The Future of Green Hydrogen: Developing a Transition Design Engineering Framework to investigate sustainable pathways for the UK energy system.

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Abstract

This work adapts current transition frameworks for use by stakeholders to streamline integration of new technologies within existing, malfunctioning systems.

Previous literature explored include Transition Design, which analyses stakeholder relationships, and Transition Engineering, which analytically models the system. This report creates an alternative Transition Design Engineering framework, combining existing methods with Design Engineering thinking. The designed framework shapes an alternative understanding of the current and potential future wicked problems within systems through thematic analysis of stakeholder interviews and documentation. An ideal future scenario and an aggressive roadmap towards it is envisioned.

The framework's effectiveness is tested using the case study of Green Hydrogen, which is a clean fuel capable of reducing reliance on fossil fuels; however, there are barriers to the technology's wide-scale rollout. Wicked problem mapping found that the current energy system is bounded in a negative feedback loop, whereby solutions currently reinforce dependence on fossil fuels. An ambitious future scenario is developed, where surplus renewable energy is stored as Hydrogen. This future system creates positive feedback loop and has the potential to decrease energy price overtime, contrasting to the continued use of fossil fuels, which will continue to rise in price as resources deplete.

Validation was conducted using stakeholders, testing the Green Hydrogen scenario and the Transition Design Engineering Framework. Innovators and policymakers from the energy system agreed that this framework could be used for many applications to improve the efficiency of transitions and the understanding of wicked problems within systems, to inhibit future systems bounded by wicked problems and negative externalities.

1 Introduction

National strategies (Appendix 1) are planning to rely heavily on electrification of all sectors (1); however, particularly in the transport sector, there are flaws within this rationale such as: depleting lithium sources, battery degradation, lack of storage facilities for renewables, safety, battery recycling, need for increased electricity capacity of the grid and the impracticality of heavy electric transport (2–4). This means future transitions cannot entirely rely on electrification. Hydrogen could be the key to the UK's future energy system within sectors that cannot be electrified easily and for storing surplus renewable energy (5), which we currently curtailed (6). Previous sustainable transitions have not been efficient. For example, the UK Government first implemented interventions to increase demand for Electric Vehicles (EV) in 2010 (7); however, 12 years on, their uptake is still disappointing. The Department for Transport technology tracker showed that only 24% of those planning to buy or lease a vehicle

Table 1: Summary of Forecast and Roadmap Frameworks in literature

	Advantages	**Disadvantages**
Forecasts	Data and outcomes of models can be represented clearly in graphs	Reports only analyse small section of system. Models are created with a lot of uncertainty. Doesn't include stakeholder opinion
Roadmaps	Uses stakeholder opinion and surveys	Communicating outcomes of report visually is harder as there's no data.
Both Methods	Create clear interventions needed for Hydrogen to be used	Don't consider the whole energy system, and the technology and stakeholder problems to be solved

in 5 years time (or longer) said it would be likely to be an EV (8). 73% of respondents stated that the disadvantage of EVs is the lack of charging points, and 71% said it was due to their high cost (8). Also, the aforementioned negative externalities of high EV utilisation were not considered. This highlights the undesirable outcomes of developing technology without considering the necessary system-wide changes. To end a repeat of failed, slow technology rollouts, we need a framework that allows innovators and policymakers to evaluate the whole system.

2 Literature Review

This review analyses the current Hydrogen transition work and then evaluates how Transition Design and Transition Engineering could shed light on a clearer path to net zero. The gaps identified in current frameworks will be used to produce research questions to be answered by the Transition Design Engineering framework developed for this report.

2.1 State of the art Hydrogen Transitions

McDowall and Eames's review (9) evaluated 40 papers on the future of Hydrogen. Here, forecasts were defined as 'quantitative methods to predict futures based on current trends or based on surveys of expert opinion' (9). Roadmaps outline a desirable future using research from stakeholder workshops. Forecasts and roadmaps produced since this review are investigated. A summary of findings are displayed in Appendix 2.

Analytical forecasts in the literature include a multi-objective optimisation (10), system dynamics model (11), and a Monte Carlo simulation (12). The Kotze paper (11) concludes that Hydrogen could play an essential part in the heavy-duty transport sector; however, we need to be realistic about its use cases. The Bloomberg NEF (13) report uses an economic model, concluding that the most financially viable method for using Hydrogen will be within industries where electrification will not be economical and storing unused renewable energy, similar to the Surf n' Turf project (14). The report's main conclusion was that strict policy measures are needed for Hydrogen to be financially viable. The numerical nature of these papers means outcomes can be presented clearly in graphs. The four analysed models used significant assumptions and hypothesised technology that may be viable for their timelines (between 2030 and 2050). There are many uncertainties, so it is questionable if using analytical modelling adds value to the Hydrogen transition.

Roadmap papers use stakeholders to develop a roadmap for future interventions. The reports from Arup (15), the Committee on Climate Change (16) and the Energy Research Partnership (17) show steps to a desirable low carbon future using Hydrogen; however, they state short term goals that seem impossible to implement. For example, the ARUP report recommends that there should be wide scale blue hydrogen production by 2030 (Appendix 3a). The Future Energy Scenarios report (18) contrasts the 2050 outcomes for four different scenarios and differs by introducing how Hydrogen could benefit the whole energy system by increasing storage and system flexibility instead of focusing on Hydrogen decarbonising one sector. Their' Leading the way' strategy showed the most significant, fastest reduction in carbon emissions (Appendix 3b); however, this paper lacks a step-by-step roadmap for this scenario to be achieved. The UKRFC found a discrepancy between the visualisations used in energy transitions that have better data (such as energy flows or economic cost) but the transition documents with less tangible data such as societal trends are harder to model (19). There is a significant gap between analytical modelling and stakeholder opinion in the current energy roadmaps and forecasts (Table 1). There is a need for research on Hydrogen visions considering all stakeholders and their conflicting opinions within the system.

2.2 Transition Disciplines

2.2.1 Transition Design

Transition Design is an emergent discipline and extends the concepts seen in the Hydrogen roadmap and forecast literature. The tool enables a 'design-led societal transition towards more sustainable futures' (20). The Transition Design process can be used to solve wicked problems that:

1. Involves multiple stakeholders with conflicting agendas
2. Straddles disciplinary boundaries
3. Are ill-defined where stakeholders rarely share an understanding of the problem
4. Are continually changing and evolving
5. Have problems exist at various levels of scale and are interdependent and interconnected
6. Cause any interventions in one part of the system to ramify elsewhere in unpredictable ways
7. Cause interventions to take a long time to evaluate and problems a long time to resolve. (20)

The stages of transition design include mapping:

1. The wicked problem
2. Stakeholder relations and interactions in the system
3. A future vision which can be backcast to the present day.
4. Critical interventions to achieve the future vision (20)

Transition Design shows a nuanced view of a system, shedding light on the wicked problems of systems caused by conflicting stakeholder opinions. The framework helps achieve a nuanced understanding of the system, which is inaccessible by current energy road-mapping methods. The thinking used presents an excellent opportunity for the green Hydrogen case study; however, the current framework has only been applied to smaller community problems such as the Ojai water shortage (21). Therefore, the framework needs to be extended to analyse technology suitability within a more extensive system.

2.2.2 Transition Engineering

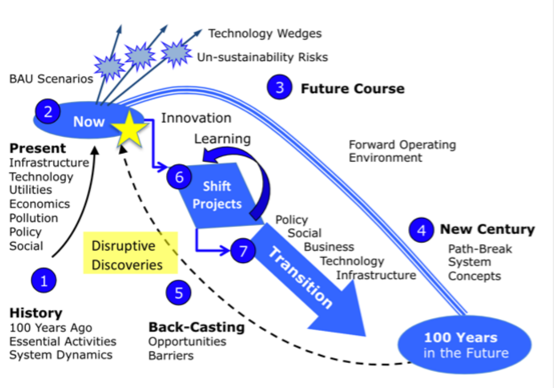


Figure 1: Steps used in Transition Engineering (22)

Transition Engineering (22) is another framework used to solve wicked problems, specifically global warming and the oil crisis, but it has also been used for transport (23). The stages of Transition Engineering can be seen in Figure 1. More focus is on analytically modelling the system than Transition Design, focusing on creating economically viable transitions by evaluating the Energy Return on Investment (EROI). Consequently, Transition Engineering literature does not discuss Hydrogen use due to its low EROI (22,24). This highlights the contrasting energy transition maps produced when focussing solely on numerical output and neglecting stakeholder opinion and the broader system.

2.3 Research Questions

Transition Design provides insight into the unseen wicked problems of a system but lacks insightful visual outputs and feasibility studies. Transition Engineering uses analytical modelling, but the examples lack the steps to analyse stakeholder opinions. Therefore this report will aim drawn from both modelling and stakeholder opinion to provide an alternative analysis not provided in previous literature (Figure 2). This gap highlights the need for a project that considers:

Table 2: Methodology choices between transition design and transition engineering techniques for this paper

Step	**Aims**	**Method for the Green Hydrogen Case Study**
1 - Wicked Problem feedback loop of the whole system	What is the main negative feedback loop in the current system?	Map of all problems but then distil the insights into a wicked problem.
2 - History of the wicked problem	How have transitions been triggered in the past in this system?	From literature, identify the triggers that have caused the energy transitions.
3 - Today's system	What is the current system, including policies, economics and environmental impacts?	The current UK energy use is investigated analytically to see current inefficiencies. Stakeholder opinions are mapped
4 - Possible futures	What are the outcomes of the preferable future scenarios of different stakeholders?	Evaluate roadmaps from different stakeholders and analyse the impact on the key changes needed within that system.
5 - Full potential future vision for technology	What is the future potential for this technology with wide scale use in 2050?	Present the ideal scenario for the future with this technology
6 - Back casting the vision	What are the main differences between the current and future scenario?	Map the positive feedback loop that could encourage this future?
7 - Transition pathway	What interventions are needed to enable these to happen?	Map the interventions from different stakeholders will enable this transition

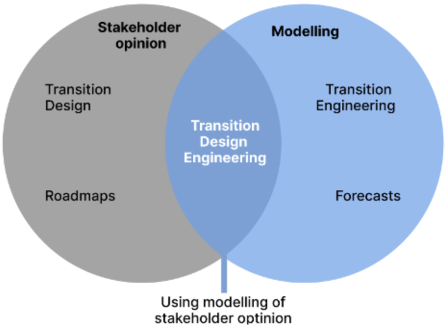


Figure 2: Transition Design Engineering fills the gap from current frameworks

1. Both micro and macro problems for the green hydrogen economy
2. Problem contextualisation on a radically larger scale, enabling a systemic understanding of the problem
3. The visible and invisible drivers and their influence
4. Identifying conflicting opinions between multiple stakeholders creating a barrier to a future energy system with synergy.
5. Action plans and incentives for all stakeholders (science, technology, policymakers, government, funders, and energy consumers).
6. Inclusion of how current smaller projects could be used within this transition to reduce the possibility of redundant infrastructure in the future
7. Plans to integrate hydrogen to increase energy flexibility, including future decentralisation of energy systems.

To ensure this project will produce more effective interventions than in previous literature, the project will be focused on five research questions.

1. How can the current transition frameworks be adapted to be used to accelerate the development of sustainable systems rather than singular technologies?
2. What are the wicked problems barricading the transition to using Green Hydrogen?
3. What is an ideal future scenario for the UK in 2050 which uses Green Hydrogen?
4. What interventions are needed for Hydrogen to be a practical tool for a net-zero energy system in the future?

5. How can the analysis of stakeholder opinions be presented in clear visual representations to educate stakeholders on the attitudes within the system?

3 Methodology

The Transition Design Engineering framework developed in this report incorporates both methods (Transition Design and Transition Engineering). It blends the tools to enable an alternative view of the problem, understanding the imbalances between stakeholders. Through rigorous analysis and theoretical considerations, suitable interventions are created. The methodology was iterated while investigating the case study on Green Hydrogen.

3.1 The Transition Design Engineering Framework

Each step of the framework develops insights based on research collected from the following data sources:

Stakeholder Interviews The main types of stakeholders within the system are first identified. The green Hydrogen case study identified these as large energy companies, Hydrogen fuel cell manufacturers (both commercial and lab-based), energy transition consultants, and policy. Six interviews took place, with each person having an executive role in each sector. Interviews were between 30 minutes to 1 hour 30 minutes and were semi-structured. The questions asked can be found in Appendix 4. After each interview, a thematic analysis of the results was completed.

Conferences Opinions from conferences were used to validate insights from the interviews for each stakeholder group. Opinions from five conferences were used. Notes were taken during the conferences, and these were analysed together after the event.

Reports Additional information about current roadmaps and companies' visions were analysed to validate opinions further.

The Transition Design Engineering framework (Table 2) follows the seven steps from Transition Engineering, with each step's aim adapted to focus more on stakeholder opinion. The main outcomes from the framework are:

1. Identifying the wicked problems within the current system (steps 1-3)
2. Exploring alternative future scenarios, and opportunities for the technology with different stakeholder imbalances (steps 4 – 5)
3. Identifying the pathway to facilitate the true potential of technology (steps 6-7)

3.1.1 Identifying the wicked problems within the current system

Figure 3: Wicked problems as explained in transition engineering (2)

The negative feedback loop in the current system Initially, the wicked problem mapping from Transition Design was used (Appendix 5); however, with many alternative technologies throughout the value chain, each with specific problems, this map did not bring much insight into the system. Transition Engineering depicts wicked problems as a constant loop (Figure 3) where both continuing and stopping an action within society causes negative consequences (23). The cycle is the main problem that needs to be broken for a sustainable future. The developed framework instead identifies the main negative feedback loop in the current system to identify how the new technology could break this loop rather than add to it.

Historical and Current Energy Sector The historical transitions of the system (like in Transition Engineering) are then investigated to understand the factors that cause shifts within the system (22). First, previous energy transitions are studied in the literature; then, the current system is analysed using data and stakeholder opinions.

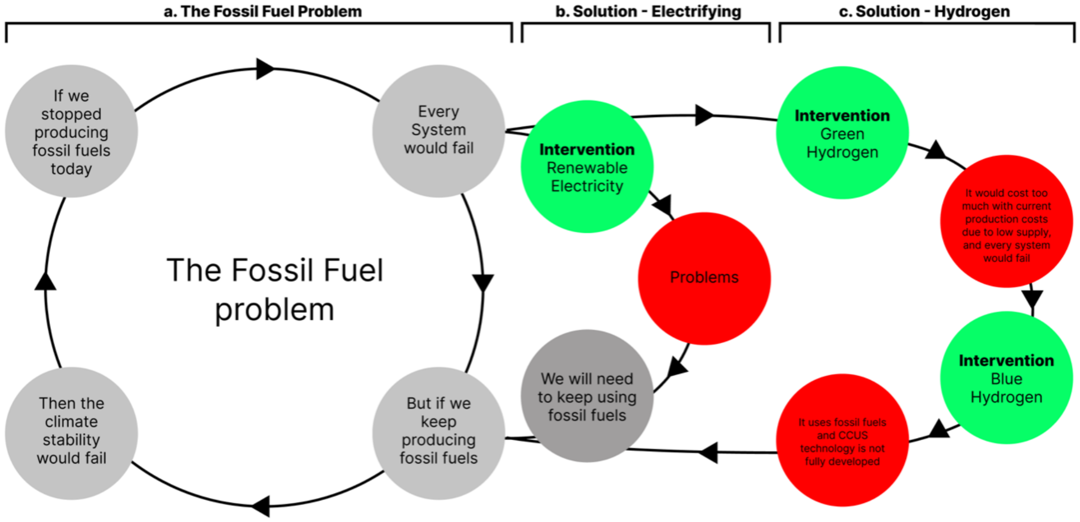


Figure 4: Wicked Problem Feedback loop: a, of using fossil fuels. b, the additional wicked problem loop with increased electrification of sectors (26–31). c, with the use of blue hydrogen

3.1.2 Exploring alternative future scenarios with different stakeholder imbalances

The roadmaps produced by different stakeholders vary, so these are investigated to evaluate the negative externalities associated with these futures. The current roadmaps that add to the negative feedback loop are identified. Stakeholder interviews are then conducted to understand their motivations and fears for transitioning to this future scenario. Next, an ambitious future using the new technology is envisaged.

3.1.3 Identifying the pathway to facilitate true potential of the new technology

There will be fundamental differences between the current and the future scenario. As with the historical analysis, the primary triggers that could cause an energy system transition are identified. The critical steps to making the preferable vision are outlined in actionable policies and interventions.

3.1.4 Validation

Previous work does not use a tool to validate the insights and frameworks, however this was felt to be a necessary final step to identify the potential applications and impacts of this work. The project will be validated by consulting with stakeholders from each group within the system, regardless of their power for change within the system. Stakeholders will be asked three sets of questions on the framework (Appendix 4). A thematic analysis will then be conducted to identify the perceived benefits of the framework, the potential future applications and the limitations.

4 Case study of Green Hydrogen

To many, the transition to using Hydrogen is not seen as an immediate priority for climate change; however, in multiple roadmaps, including the UK's Net Zero strategy(25), its use is integral to meeting our net-zero energy targets. The case study of the Green Hydrogen rollout tests the effectiveness of the framework for the use case. The insights on Stakeholder opinions were drawn from the thematic analysis (Appendix 6).

4.1 The Wicked Problem

To understand the transition to using green Hydrogen, it is integral to understand the current energy system, such as why we remain dependent on fossil fuels. The fossil fuel wicked problem can be described as seen in Figure 4a, a feedback loop developed by Krumdieck (22).

To solve the fossil fuel wicked problem, society has introduced solutions such as aiming to electrifying every sector and increasing the use of renewable electricity. As a result, decarbonising the energy grid using just electrification would cause another cycle of wicked problems to be created, causing a continuation of reliance on fossil fuels (Figure 4b).

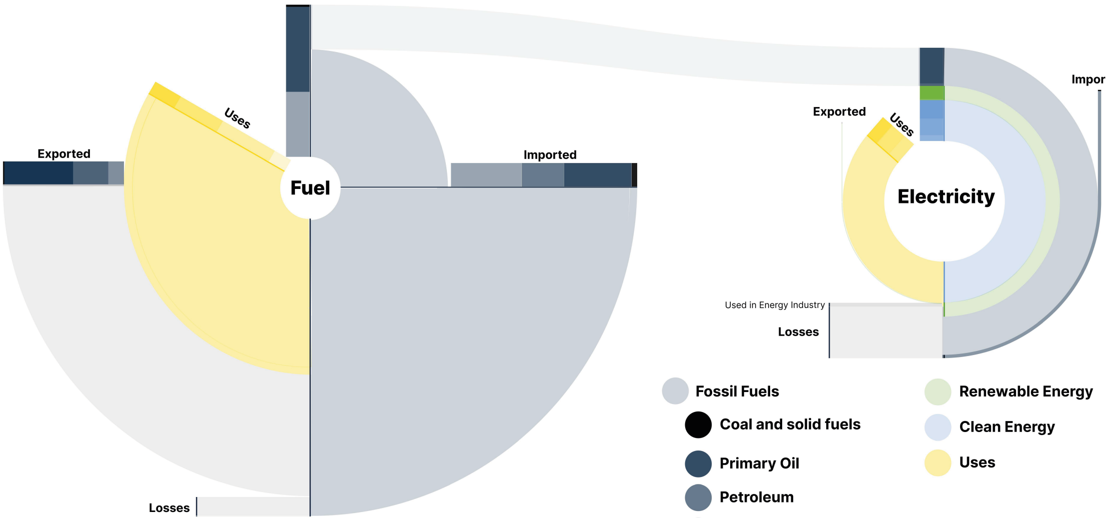


Figure 5: UK energy usage, visualised to scale from 2020 ONS data (33)

4.2 History of energy transitions

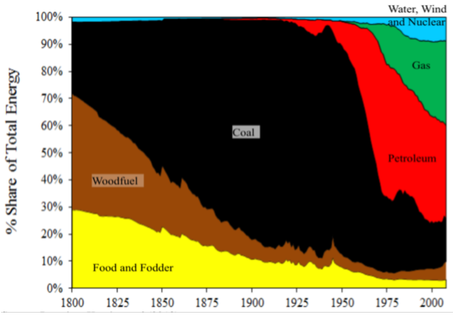


Figure 6: Share of Primary Energy Consumption in Europe (25)

Krumdieck (22) and Fouguet (32) highlight the importance of understanding the history of energy transitions to understand how the wicked problems emerged. This section aims to understand the triggers that previously caused a switch from coal-based to petrochemical-based feedstocks in the United Kingdom (Figure 6). Fouguet (32) concluded that the fastest energy transitions have occurred over 30 years, and these occur when the new technology provides a cheaper and better-quality service. This incentivises people to pay a premium for the then niche energy source. Prices cause the tipping point from niche applications to mass uptake of the new technology (32). Therefore, to trigger the start of an energy transition, the benefit of the new fuel needs to be clear for people to pay a premium. The energy source then needs to be able to decrease in price in the remote future to become competitive with current solutions.

4.3 Present: Current energy use

Energy use today is presented in Figure 5, a diagram constructed using data from the Digest of UK Energy Statistics 2021 (33) to give better insight into fuels vs electricity used within the system than presented in government Sankey diagrams (Appendix 7) (33,34). The alternative diagram (Figure 5) shows how many industries rely on fuel, showing the tremendous task of electrifying all sectors. The high dependence on fossil fuels means that a significant infrastructure could potentially be redundant with future transitions (35).

4.3.1 Stakeholders in the system

For the boundaries of the system analysed for this report, the main stakeholders were identified, as shown in Table 3.

4.3.2 Stakeholder positioning

Stakeholders were first asked about their opinions on the wide use of Hydrogen. Financial and political power can delay energy transitions (36), and from assessing stakeholders' opinions within the system from interviews and conferences, it was clear that there are contrasting opinions between stakeholder groups. The government are currently supporting Hydrogen development with their Hydrogen Strategy (Appendix 1), which is produced in consultation with large energy companies, Ofgem, catapult

Table 3: Stakeholder's interviewed

Stakeholder Group	Part of Hydrogen value chain focus	Company interviewed
Large energy companies	Whole system	BP
Hydrogen technology producers	Lab based hydrogen technology	RMS power
Hydrogen technology producers	Commercially available hydrogen technology	Ceres power
Government and policy advisors	Whole system	Policy Officer for renewables at BEIS
Independent renewable energy consultants	Whole system	ARUP
National infrastructure companies	Transporting hydrogen	SNAM

companies and academics. The plans from the Government Ten-point plan are met by releasing grants, such as the Net Zero Hydrogen Fund (25,37). Companies and researchers can then propose their projects to receive this funding. From the thematic analysis (Appendix 6), the large energy companies, the government, and regulators were the most cautious stakeholders (Figure 7). Large energy companies were apprehensive about Hydrogen's safety, efficiency, and investment risk. The government official was a little more optimistic; however, they believed it would take a long time to roll out their current policy structure. In contrast, Hydrogen companies were very optimistic about their technologies. The government stakeholder commented that the Hydrogen companies and academics are optimistic due to a lack of understanding of the wicked problems within the system.

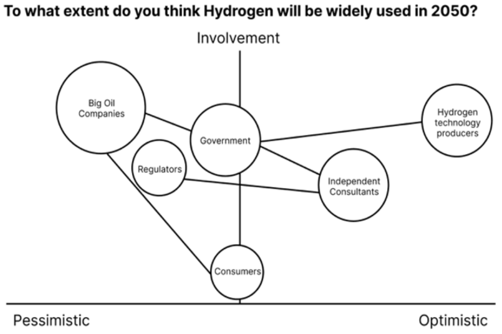


Figure 7: Representation of stakeholder power vs their perceived optimism on the future of hydrogen from interview. (Size of circle is a representation of power) (Appendix 6)

Interviewees were then asked about the relationships and conflicts between stakeholders; the results are represented in Figure 8.

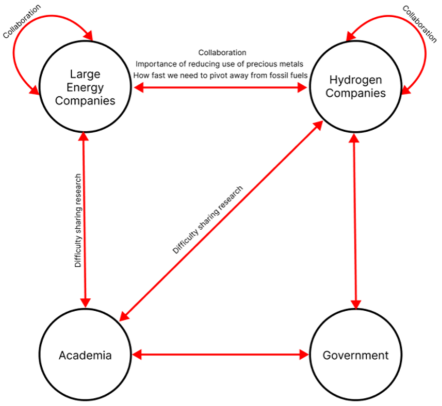


Figure 8: Perceived stakeholder conflicts within the energy system for interviews (Appendix 6)

4.4 Alternative future scenarios

The stakeholders with the most power in the system are large energy companies and governments. The preferable future scenarios for these stakeholders are analysed (25,38,39) to identify the potential future wicked problems, such as the financial and environmental impacts, of different stakeholders holding the most power in the energy sector.

UK government The government have produced three 2050 net-zero scenarios: high electrification, high resource, and high innovation (38). In the high electrification scenario (Figure 9) Hydrogen is produced from electricity generation, mainly produced from wind, solar and nuclear. Hydrogen is made using electricity and bioenergy. In contrast, the other two scenarios (One is presented in Figure 10) produce much of their Hydrogen using fossil fuels. All scenarios heavily rely on carbon capture to reach a net-zero scenario (Figure 11 – 12).

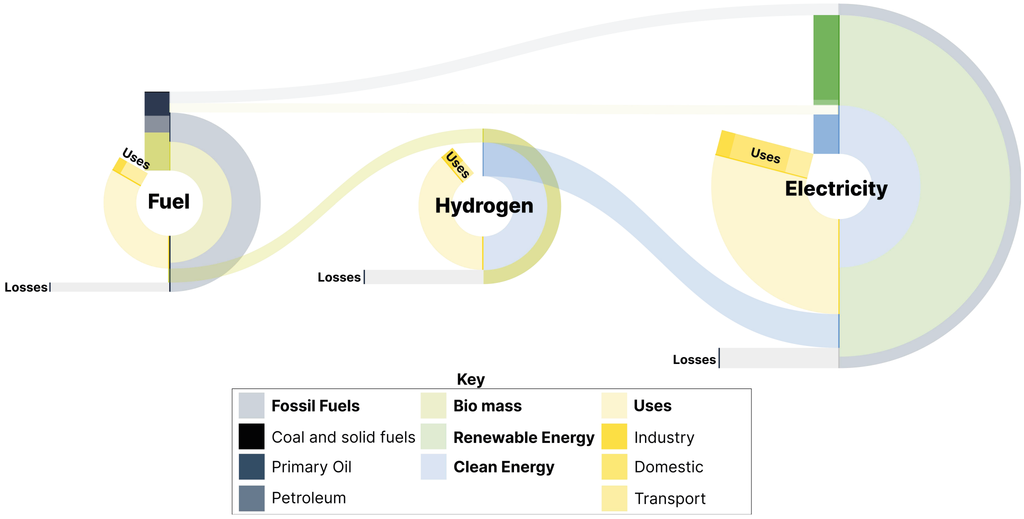


Figure 9: Government High Electrification 2050 Scenario

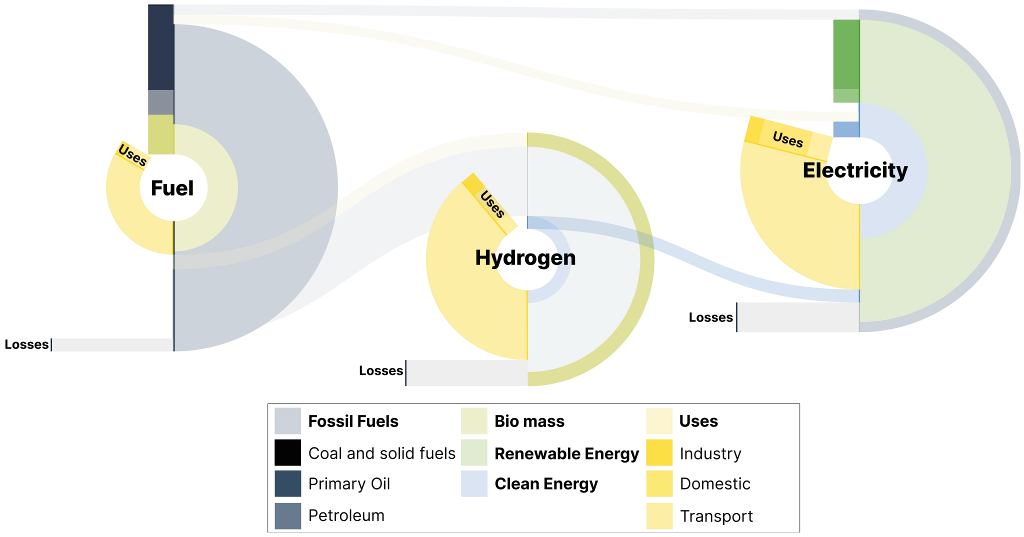


Figure 10: Government High Resource 2050 Scenario

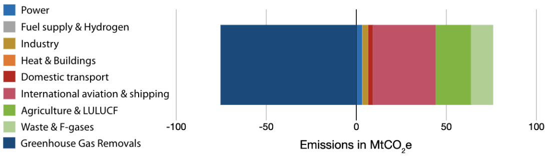


Figure 11: Emissions from Government Electrification 2050 Scenario (25)

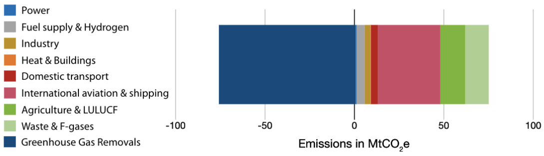


Figure 12: Emissions from Government High resource 2050 Scenario (25)

Large Energy Companies BP's energy outlook evaluates three possible global transition scenarios: accelerated, net-zero and new momentum (38). Like the government scenarios, natural gas, oil and coal are still facilitated; however, a contrasting opinion is that coal will still be used for electricity generation (Appendix 8). This is also seen in Shell's 2050 scenario (Appendix 9). Green, blue and BECCS Hydrogen are planned to be produced (Appendix 8).

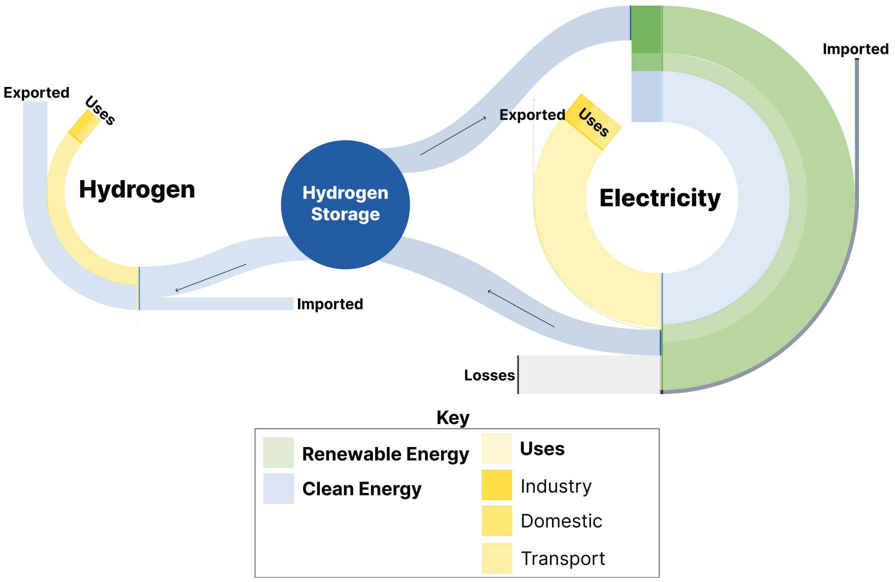


Figure 13: 2050 scenario using Green Hydrogen

4.4.1 Wicked problems caused by future scenarios

The future scenarios planned by the above stakeholders could leave the UK with as many, if not more, wicked problems as we experience today. As discussed in section 4.1, focusing on just using renewables creates a new wicked problem loop. There are also future price and carbon emission issues with the roadmaps above.

Reliance on Fossil Fuels The future scenarios planned by the above stakeholders could leave the UK with as many, if not more, wicked problems as experienced today. The above scenarios continue to rely on fossil fuels, which are forecasted to rise in price until 2050 (Figure 16 and Figure 17).

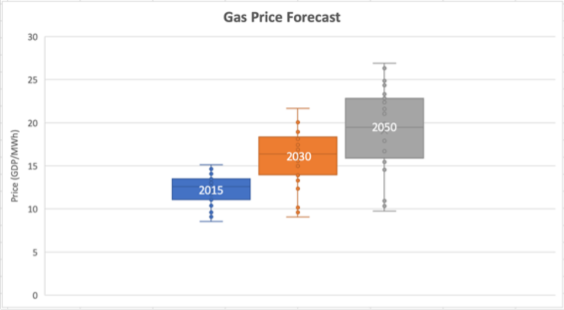


Figure 14: Gas Price Forecast (57)

Carbon capture Carbon capture is utilised in the scenarios, which adding additional cost and complexity to the energy transition (40).

Increasing Nuclear Since the Ukraine conflict, government energy security strategies have increased nuclear energy production (41). The price of nuclear energy is very high due to the installation costs, and the source from BP said that there is no possibility of decreasing this price over time. Current nuclear power stations do not provide flexible energy production, meaning energy would be wasted (42).

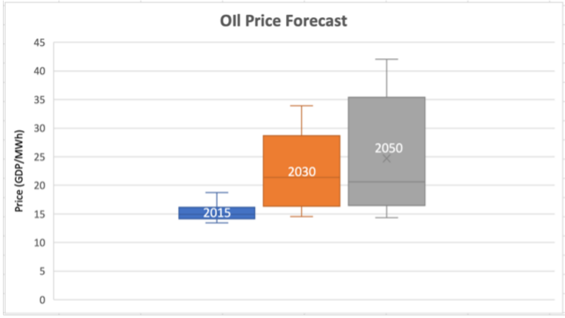


Figure 15: Oil price forecast (57)

Blue vs green Hydrogen The use of blue Hydrogen does not break us out of the negative feedback loop (Section 4.1). It causes additional wicked problems within the system and continued reliance on fossil fuels (Figure 4c). Green Hydrogen is produced using electrolysis using renewable electricity; however, it is costly due to low supply, so it cannot be implemented at scale. The UK is focusing half of its Hydrogen on being blue in its roadmap (43), a clean fuel produced using fossil fuels with carbon capture, utilisation and storage (CCUS). This technology is cheaper at present; however, it relies on fossil fuels which adds to the cycle of the wicked problem. As mentioned by all stakeholders, blue Hydrogen has a place to increase demand and provide cheap Hydrogen short term; however, a 2050 scenario using a large quantity of blue Hydrogen is not preferable for energy prices.

4.5 Future vision

Current net-zero roadmaps are not very ambitious, with oil and gas still being utilised. Future visioning aims to brainstorm the most desirable usage of the technology in 2050 without consideration of the current barriers within the system. Using green Hydrogen hand in hand with renewable electricity is a clear solution to breaking away from the fossil fuel loop. The presented future scenario is flexible, solves the current problems with intermittent renewables and brings opportunity for energy price reduction over time. The preferable future scenario is flexible to allow for future developments without infrastructure redundancy (Figure 13). If there are future technological developments (such as nuclear fusion), this system will still work, be clean, and with scaling, it could minimise energy prices. Even modelling cannot predict which sectors will use electricity or Hydrogen, so we should aim for a future scenario which facilitates either. Hydrogen will be solely produced from renewable energy, storing electricity that currently is curtailed. For example, in 2020, 6% of Britain's wind energy had to be curtailed, equal to annual energy usage in Wales (6). Nuclear power will be generated as a base level of electricity generation.

4.6 Back casting

The next step of the framework involves finding the main differences between the current scenario (Figure 5) and the future vision (Figure 13). First, the technology challenges for the whole Hydrogen production chain will be investigated, followed by the changes in stakeholder behaviours.

4.6.1 Technology changes

Hydrogen production requires electrolysis to split water molecules. There is a great challenge at present in ensuring the Hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER) is efficient and cost-effective to ensure green Hydrogen production is commercially viable (44). Listed in Table 4 are the current Hydrogen electrolysis methods. In summary, there is a need for an electrolysis process that is both efficient and cost-effective, making them suitable for larger-scale production. This could be possible from recent developments in Anion Exchange Membrane (AEM) (45–47) and non-noble nanoparticle catalysts (4,48).

Hydrogen transport The most economical approach for transporting Hydrogen is to convert the current wrought-iron pipeline to polyethylene pipes to allow pure Hydrogen to be carried in them. Modelling from SNAM shows that when Hydrogen is transported compressed, it could carry 80% of energy as the same volume of natural gas (26). The European Backbone Project, an analysis produced by 23 European gas companies, predicted that 70% of the 40,000km of gas pipelines could be refurbished (49). This costs 10-25% of building a new one (49).

Hydrogen storage A few methods are available for storing Hydrogen, with promising technology developments leading to efficient, safe, and cheap solutions (Table 5).

Table 5: State of the art Hydrogen Storage methods

Storage method	**Explanation**
Salt Caverns	This could provide cheap Hydrogen storage below €10/MWh. This is especially a very good option for the UK (26)
Hydrogen Flow batteries (50)	RFC have a lab-based technology, which uses Hydrogen manganese chemistry with lower levelized cost of storage
Metal Hydride storage (51)	GKN have produced a metal hydride storage, that has already been rolled out to store renewable electricity. It claims to be safe, recyclable and efficient.

4.6.2 Social changes

For a successful rollout of Hydrogen, there needs to be more synergy between stakeholders in the system. The government stakeholder commented on how the system is stuck in the mindset of competition to maximise profits rather than collaborating. Stakeholders are

Table 4: Hydrogen Electrolysis methods (45)

Hydrogen Electrolysis method	Advantages	Disadvantages
Alkaline Electrolysis	Mature technology, Non-PGM catalyst, Long term stability , Low cost, Megawatt range, Cost-effective	Low current densities , Crossover of gas, Low dynamic, Low operating pressure, Corrosive liquid electrolyte
Polymer electrolyte membrane (PEM)	Higher performance, Higher voltage efficiencies, Good partial load, Rapid system response, Compact cell design , Dynamic operation	Higher performance, Higher voltage efficiencies, Good partial load, Rapid system response, Compact cell design Dynamic operation
Anion Exchange Membrane (AEM)	Non-noble metal catalyst, Noncorrosive electrolyte, Compact cell design, Low cost, Absence of leaking, High operating pressure	Laboratory stage, Low current densities, Durability, Membrane degradation, Excessive catalyst loading

working on trying to solve the same problems, which could be solved faster if working together. Therefore, more collaboration is needed in the Hydrogen space to reach the desired future scenario.

4.7 Transition Pathway

4.7.1 Stakeholder insights

The primary conversations around transition change were around how policy was vital for there to be a change; however, companies could have a significant role in using net-zero technologies. Alvera backed this, 'The first movers in Hydrogen will be companies' (26) All stakeholders agreed that blue Hydrogen would need to be used during the transition; however, there will be a switch to green Hydrogen when it becomes price competitive. The representative from Ceres power believed that Local governments need to put in incentives. The change will be made once a date is set for fossil fuels to be phased out of industries. We need a policy that bans fossil fuels in industry after 2040 – but we also need to increase taxation to redistribute these funds to business making steps to net-zero. The stakeholder from RFC power, Ceres and ARUP mentioned the need for a carbon tax to implement a change.

4.7.2 First Trigger

As discussed in section 4.2, the energy price is an integral part of triggering a transition and is a topic of great concern in 2022. This is due to consumers demanding change. Due to the Ukraine conflict, the increase in prices of fossil fuels is considerably more than predicted (Figure 16). There have been substantial spikes in energy prices, with domestic gas prices increasing by 95% and domestic electricity prices by 54% in April 2022 (52). In contrast, renewable energy prices have seen a fall in costs; offshore wind costs have fallen to £45/MWh in the last decade, which means it is now competitive with the £50/MWh gas generation cost (53). The representatives from SNAM, UK Government and ARUP commented on the obvious change in opinions since the conflict, with an increased need for energy security and concern over increasing living prices. This is a clear sign that the trigger for an energy transition is happening now. It's preferable to invest in Green Hydrogen, which could be produced in the UK, rather than increasing fossil fuel production.

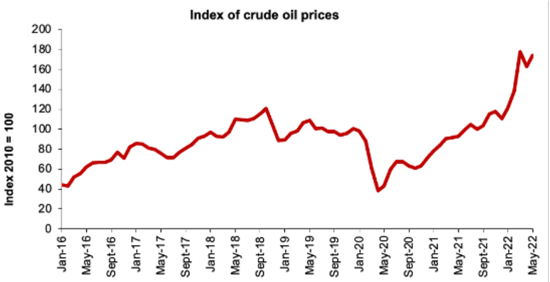


Figure 16: Crude oil prices (54)

4.8 Future pathway

If a future vision where green Hydrogen and electricity are utilised, it creates a shift in the system. The history of previous energy transitions shows how new energy sources must be price competitive for mass uptake. The advantage of using green Hydrogen and renewable energy is that a positive feedback loop is created. An innovation that decreases the price, increases the demand or installs more

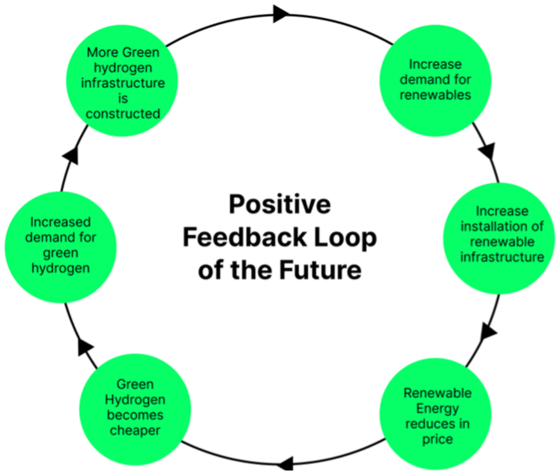


Figure 17: The positive feedback loop of the future

infrastructure for either technology, decreases the energy price within the whole system (Figure 17). This contrasts with the current system, which is stuck in a negative feedback loop (Figure 4). Therefore, it can be concluded that any future policies and interventions that drive change in one of these six categories (Figure 17) will improve the whole energy system. This diagram can be used by stakeholders to understand the interventions necessary for the roll-out of their technology by different groups in the system, to encourage collaboration (Appendix 10 shows an example of this). Some examples of interventions that would benefit the system are discussed below

Decentralised Energy For a faster acceleration of the energy transition, both industry and consumers need to have complete control over their energy. As the stakeholder from Ceres power mentioned, decentralised Hydrogen production is already being used by companies. It is a way for companies to develop the Hydrogen and renewable technologies they need within proximity. To increase the uptake of decentralised production by companies, monetary incentives need to be created by the government. In a 2013 study run by the UKERC, 81% of respondents said they wanted to reduce their energy consumption (36). Consumers could have more control over their energy by using demand control appliances with IoT systems to control their energy use. Consumers could choose to run their appliances when demand is lower when energy prices are lower (55). They could also choose the type of energy they use, allowing the select consumers to pay a premium for net-zero energy to do so with more ease.

Carbon Tax All stakeholders mentioned the need for incentives for a transition to net zero. The Ceres representative emphasised how carbon taxes are a way to shift energy consumption to the use of renewables. Tax revenues could be redistributed to firms willing to change and shift behaviour. The stakeholders from RFC and ARUP also mentioned the need for a carbon tax.

5 Discussion

5.1 Insights from the Green hydrogen case study

It is clear that Green Hydrogen will be needed in the future and could be a tool to break away from the fossil fuel cycle; however, there are currently complex problems within this system that barricades a solution from being integrated. Current literature failed to develop insights into the technological and stakeholder conflict barriers preventing the successful rollout of Green Hydrogen. The Transition Design Engineering framework developed in this report allowed for a deep understanding of the current energy system's problems, which led to a future scenario that displays how Green Hydrogen's true potential can be utilised (Figure 13). Despite most stakeholders agreeing that green Hydrogen will be used in the future, the decision-makers within the energy space will inevitably govern the rollout. Large companies have personal gains from the continued use of fossil fuels, which could explain the reliance on blue Hydrogen within government plans. In contrast, consumers were found to have little control over the current energy system due to its centralised nature.

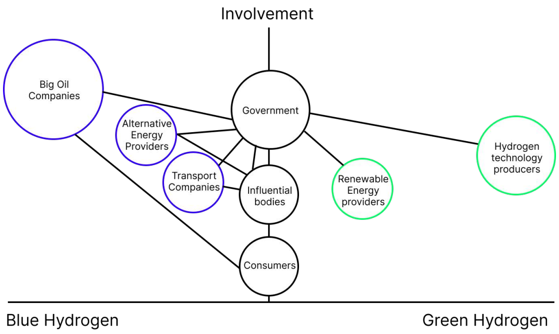
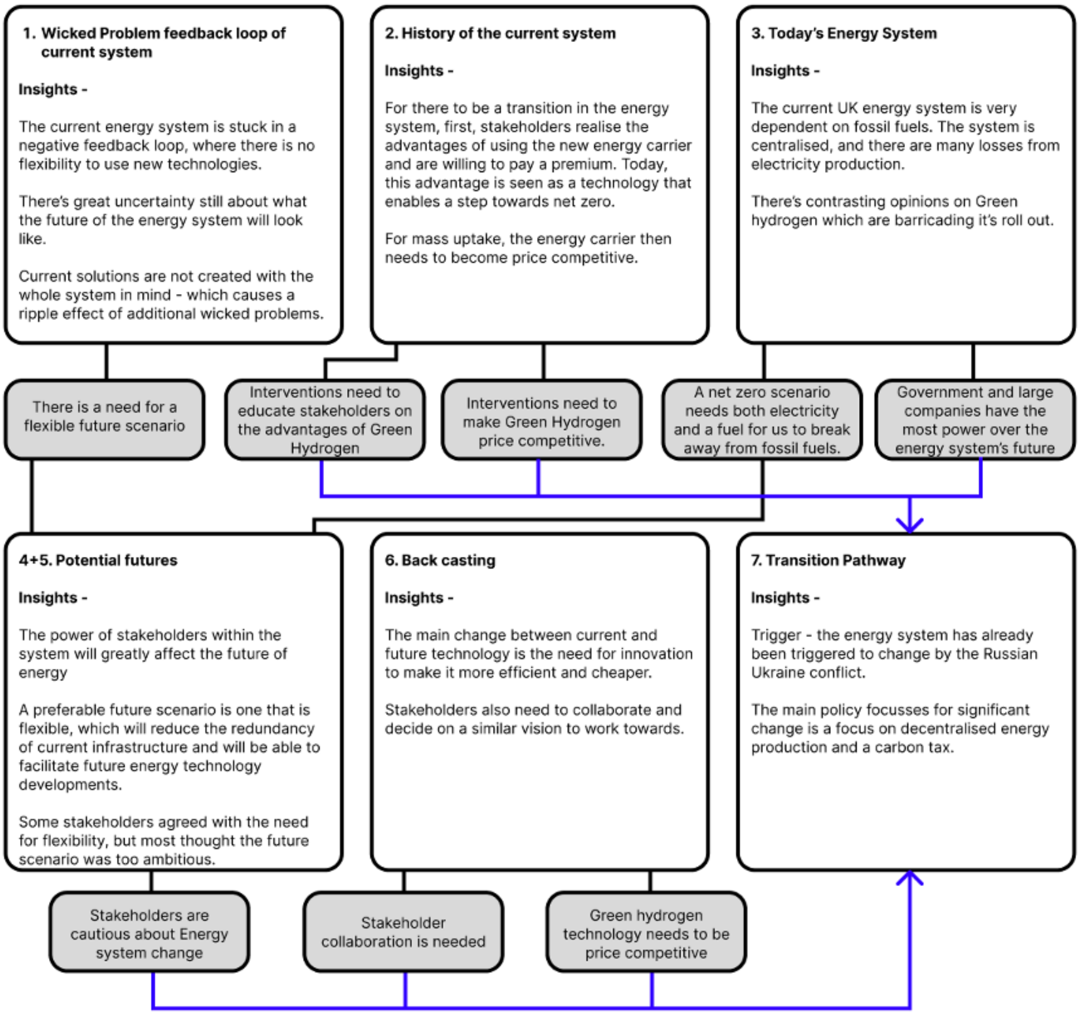


Figure 19: Contrasting Stakeholder opinions on Blue vs Green Hydrogen (Appendix 6)



1. Wicked Problem feedback loop of current system

Insights -

The current energy system is stuck in a negative feedback loop, where there is no flexibility to use new technologies.

There's great uncertainty still about what the future of the energy system will look like.

Current solutions are not created with the whole system in mind - which causes a ripple effect of additional wicked problems.

2. History of the current system

Insights -

For there to be a transition in the energy system, first, stakeholders realise the advantages of using the new energy carrier and are willing to pay a premium. Today, this advantage is seen as a technology that enables a step towards net zero.

For mass uptake, the energy carrier then needs to become price competitive.

3. Today's Energy System

Insights -

The current UK energy system is very dependent on fossil fuels. The system is centralised, and there are many losses from electricity production.

There's contrasting opinions on Green hydrogen which are barricading it's roll out.

4+5. Potential futures

Insights -

The power of stakeholders within the system will greatly affect the future of energy

A preferable future scenario is one that is flexible, which will reduce the redundancy of current infrastructure and will be able to facilitate future energy technology developments.

Some stakeholders agreed with the need for flexibility, but most thought the future scenario was too ambitious.

6. Back casting

Insights -

The main change between current and future technology is the need for innovation to make it more efficient and cheaper.

Stakeholders also need to collaborate and decide on a similar vision to work towards.

7. Transition Pathway

Insights -

Trigger - the energy system has already been triggered to change by the Russian Ukraine conflict.

The main policy focusses for significant change is a focus on decentralised energy production and a carbon tax.

Figure 18: Insights from the Transition Design Engineering Framework, used to explore the Green Hydrogen

5.1.1 Synergy of Stakeholders

The key catalyst for change will be collaboration between stakeholders. Companies can only do so much without infrastructure, so we need better collaborations with the government and companies. We need more electric charging points, and Hydrogen refuelling stations for heavy vehicles. Governments should lay out more ambitious roadmaps, consult a broader range of stakeholders and understand the motivations and fears of stakeholders further in future reports on new technologies.

5.1.2 Validation

A validation tool was devised to assess the effectiveness of the Transition Design Engineering framework and the green Hydrogen case study. Stakeholders were asked the questions outlined in Appendix 4. A thematic analysis highlighted the key opinions of stakeholders on the framework. The complete analysis and quotes can be found in Appendix 11. Overall, stakeholders were interested in the new perspective on the energy wicked problem that the new framework analysis gave. They also particularly liked that the future vision was flexible. The future applications of this framework were: private companies when innovating new technology, investors for encouraging collaboration and accelerating government policy making. The limitation of the framework they felt was the lack of numerical modelling, which could be included in future research.

5.1.3 Limitations

Even though some stakeholders mentioned that the future scenario needed more of a numerical element, it was decided that the report's scope should not include this. Due to the uncertainty of the transition and the high concentration of research in energy system modelling, instead the purpose of this paper was to create a future vision to find a scenario that all stakeholders can work towards to create a synergy of opinions. Future work could extend upon this framework to add numerical backing to increase the feasibility and reliability of the future scenario.

6 Conclusion

This work aimed to adapt current transition frameworks to create a method for innovators and policymakers to evaluate the whole system to optimise the transition to new technology. The framework was able to:

- Contextualise the wicked problem within the current system
- Evaluate the trigger needed for an energy transition
- Adapt current energy flow diagrams to provide further insight into the transition required
- Create a new perceptive for a future vision for Green Hydrogen use in the UK
- Evaluate the key changes and interventions needed to reach this future scenario

Stakeholders from the energy system agreed that this framework could be used for many applications to improve the efficiency of transitions and the understanding of wicked problems within systems. This study contributes to and enhances the landscape of techno-economic analysis of systems and transition frameworks.

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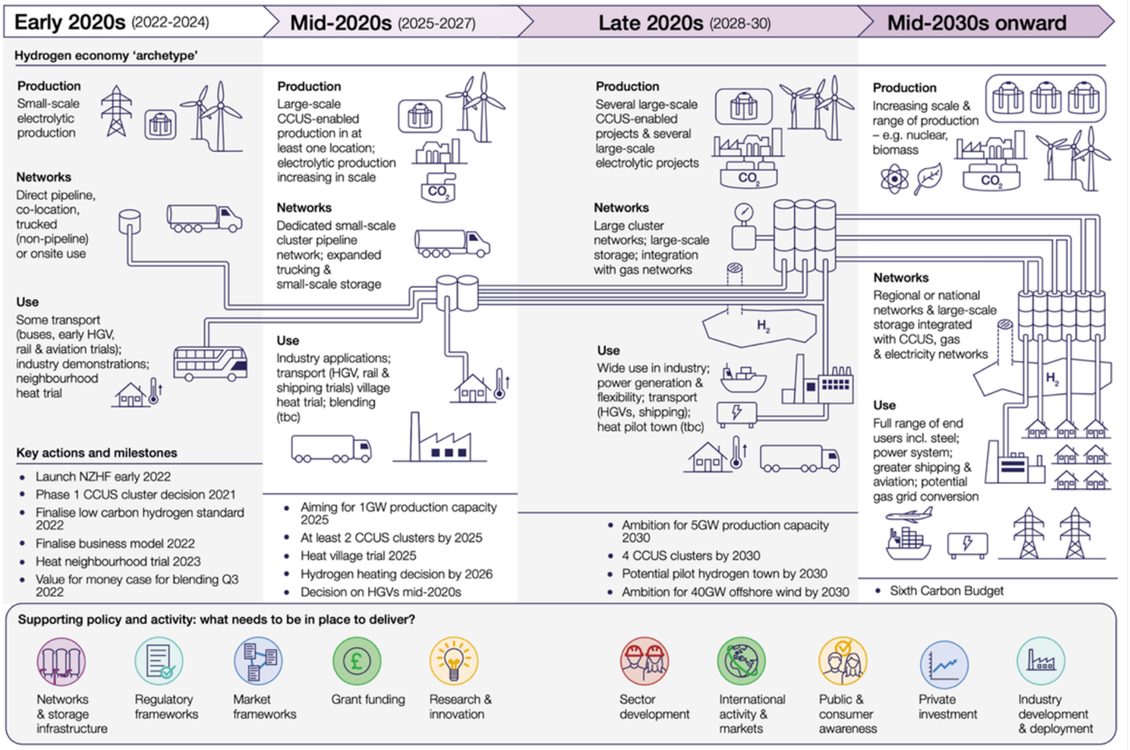
8 Appendix

Appendix 1 - UK Hydrogen strategy (43)

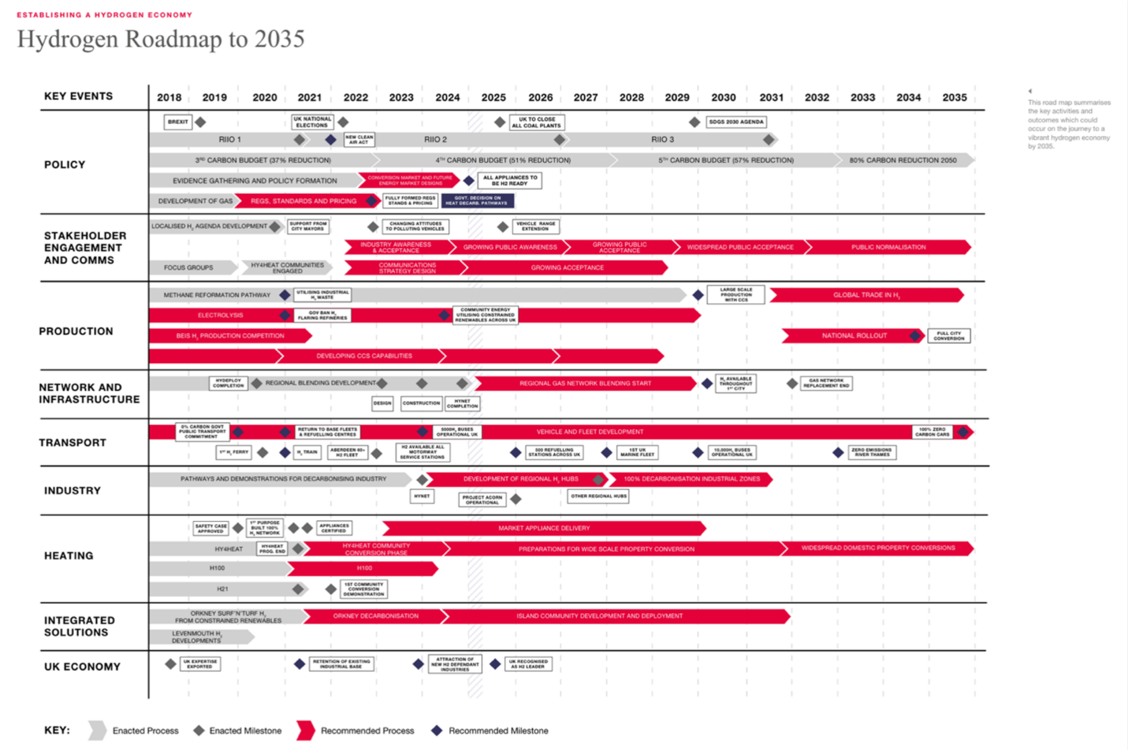


Appendix 2 - Summary of Literature Review findings

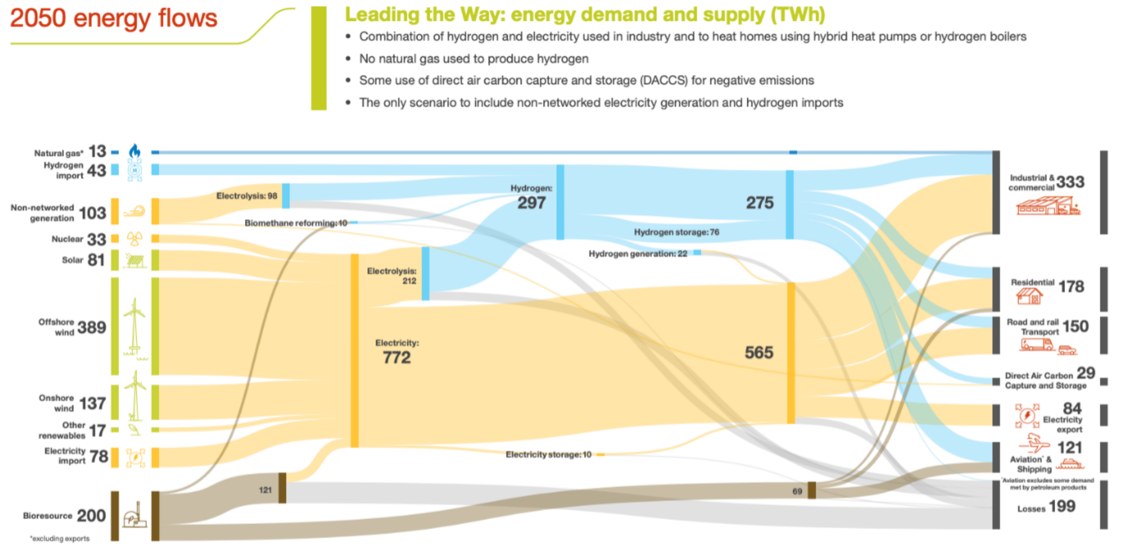
Relevant Literature		Time scale	Method		Comparison of multiple transitions	Energy system structure		Sector			
			Analytical	Stakeholder workshops		Centralised	Decentralised	Production	H2 Application	Several sectors separately	Whole system synergy
Forecasts	Jamshidi, M., & Askarzadeh, A. (10)		✓				✓	✓			
	Kotze, R., (11)		✓			✓			✓		
	Fan, Z (12)		✓			✓				✓	
	Hydrogen council (56)		✓			✓			✓		
Roadmaps	Arup (15)	2035		✓		✓					✓
	Committee on Climate Change (16)	2030-2050		✓	✓	✓			✓		
	Future Energy Scenarios (18)	2050	✓	✓	✓	✓	✓				✓
	ERP (17)	2050		✓	✓	✓	✓			✓	
This project		2050		✓	✓		✓				✓

Appendix 3

Appendix 3a - ARUP report (15)



Appendix 3b - 2050 Energy flow with the ‘Leading the way’ strategy (18)


2050 energy flows

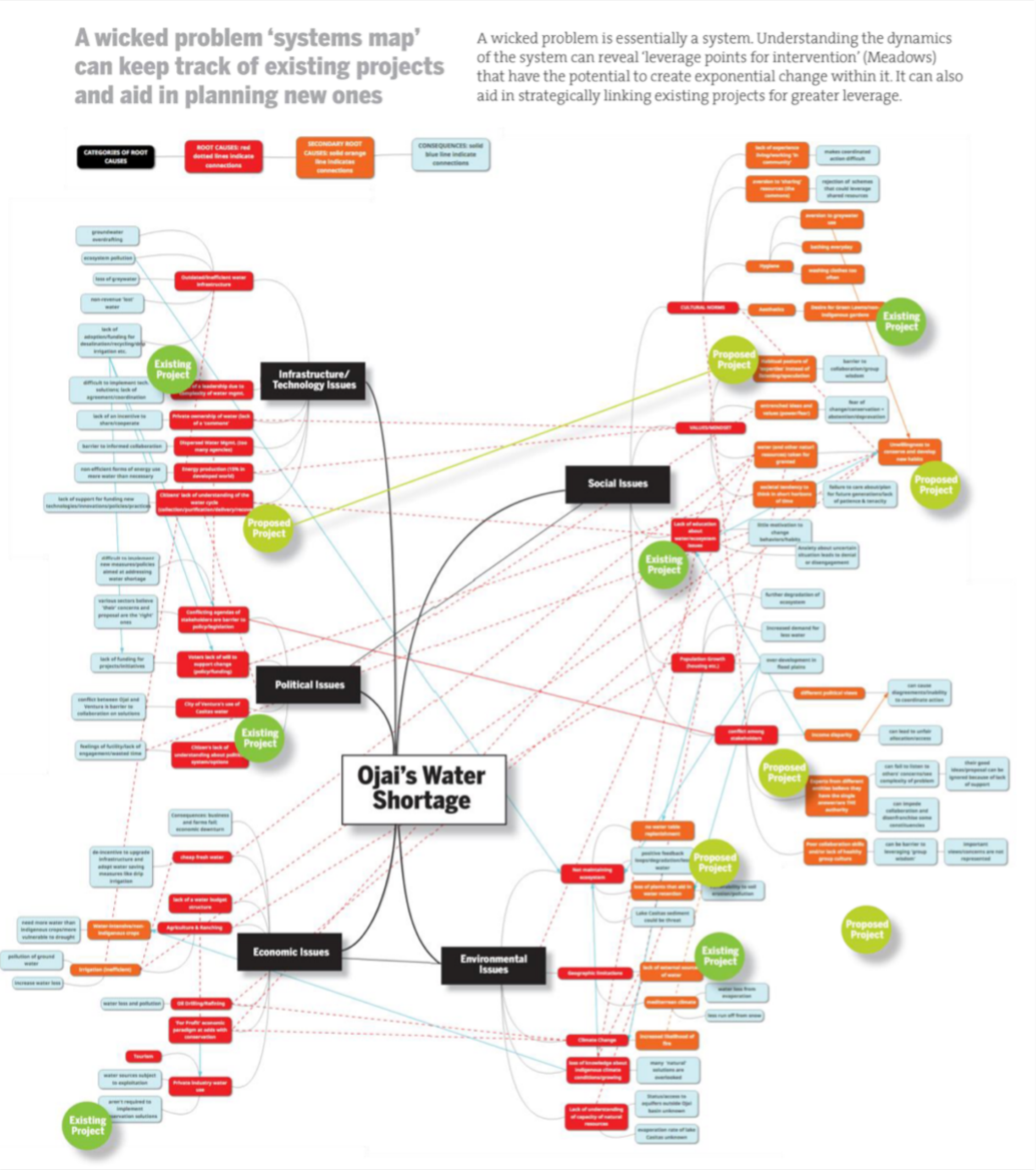
Leading the Way: energy demand and supply (TWh)

- Combination of hydrogen and electricity used in industry and to heat homes using hybrid heat pumps or hydrogen boilers
- No natural gas used to produce hydrogen
- Some use of direct air carbon capture and storage (DACCS) for negative emissions
- The only scenario to include non-networked electricity generation and hydrogen imports

Appendix 4 - Interview Questions

Introduction Questions	Framework Questions	Validation Questions
Do you think Hydrogen realistically will be used widely in 2050?, If so, for what applications?, What needs to change for us to get there?	The Framework and Insights are described step by step. Comments are invited while describing the project	What are you opinions on the roll out strategy and insights from the study?, Do any other interventions need to be added to get the this 2050 scenario? Could you see this framework being used within your industry, or for other technologies and systems?

Appendix 5 - Transition Design Wicked Problem Map (21)



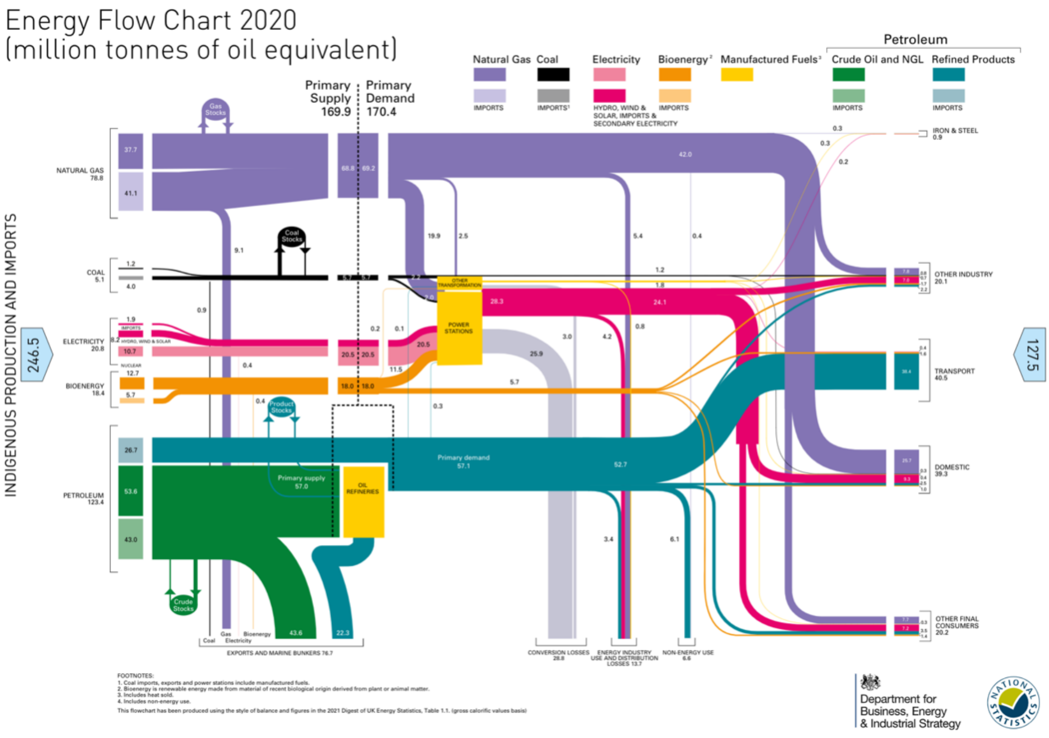
A wicked problem 'systems map' can keep track of existing projects and aid in planning new ones

A wicked problem is essentially a system. Understanding the dynamics of the system can reveal 'leverage points for intervention' (Meadows) that have the potential to create exponential change within it. It can also aid in strategically linking existing projects for greater leverage.

Appendix 6

Question	Stakeholder	Theme	Example Quote
Wicked problems for Hydrogen	BP	Safety, Price, Inefficiency, Risk	“There is a big risk with investing into Hydrogen as we want to minimise stranded assets.”
	Ceres Power	Price, precious metals, uncertainty within technology	“Biggest challenge is that electrolysis is slow. We can’t test how long they will last at the moment - so it’s very unknown how many cycles they’ll be able to go through.”
	RFC	Price, Infrastructure , Policy	“The technology for hydrogen vehicles is already there, such as the Toyota miri, however the hydrogen gas refill stations have been removed from London. Also, hydrogen vehicles are much more expensive”
	SNAM	Price, Demand	“It’s not the solution to all out problems”
	ARUP	Price, Demand	“for hydrogen you need lots of infrastructure to store and transport - and then you need to identify where this is most needed.”
	Government	Location, Infrastructure , Policy	“Decisions and roll out needs to happen so quickly, but we have never had to implement new policies and make changes so quickly.”
Applications for Hydrogen	BP	Heavy duty vehicles, Heavy Industry	
	Ceres Power	Heavy industry, Transport	
	RFC	Transport	
	Government	Heating, Heavy industry	
Stakeholder positioning	BP	Government	“Decisions within energy are largely based on politics, as policies will be made to please voters.”
	Ceres Power	Large energy companies	“Big oil companies think they can keep producing – but they can’t. The need to realise that we need to stop relying on fossil fuels and pivot in order to be successful.”
	RFC	Large energy companies	“Lab based research needs to be done by bigger companies, but industry and research goals don’t align.”
	ARUP	Government, Private companies, Regulators, Consumers	“Government and private companies are really up for change and innovation, but are nervous.”
	Government	Large energy companies, Regulators	“When making policy oil and gas companies, Ofgem, bodies and internal government are consulted.” “All these companies are trying to do the same thing and are trying to solve the same problems, but they’re not talking to each other.”
Transition Pathway	BP	Risk	
	Ceres Power	Power imbalances, Collaboration, Location, Decentralisation	“We can use Hydrogen in locations near industry consumption.”
	RFC	Carbon Tax, Demand	“Consumers won’t demand change until there is a change in taxes or access.”
	SNAM	Infrastructure	“Hydrogen first will be transported a small % in gas grid, eventually increasing percentage.”
	ARUP	Carbon Taxes, Policy, Cost, Demand, Infrastructure	“For Hydrogen to be more attractive to stakeholders we need policy to drive change. I believe in carbon taxes to drive people to change as it needs to come from top down.”
	Government	Energy security, Renewable energy, Prices, Delays	“People want their energy to be made in the uk - so there is a big shift in opinions.”.

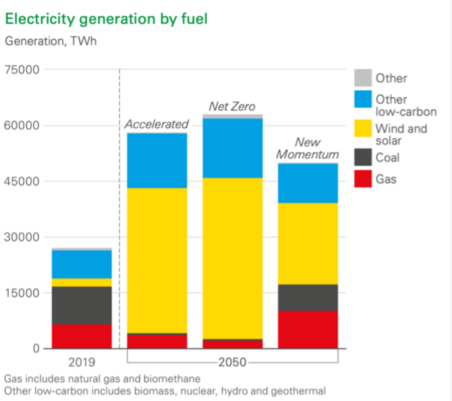
Appendix 7 - Government Energy Flow Chart 2020 (34)



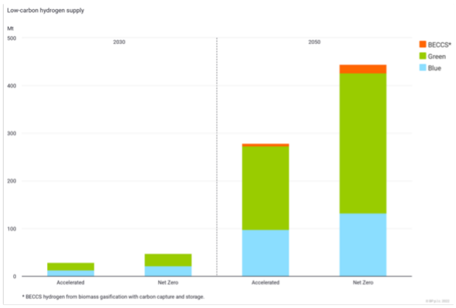
FOOTNOTES:
1. Coal imports, exports and power stations include manufactured fuels.
2. Bioenergy is renewable energy made from material of recent biological origin derived from plant or animal matter.
3. Includes heat sold.
4. Includes non-energy use.

This flowchart has been produced using the style of balance and figures in the 2021 Digest of UK Energy Statistics, Table 1.1. (gross calorific values basis)

Appendix 8 - Figures from BP's 2050 scenario (38)

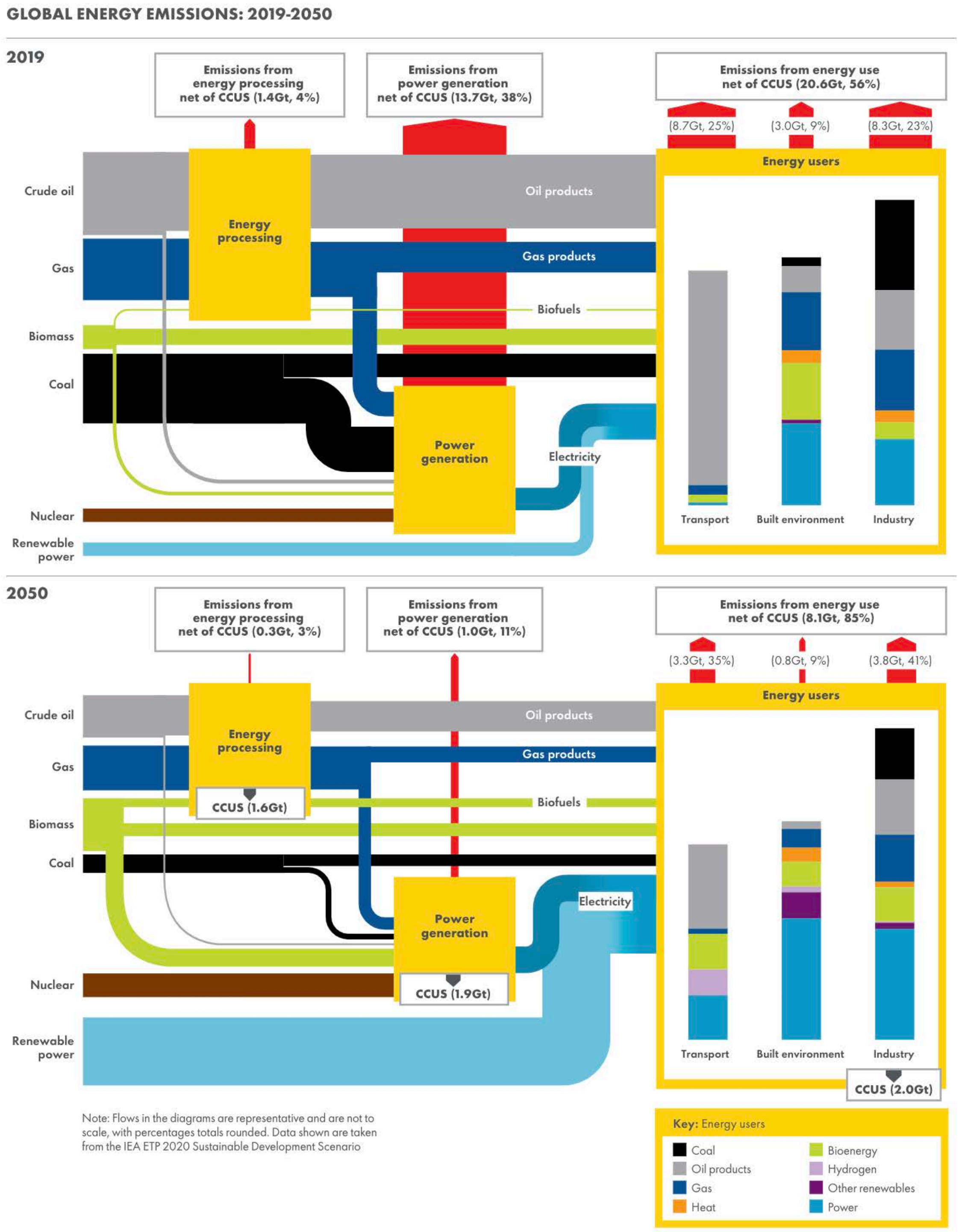


Energy production in BP's 2050 scenario



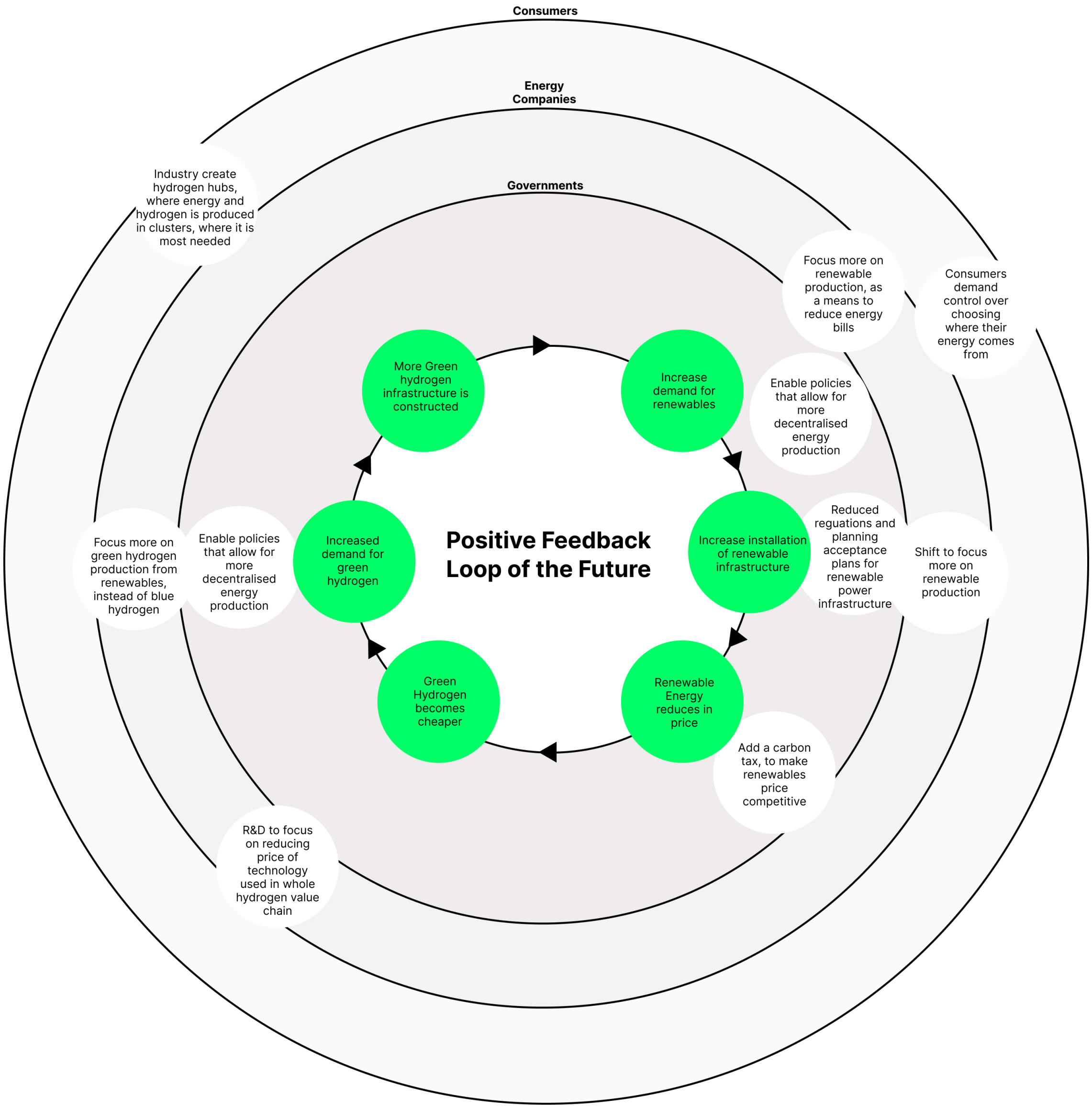
Hydrogen production in BP's 2050 scenario

Appendix 9 - Shell Scenario (39)



Note: Flows in the diagrams are representative and are not to scale, with percentages totals rounded. Data shown are taken from the IEA ETP 2020 Sustainable Development Scenario

Appendix 10 - Example of interventions that would benefit the whole energy system



Appendix 11 - Validation Thematic analysis

Theme	Sub-theme	Insight	Example Quote
Framework and Green Hydrogen scenario	Visuals	Stakeholders found the circular Sankey diagrams clear to read	“I like the clarity of the circular diagrams.”
	Modelling and stakeholder opinion	Government mentioned that the framework uses techniques used when making policy, however they don’t have set steps like in the framework	“It’s good that the framework has been informed using the modelling of stakeholder opinions from industry. For policy in government, they don’t use on singular framework but we use both modelling and stakeholder engagement.”
	Flexibility	Multiple stakeholders agreed that the uncertainty of the transition requirement a flexible future scenario is require	“Flexibility in the system will be very important.”
	Identifying wicked problems	Stakeholders liked the clear way in which the wicked problems were identified in the framework	“The energy transition causes a polynomial explosion of wicked problems. There is a great need for any framework that reduces the polynomial explosion of an energy transition.”
Applications for Framework	Private companies – making technologies	Private companies that apply to government grants need to understand how their technology fits within the system	“You see when people apply for government grants that the unsuccessful ones don’t understand the whole system and how their technology works within that system and what is feasible.”
	Private companies – investing in technologies	The framework could be used to fully understand future of system, to reduce risk in investment	“There is a need for any framework that can help them understand the value chain and minimise risk of investments”
	Collaboration	Multiple stakeholders mentioned how this framework could be used by all stakeholders to identify the problems they can solve together	“The collaboration of all of industry is truly needed for Hydrogen to scale. There are lots of individual good solutions, but to make it economical people need to work together.”
	Government Policy	Government mentioned that the framework uses techniques used could speed up the policy making process, as they need to learn so much about a system without much prior knowledge.	“This definitely makes sense and definitely is the right thing to move forward with.”
Limitations	Numerical Modelling	Stakeholder mentioned a need for numerical backing of future scenario, for example percentages of hydrogen and electricity that will be used	“I definitely think that you need more numerical element, but this way of thinking is really useful for this industry”

1.11.1 Stakeholder Quotes

BP "The energy transition causes a polynomial explosion of wicked problems. There is a great need for any framework that reduces the polynomial explosion of an energy transition and helps stakeholders understand the value chain and minimise risk of investment" "This approach would be good where there's complexity of forms of technology such as with biofuels" But precision and numbers are needed to improve the outcomes of the framework.

Ceres "It would be helpful to [use this framework to] bring the whole ecosystem together. The collaboration of all of industry is truly needed for Hydrogen to scale. There are lots of individual good solutions, but to make it economical people need to work together." They particularly liked that this framework identified the barriers to see why this technology is not being rolled out.

RFC "This framework would be useful for companies to work out who to work with. Companies don't need to know everything, as all the knowledge is there. The barriers can be overcome by working together"

SNAM "The future scenario is extremely useful" "I definitely think that you need more of a numerical element, but this way of thinking is really useful for this industry"

ARUP "The framework sounds really logical and an interesting piece of work" "I completely agree that this framework could be used with stakeholders, and I'd be interested in understanding the methodology further"

Government “It's good that the framework has been informed using the modelling of stakeholder opinions from industry. For policy in government they don't use on singular framework but we use both modelling and stakeholder engagement. This definitely makes sense and definitely is the right thing to move forward with.”