



Contents lists available at ScienceDirect

Technological Forecasting & Social Change



Reconciling qualitative storylines and quantitative descriptions: An iterative approach

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ARTICLE INFO

Article history:

Received 15 April 2016

Received in revised form 10 February 2017

Accepted 26 February 2017

Available online xxx

Keywords:

Scenarios

Storylines

Energy

Climate change

Interdisciplinary

Quantification

ABSTRACT

Energy system transition research has been experimenting with the integration of qualitative and quantitative analysis due to the increased articulation it provides. Current approaches tend to be heavily biased by qualitative or quantitative methodologies, and more often are aimed toward a single academic discipline. This paper proposes an interdisciplinary methodology for the elaboration of energy system socio-technical scenarios, applied here to the low carbon transition of the UK. An iterative approach was used to produce quantitative descriptions of the UK's energy transition out to 2050, building on qualitative storylines or narratives that had been developed through the formal application of a transition pathways approach. The combination of the qualitative and quantitative analysis in this way subsequently formed the cornerstone of wider interdisciplinary research, helping to harmonise assumptions, and facilitating 'whole systems' thinking. The methodology pulls on niche expertise of contributors to map and investigate the governance and technological landscape of a system change. Initial inconsistencies were found between energy supply and demand and addressed, the treatment of gas generation, capacity factors, total installed generating capacity and installation rates of renewables employed. Knowledge gaps relating to the operation of combined heat and power, sources of waste heat and future fuel sources were also investigated. Adopting the methodological approach to integrate qualitative and quantitative analysis resulted in a far more comprehensive elaboration than previously, providing a stronger basis for wider research, and for deducing more robust insights for decision-making. It is asserted that this formal process helps build robust future scenarios not only for socio political *storylines* but also for the quantification of any qualitative storyline.

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1. Introduction

In recent years, the energy sector has undergone strong and prolonged change which is set to continue (IEA, 2015), giving rise to high levels of uncertainty moving forward (Hughes et al., 2013). In this setting, scenarios and storylines offer a means by which these uncertainties can be captured by exploring possible (although not necessarily equally likely) futures. Storyline approaches of this type have therefore become widely used in the energy arena as a method of adding context and solving problems (Hughes and Strachan, 2010). Examples of scenario development and analysis can be found in the UK in

academia (Jardine and Ault, 2008; Burt et al., 2008; Kannan and Strachan, 2009; Ault et al., 2008; Eames and McDowall, 2006), government (DECC, 2010) and from system operators (NationalGrid, 2011) alongside international examples from Denmark (Lund et al., 2010) and Japan (Ashina et al., 2012), together with global examples (Calvin et al., 2009; Gurney et al., 2009). The development of future energy system scenarios is highly prevalent and has become common practice in many fields in order to demonstrate system change through modeling and analysis (Hughes and Strachan, 2010).

In the UK the DECC 2050 pathways were designed by the Department of Energy and Climate Change (DECC) to try and answer questions with regard to demand, electricity production, fuel sourcing, technology choices and decarbonisation of the energy supply out to the year 2050 (DECC, 2010). The analysis, that accompanied the release of the DECC 2050 calculator (DECC, 2010, 2011), presented six *illustrative* pathways to demonstrate the variety and wide range of possible futures that could be explored, with no preference stated or panacea promoted. These pathways, draw on previous work (Elders et al., 2006, 2008), which

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examined six future electricity network scenarios for Great Britain in 2050, concluding that the main influences of scenario development will be from highly uncertain economic, political and technological factors.

Scenarios may be classified in many ways and one prevalent divide is between quantitative scenarios and qualitative storylines (Fortes et al., 2015). Both approaches bring their respective advantages when carrying out future-oriented research. Qualitative storylines provide a wider view of a transition, capturing features such as governance and behavioural change. Quantitative scenarios provide technical depth, describing the transition with empirical real-world data. However, qualitative storylines lack technical robustness and can often be fraught with bias from its development. Quantitative models too can be developed from a biased perspective and with a more narrow focus can only represent specific elements of a system under transition. In order to reduce bias, from either perspective or technique employed, research groups are starting to combine approaches, and experimenting with their integration to benefit from the richness that this supplies. A critical survey of energy scenarios to 2050 saw “little evidence of such combined approaches” (Söderholm et al., 2011) in the literature but did argue there are “strong arguments for paying increased attention to governance and legitimacy issues in the identification of policy-relevant scenarios for quantitative modelling”.

Such a combined approach was developed by the Realising Transition Pathways (RTP) consortium when assessing the UK’s transition to a low carbon economy (Realising Transition Pathways, 2016). This interdisciplinary research grouping comprised nine UK academic institutional partners, bringing together power systems engineers, environmental scientists, social scientists, energy economists and socio-technical transition scholars. The research within the RTP consortium centres on the analysis and examination of three transition pathway storylines developed by the first phase of the project, the ‘Transition Pathways to a low carbon economy’ (TP) consortium. These transition pathway storylines describe plausible evolutions of the UK towards a low carbon economy to 2050 (Foxon et al., 2010).

The three RTP pathways are differentiated by their dominant governance logics. The first entitled ‘Market Rules’ is based on a ‘business as usual’ approach in which there is a continuation of the UK’s current governance pattern with minimal interference in the market. Large vertically integrated firms continue to supply the majority of the energy to the UK’s passive consumers through the use of large-scale centralized plant and high level goals for the system, specified by the government, are delivered through institutional oversights and investment mechanisms. In contrast, Early and firm action is taken by the government in pathway ‘Central Co-ordination’ with the government stepping in to create a Strategic Energy Authority to ensure that emission reduction targets are met by encouraging the development of new supply side technologies, and pushing for delivery of such technologies. This leads to a mixture of large scale wind, nuclear and carbon capture and storage (CCS) coal and gas plants to supply a demand which has changed as the government acts to encourage increased efficiencies of products and housing influencing user behaviours. In the pathway ‘Thousand Flowers’ however there is a local, bottom-up, drive from individuals, community groups and local authorities engaging with, and actively participating in, the energy system. This allows for a diversity of local solutions to fulfil demand challenging the current dominance of large scale energy companies and sees 50% of demand being fulfilled by distributed generation.

Transition pathways (classed as socio-technical storylines), as described in (Foxon et al., 2008) and (Foxon et al., 2009), are derived from an engineering and social examination of the key actors associated with “the co-evolution of technologies, institutions, business strategies and, also, user practices” and can be defined as highly qualitative in nature. The storylines were developed from the multi-level perspective of transition dynamics (Kemp, 1994; Geels, 2002) taking in the political, social and cultural landscape, socio-technical regimes and technological

niches. The project’s conceptual and analytical framework lays out the full argument for this methodology and approach (Foxon, 2008).

For the purpose of numerical and empirical examination it was necessary that these qualitative storylines were quantified. Quantification was undertaken by an interdisciplinary team working to create numerical descriptors as well as expand and develop the transition pathway storylines. This paper presents an iterative approach to the quantification of the pathways, which takes account of the socio-political drivers for the pathways to develop quantitative descriptions that are coherent and consistent with the qualitative storylines.

Quantitative storylines are those identified as having little or no qualitative drivers or descriptors (Fortes et al., 2015) and although technically rigorous, they typically lack the inclusion of social actors, thus weakening the robustness of insights (Söderholm et al., 2011). The method proposed herein for the quantification of qualitative storylines increases robustness of findings by adding depth of knowledge to a greater breadth of understanding, and by placing the work in an interdisciplinary context. Drawing on expertise and insights from many disciplines adds greater credibility to analysis, with contributions from multiple fields of study. Consequently, better insights could be drawn and smaller nuances be recognised and then investigated.

This methodology for quantification of qualitative storylines has similarities to the SAS (story-and-simulation) approach to scenario development (Alcamo, 2001; Alcamo, 2008). However a key disadvantages of the SAS approach is the time and money overhead for organisation and workshops etc. and a necessity for a dedicated team to be cycling through the methodology stages. The methodology proposed by this paper instead runs in parallel to, and is significantly complemented by, a greater field of (interdisciplinary) exploration and analysis of storylines and the related fields. Iterations of quantifications are performed alongside other (consortium) research, by an existing team who are already embedded in the landscape of the storylines and therefore able to make deployments across the breadth of the storylines as well as at depth in their respective specialisms.

Trutnevyte et al. (2014) discusses the landscape of models within the Realising Transition Pathways consortium and the process of linking those models to transition pathway storylines in an effort to improve them both. The work of this paper builds on this effort and presents a formal approach to storyline quantification: the iterative approach, to ‘bridge’ this gap further and provide an approach that can be applied by others. This methodology works to create a technologically feasible quantification of a qualitative storyline whilst staying true to its central philosophy. Trutnevyte et al. (2014) identified that the process and product of scenario analysis are equally important. Energy transitions are very complex and through the interdisciplinary quantification of a storyline there is a transfer of knowledge. It is asserted that this formal process helps build robust future scenarios not only for socio political storylines but also for the quantification of any qualitative storyline.

The remainder of this paper will begin in Section 2 by introducing then describing a methodology for the quantification of qualitative storylines. Section 3 then details the results of the application of the methodology to the transition pathway qualitative storylines over two iterations including results from an investigation stage. Section 4 discusses the results detailing the improvements the iterative approach facilitated and finally Section 5 concludes.

2. Methodology

2.1. Introduction

A four stage interdisciplinary methodology was developed by the RTP consortium for the quantitative elaboration of the transition pathways storylines. This methodology expands on previous work carried out in the consortium (Barnacle et al., 2013), providing a formal process for the quantitative component of the complete (both qualitative and quantitative) elaboration of social-technical scenarios. This framework

was employed to increase the consistency between qualitative storylines and quantitative models. The resulting unified platform resulting from this process, allowed insights to be deduced more readily across multiple disciplines, leading to more robust findings which better support current decision-making. The quantitative elaboration of the storylines was mostly carried out by and coordinated by a dedicated team within the Transition Pathways consortium, known as the Technical Elaboration Working Group (TEWG). In phase 2 of the project, Realising Transition Pathways, this role was continued by a similar team known as the Technical Collaboration Group (TCG).

A generic version of the iterative methodology can be seen in Fig. 1. The 4 stages of the methodology as shown in Fig. 1 are applied by the TP and RTP consortia in a less generalized version as seen in Fig. 2 with verification and investigation methodologies specific to the consortia and their objectives. In generality though this 4 stage methodology could be applied structurally in the same way to a variety of projects that start from a qualitative storyline and want to develop qualitative descriptions. For the TP and RTP consortia the verification process must be selected to properly address the particular problem(s) under consideration along with appropriate choices for the investigation stage. Through the application of this iterative process significant added value can be brought.

With reference to the TP/RTP specific methodology as seen in Fig. 2 the three transition pathways storylines previously developed by the consortium (Foxon, 2013) provided the preliminary basis of this process. The first stage of the methodology, 'Initialisation' generated the initial demand and supply side quantifications of the storylines. This led to stage two, the 'Unification' of the demand side and supply side quantifications. Establishing that generation met demand projections across the time projections and was completed during stage three, 'Verification', using the Future Energy Scenario Assessment (FESA) tool (Barnacle et al., 2013). These first three stages of the methodology were carried out independently of each of the three transition pathway narratives, but in parallel to one another, to give more flexibility to their distinct elaboration. At each stage of the process, the elaboration of the Market Rules pathway naturally tended to precede the other two pathways and was used to develop the evolving methodology alongside the verification tools and techniques. Finally, outputs were tested using various methods in the fourth and final stage of 'Investigation'. This final stage was critical not only to establish better links between the storylines and the multiple models and assessment tools employed (Trutnevyte et al., 2014), but also to assess the plausibility of the quantifications

more comprehensively (Realising Transition Pathways Engine Room (RTP), 2015), and to identify areas which required further consideration.

2.2. Stage 1: initialisation

The three core Transitions pathways storylines, which form the qualitative elaboration of the pathways, were used as the basis for the development of their quantitative descriptions. The storylines were developed based on a critical review of international scenarios, stakeholder workshops with policy experts, businesses and NGOs, and interviews with critical energy system 'gatekeepers' (Hargreaves and Burgess, 2009). A more detailed account of their development can be found here (Foxon et al., 2010; Foxon, 2013). An interdisciplinary team from across the TP and RTP consortia evaluated these pathways, adding richness by drawing on their own particular expertise, whilst remaining faithful to the respective pathway's logic. These pathways were explored using a range of modelling and assessment tools, which required input assumptions and further elaboration from the storyline. Depending on the individual researcher's focus and expertise, similar assumptions may diverge, in particular when not explicitly covered by the storyline (Trutnevyte et al., 2014).

The initial quantification of these social-technical storylines began by extracting specified numbers, or indicative phrases such as "high rate of deployment" from the actual storylines (Foxon, 2013). Particular attention was given to dates of importance indicated across the timeline out to 2050. Alongside this key themes from the political, social and cultural landscape were drawn out, for example government strategies to encourage specific forms of generation, social unease and resistance to technologies or shifts in cultural 'norms' of energy practice in the home. Researchers then extrapolated these particulars in accordance to their own field, increasing richness relating to their specific knowledge area. Undertaking this analysis with an interdisciplinary team strengthened the pathways, adding confidence and depth to the wide scope covered. Traditionally, demand side modelling is carried out first, followed by supply side, however this project deviated slightly from this approach in an effort to interrogate the interplay of the two sides (Barton et al., 2013).

A bottom-up, sectorial approach was taken in the demand quantification giving particular attention to residential energy use and private passenger transport. For residential energy use, modelling demand included a representation of the building stock including space and water heating technologies and appliance usage and efficiency. As the system transitions through the *storylines* changes are made the building stock and technologies usage and efficiency to represent changes in end-user behaviour. Across all three pathways socio-economics contributes a growth in domestic demand across lighting, cooking, heating and appliance use. UK Market figures were drawn on to determine growth in housing stock and the demolition rates of existing homes seeing the number of domestic properties, across all pathways, go from 25.3 Million in 2000 to 35.6 million in 2050. For industry (services sector and other transport's electricity) use was projected based on results from the existing modelling by the UK Department of Energy and Climate Change (DECC), tailored to match the trends in the pathway's storylines. A more detailed account of the demand side modelling is available here (Barton et al., 2013).

The supply side quantification was first shaped by drawing on data from the Digest of UK Energy Statistics (Change, D.o.E.C., 2014) and data from the National Grid's Seven Year Statement ((MA), M.E.A., 2005). This data was used to determine near term certainties, and offer guidance on long-term trends across the set of storylines. The generation mix for each transition pathway storyline was then developed, primarily based on the storyline's aforementioned indicative phrases and specifics, in the view to deliver sufficient generation capacity to meet demand. Proposed supply schemes were analysed by the interdisciplinary consortium team to ensure that technological limitations

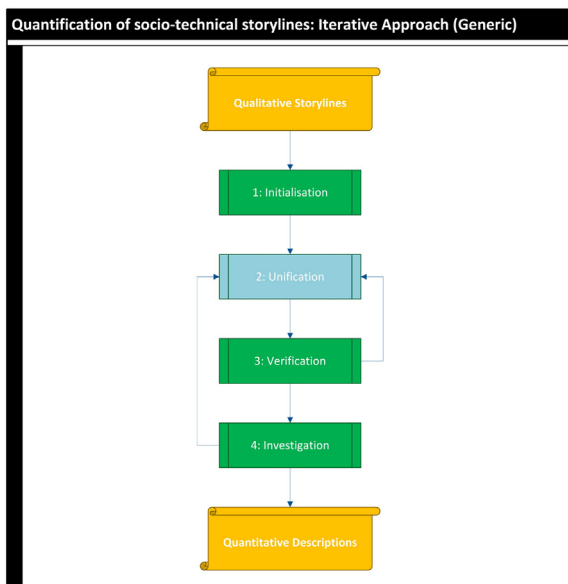


Fig. 1. Generic methodology framework: bridging storylines to quantitative descriptions.

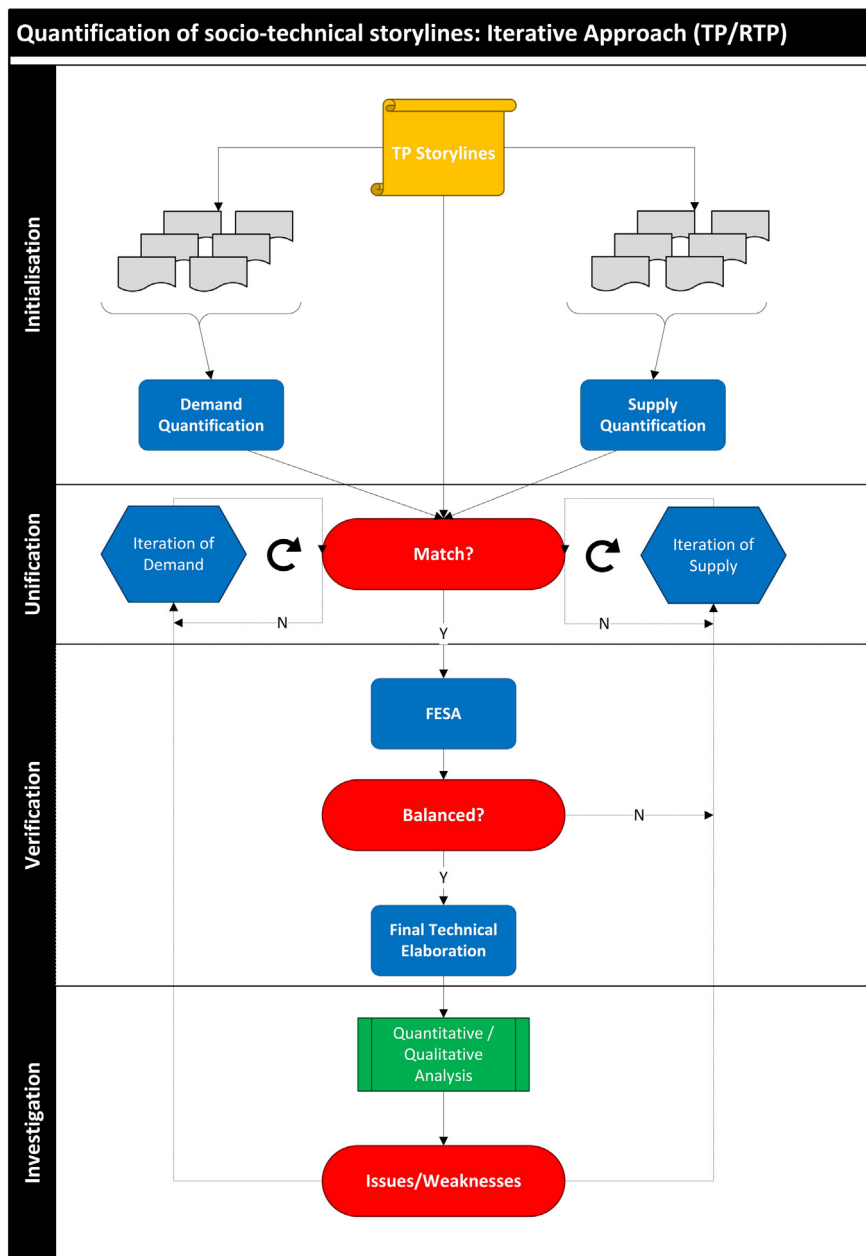


Fig. 2. TP/RTP methodology framework: bridging storylines to quantitative descriptions.

(build rates, plant capacity factors etc) were adhered to, the socio-economic and political forces and drivers of the storylines were acting as anticipated and as intended and that key actors in the system were not over-burdened by change or ignored in their influence on change. A further account of the supply side modelling can be found here (Barnacle et al., 2013).

The output of this initialisation stage was an initial quantification of the supply and demand of the GB energy system in five year intervals for all three transition pathways.

2.3. Stage 2: unification

The initial quantifications of demand and supply for the pathways were developed in parallel and not together, drawing on different input expertise. After the initialisation stage, it was necessary to unify both sides of the energy system represented. This was not only to ensure consistent interpretation of the storylines but also to ensure uniformity of final annual power produced and consumed. Unifying supply

and demand was a highly iterative process which benefited greatly from an interdisciplinary approach. Not only did interdisciplinarity ensure a more robust representation of the storylines across supply and demand but it also circumvented a more conservative traditional approach, entrenched in today's thinking (Peter et al., 2007).

As a result, a more realistic, uniform and robust quantification of the pathways was developed, from a wider knowledge base. The three technical quantifications of the pathways were produced for the UK energy system out to 2050 which were not just evolutionary, but revolutionary in some cases also. Large systemic changes are seen in all three pathways, particularly in Thousand Flowers which sees a move to a highly distributed system. This technical elaboration of the storylines benefited from the historical analysis of the dynamics of transitions. This analysis provided insights into past branching points which explored large systemic transformations which occurred in a comparatively short timeframe (Arapostathis et al., 2013). It also drew on an assessment of the role of actors and institutions in energy system transitions using an action space approach (Foxon, 2013). The unification of demand

and supply, was a flexible process to permit the integration of findings from research across the TP and RTP consortia's multidisciplinary and interdisciplinary analysis, and also data from further afield including sources such as (DECC, 2014; BERR, 2008, 2009; NationalGrid, 2014a, 2014b). Nonetheless it was always ensured throughout the process that the quantitative descriptors remained in keeping with the original logic of the respective pathways.

2.4. Stage 3: verification

The initialisation and unification stages depicted overall demand and supply statistics for the GB power system to 2050. Although the system balanced in terms of units of electricity generated/consumed annually, with no explicit dispatch, the generation mix on an hourly basis remained unknown. Accordingly, each pathway was assessed in turn using the FESA model to establish their technical plausibility, functionality over different temporal load profiles, and if system balancing was possible. FESA is a single year, single node, UK power dispatch and demand balancing model, incorporating hourly dispatch using real, concurrent weather data from across the UK to calculate renewable potential (Barnacle et al., 2013; Barton et al., 2013). Met Office weather data from 2001 for temperature, wind speeds, wave height and solar radiation was paired with energy demand data to predict the output of onshore and offshore wind, wave power, photovoltaics and solar water heating systems, in conjunction with predicting the operation of Combined Heat and Power (CHP) and electrical heating. Electricity supply from uncontrolled and inflexible generation (such as variable renewables) were subtracted from demand on an hourly basis to establish the net demand which must be met by dispatchable generation (thus automatically feeding in renewables and leaving aimed to leave them unconstrained). As a result, FESA not only models the peaks and troughs of demand but highlights system balancing issues that must be overcome. Therefore, FESA was able to inform necessary changes to generation capacity and capacity factors to achieve system balancing. Furthermore, FESA revealed the potential for Demand Side Participation (DSP) implementation (Barton et al., 2013). It can predict the level of time shifting of 'smart loads' that can be employed to make use of surplus electricity and also level out demand.

FESA's findings were fed back into the supply quantification of the pathways through the feedback loop seen in Fig. 2. As the flexibility provided by DSP was already contained in the demand side quantification only the supply side quantification required adjustment to ensure system balancing. In investigating FESA's findings, many aspects were considered to determine the suitability of the supply quantification to meet demand and what adaptations were needed to be made to ensure said suitability. The utilisation of plant (capacity factors) were investigated and revised to ensure that plant operation was economical and justifiable. Periods of net over-generation and shortfall of generation were studied and new-build plant or interconnector capacities altered, to ensure system balancing. Similar to the matching carried out in Section 2.3, system balancing was a highly iterative process benefiting significantly from an interdisciplinary approach. Each change implemented to the supply side quantification was validated by the TEWG/TCG for robustness in order to ensure that these new updates were probable and in keeping with a pathway's ethos. New quantifications were then reassessed by the FESA model to ensure the system was balance.

The final output of this verification stage was the first version of the technical elaboration of the transition pathways. These formed the quantitative descriptions of the pathways which provided a consistent basis for wider modelling and analysis carried out across the TP and RTP consortia.

2.5. Stage 4: investigation

Both the qualitative storylines and quantitative descriptions of the pathways provided a coherent foundation for the modelling and

research across the TP and RTP consortia. Outputs from multiple analyses were then more readily comparable and could be combined to deduce crisper cross-cutting findings to help tackle energy and climate change issues. The quantification of the transition pathway storylines formed the input assumptions for empirical quantitative modelling and qualitative analysis, whilst the storylines provide a wider political, social and cultural context.

Using the qualitative storylines and quantitative descriptions as a consistent platform for all modelling and analysis, across various fields, insights derived from this research can also be used to test the pathways and feedback into another iteration of the quantification of the pathways. Various modelling was carried out on the pathways, assessing the technological, economic and environment consequences of these plausible energy futures (Trutnevyte et al., 2014). These models were diverse in nature in order to provide a comprehensive investigation. This multi-model approach was used to generate a broad spectrum of findings, rather than being limited to a single model. Given that the focus, and system boundaries of each model can vary significantly, their characteristics and scope were mapped in a 'landscape of models' (Trutnevyte et al., 2014).

This process was used to determine and map the breadth covered by the TP and RTP models, and identify their depth of knowledge and principal expertise. Thus, where models overlapped, insights could be checked and validated and areas lacking depth could be highlighted. The Central Co-ordination pathway was used to map out the contributions of each model (Trutnevyte et al., 2014). An even more interdisciplinary approach was taken to explore the feasibility of the Thousand Flowers pathway. A full examination was undertaken of the technical and institutional transformation necessary to move from a centralised system to this highly distributed energy future (Realising Transition Pathways Engine Room (RTP), 2015). A series of interdisciplinary workshops were held to explore the feasibility of this pathway, drawing on contributions from energy industry stakeholders and the cumulative research of the consortium. The workshops comprised researchers from across the project, including power system engineers, social scientists, energy economists and socio-technical transition scholars, along with invited speakers from community energy groups, Ofgem (Office of Gas and Electricity Markets—The UK's regulator of electricity and gas markets) and external academics.

Further, a technology specific sociotechnical analysis was carried out on bioenergy technologies in the pathways; such as biomass based district heating, CHP, boilers and power stations. This study involved the identification of challenges that may impact the rate of deployment of each technology, derived from the quantification of the pathways, and then the exploration of the roles of different actors and institutions in facilitating technology penetration. This work improved system resolution for more effective technology specific policy recommendations and provided an avenue for a realistic appraisal of the level of uptake of technologies depicted in each pathway.

All issues, weaknesses and incomplete areas of the qualitative storylines and quantitative descriptions of the pathways were consolidated from all the above methods of investigation. As all methods began with the storyline, and quantitative descriptions of the pathways, it reduced ambiguity across their output allowing implications to be interpreted more readily across methods. Collectively, these findings directed the next iteration of the quantification of the pathways.

2.6. A closed loop system

The first iteration of initialisation through to verification (stages one to three) to generate a technical elaboration of the transitions pathways was a very flexible process. This allowed researchers freedom to explore their respective niches and interpret the pathways accordingly, providing greater breadth of analysis for investigation. Subsequent iterations that led from the investigation of the qualitative storylines and quantitative descriptors followed a more structured approach focussing on

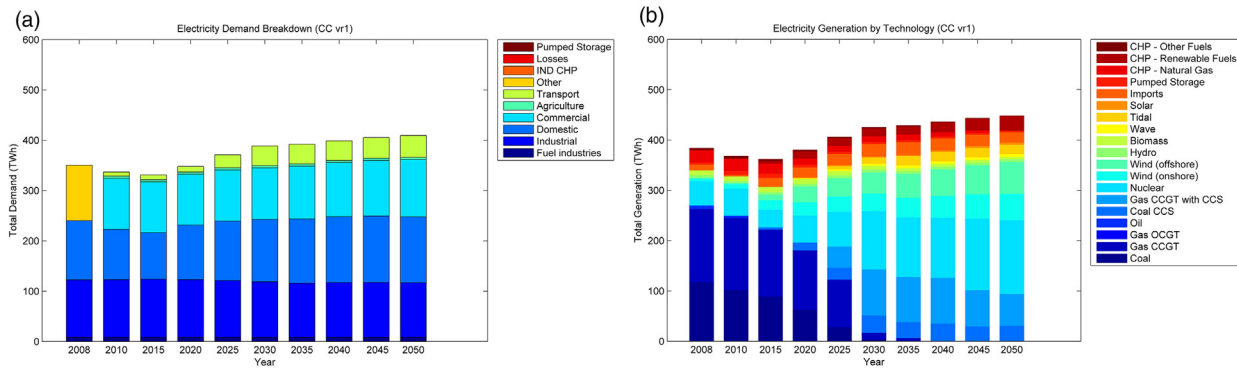


Fig. 3. a&b. Demand and supply quantification for the Central Co-ordination (CC) transition pathway (vr1).

issues highlighted by the investigation stage. The irregularities and issues raised from across the research were consolidated in order to revise the quantification of the pathways. In the context of the TP and RTP consortia this process required collection of data from consortia meetings, focussed working group workshops and telephone conferences, then the use of a wiki to store and edit documents, in order to determine a comprehensive and consolidated set of actionable findings. Each point raised was inspected, the underlying assumptions retraced, and revisions proposed. All proposed revisions of the quantifications were researched and fully evidenced as required then discussed by the TEWG and TCG during meetings or telephone conferences before being ratified and actioned such that changes were made to the quantitative descriptions. Revisions to the qualitative storylines were not found to be necessary.

Reduced flexibility for this stage, allowed for the quantification of the pathways to be improved without interfering with the integrity of the rest of the quantification. That is, that all updates being made to the quantification were cross-checked to determine the effects on other areas and ensure that the reliability and robustness of the quantification was improved and not diminished by changes. Again, an interdisciplinary approach was crucial to add robustness and avoid being trapped in a particular niche, but instead look across the landscape to ensure greater certainty and confidence.

The number of iterations carried out using this proposed methodology is very much dependent on the level of detail required and resource available. Certainly, a break-even point must be reached, where the depth of knowledge from the niches is extracted, but which can also be consolidated with the wider view of the landscape. Three full iterations of the quantitative descriptions were carried out in the RTP consortium in order to address weaknesses but also to update the quantification of the pathways accounting for changes in energy trends over the lifetime of the consortia (2008–2016), for example the surprisingly rapid growth in rooftop solar photovoltaics.

3. Results from the application of proposed methodology

This section presents the development of the quantitative descriptions, and their iterations as described in the methodology. The first version of the quantitative descriptions was completed by the TEWG during the TP consortium and is labelled in the following text and graphs as 'Version 1' or 'vr 1'. The demand and supply quantifications for the Central Co-ordination can be seen in Fig. 3a&b and for Market Rules and Thousand Flowers in Figs. 4a&b and 5a&b respectively. Version 1 results, the initial technical elaboration of the transition pathways, are presented in the section followed by a discussion of the irregularities and inconsistencies highlighted during 'Investigation', stage 4 of the process, in Section 3.2.

After the investigation phase, an iteration was completed of the methodology (as in Fig. 2) returning to the unification and verification stages and thus producing a revision of demand and supply quantification. The updated demand and supply quantifications for the transition pathways labelled as 'Version 2' or 'vr 2' are discussed in Section 3.3 and can be seen in Figs. 6a&b, 7a&b and 8a&b for Central Co-ordination, Market Rules and Thousand Flowers respectively. The scales on the vertical-axes of Figs. 2–9 have been kept equal such that all graphs are directly comparable. It should be noted that due to a lack of disaggregated figures being available, the commercial, agricultural and transport demand are combined in to the category 'Other' in Figs. 2–8.

Within the TP consortium the TEWG generated preliminary quantifications of the transition pathways storylines using the iterative methodology in Fig. 2. A thorough initialisation stage was completed as described in Section 2.2 followed by unification and verification stages as described in Sections 2.3 and 2.4. Numerous iterations were completed between the unification and verification stages to ensure a balanced system that was representative of the storylines and the greater context by gathering data from a wide range of published sources and industry stakeholders' inputs. It is difficult to properly enumerate the number of

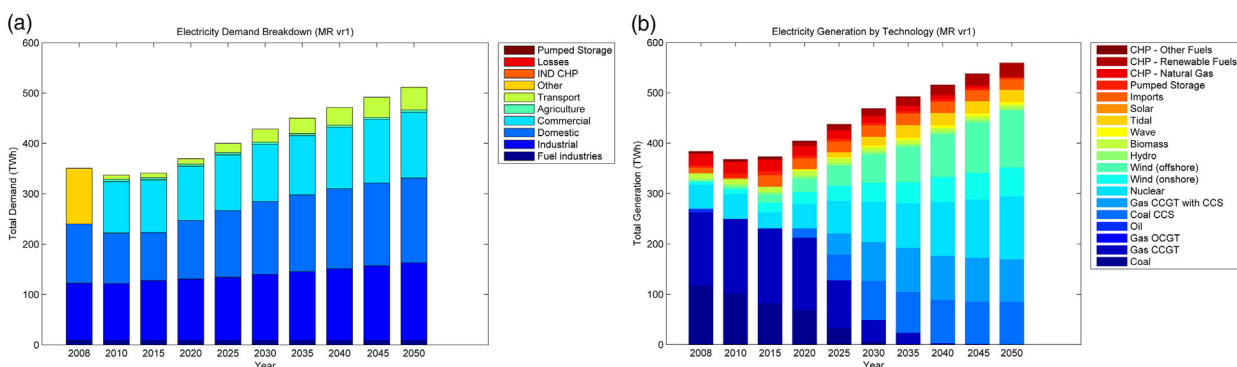


Fig. 4. a&b. Demand and supply quantification for the Market Rules (MR) transition pathway (vr1).

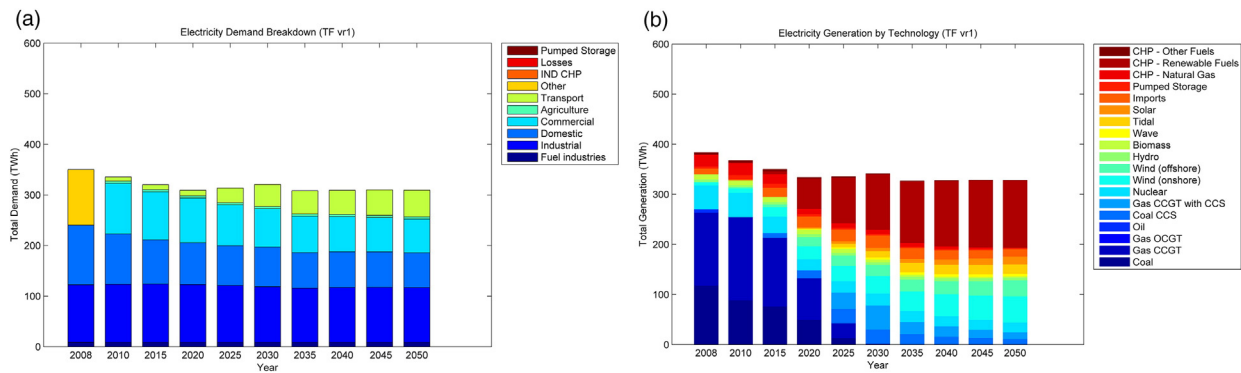


Fig. 5. a&b. Demand and supply quantification for the Thousand Flowers (TF) transition pathway (vr1).

iterations of the unification and verification stages to gain the version 1 quantifications due to the concurrent development of quantifications for the three transition pathways, overlapping of work and partial iterations to investigate sensitivities. Each iteration did become more expedient however as methodologies for gathering data (used shared document repositories and a wiki for example) evolved and the consortium became more aware of FESA and the role it played.

The 'Version 1' results presented here are a result of this work and were the inputs used in the investigation stage, the results from which are presented in Section 3.2.

3.1. Version 1 quantifications

From Fig. 3a, the annual demand in the Central Co-ordination pathway is observed to slowly increase from 350.5 TWh in 2008 (the base year of all analysis) to 409.5 TWh in—an increase of 16.9%. Non-domestic demand sees little change, however domestic demand increases 13.2 TWh, up 11.2% from 2008 to 2050, and the electrical demand from the transport sector increases from 8.2 TWh in 2010 (when disaggregated figures first appear) to 43.4 TWh in 2050. This change of +429% is due to the growth of battery electric vehicles and plug-in hybrids from a very small base in 2010. The quantification of supply for the Central Co-ordination pathway is seen in Fig. 3b and is itemised with respect to technology/fuel source where appropriate. Gas and coal plants without CCS are slowly phased out of the system, with no traditional coal plants running by 2035. Only one gas CCGT (Combined Cycle Gas Turbine) plant is kept open past 2035 which is used only to help meet the winter peak. Nuclear generation increases three fold to 146.38 TWh in 2050 and installed capacity of both onshore and offshore wind generation increase over the period to 52.56 TWh and 63.07 TWh of electricity being generated from each respective technology in the year 2050.

The Market Rules transition pathway's demand projection is shown in Fig. 4a and shows the largest change in demand across the set of

pathways with an increase of 46% from 350.5 TWh in 2008 to 511.6 TWh in 2050. Although demand from agriculture and fuel industries remains constant there are significant increases in industrial and commercial demand—increasing by 35.7% and 28.3% respectively. The most significant changes are to domestic demand, which increases by 42.8%, to 168.3 TWh in 2050, and electrical demand from the transport sector increasing to 45.1 TWh, representing more than a fivefold increase due to the growth of battery electric vehicles and plug-in hybrids. To meet increased demand the generation profile of the Market Rules pathway evolves as in Fig. 4b. As in the Central Co-ordination pathway, traditional coal fired generation is phased out, along with all but one gas plant and replaced by gas and coal fired CCS plants. However, a larger growth of CCS is seen in Market Rules (totalling 168.68 TWh) in 2050, compared to in the Central Co-ordination pathway (94.47 TWh). The increase in nuclear (163%), onshore wind (897%) and offshore wind generation (8576%) is also stark alongside increased deployment of other renewables (hydro, biomass, wave, tidal and solar), with a combined generation of 41.26 TWh in 2050, up from 15.11 TWh in 2008.

In contrast to Market Rules, the Thousand Flowers transition pathway sees a decrease in demand of 11.7% from 350.5 TWh in 2008 to 309.5 TWh in 2050 as seen in Fig. 5a. The electrification of transport means that is the only sector with increased demand in this pathway, more than a six fold increase to 52.7 TWh in 2050. The strongest demand decreases are from the commercial sector, down a third from to 66.5 TWh, and the domestic sector, down 41.5% to 68.9 TWh in 2050. Decreased demand means traditional gas and coal power plants are phased out by 2035 with the introduction of CCS plants. As seen in Fig. 5b however, even these cleaner fossil fuelled plants have reduced output out to 2050. Gas and coal fuelled plants were responsible for generating 263.58 TWh in 2008 which reduces to just 24.64 TWh in 2050. Nuclear generation in also reduced out to 2050 with a decrease in output of –58.7% while renewables (excluding CHP) increase from a 6% to 40% of total generation by 2050 (131 TWh). The largest change in the generation scheme for the Thousand Flowers pathway, is the

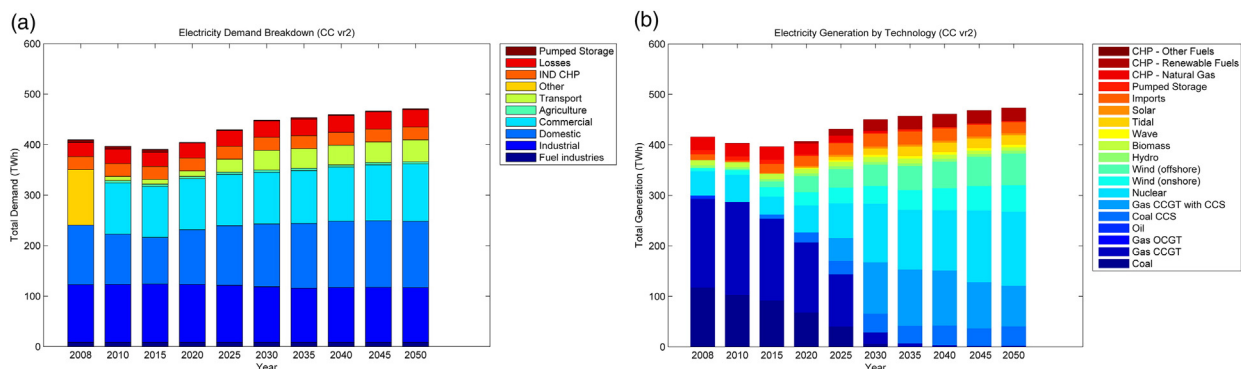


Fig. 6. a&b. Demand and supply quantification for the Central Co-Ordination (CC) transition pathway (vr2).

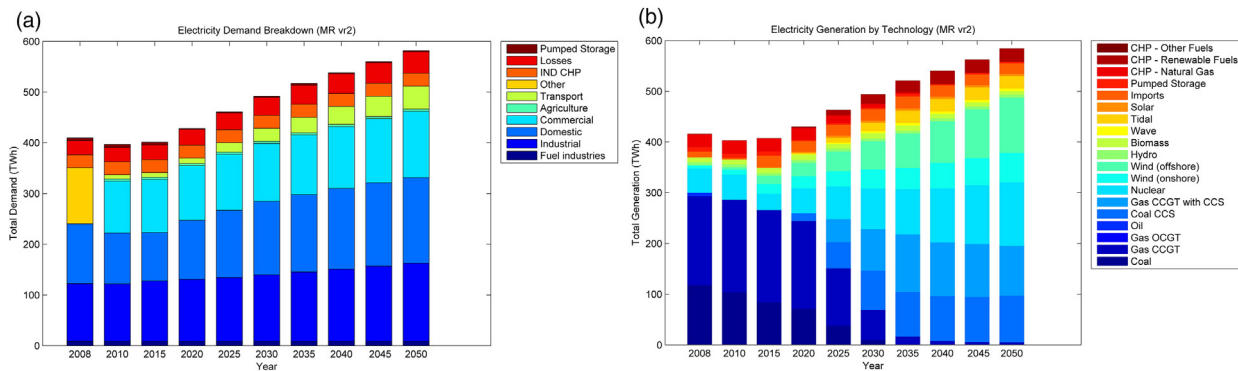


Fig. 7. a&b. Demand and supply quantification for the Market Rules (MR) transition pathway (vr2).

increase in electricity from CHP, with output reaching 134.63 TWh by the year 2050, by which time, all CHP fuelled by renewable fuels. Dominance of CHP technology comes from the pathway narrative and the transition of passive consumers to active system participants. An initially small market share of the technology from energy service companies offering packages to consumers based on a variety of technologies, including CHP grows. As domestic users become more active participants in the system there is an increased take up of community and local energy schemes including community scale CHP. After strong competition between technologies CHP emerges as a leader with 'dominant designs' prominent in the market. It should also be noted that more than 50% of electrical demand is met by smaller scale generation located in the distribution network, i.e. distributed generation.

3.2. Investigation stage conclusions

The investigation of the qualitative storylines and quantitative descriptions of the transition pathways (as described in Section 2.5) raised issues to be reviewed and irregularities to be addressed. Findings from the consortium's series of investigations were scoped across the disciplines and institutions that participated, consolidated into themes or overlapping topics and then inspected across the pathways in which they were present to identify the revisions necessary. The interdisciplinary nature of the consortium meant that there was a diversity of topics raised. Examples include engineering analysis of maximum capacity factors of generating plant and changes to perceived limitations of installation rates, economic investigations with regard to the affordability of new generating plant with low usage and new forms of financing alongside socio-political studies regarding the increased role of domestic consumers, changes to practices and the changing roles of regulators and large power companies.

Some errors in the initialisation stage were drawn out when investigation of the pathways including a misallocation of a small proportion of gas fired generation. The investigation stage also highlighted a need for consistency with accounting between the demand side and supply side descriptions, especially relating to self-use of electricity in generation plants and the accounting of transmission and distribution losses. Similarly, as the quantitative descriptors were used by a range of consortium members in diverse ways mechanics of the quantifications themselves were adapted and updated—the way spreadsheets were designed and inclusions and exclusion within them—and more thorough definitions of terms and list of inclusions and exclusions were given alongside the descriptors to aid clarity and understanding.

What follows are some examples of topics raised from across the breadth of the investigation stage and an account of improvements carried out in iterations: an engineering problem relating to capacity factors, a shift in the UK's energy system landscape and the resulting impacts on installation capabilities, an example of a re-accounting in the quantifications to increase consistency and social science and interdisciplinary analysis of the increased role of domestic consumers.

3.2.1. Capacity factors: technical maximums and clarifications.

Work conducted by Mott MacDonald determined technical maximum capacity factors for a variety of generation technologies, a number of which had been exceeded in version 1 of the pathway quantitative descriptions therefore the descriptions had to be revised. Furthermore, the term 'capacity factor' as used in the pathways descriptors was ambiguous due to the lack of a standard definition found in the literature where 'capacity factor' can or cannot include self-use and maintenance penalties. The definition used in this analysis for capacity factor was therefore expressly defined as:

$$CF = A_{ave} \times LF_{ave} \times (1 - PR) \quad (1)$$

where CF is the capacity factor and A_{ave} the average availability of the plant, LF_{ave} is the average load factor and PR the plant power requirement (self-use).

In this analysis capacity factors have therefore been defined to include self-use and average availability to take account of maintenance etc. This removed the uncertainty raised from multiple modelling environments applying different penalties and ensured a consistency for valid comparison of results. The application of this definition across all pathways, in conjunction with maximum factors in, ensured the quantitative descriptions were technically feasible and consistent. As a result of this revision a number of capacity factors in the supply side descriptors were reduced and capacity of installed plant increased as necessary across the pathways.

3.2.2. Installation rates

Since the initialisation of the version 1 descriptors in 2008/2009, installation of renewables (onshore wind and in particular roof-top solar) in the UK increased at unprecedented rates. The introduction of Feed In Tariffs (OFGEM, 2010) grew the roof top solar industry and left the installation rate maximums of technologies in the descriptors out-dated and seem archaic. Therefore, to reflect more recent trends, the installation rates of these technologies were increased, in order to provide more representative feasible (and in some cases likely) trajectories in to the future.

A danger in re-framing the pathways in this way (and with all future pathways or scenarios work) to maintain accuracy and reflect the here and now, the world we recognise, is the issue of 'scope creep' and a pervasive and never-ending process of updates and modernising. With this in mind it was just in this one area where the landscape of the system had shifted so dramatically that the quantifications were heavily revised. Elsewhere, work moved forward and to make good use of the framing of possible futures that had been established, to look at the insights brought forward and reflect on their benefits and disadvantages.

3.2.3. Micro-CHP in the Thousand Flowers pathway

Micro-CHP systems bridge the gap between demands and supply modelling as they are designed to be heat-led. However, the demand-

side and supply-side descriptions had dealt with micro-CHP energy production in isolation. Therefore, the quantity of electricity produced by domestic and commercial micro-CHP units, which are included in supply-side figures, were revised. New electrical output figures were determined through the heat demand model, used in the production of the demand-side descriptors, to ensure accuracy and consistency. There was also a revision of the size of installed micro-CHP units with a new assumption that units are sized to the average heat load of a building (or buildings).

3.2.4. Overburdening of domestic energy users

Within the Thousand Flowers Pathway the domestic consumer becomes an active participant in the energy system and a key actor for change. Domestic, local and community energy projects are common place alongside demand side participation becoming a norm and demand side management used frequently to match demand with intermittent and non-dispatchable generation. Concerns were raised that this shift in usage behaviours and practices alongside becoming generators and active system participants (and directors) was too severe in the timeframe of the pathways and that too much of the burden of the system's operation was being placed on the domestic consumer.

Consortia work examining user practices (Higginson et al., 2014) concluded that practices can be shifted and that there exists already today an inherent flexibility, although the best way to access and signal shifts and changes in practices (and therefore demand) is unclear (Higginson et al., 2014). An examination of the Thousand Flowers pathway as a whole (Realising Transition Pathways Engine Room (RTP), 2015) concluded that there would need to be a shift in societal attitudes that would both drive the transition along a path of distributed generation, control and more active participation as well as support that transition to its goals (Realising Transition Pathways Engine Room (RTP), 2015).

3.3. Version 2 quantifications

The results of the investigation stage (discussed in Section 3.2) made necessary a number of changes to the quantitative descriptors. Another application of the TP/RTP methodology as in Fig. 2, namely looping back to, then iterating between, the unification and verification stages, was therefore completed from Version 1 quantitative descriptions and the consolidated investigation results as inputs. Below is an account of the Version 2 descriptors generated as a result of this work and which represent more robust and accurate quantification of the transition pathway qualitative storylines.

Version 2 demand and supply descriptions were combined into FESA time-step model using the DECC 2050 Calculator pathway

representations for all non-electric energy use. The DECC Calculator added confidence that the pathways met the UK's target reductions in greenhouse gas emissions, including gases other than carbon dioxide. From 2008 levels of 467 gCO₂/kWh the 2050 carbon intensity of electricity was 24 gCO₂/kWh for Market Rules, 15 gCO₂/kWh for Central Co-ordination and 9 gCO₂/kWh in Thousand Flowers, meaning a reduction of emission in the grid per kWh generated of 95%, 97% and 98% respectively.

All three pathways always meet demand though where Central Co-ordination has no curtailed surpluses, Market Rules suffers from (just) 1 GW of curtailed power for 1 h of the year in 2050 due to the prevalence of controllable and dispatchable generation meaning supply can demand can be matched. In contrast, the Thousand Flowers is extreme as generation is curtailed from 2030 onwards, up to 22 GW of power and 3.36 TWh in the year by 2050. In the context of the Thousand Flowers pathway curtailment is due to a large proportion of generation being non-dispatchable and both storage and interconnection capacity limited.

The quantitative descriptors produced from this further iteration and new application of the methodology can be seen in Figs. 6a&b, 7a&b and 8a&b for the Central Co-ordination, Market Rules and Thousand Flowers pathways respectively. For a comparison of the changes made to the demand and supply quantitative descriptors from version 1 to version 2 see Figs. 9a, b & c and 10a, b & c respectively. As seen in Fig. 9a, b & c the final demand statistics have not changed (although there were a number of internal changes), but rather there was an inclusion of losses and pumped storage demand as identified as a result of work described in Section 3.2.

The specific sources of heat assumed for district heating schemes supplied by waste heat and geothermal energy were clarified, and checked for feasibility. It was specified that waste heat was derived from retrofit of heat capture technologies at existing large thermal power plants or industrial units (e.g. refineries), whilst geothermal energy was derived from heat recovered from deep aquifers. The changes were represented in quantifications of demand by introducing additional vectors 'heat transport' and 'environmental heat' for district heating and geothermal respectively.

The major technology trends of the supply mix as described in Section 3.1 remained constant for all three pathways in the finalisation of version 2 of the quantitative descriptors, as can be seen in the comparison graphs in Fig. 10. However, significant changes between the two versions can be seen in the gas generation and CHP categories across all pathways. These major changes were the result of a more comprehensive inclusion of industrial CHP and the subsequent re-balancing of the system that was required. Market Rules and the Thousand Flowers pathways both see a significant increase in installation rate of solar generation in version 2 over

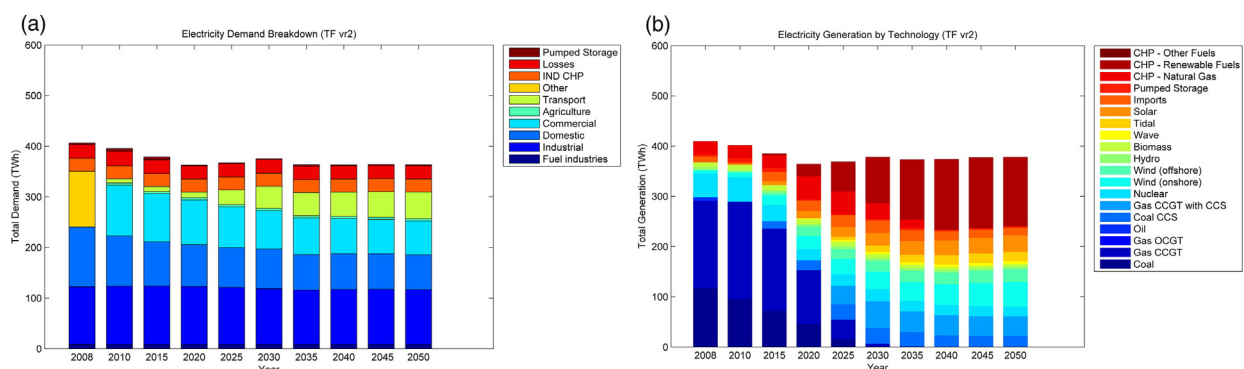


Fig. 8. a&b. Demand and supply quantification for the Thousand Flowers (TF) transition pathway (vr2).

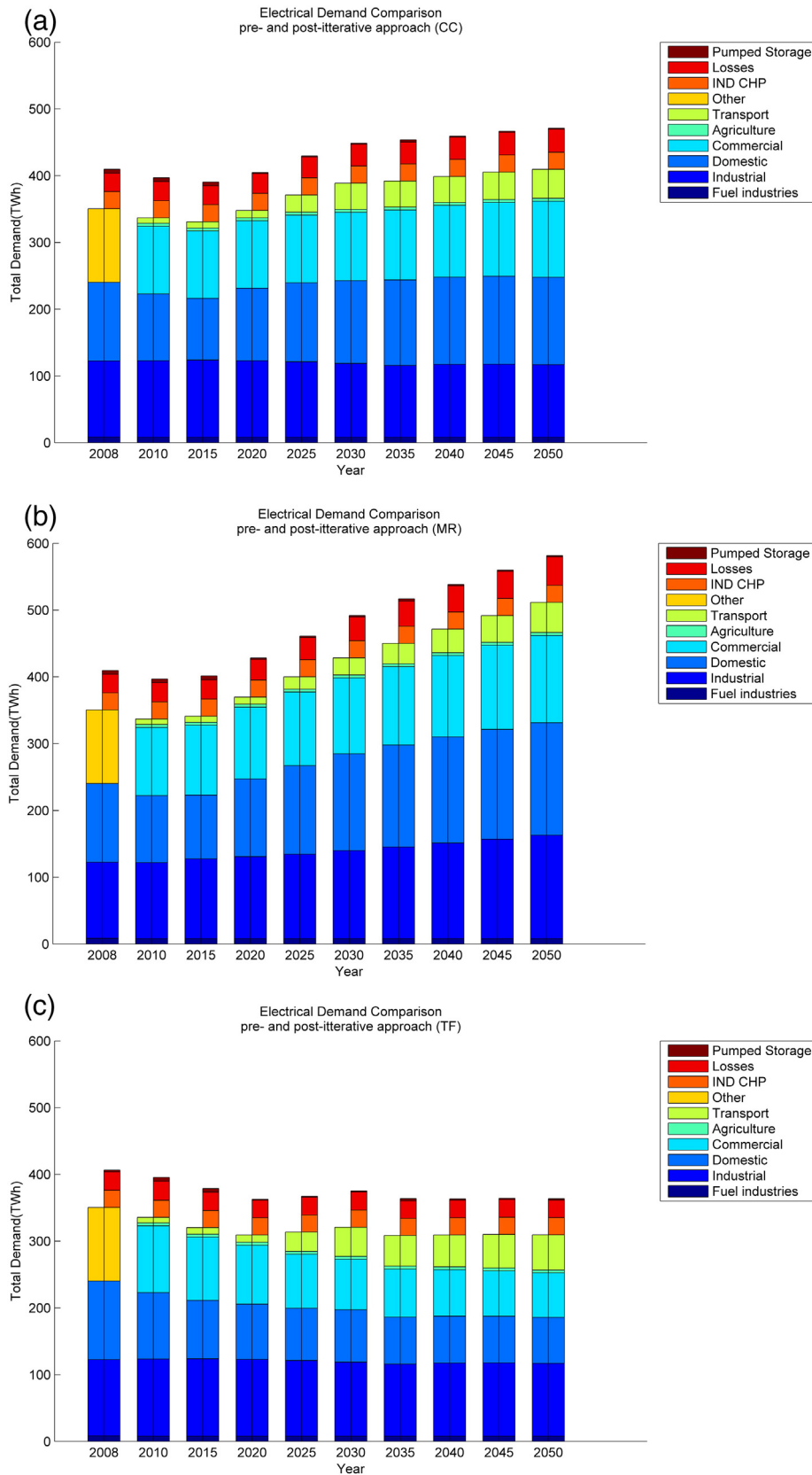


Fig. 9. a, b&c. Demand quantification comparison of vrs 1 and 2.

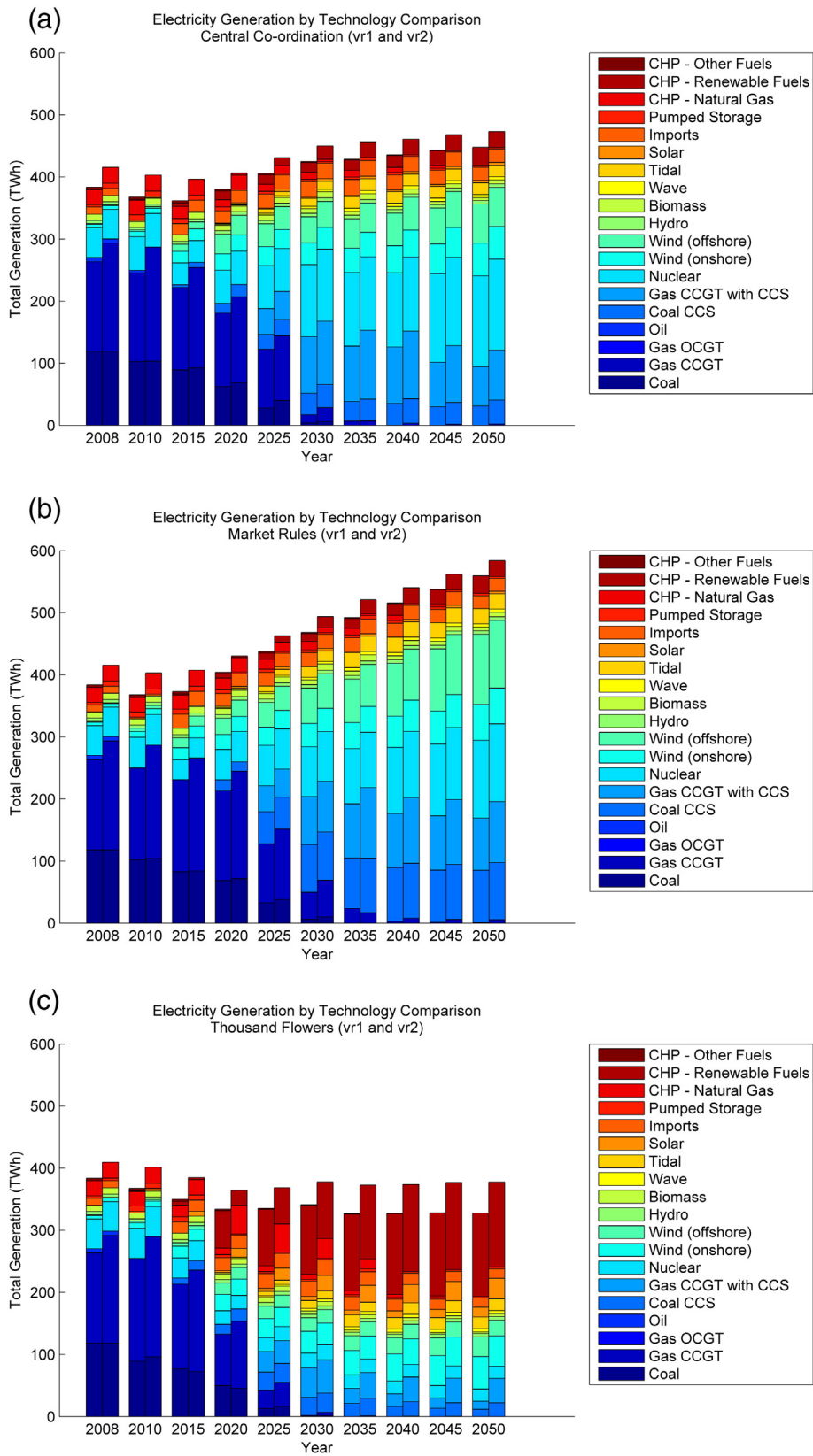


Fig. 10. a, b&c. Supply quantification comparison of vrs 1 and 2.

version 1, and a decrease in the installation rate of offshore wind generation more in line with current operation and practice. The divergence between the two versions for these technologies can be seen most clearly in Tables 1 and 2.

4. Discussion

The first iteration of the quantitative descriptions (version 1) of all three of the transition pathways represented balanced electrical

Table 1
Comparison of annual generation figures (TWh) from a selection of technologies in the Market Rules pathway from versions 1 and 2.

Market Rules		2008	2010	2015	2020	2025	2030	2035	2040	2045	2050
Wind (offshore)	vr 1	1.30	5.23	16.11	26.28	39.62	56.93	70.06	85.07	100.07	113.21
	vr 2	1.30	5.23	16.11	26.28	39.19	55.51	67.51	82.13	96.57	109.14
	change	0.0%	0.0%	0.0%	0.0%	– 1.1%	– 2.6%	– 3.8%	– 3.6%	– 3.6%	– 3.7%
Solar	vr 1	0.02	0.02	0.04	0.09	0.12	0.15	0.18	0.18	0.18	0.18
	vr 2	0.02	0.50	1.72	2.93	4.14	4.14	4.14	4.14	4.14	4.14
	change	0.0%	96.0%	97.4%	97.0%	97.2%	96.5%	95.8%	95.8%	95.8%	95.8%

systems. They were however the first step of the iterative process and version 2 of the descriptions were much more technically and contextually consistent. By allowing a flexible period of interdisciplinary investigation of version 1, a number of issues were raised and then addressed, which would not have been possible without the loops introduced by the iterative approach adopted. The interdisciplinary nature of the team meant that a cross-discipline awareness was garnered by participants in the work. This meant that all considerations of issues raised on the iterations were made with a view of technical, economic, social and political aspects so that expertise from these fields could be drawn on and integrated leading to more robust outputs.

Through addressing each of the issues raised, by completing related analysis and research and altering the quantitative descriptions accordingly, the work is more technically feasible and more robust overall. This led to the development of the methodology described in this paper that has been framed around the work of the transition pathways projects. It is widely recognised that much research work in social science, economics and engineering needs to link qualitative and quantitative work but the consistent framing of this can be difficult.

Key to realising the potential benefits of the methodology is the iterative approach adopted, to enable refinement and tuning of, in this case, three pathways. The involvement of a multi-disciplinary team and integrated working amongst them is a common set of circumstances for major collaborative research projects but drawing the domain expertise, models, data and technical language together can obviously be difficult. In a more 'traditional' project structure, you might for example expect that one group of societal domain experts would generate a set of qualitative storylines, a group of engineer experts would quantify, and in doing so raise questions of the storylines. This would go back to the societal experts for revision, and so on, but with the high likelihood that at each step, one group has only a tentative understanding of the meaning of the concerns raised by the other. Clearly a collaborative approach would be a sensible refinement to this but again it is not always the most productive. In any case, with sufficient time, such iterations might lead to robust outcomes. With the intensive and integrated approach adopted here, misunderstandings and resulting errors were rapidly identified, and meaningful and internally consistent improvements could be agreed, in a consensual and efficient way. The methodology then provided a consistent and consensual way of bringing together the correct elements, in this case the qualitative and quantitative pathways work, testing and refining them to yield an internally agreed consistent set of outputs to facilitate research work.

The verification stage is an important part of implementing the methodology. In the case of the transition pathways work there was a clear way of quantifying this, to ensure a balanced electrical system, and this was facilitated by FESA. This stage may not always be as obvious

for some projects. Furthermore for the pathways a further refinement concluded that all version 2 quantitative descriptions could balance electrically and drew out a number of insights, including the various choices for the possible generation mixes and alignment with emissions targets and other pathways (e.g. DECC 2015).

A number of the changes made between versions 1 and 2 (as described in Section 3.3) had large impacts and knock on effects to both balancing and feasibility. This is an issue for the implementation of this proposed iterative methodology, as one may find that there are several dominant behavioural modes present. This was especially true for the pathways when addressing the accounting errors of gas-fired industrial CHP and CCGT plants, as CCGT plants were often used to cover winter peaks. Also, the increase in demand for biogas and biomass sources, due to the fuel switching of CHP units, was a concern.

These are prime examples of the potential for misunderstanding if complex scenarios are assembled in a discipline-specific or sector-specific manner. CHP plants sit on the boundary between the traditional 'demand' and 'supply' sides of the energy system. In the assembly of the first set of pathway descriptions the demand-side team and the supply-side team each believed they had addressed CHP, but did so in their own way and using different data sources. Outwardly, no problems were evident, but with further interrogation these proved to be inconsistent and incomplete. Collaborative work in the second iteration of the methodology to create the version 2 descriptors was able to address these problems rapidly and conclusively.

As well as increased technological feasibility and ensured system balancing, versions 2 of the quantitative descriptions were also seen as being more 'true' to the individual pathways' ethos' s. This was due to the greater time for reflection that the iterative approach allowed, during which some further differentiation between the quantification of the pathways could be introduced. Similarly, the flexibility of the iterative approach permitted the quantification of the Thousand Flowers pathway to evolve freely, resulting in a far more innovative pathway which is an outlier in the field of GB energy system scenarios (Foxon and Pearson, 2013). Technically feasible quantitative descriptions such as those for Thousand Flowers would never evolve from a purely technical starting point as the proliferation of distributed generation is to an extent that is past the boundary of conventional thought. It is only when considering changes in system participants' practice and greater participation of societal actors in a collaborative and communal system that the scale of the pathway becomes feasible. Similarly Thousand Flowers would not have been delivered by purely a socio-political research team as it was through consideration of grid dynamics and intermittency that CHP became a highly dominant technology and a role was found for large scale generators and the existence of integrated companies will in the architecture of the system and its institutions. It was the

Table 2
Comparison of annual generation figures (TWh) from a selection of technologies in the Thousand Flowers pathway from versions 1 and 2.

Thousand Flowers		2008	2010	2015	2020	2025	2030	2035	2040	2045	2050
Wind (offshore)	vr 1	1.30	2.48	5.67	18.40	20.15	21.90	23.65	26.28	28.91	31.54
	vr 2	1.30	2.48	5.67	18.40	20.15	21.90	22.50	23.63	24.38	25.50
	change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	– 5.1%	– 11.2%	– 18.6%	– 23.7%
Solar	vr 1	0.02	0.02	0.28	2.77	5.26	6.57	7.88	10.51	13.14	15.77
	vr 2	0.02	1.96	7.78	13.61	19.44	25.26	27.20	29.15	31.09	33.03
	change	0.0%	99.0%	96.5%	79.7%	73.0%	74.0%	71.0%	63.9%	57.7%	52.3%

iterative, interdisciplinary nature of the processes shown in Fig. 2, the reconciliation of insights, perceptions and conventions/canons from across disciplines and, that allowed for the Thousand Flowers Pathway's determination.

The Thousand Flowers pathway quantitative description is therefore a perfect example of the strength of the interdisciplinary technical elaboration of the storylines.

The interdisciplinary and iterative working methods of the quantification process and of the TP and RTP consortia not only improved the quality of research and its published outputs but also improved the understanding and capabilities of the individuals within the team, turning a multidisciplinary team into an interdisciplinary team.

5. Conclusions

This paper has proposed a new approach to whole systems analysis and scenario development that helps reconcile qualitative storylines and quantitative descriptions through the development of a structured methodology.

The wider scope of investigation facilitated by this interdisciplinary approach allows for a coherent first stage of initialisation to act as the bedrock of study. As demonstrated in the context of results from the elaboration of the transition pathways storylines, the further stages of unification, verification and investigation permits the quantification of well-rounded descriptors which benefit from a breadth of domain expert knowledge, from a number of fields, all with an appropriate depth. The *version 1* results from the first set of iterations demonstrated balanced energy system quantifications which were used as a consistent base for storyline analysis in the Transition Pathways consortium.

The iterative nature of the methodology is a key element that enables refinement whilst allowing contributors to individually and collectively gain insights from the qualitative and quantitative analysis. Therefore, in the case considered in this paper the methodology provided a framework for the revision of descriptors of the transition pathway storylines leading to the *version 2* descriptors which were more accurate, consistent and robust than those determined previously. Simultaneously, the iterative, and therefore evolutionary, nature of the elaboration methodology allowed for more innovative scenario developments (as is exemplified by the Thousand Flowers pathway) that are free from the constraints of the current regime and discipline specific norms and conventions but remain grounded.

This proposed methodology for the quantification of qualitative storylines is, to the best of the authors' knowledge the first of its kind to reconcile qualitative and quantitative scenario descriptors. Its application, both within the energy sector and to other fields with supply and demand, to the elaboration of future-orientated research (i.e. scenarios) would be advantageous.

Acknowledgements

This work was conducted as a part of the Realising Transition Pathways project, supported by the UK Engineering and Physical Sciences Research Council (Grant EP/K005316/1). The funding source was not involved in the study or in writing this paper. The authors thank the other members, especially Evelina Trutnevte, of the Realising Transition Pathways and the preceding Transition Pathways projects, who developed the transition pathway storylines and participated in technical elaboration (then collaboration) groups. Data associated with research published in this paper is accessible at <http://dx.doi.org/10.15129/48d2e52e-5a88-4215-aac7-907e901a376a>.

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