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Model archaeology

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Introduction

- Energy system models have opaque structures
  - changes between model versions?
  - extent of changes described in research papers.
- We wanted to develop a UK TIMES Model (UKTM).
- Inform development of UKTM by reviewing development of UK MARKAL over several years.
- Developed a formal methodology for this that we call “model archaeology”.

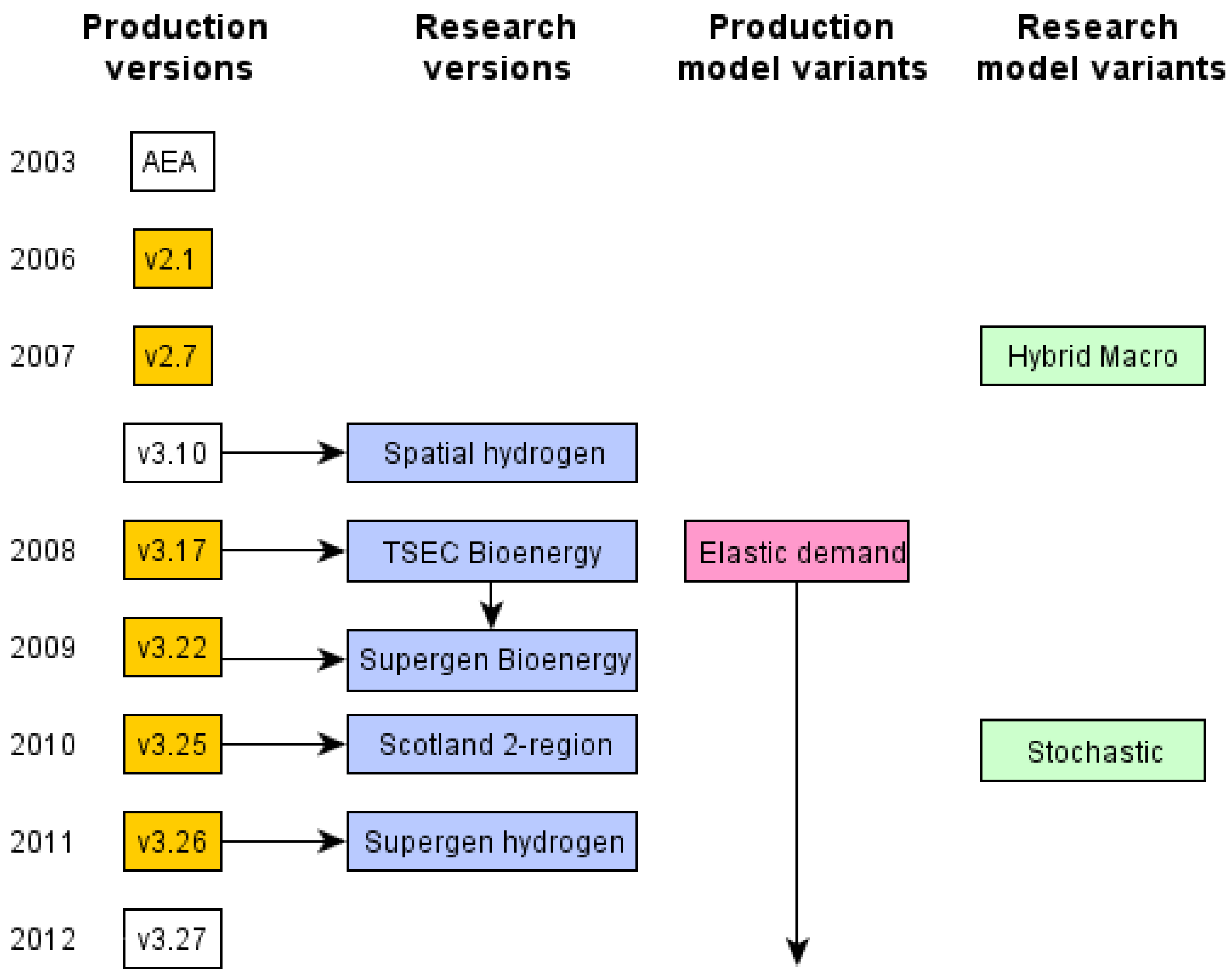
Model archaeology

- Quantitatively examine the balance and evolution of energy system models through the *ex post* analysis of both model inputs and outputs using a series of metrics.
- These metrics help us to understand how models are developed and used and are a powerful tool for effectively targeting future model improvements.

Input metrics

1. Model paradigm and equations
2. Spatial and temporal dimensions
3. Energy system structure (model topology)
4. Modelled system constraints
5. Parameter data

Case study of UK MARKAL



Model paradigm and equations

- UK MARKAL always run using the ANSWER interface.
- No changes to the underlying equations within the MARKAL source code.
- Several UK MARKAL variants developed:
  - Hybrid macro research version.
  - Elastic energy service demands since v3.17.
  - Stochastic version to examine perfect foresight.

Spatial and temporal dimensions

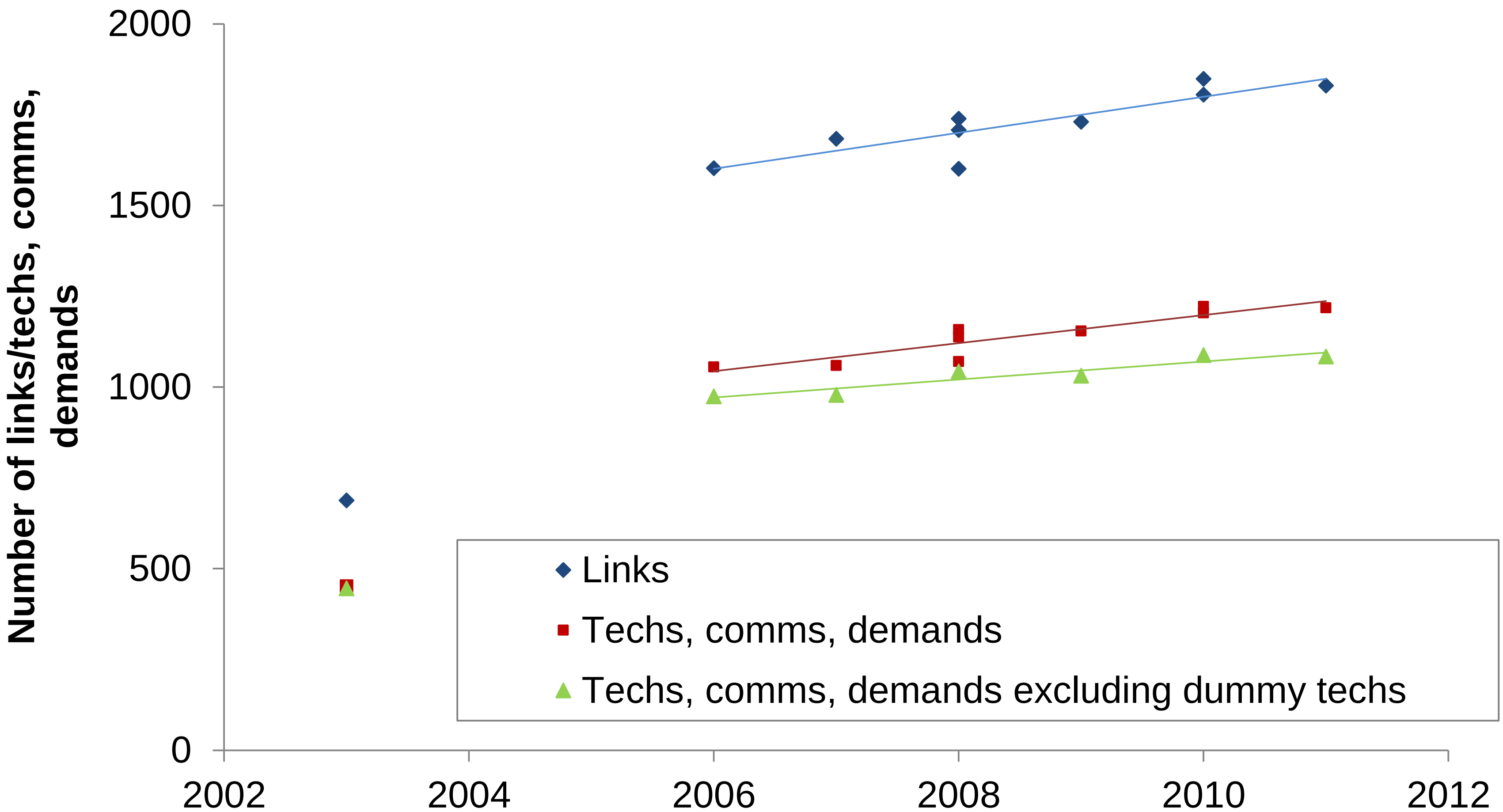
Spatial dimensions:

- Single region model in all production versions.
- Spatial hydrogen research version:
  – nine UK demand regions, six supply points, and a set of 200 infrastructure development options for hydrogen pipelines.
- Two-region model that includes Scotland and Rest-of-the-UK.

Temporal dimensions:

- Runs to 2070 in earlier versions and 2050 from v3.25 onwards.
- 3 seasons and 2 intraday timeslides in production versions.
- 4 seasons and 5 intra-day time-slices in a higher-resolution version.

Energy system structure (model topology)



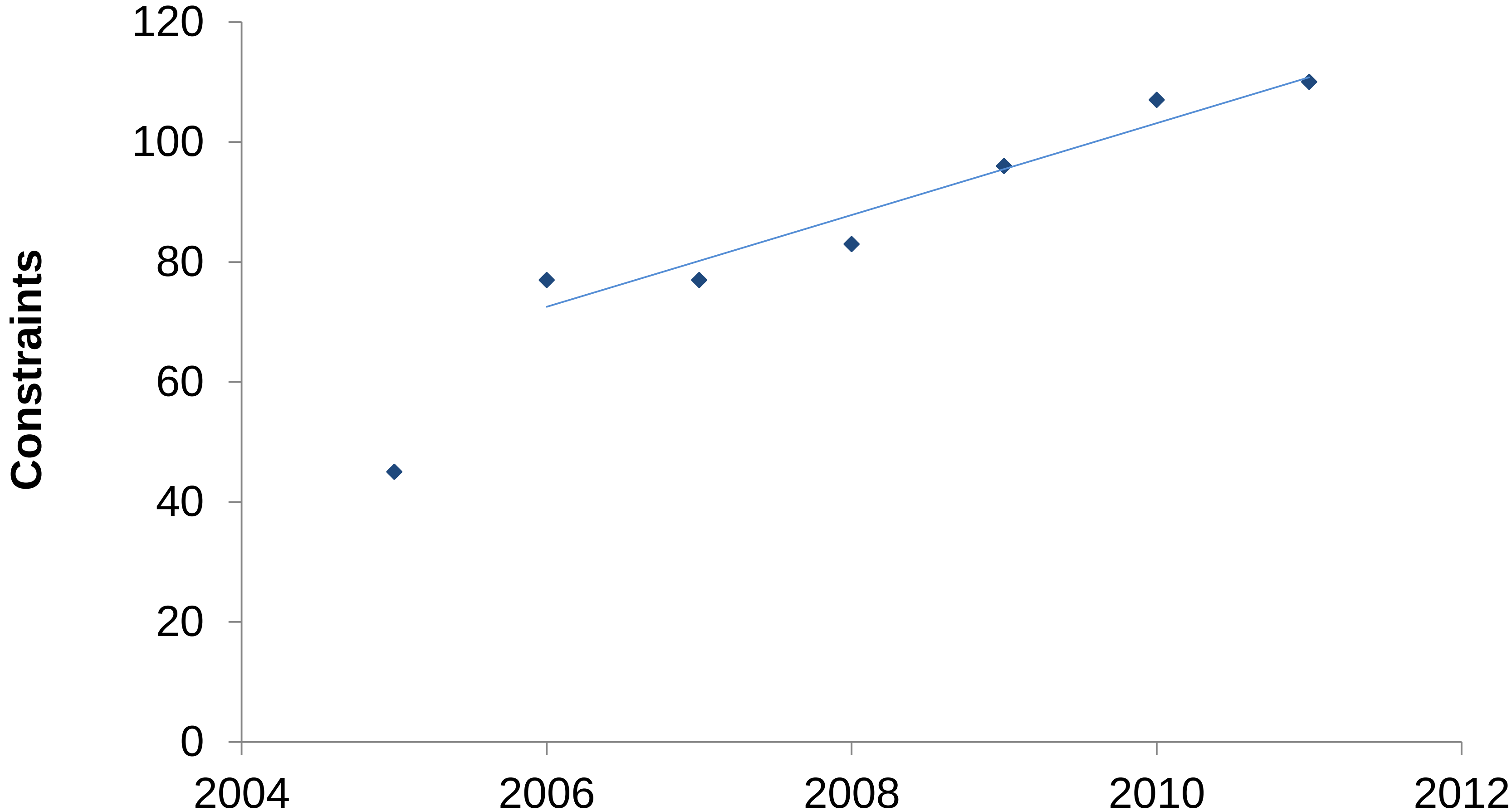
Diverse technology statistics

Sector	Technologies		Fraction from v2.1 in v3.26	Tech diversity/Mte CO_2 emissions	Tech diversity/TJ equivalent demand
	v2.1	v3.26			
Resources	117	130	97%	-	-
Electricity	94	140	81%	0.9	-
Process	114	111	78%	2.8	-
Residential	92	123	93%	1.4	66.3
Service	36	52	100%	2.8	53.3
Industry	98	93	94%	1.3	46.3
Transport	110	117	84%	1.0	65.2
Total	**661**	**766**	**89%**	**1.5**	**57.5**

Change in the number of diverse technologies between model versions

Version	Year	Electricity		Process		Residential		Transport	
		+	–	+	–	+	–	+	–
v2.7	2007	0%	–0%	0%	–0%	0%	–0%	0%	–0%
v3.17	2008	40%	–15%	17%	–22%	37%	–82%	19%	–16%
v3.22	2009	2%	–2%	2%	–1%	135%	–4%	0%	–0%
v3.25	2010	10%	–1%	3%	–1%	0%	–0%	4%	–0%
v3.26	2011	9%	–1%	0%	–0%	4%	–0%	1%	–2%

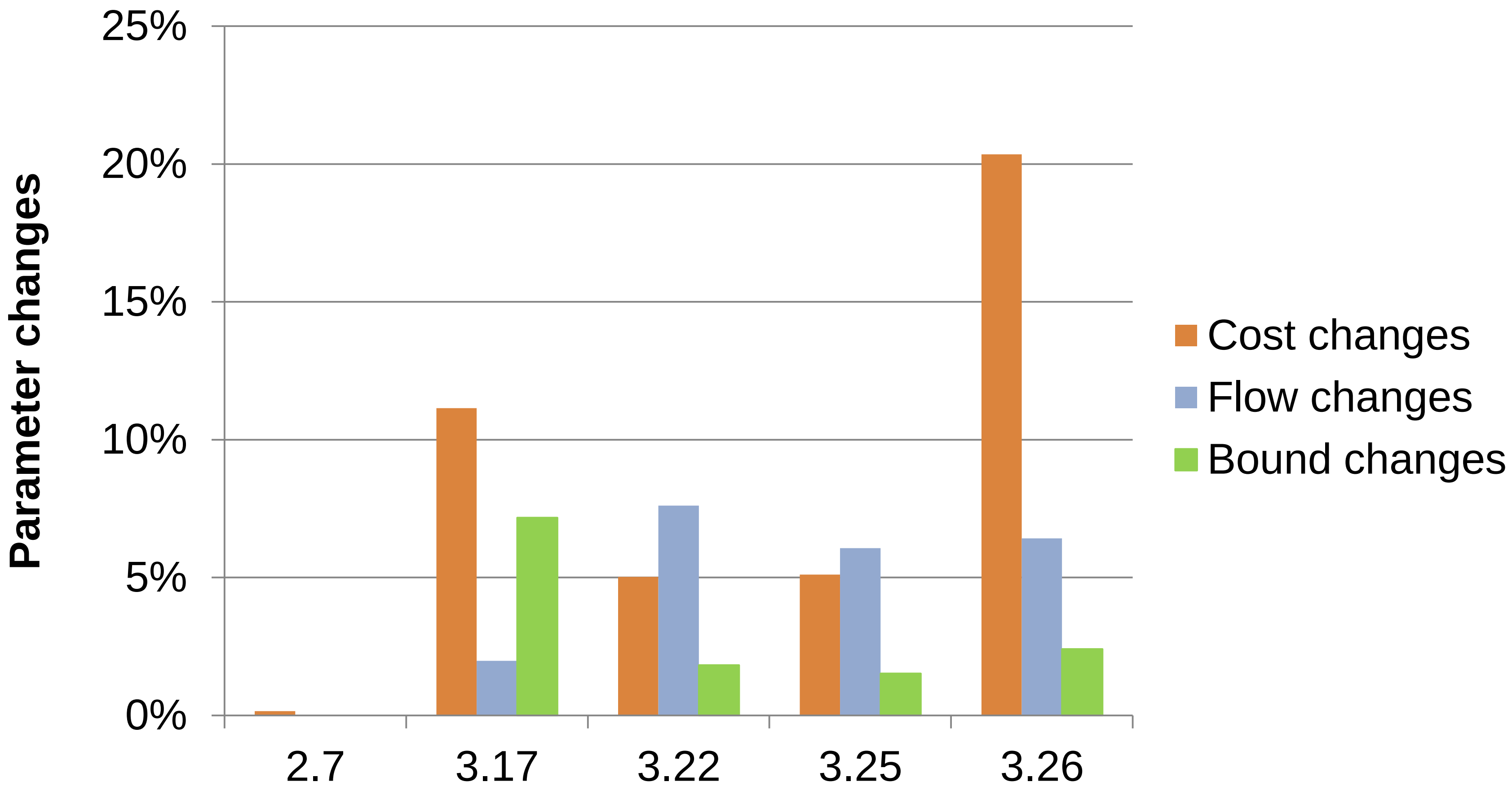
Number of user constraints



Number of constraint *changes* (additions + deletions)

	Constraints in v3.26	Total number of additions and deletions				
		v2.7	v3.17	v3.22	v3.25	v3.26
Resource	3	0	0	0	0	0
Electricity	24	0	11	1	10	3
Process	3	0	2	0	3	0
Residential	23	0	13	14	4	0
Service	6	0	1	0	2	0
Industry	9	0	0	0	2	0
Transport	42	0	23	0	6	0
Total	**110**	**0**	**50**	**15**	**27**	**3**

Parameter data



Technologies with parameter changes

	Total number of parameter changes				
	v2.7	**v3.17**	**v3.22**	**v3.25**	**v3.26**
Resource	0%	34%	0%	23%	40%
Electricity	18%	19%	32%	19%	39%
Process	1%	6%	0%	5%	0%
Residential	11%	27%	21%	4%	30%
Service	56%	0%	0%	0%	0%
Industry	0%	0%	1%	3%	0%
Transport	0%	11%	0%	35%	25%
Total	**7%**	**15%**	**9%**	**15%**	**23%**

Overall technology changes by sector

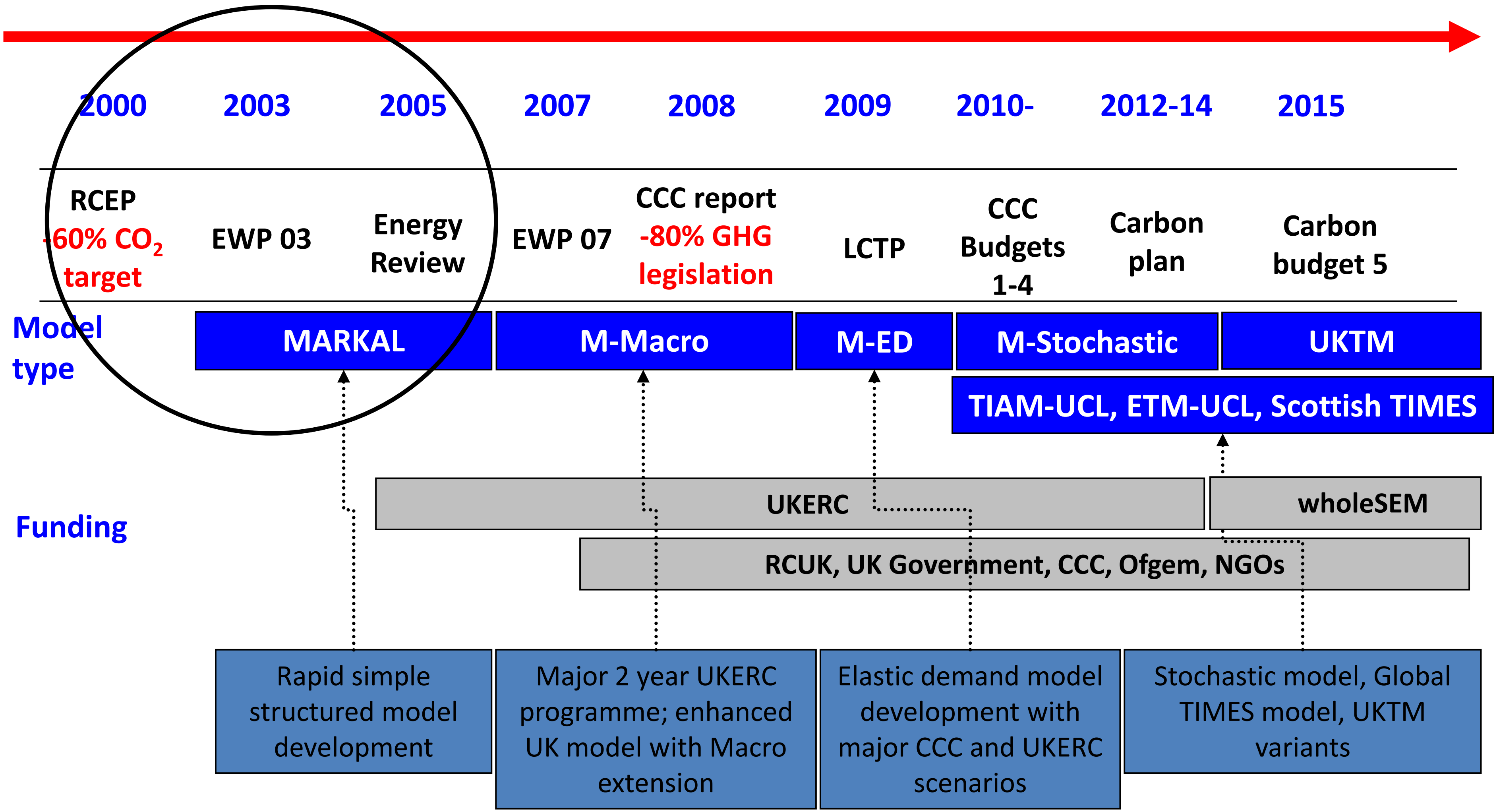
Sector	Number of technologies		Fraction of v2.1 techs subsequently changed	Techs in v3.26 added or changed since v2.1
	v2.1	v3.26		
Resources	117	130	51%	57%
Electricity	134	177	75%	83%
Process	123	122	15%	32%
Residential	98	131	99%	99%
Service	40	56	58%	71%
Industry	133	128	3%	4%
Transport	540	511	30%	45%
Total	**1185**	**1255**	**47%**	**55%**

Evolution of UK MARKAL

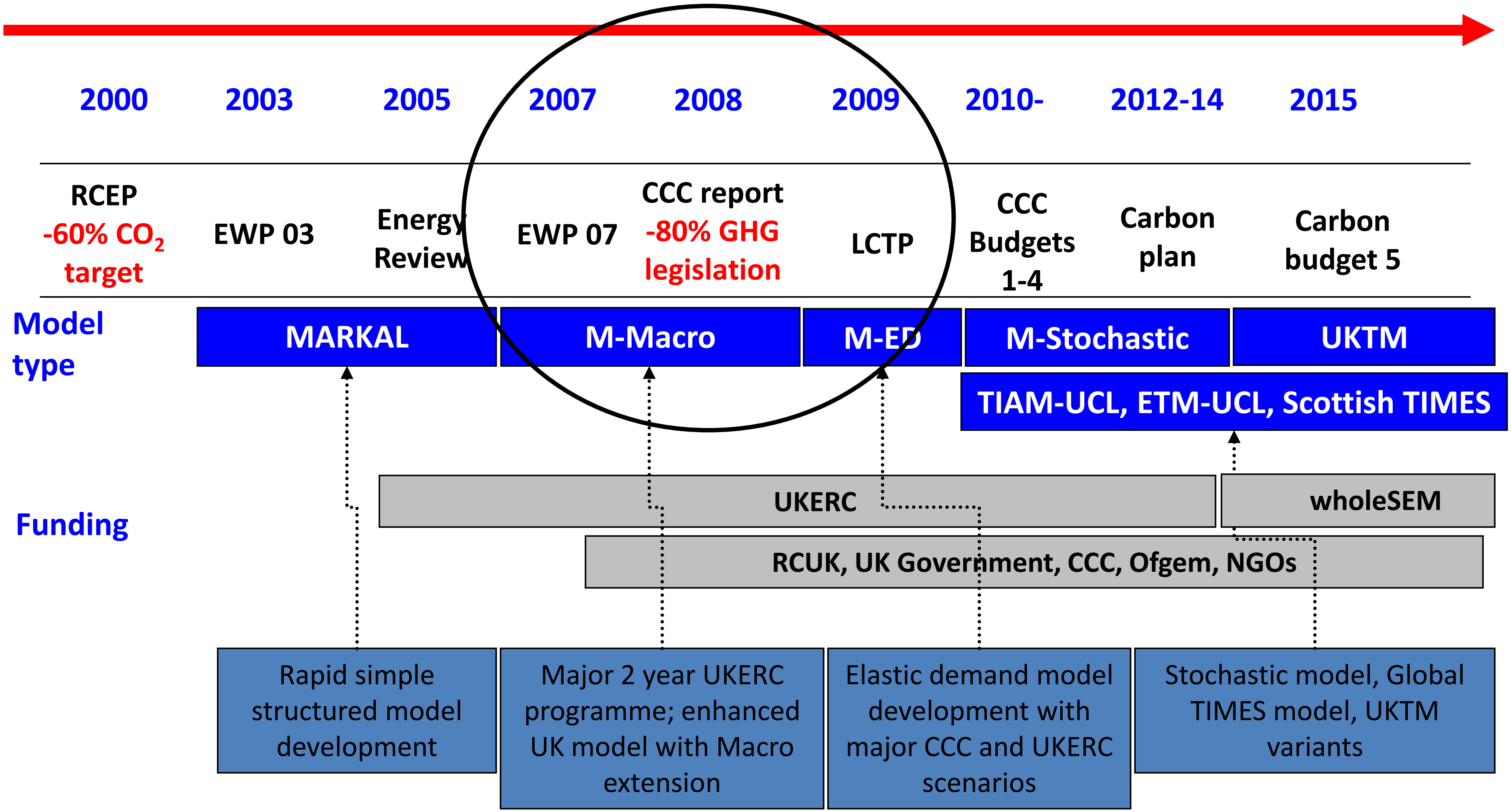
We examined publications using the model:

- Stage 1: Initial development
- Stage 2: Experimentation and incremental improvement
- Stage 3: Reflection
- Stage 4: Maturity and reimagining

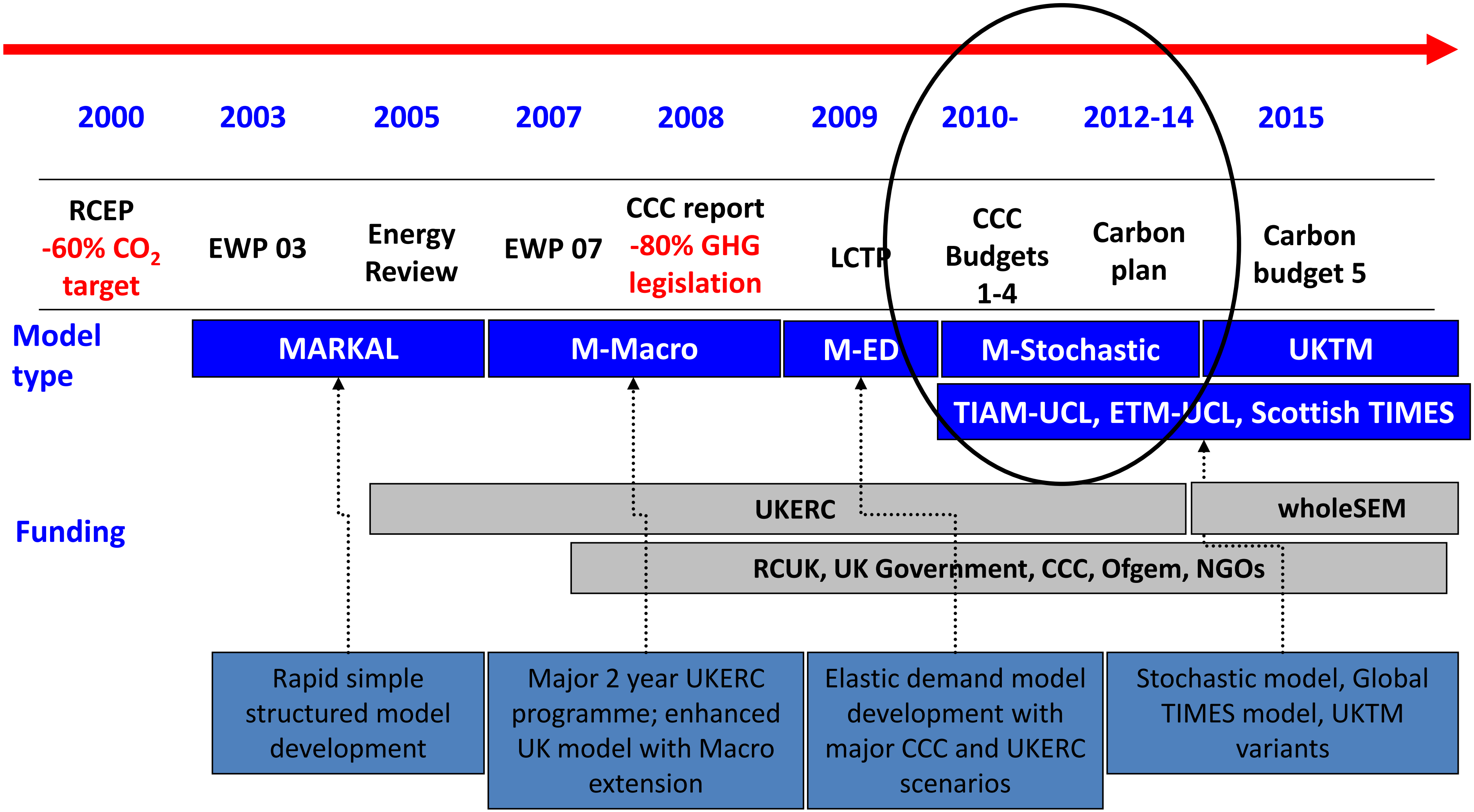
Stage 1: initial development



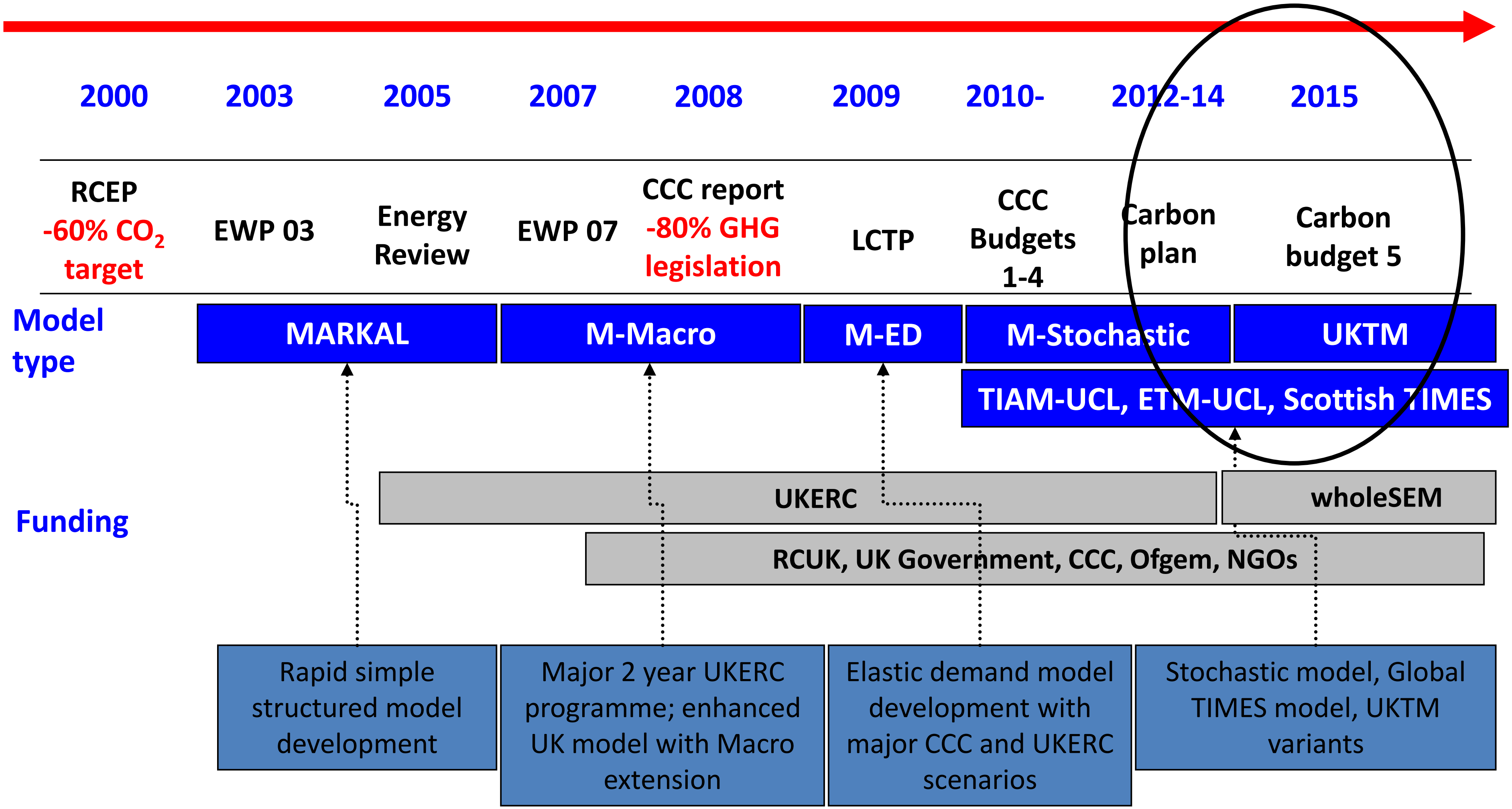
Stage 2: Experimentation and incremental improvement



Stage 3: Reflection



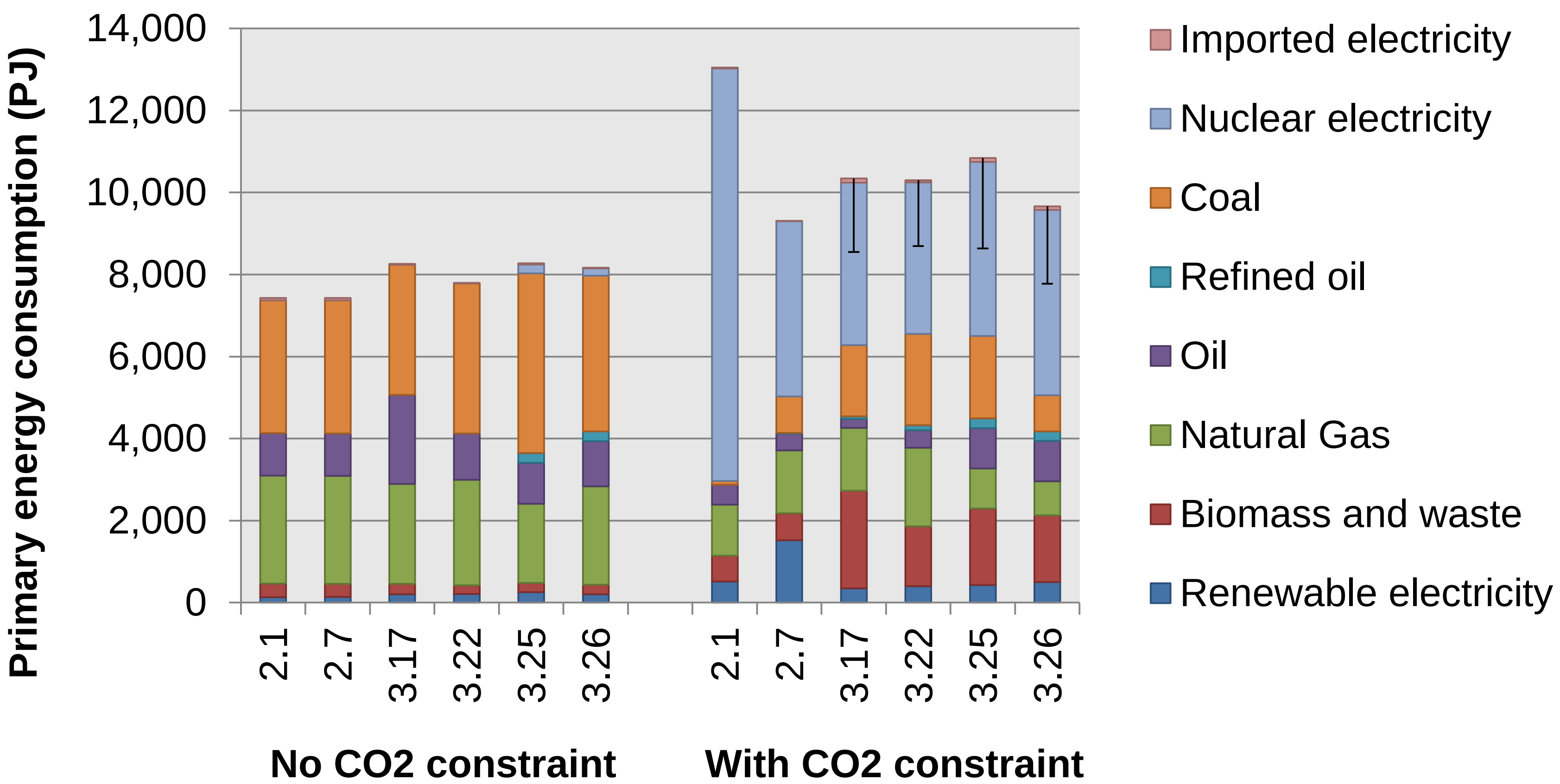
Stage 4: Maturity and reimagining



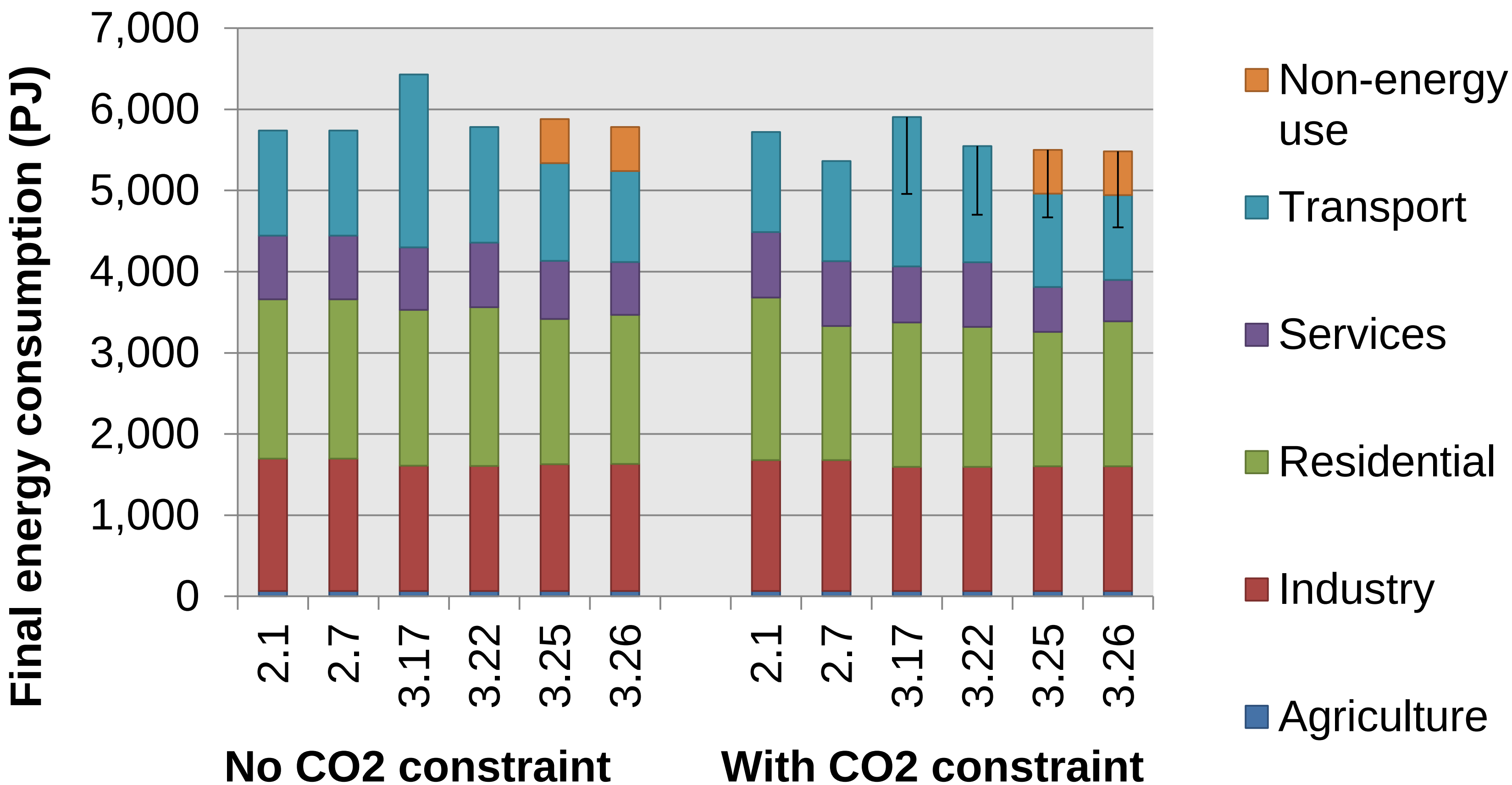
Output metrics

- Test each model with the same two/three scenarios:
  - Reference scenario with no emission cuts
  - 80% reduction in CO_2 emissions in 2050
  - 80% reduction in CO_2 emissions in 2050 with elastic demands, for model versions 3.xx with this capability

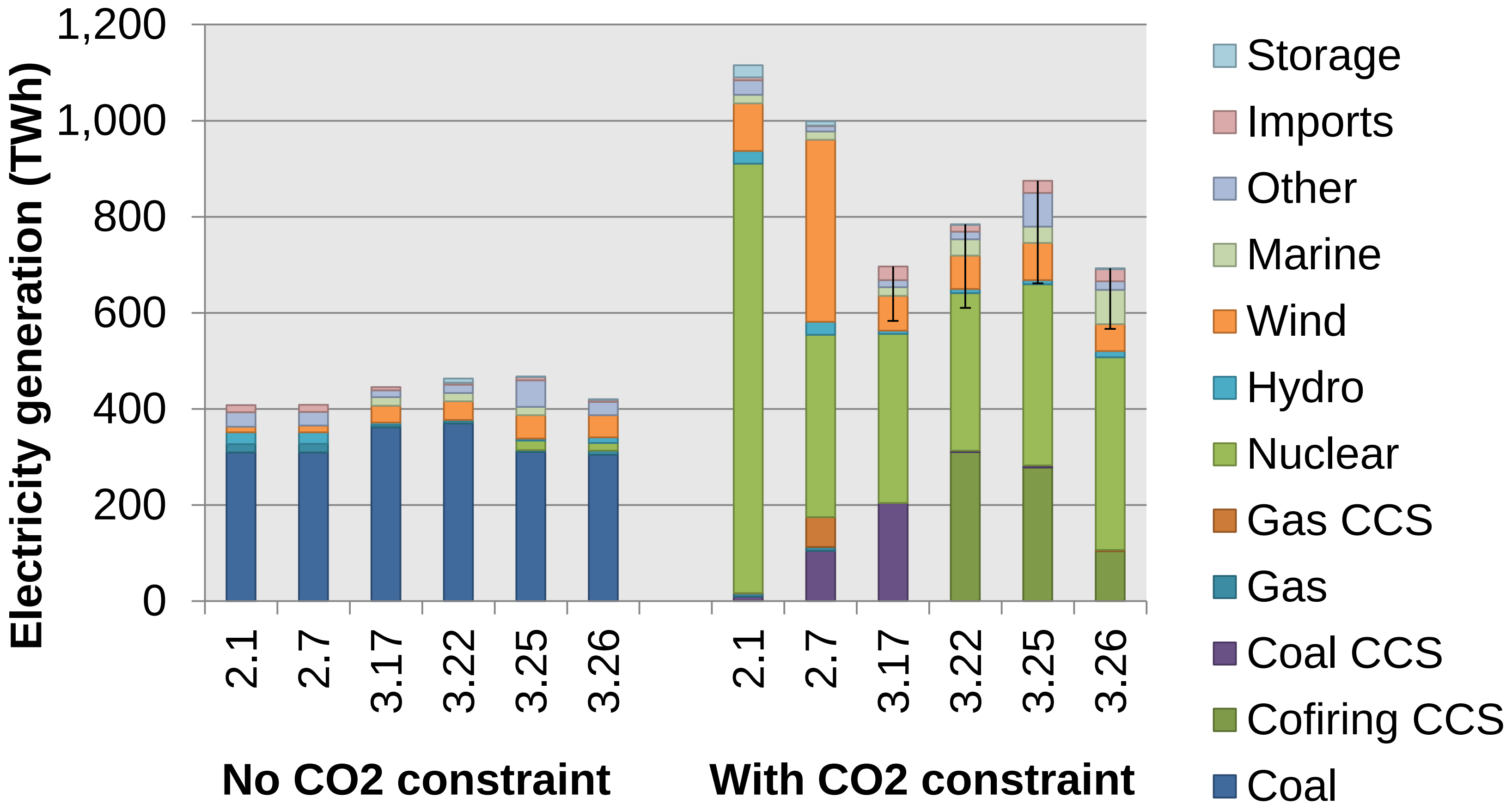
Primary energy consumption in 2050



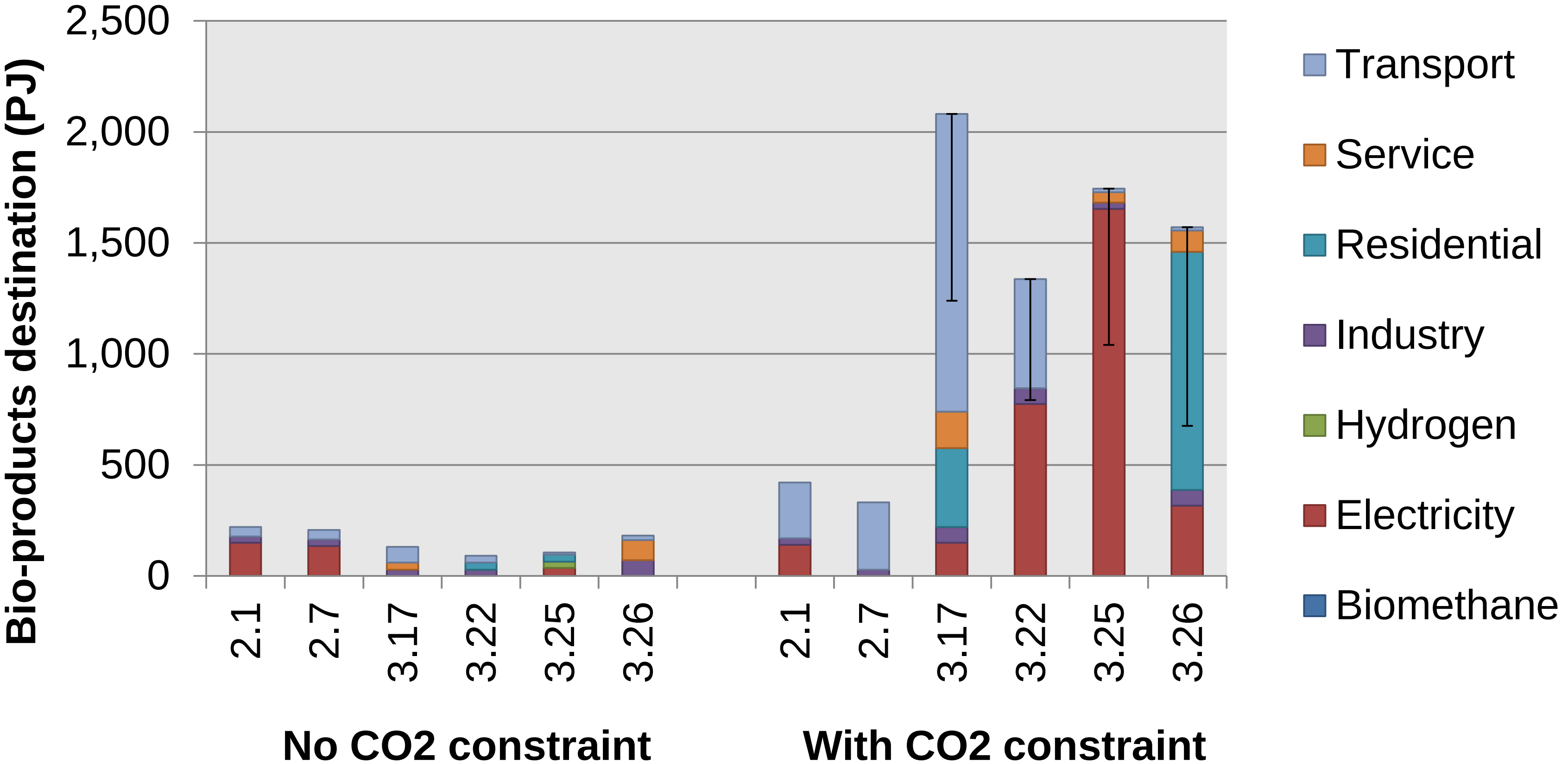
Final energy consumption in 2050



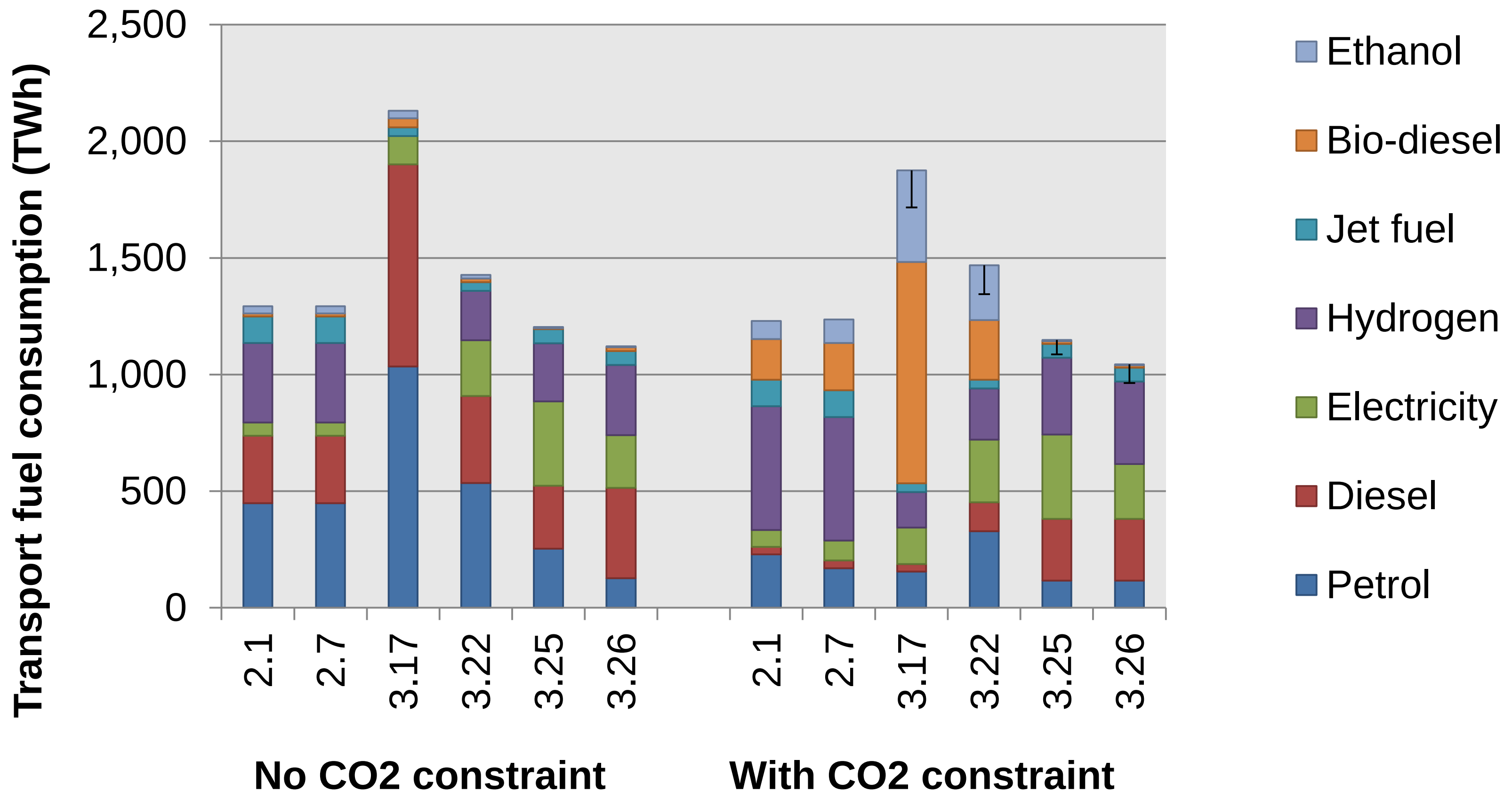
Electricity generation in 2050



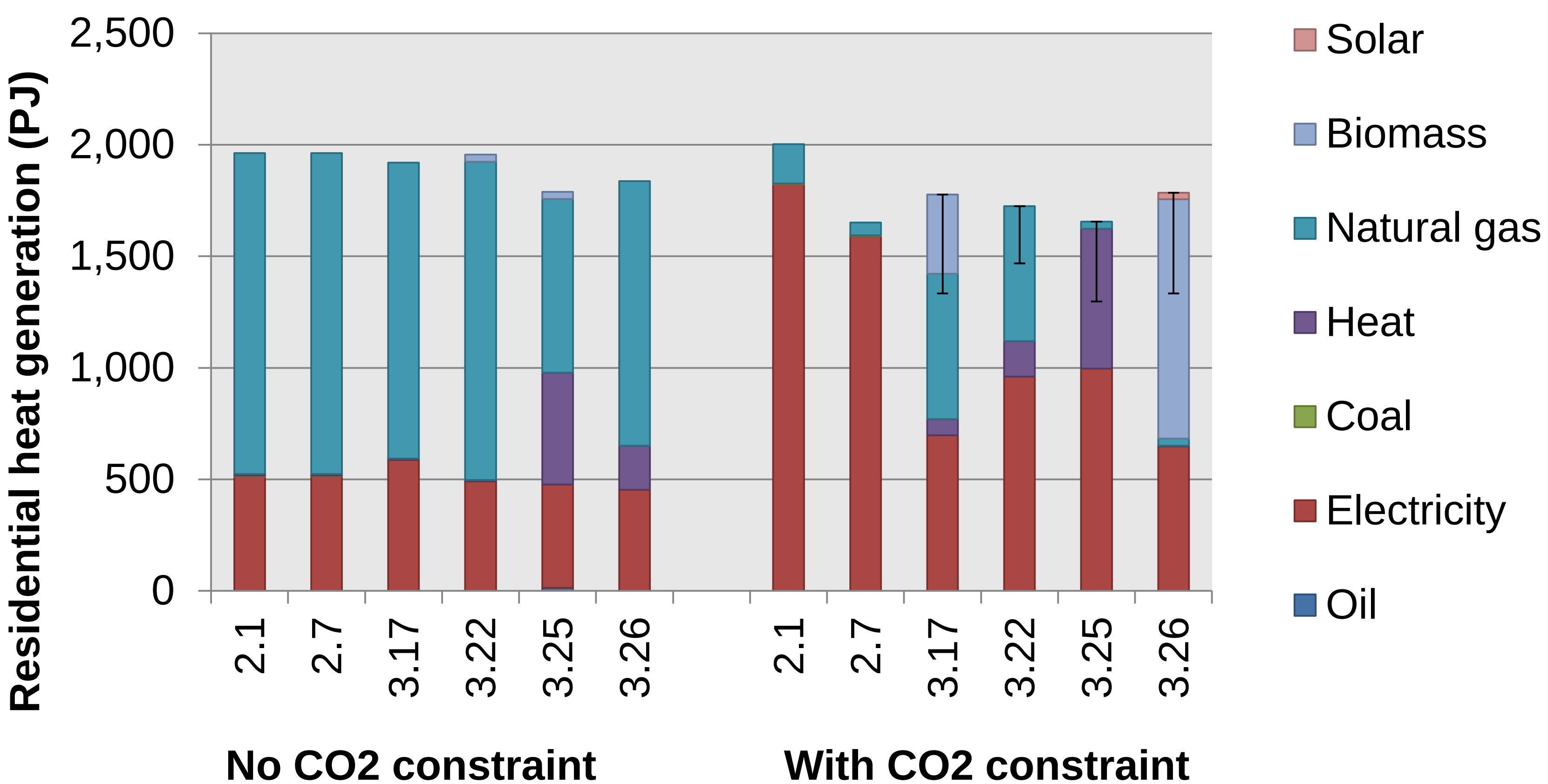
Consumption of biomass products in 2050



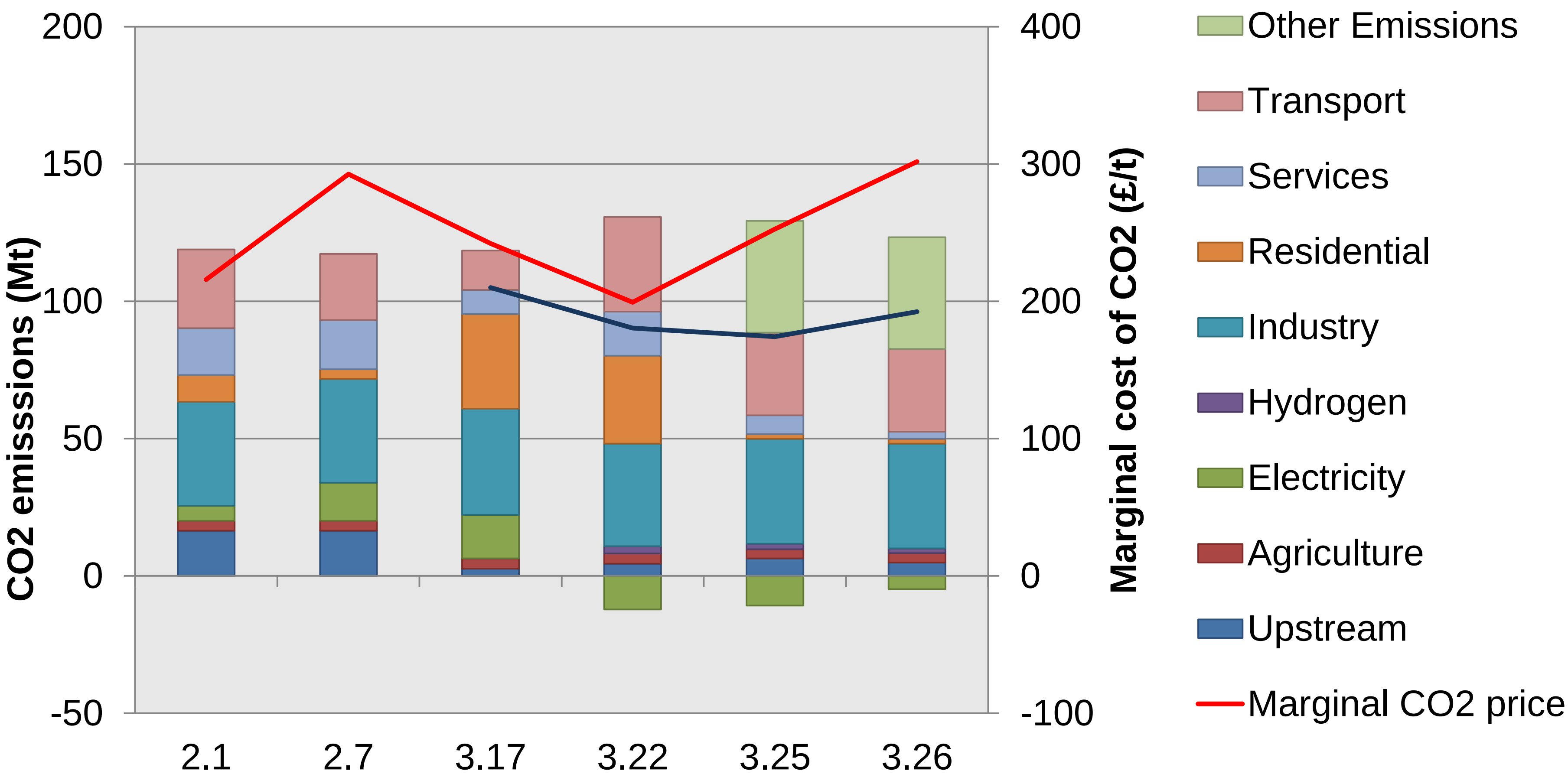
Transport fuel consumption in 2050



Residential heat generation in 2050



CO_2 emissions in 2050



Relationships between input and output metrics

1. Impact of model changes within sectors on these outputs
2. Impact of model changes between versions

Need to convert outputs in graphs into indices

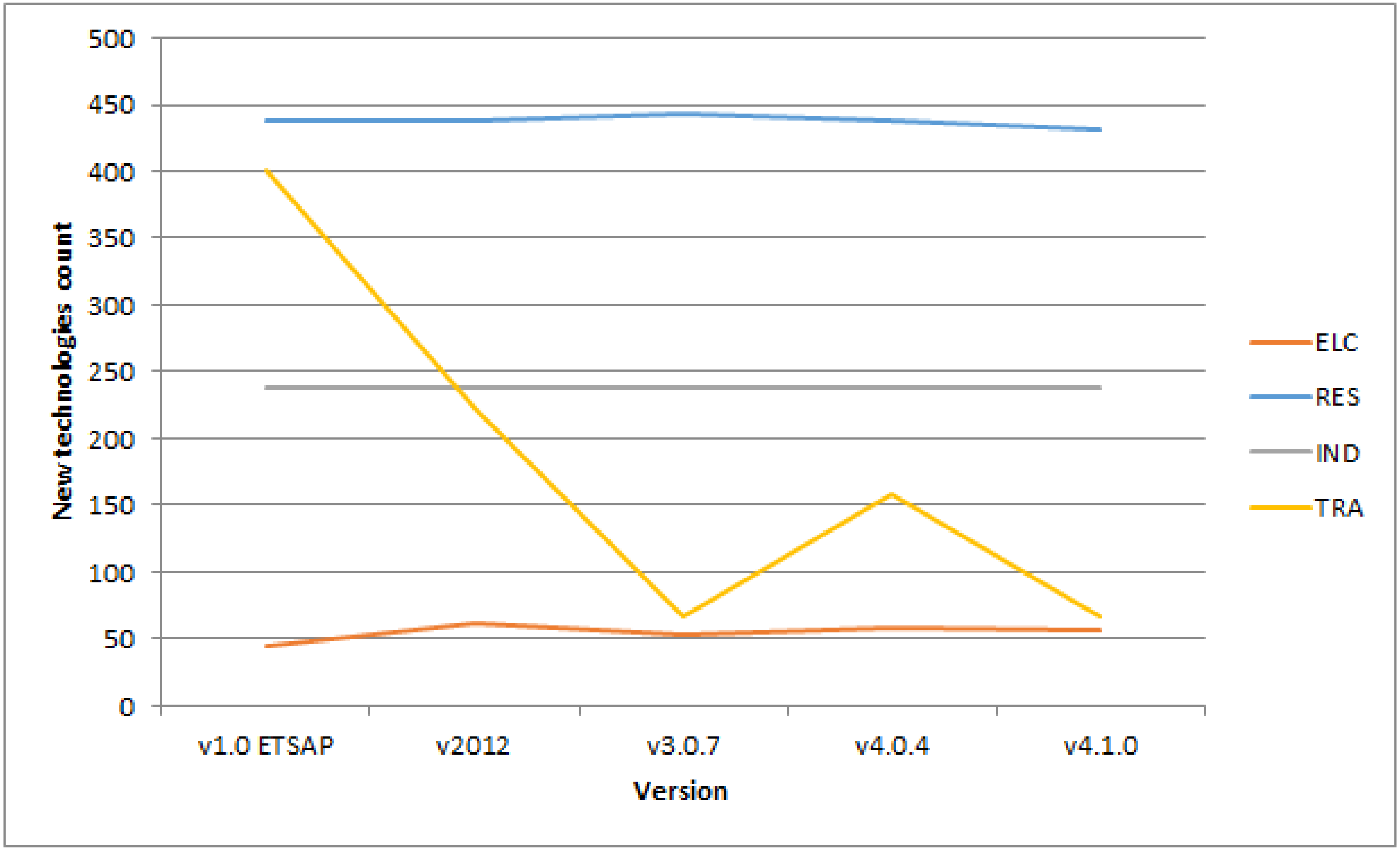
Relationships between input and output metrics

- Primary and final energy consumptions do not greatly change between most versions.
- Large variations within some individual sectors.
- Weak links between number of changes to input data and changes to outputs for most sectors.
- All types of model changes (topology, constraints, parameters) strongly influence the outputs.

Conclusions from UK MARKAL

- UK MARKAL development has been influenced by the interests of the UK government and the research projects funding model development.
- Energy system costs tend to increase in subsequent model versions.
- There is clear evidence of a strategy to balance model complexity and accuracy over time.
- Model archaeology compels the modeller to perform a systematic review of the model and the modelling process, and can improve the transparency of research model studies.

Postscript: TIAM-UCL technologies (early results)

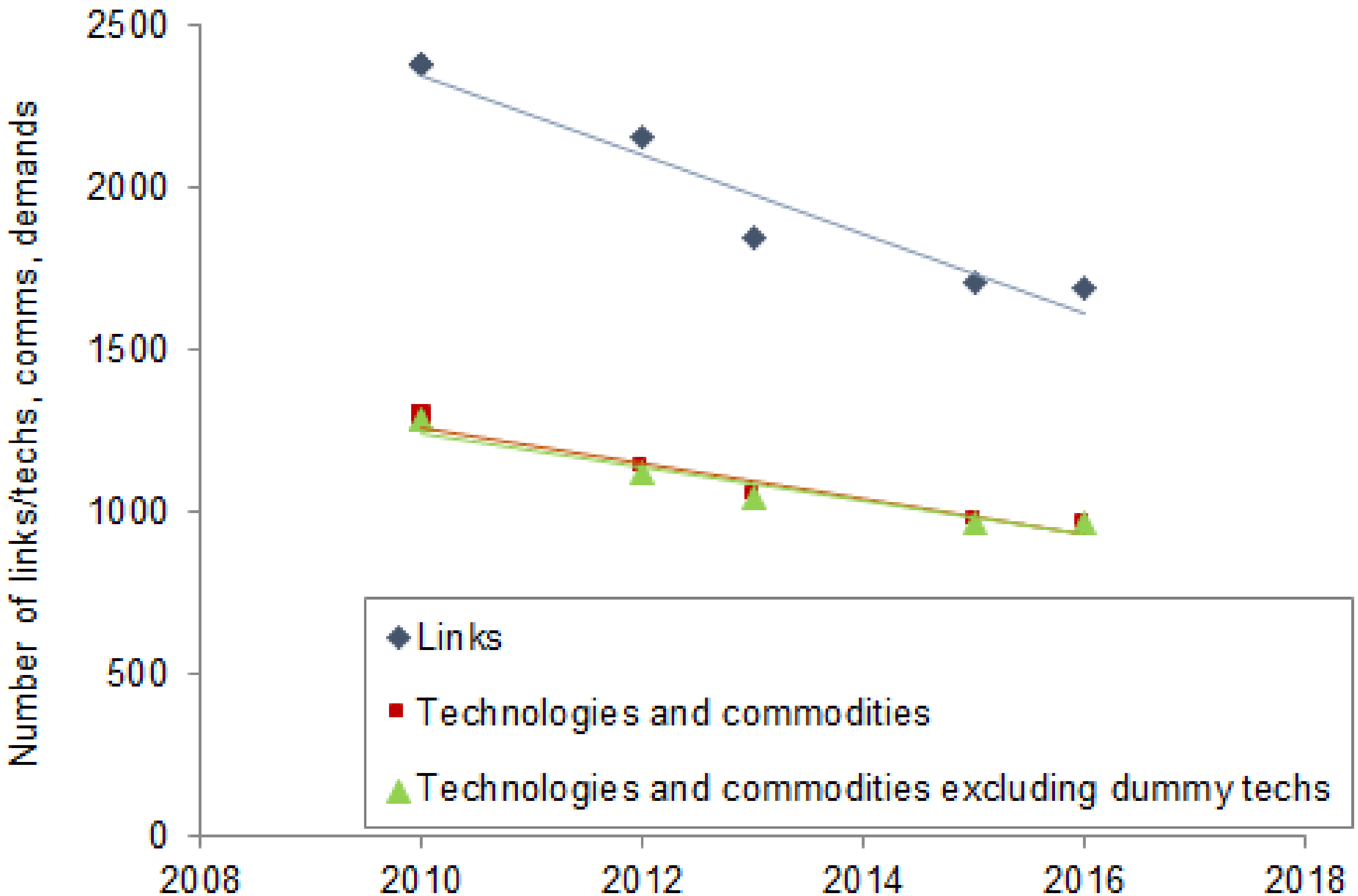


Topology changes (technologies)

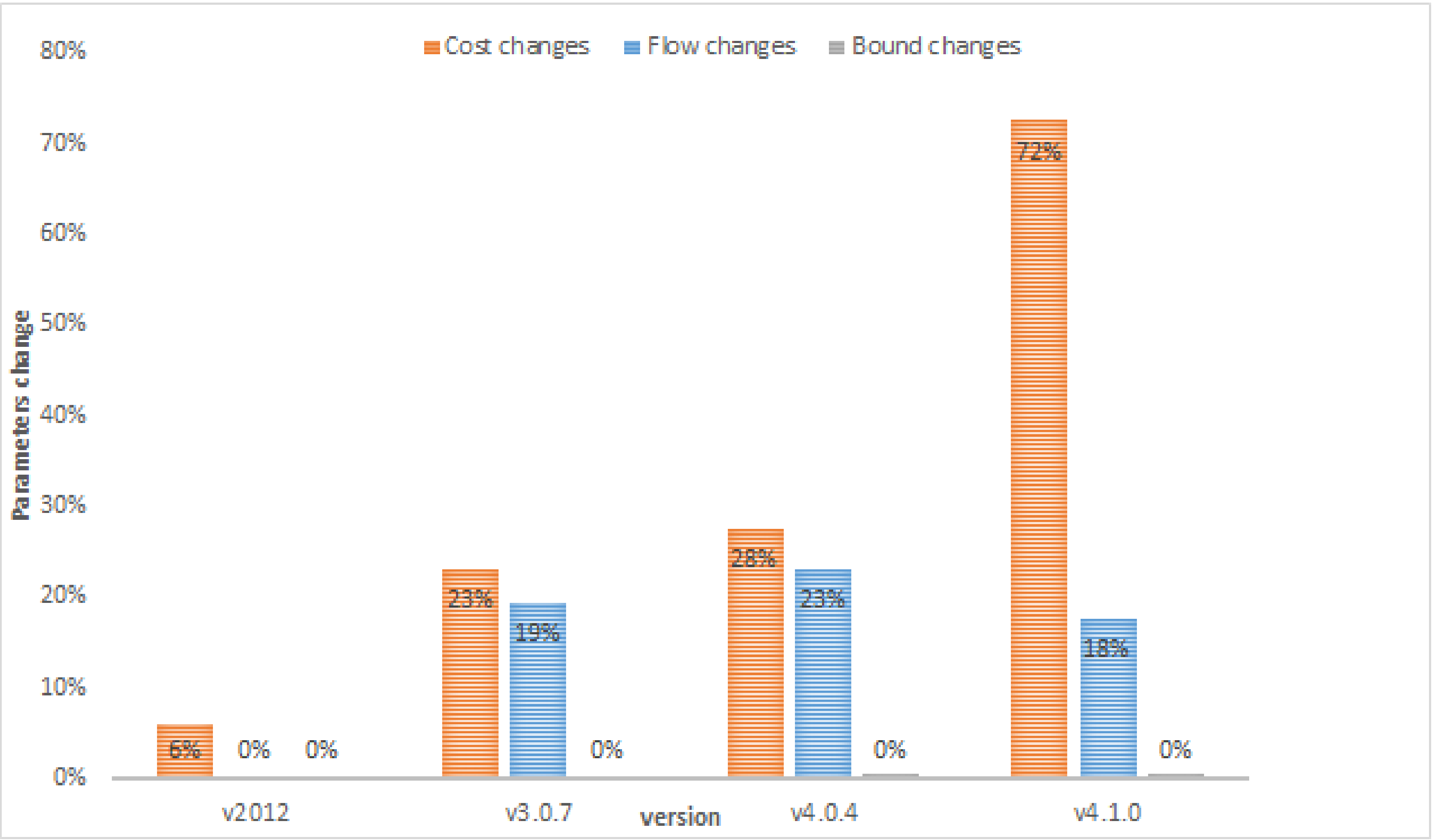
Version	Year	Electricity		Residential		Industry		Transport	
		+	–	+	–	+	–	+	–
v2012	2012	38%	0	0	0	0	0	21%	66%
v3.0.7	2013	23%	-35%	2%	-1%	3%	-3%	30%	-100%
v4.0.4	2015	37%	-30%	1%	-2%	3%	-3%	237%	-100%
v4.1.0	2016	31%	-34%	2%	-4%	3%	-3%	42%	-100%

Postscript: TIAM-UCL (early results)

Number of links, techs & comms



TIAM-UCL parameter changes



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Thank you for listening

http://link.springer.com/article/10.1007/s10666-014-9417-3/fulltext.html

Environ Model Assess (2015) 20:83–102
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Characterising the Evolution of Energy System Models Using Model Archaeology

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Abstract In common with other types of complex models, energy system models have opaque structures, making it difficult to understand both changes between model versions and the extent of changes described in research papers. In this paper, we develop the principle of model archaeology as a formal method to quantitatively examine the balance and evolution of energy system models, through the ex post analysis of both model inputs and outputs using a series of metrics. These metrics help us to understand how models are developed and used and are a powerful tool for effectively targeting future model improvements. The usefulness of model archaeology is demonstrated in a case study examining the UK MARKAL model. We show how model development has been influenced by the interests of the UK government and the research projects funding model development. Despite these influences, there is clear evidence of a strategy to balance model complexity and accuracy when changes are made. We identify some important long-term trends including higher technology capital costs in subsequent model versions. Finally, we discuss how model archaeology can improve the transparency of research model studies.

possible to ensure quality assurance for users and replicability for practitioners [1]. Historically, modellers' efforts in this regard have been in terms of comparable documentation [2], model comparison exercises [3] and a very limited attempt at ex post evaluation of modelling results [4].

Model transparency and repeatability are even more relevant for energy system models as these technology-rich, economic optimisation models, such as MARKAL/TIMES [5], MESSAGE [6] and OSeMOSYS [7], have become critical tools for informing policy and business decisions in low-carbon energy technologies in many countries [e.g. 8, 9]. One issue for many consumers of the outputs of these models is that the complex structures, containing thousands of resources, technologies, commodities and energy demands (the 'reference energy system' or RES), tend to make the models opaque to outsiders.

Model understanding and transparency would be difficult enough if energy system models were static; however, these complex modelling tools are frequently changed within a cycle of model development, policy use and application to decision-making [10]. As a result, such model changes, which

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