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value

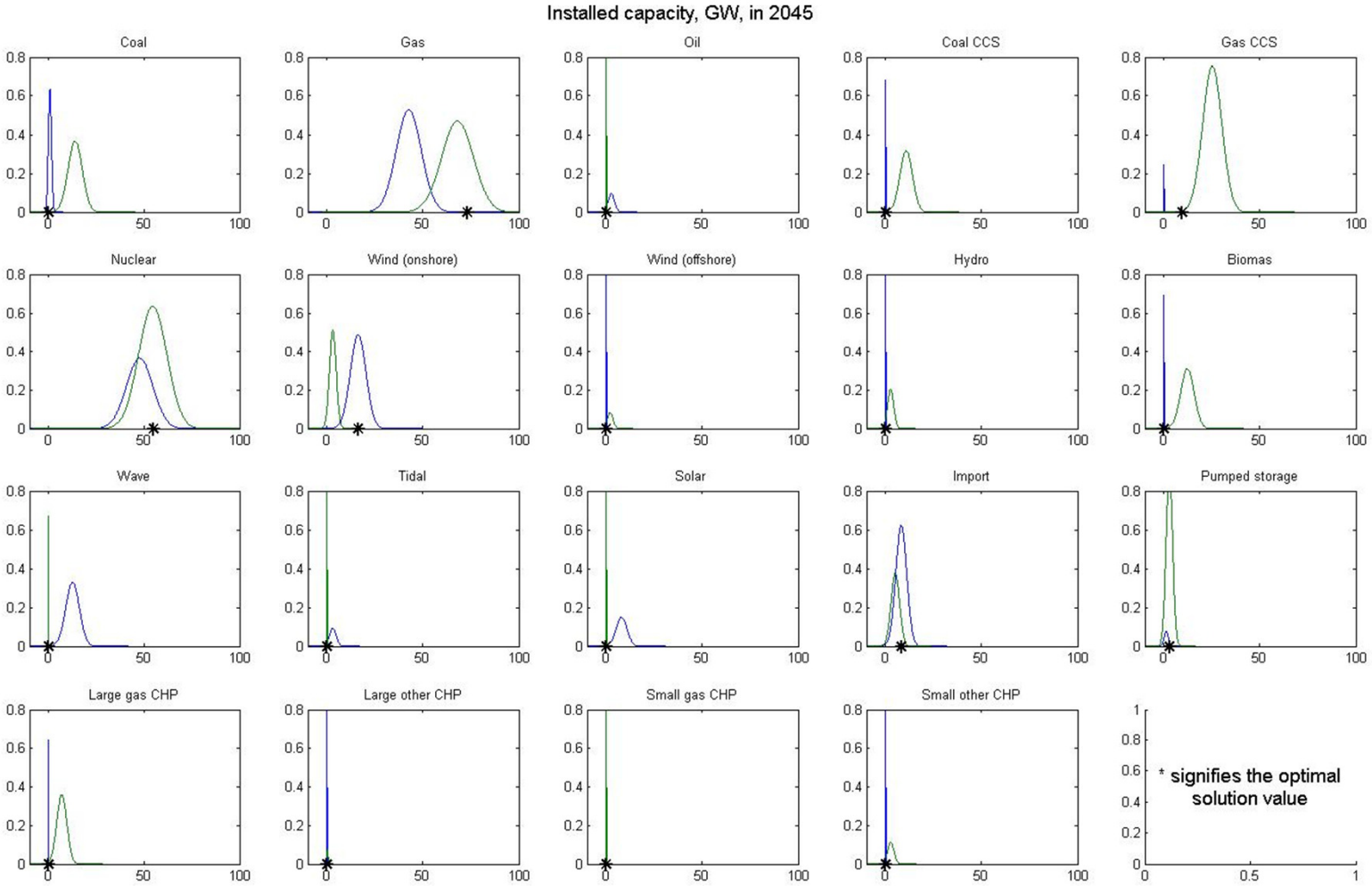

Installed capacity, GW, in 2020
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value

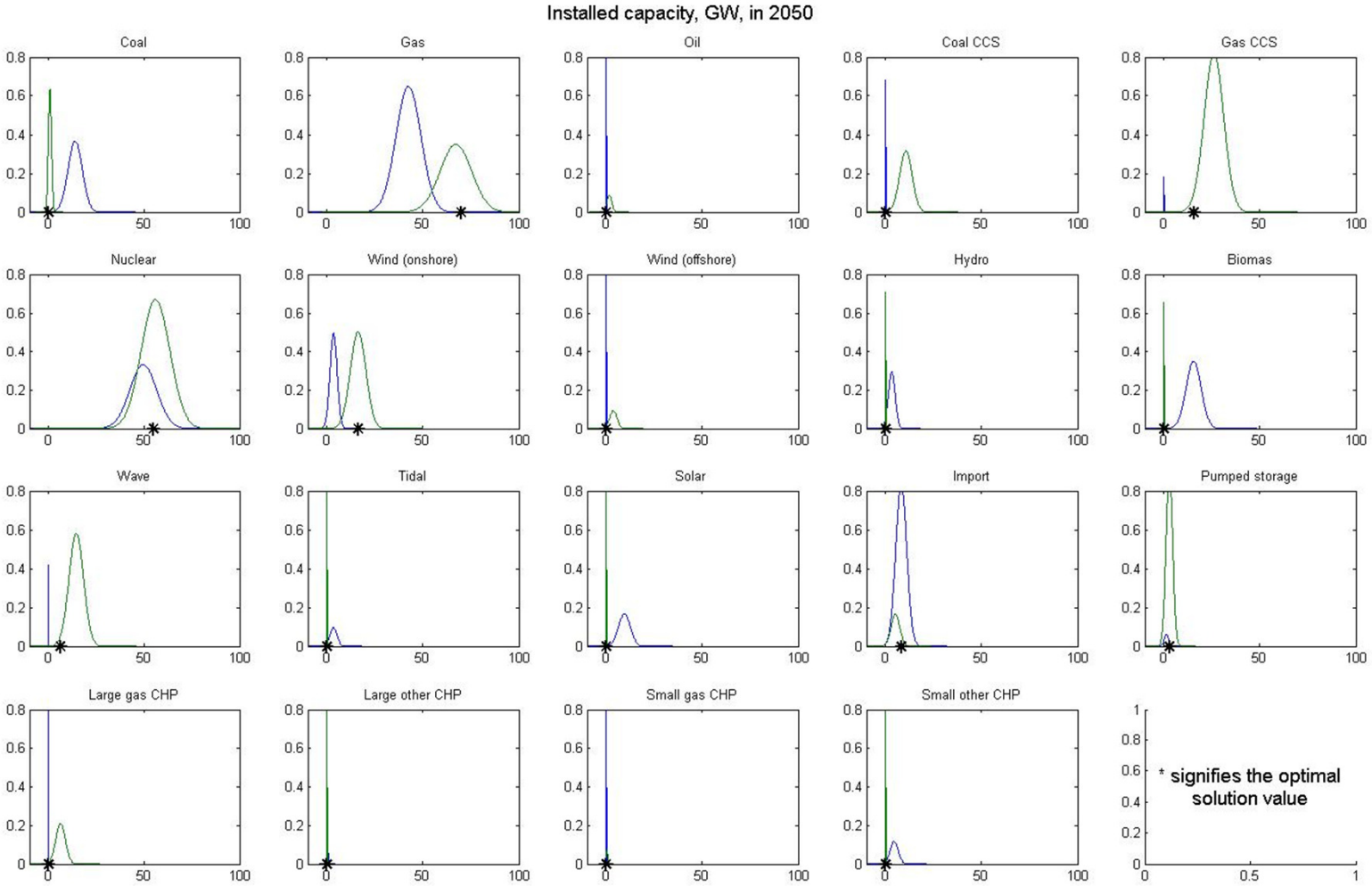

Installed capacity, GW, in 2025
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value


Installed capacity, GW, in 2030
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value


Installed capacity, GW, in 2035
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value


Installed capacity, GW, in 2040
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value

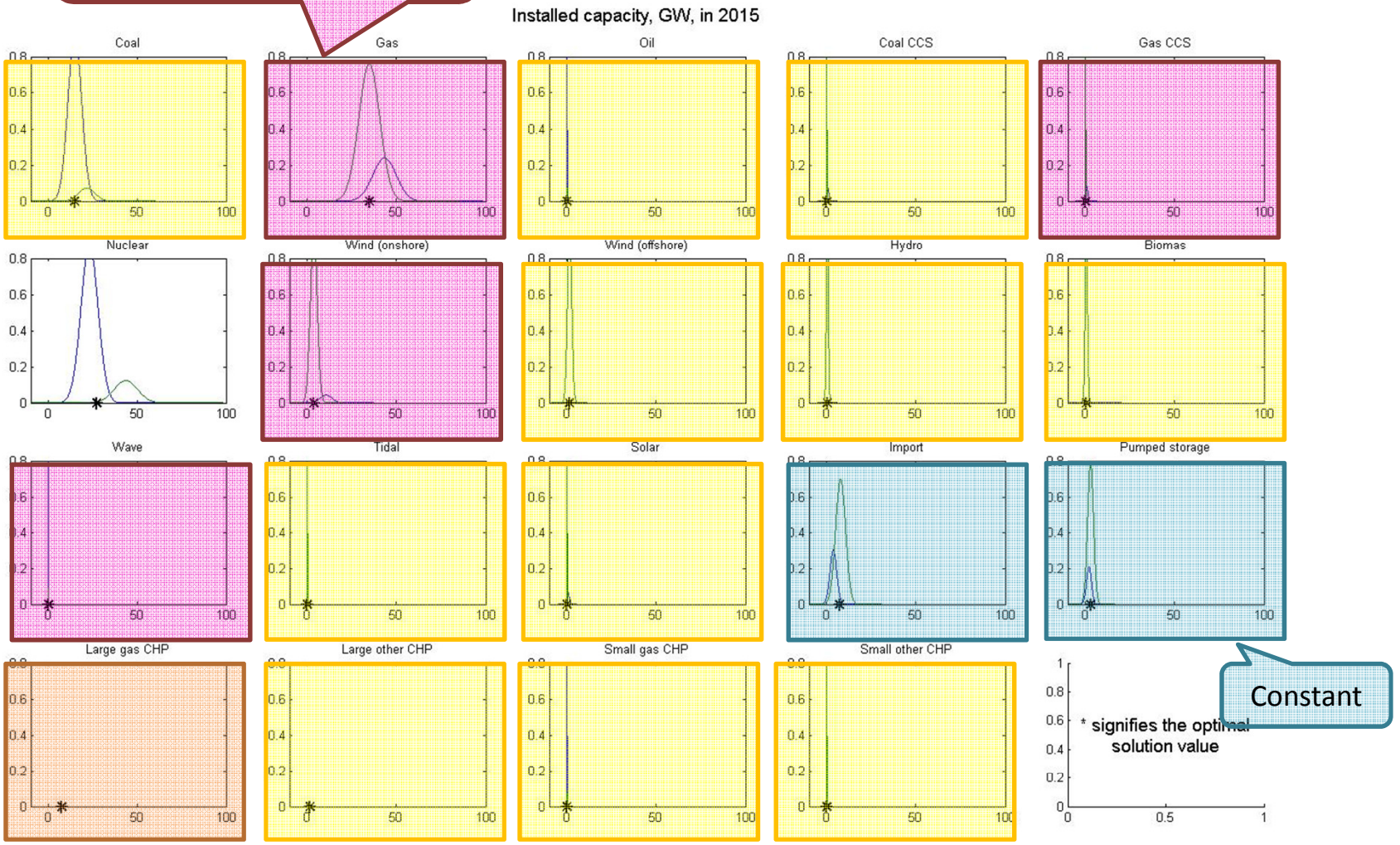

Installed capacity, GW, in 2045
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value


Installed capacity, GW, in 2050
Coal
Gas
Oil
Coal CCS
Gas CCS
Nuclear
Wind (onshore)
Wind (offshore)
Hydro
Biomas
Wave
Tidal
Solar
Import
Pumped storage
Large gas CHP
Large other CHP
Small gas CHP
Small other CHP
* signifies the optimal solution value

Trends in Installed Capacity

- Installed Capacity tells a different story from generation
- Nuclear is obviously a large player with massive growth
- But - it is clear that other generators are in supporting roles with increasing spread in the Gaussians meaning they must be running at low capacity factors

Steady Growth throughout the pathways

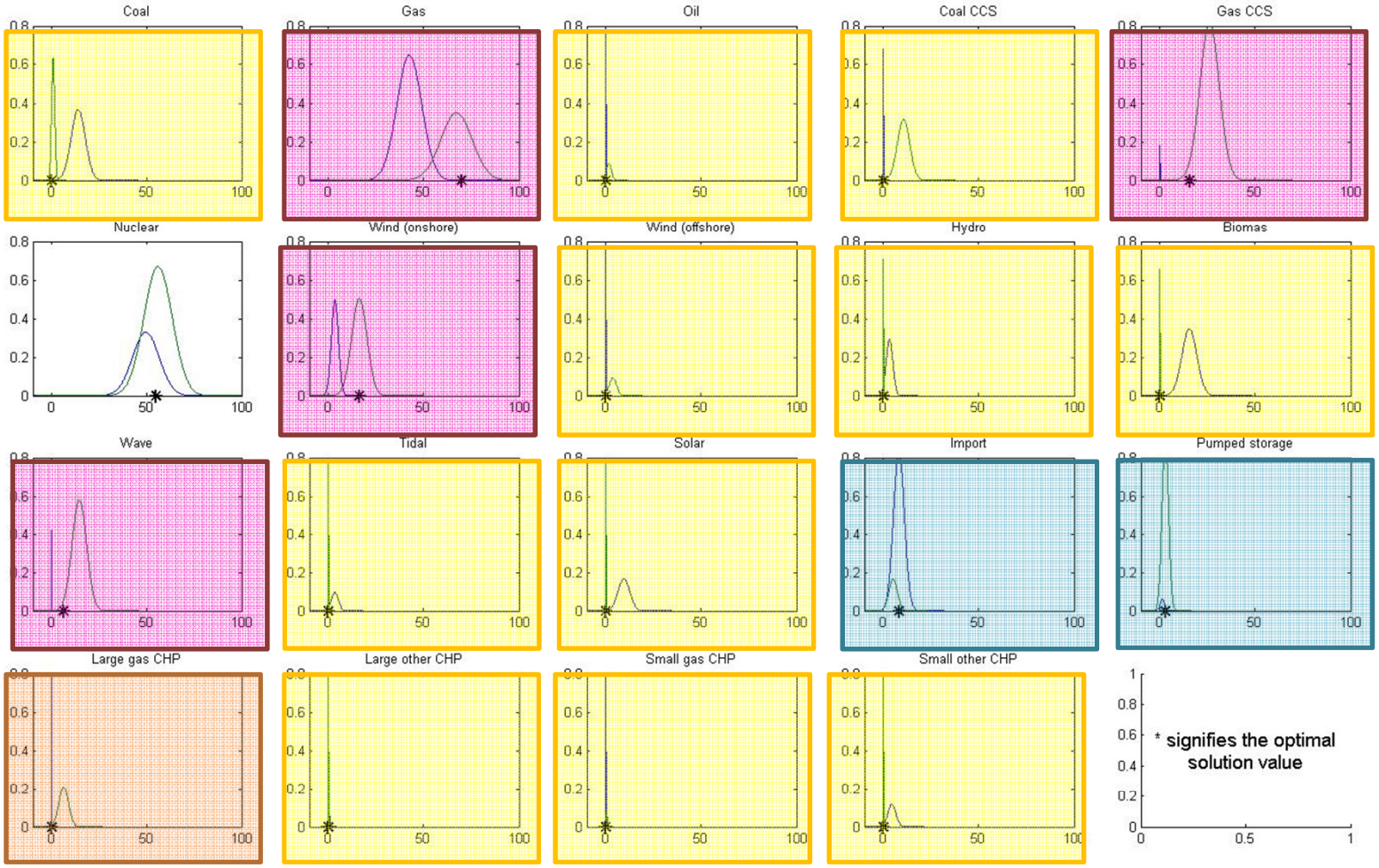


Constant

Reduction in capacity

Optimal values remains at zero, but with a spreading Gaussian of the near optimal solutions

Installed capacity, GW, in 2050



Summary

For our generated **EXPANSE** data set:

- The simple descriptive plots of the generated pathways allows us to get a better understanding of the relationships imposed by the modeller
- The fitting of Gaussian Mixtures provides a way to see how good we are at specifying the range of behaviours with time
- The mixture model can be used to give discrete operation states for models which can usefully limit the range considered for inputs

In each case, the modeller can act on this information to check and/or improve the study cases

Next Steps

This is just a start, initial findings, where can it go next

- Formal model selection criteria can be used to identify and justify how many distinct behaviours are in the data that arises for **EXPANSE** and similar scenario research (dimensionality reduction)
- *Mover-stayer model* extensions to determine improved characterisation of moving between regimes from time-step to time-step
- The relationship with the electrical power system is an important aspect of the problem not fully considered

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REALISING TRANSITION PATHWAYS