COOPERATIVE RESEARCH CENTRE FOR COAL IN SUSTAINABLE DEVELOPMENT (CRCCSD)
PROGRAM P1.2: SUSTAINABILITY DIMENSIONS AND IMPACTS

Dear CRCCSD Industry Partner:

What follows is the ninth (and final) brief discussion paper in a series written specifically for industry partners, designed to explain the key ideas behind the approach programme P1.2 is taking to sustainable development, discuss the consequences for coal-chain industries as part of a network of energy and chemical industries, and provoke dialogue and feedback. Discussion papers 1-8 are available at http://www.ccsd.biz/research/project1.2.cfm and at http://www.newcastle.edu.au/centre/casrg/research/ccsd.html.

In programme P1.2 we have developed a distinctive, forward-looking, strategic approach to sustainable development that we judge is both sound in itself and able to offer coal chain industries a superior framework and principles within which to prepare and evaluate their own responses to the increasing need for sustainable development.

The concepts and principles involved are recently emerged and may be novel to your thinking. It may not be obvious at first glance how they fit your situation. You may be able to provide us valuable examples of how they do fit your company/industry, and/or provide welcome improvement to our understanding and application of them. On all these counts we wish to be proactive in communicating them to you for your evaluation and feedback.

We recognise that your time is limited and valuable, so we will try to keep communications short and straightforward.

We thank you for attending and look forward to your feedback.

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Adaptive Analysis for Energy Policy

EXECUTIVE SUMMARY

Given a 2015-2025 technology decision bottleneck (where a wide variety of prospective energy technologies have expected wholesale cost profiles that converge on the same range, $50-90/MWh electricity equivalent), a four-period structure to energy scenario construction makes most sense: T1) short term, 2007-2013 – select initial steps; T2) 1st intermediate term, 2014-2025 – build adaptive development capacity portfolio; T3) 2nd intermediate term, 2026-2050 – energy system transformation, specialise portfolio; T4) long term, 2051-2100 – post-fossil-dominance, post-resource-intensity transition. To open up adaptive options scenarios are constructed from their end-states backwards through these stages (= backcast, rather than forecast forward from the present – see Discussion Paper #8).

The basic physical adaptive options for any scenario are the primary-to-tertiary pathways that deliver source energy to create services, because these contribute to satisfying the Basic Energy Problem [BEP] of matching energy resources to services demanded. Pathways are created when two or more distinct flows emerge from a node, creating a flow vertex; so the adaptive options can be read off the corresponding flow diagram. 'Supply' vertices are formed where two or more flows leave a node, e.g. leave a primary resource or secondary medium node, and represent options for the use of the resource at that node (where to supply energy to), while 'demand' vertices are formed where two or more flows enter a node, e.g. enter a secondary medium or tertiary consumption node, and represent options for the satisfaction of demands (where to obtain energy from). Basically, each of these options needs to be evaluated, in their pathway context, thus providing the system-wide (diagram-wide) consequences of utilising it. From this the conditions triggering its utilisation can be identified, including any decision timing interdependencies among these decisions. For example, support for fuel cells should come in the context of appropriately timed policies for the production of chemical fuel input (carbon, hydrogen or hydrogen compound) and fixed industry and/or electric vehicles that will use their output. If all this adaptive decision analysis were completed it would provide a map of the basic adaptive options for the scenario along with their policy triggers and consequences, complete contingent strategy.

The adaptive strategy portfolio represents a still broader range of adaptive options, since it keeps open all the adaptive options that appear anywhere within its member scenarios. This pool of options forms the adaptive decision space for the strategy. It provides a systematic basis for adaptive policy formation and decision making, which will consist in a policy for supporting and modifying the portfolio that spans the widest set of most satisfactory scenarios (identified in Discussion Paper #8). Even so, there will be no mechanical procedure for deciding what to do, simply an enhanced and systematic awareness of potentialities, triggers and consequences for the energy system. This is an aid, perhaps at times a crucial aid, to judicious decision making, not a substitute for it. These long-term energy system development options that are kept open have the more important economic implications because they will structure the future possibilities for employment, environmental impacts, exports, and general quality of life. Conversely, such infrastructural shifts are easier if supported by existing industrial capacity and workforce skills.

While this is the primary focus of analysis, shorter term analysis of adaptive support of services on a daily or annual basis is also possible. A short-term adaptable energy system is one that provides several alternative pathways for meeting energy demands from available resources. This allows demands to be met even if some resources become difficult to obtain, or some pathways fail. The more applications or production methods there are for each energy medium, the more alternative demand satisfaction pathways there are, and the more robustly resilient is the resulting system. One purpose of energy policy is to encourage such flexibility.

Some pathway development options have larger strategic importance, and hence are more important to keep open, than others and this can be inferred from inspection of energy flow scenarios. Integrated gasification combined cycle technology is important because it can generate the fuel required for many alternative transport applications – hydrogen, electricity, and – if necessary – liquid fuels, whereas the choice between alternative biofuels, ethanol and bio-diesel, is less important. Photolysis and industrial photosynthesis are bottleneck technologies offering hydrogen that is much less limited by constraints on supply than that from coal and gasification of agricultural biomass. Battery and compressed air vehicles, and electrolysis hydrogen, are important as options for electrical storage – which is necessary for the reliability of any future electricity supply system that is strongly dependent on renewables.

Managing developmental risk in the public interest is the proper responsibility of government. Although private enterprise can play a substantial role, it may not automatically maintain as open, industrial development options adequate to appropriate economy-wide insurance. Assigning an appropriate distribution of responsibilities via the design of governance institutions is part of the risk management policy problem.

Introduction. These notes summarise the analysis of adaptive options for use in constructing an adaptively resilient energy policy. It follows on from Discussion Paper #8, which sets out the policy framework of backcasting scenarios and adaptive strategy construction, providing a general account of how to develop an adaptive policy. Background material on energy systems organisation and constraints and on systematic scenario choice arising therefrom can respectively be found in the Research Reports *Physical Constraints and Options in Energy Policy* and *A Framework for Energy Policy Scenario Construction*.

Preliminary note on key terms. *Resilience* is the capacity to survive risk functionally intact. *Adaptability* is the capacity to induce/initiate adaptations. *Adaptive resilience* is the capacity to adapt to risk realisations so as to preserve functionality intact. Its acquisition is the most useful way to become resilient to risk. How much resilience, and of what kinds, should be acquired, and when, is a risk management issue.

To set the scene for a discussion of adaptive options recall that the future energy situation is multiply uncertain because of uncertain global supply (‘peak oil’), uncertain demands and pressures (emergence of new industrial powers) and uncertain energy technologies (many competing technologies in various stages of development). Against this backdrop we strive for adaptive resilience. In order to appreciate what this involves and have an example scenario to work with, Section I briefly recounts the scenario time framework and the specific exemplar scenario developed in the Research Report *A Framework for Energy Policy Scenario Construction.* Following that the adaptive analysis proper begins. Readers familiar with the material of Section I are invited to skip to Section II.

I. Energy Strategy and an Example Scenario

Long term greenhouse targets apply to the second half of the twenty first century while basic technologies take 30-50 years to diffuse through, and establish themselves in, the infrastructure. Further, current technological innovation in the energy domain is large, diverse and volatile. It is also faced with a decision bottleneck fifteen to twenty years hence: a wide variety of prospective energy technologies - for both demand reduction and low emissions supply – have expected wholesale cost profiles that converge in the period 2015-2025 on the same range, $50-90/MWh electricity equivalent. While these technologies presently come with varying degrees of uncertainty in cost and performance attached, it is expected that much of the uncertainty in comparative advantage will be resolved during this period. Finally, there are also uncertainties to be considered concerning the wider environmental, social and economic impacts of these technologies, positive as well as negative, in an uncertain global context. In the light of all this, in order to minimise exposure to risk before the 2015-2025 technology decision bottleneck and to maximise adaptive capacity to respond effectively to opportunities that arise during and after that period as current uncertainty resolves (but perhaps new uncertainties open up), it is appropriate to

(I) maximise the adaptive preparedness of the portfolio of specific measures adopted, including relevant technological and skill diversity,
(II) minimise large but risky irreversible decisions, and
(III) learn efficiently about relevant developments, including exploratory demonstration/ pilot programs for the most promising emerging options.

Updating action profiles as occasion demands, this combination constitutes a do-a-little-and-learn [DALAL] strategy.

After the bottleneck period there should follow a gradual process of niche adaptation and winnowing of energy technologies toward a more mature organisation of energy service provision in the longer term, as well as adding other technological options to the portfolio as they become more promising.
To illustrate the construction, there follows in Figure 2 one possible end-state flow diagram ‘Decentralised Renewables and Hydrogen’. For comparison, Figure 1 shows the equivalent diagram for our existing energy flow organisation. (It is simplified by omitting electrified rail transport and a variety of smaller stationary flows, such as local photovoltaic augmenting wind electrical generation.)

Figure 2 shows a system configuration where electricity generation is provided predominantly by a combination of solar thermal and natural gas plant and individually limited resources: wind, hydro, with some photovoltaic, wave and tidal resources. Transport is highly energy efficient and provided predominantly by electric rail and hydrogen fuel cell vehicles, which are supplied by the gasification of coal and biomass, and by biofuels produced by emerging industrial photosynthetic processes. Thermal energy by-product from gasification technology is exploited for direct industrial use or electricity cogeneration.Some vehicles also run on natural gas refined from coal seam methane. Areas suited to forestry cultivation but not harvesting, including land regeneration, are exploited as carbon sequestration sinks. Energy storage is provided by pumped hydro-electric, compressed air and electrolysis hydrogen. The electricity grid is decentralised. Due to the relative scarcity and high cost of energy, it is to be expected that both passive local source supply and service demand management measures are also strongly implemented.[1]

A brief backcast of this scenario is provided in Appendix 1 to aid as required with appreciating the adaptive analysis now to follow.

II. Within-scenario adaptive analysis.

Energy scenarios will in general contain adaptive options within them – the within-scenario options – and portfolios of scenarios will contain the aggregate of all the within-scenario options of their trajectories. In order to understand how adaptive decision analysis proceeds using these options, we begin by considering within-scenario options.

Timeless option analysis. The basic physical adaptive options for these infrastructures can be read from the diagrams. Because flow pathways must overall run down a diagram from primary to tertiary levels, every flow vertex represents an adaptive option, its location indicating its kind. ‘Supply’ vertices are formed where two or more flows leave a node, e.g. leave a primary resource or secondary medium node, and represent options for the use of the resource at that node (where to supply energy to), while ‘demand’ vertices are formed where two or more flows enter a node, e.g. enter a secondary medium or tertiary consumption node, and represent options for the satisfaction of demands (where to obtain energy from).

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[1] Recall that these diagrams focus on qualitative energy media flows, with some comparative flows sizes indicated by flow line thicknesses and abstract away all other aspects – see the Research Report *A Framework for Energy Policy Scenario Construction*, available at www.ccsd.biz.

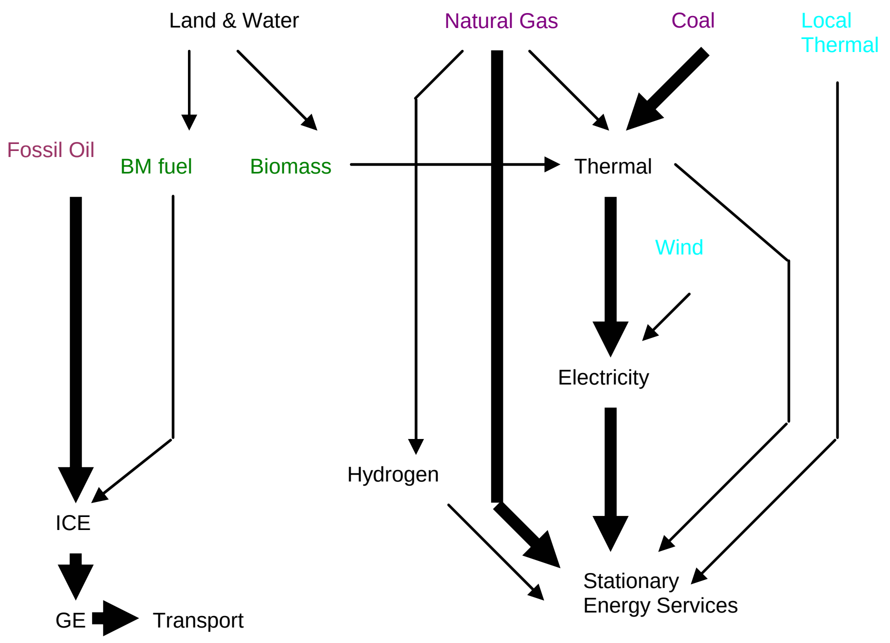
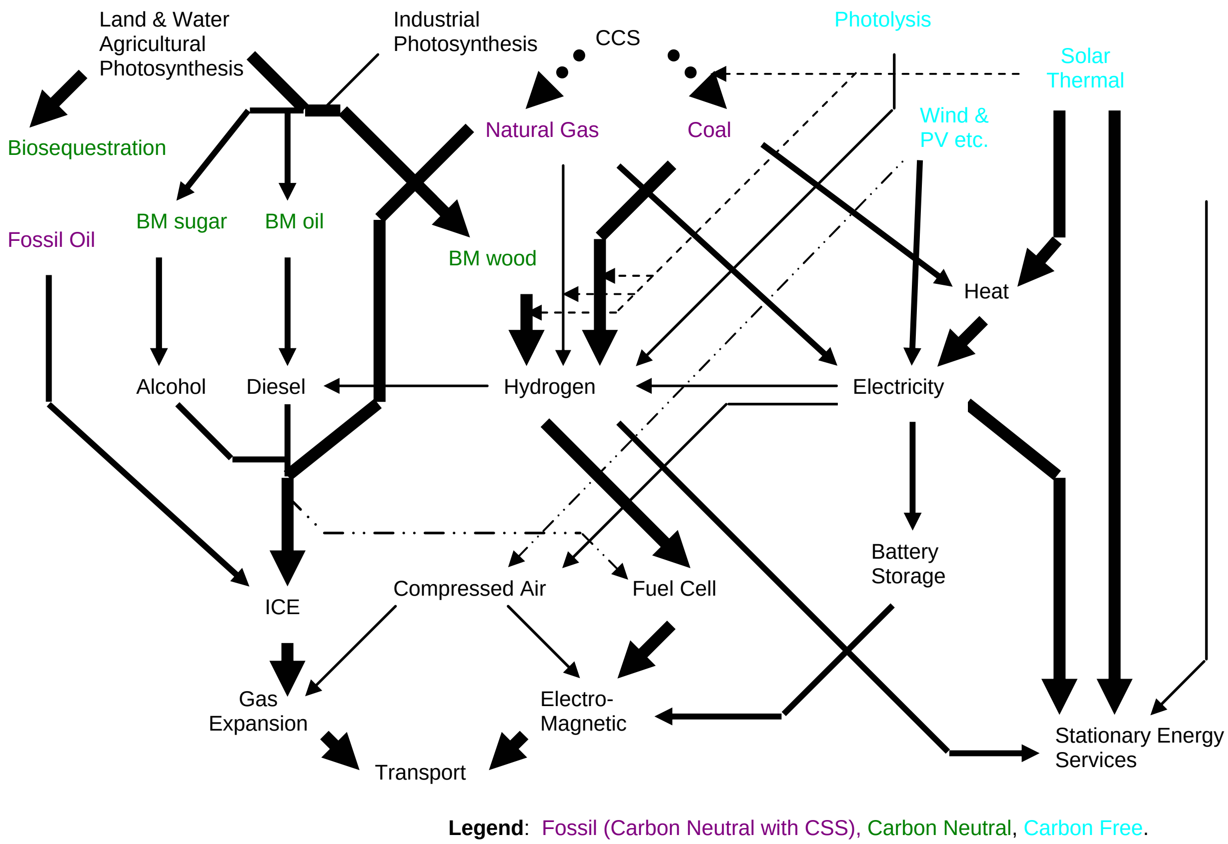


Figure 1: Current Energy Pathway Structure



Legend: Fossil (Carbon Neutral with CSS), Carbon Neutral, Carbon Free.

Figure 2: Decentralised Renewables and Hydrogen Scenario

Each of these options needs to be evaluated. However, they ultimately cannot usefully be evaluated in isolation: what matters are the pathways they create from primary resources to tertiary demands because it is these that ultimately contribute to satisfying the BEP. The supply vertices, by creating new branches, create new pathways, while the demand vertices reduce pathways by fusing them.

To provide a simple, brief, illustration consider Figure 1 again. There are six supply vertices at primary nodes and four demand vertices, two at media nodes and two at tertiary nodes, together creating 12 pathways in the diagram. Four of the supply vertices are degenerate, that is, have only one arm. The two non-degenerate supply vertices are (Dv2) the use of solar energy for growing biomass for either fuel or heat production and (Dv3) the use of natural gas to produce hydrogen or heat or as a direct fuel. Numbering the six primary nodes in sequence, left to right, and numbering the pathways they open up similarly, yields:

- (Dv1) Oil – pathway
    - (Dv1p1) Oil/ICE/GE/Transport;
- (Dv2) Solar – pathways
    - (Dv2p2) Solar/BM fuel/ICE/GE/Transport,
    - (Dv2p3) Solar/Biomass/Central Heat/Electricity/Stationary Energy Services,
    - (Dv2p4) Solar/Biomass/Central Heat/ Stationary Energy Services.
- (Dv3) Gas – pathways
    - (Dv3p5) Gas/Hydrogen/Stationary Energy Services,
    - (Dv3p6) Gas/Stationary Energy/Services,
    - (Dv3p7) Gas/Central Heat/Electricity/Stationary Energy Services,
    - (Dv3p8) Gas/Central Heat/Stationary Energy Services
- (Dv4) Coal – pathways
    - (Dv4p9) Coal/Central Heat/Electricity/Stationary Energy Services,
    - (Dv4p10) Coal/Central Heat/Stationary Energy Services;
- (Dv5) Wind – pathway
    - (Dv5p11) Wind/Electricity/Stationary Energy Services and
- (Dv6) Local Heat – pathway
    - (Dv6p12) Local Heat/Stationary Energy Services.

Many pathways are mutually fully independent, for example p1 and p3, but many are not, for example p1 and p2, because up vertices fuse them at some point. The four demand vertices in the diagram tell us, respectively, (Uv1) that there are just two ways to satisfy ICE demands, fossil oil and BM fuel, (Uv2) there are three ways to provide heat: biomass, natural gas and coal, (Uv3) there are two ways to provide electricity, heat and wind, that unpack to four ways when the three-way Uv2 choice is included and (Uv4) there are 5 ways to meet stationary energy services demands: hydrogen, natural gas, electricity, centralised heat and local heat sources (e.g. ground heat exchange, roof-top solar thermal and waste heat streams).

We can observe immediately that in this organisation, the transport and stationary sub-sectors are only weakly internally interconnected – biomass, a limited resource, being a sole, weak switching option. The transport system is thus particularly vulnerable to a loss of oil supply since there is no substantial option to replace it. By contrast there are many options to supply stationary energy demands.

Now consider activating or de-activating options. For the Dv2 vertex, one option, pathways 3 and 4, provides a carbon-neutral heat supply alongside two other carbon-neutral sources in related pathways (11 and 12) to the same services plus two further (carbon generating) alternative sources of heat (pathways 7-10). It will be important to retain this option only if constraints on all the others combined are so tight as to produce difficulty satisfying BEP; this is a key triggering condition. The other option for Dv2, pathway 2, is the only alternative to Oil for transport fuel, and a carbon-neutral one, in a general circumstance where transport is the largest single tertiary energy demand and the most difficult to carbon-neutrally satisfy. This option is the key one for easing the bite of carbon constraints in transport fuels, and the need to do so the key triggering condition for its use. Similarly, the natural gas at the Dv3 vertex offers a reduction in carbon intensity, but it is only one of three options for providing heat (pathways 7, 8) and one of four for providing electricity, 2 others carbon-neutral, all of which supply stationary energy services; so its use for heat, or directly, will be triggered by cost, availability and functional flexibility considerations. By contrast, in another option (pathway 5) it is an immediate and sole source of hydrogen in this diagram, so its use there would be triggered by the triggering conditions for hydrogen – perhaps the commitment to develop industrial electrical processes or electric vehicles that use hydrogen fuel cells to provide electricity. This gives a good feeling for how to identify the triggering conditions for options, namely in terms of the need for, or redundancy of, the pathways to which they contribute.

Evaluating an option by evaluating the pathways that contain it as a node is capturing the system-wide (diagram-wide) consequences of utilising it. From this evaluation the conditions triggering its utilisation can be properly identified, including any timing interdependencies among decisions, most obviously concerning other pathway elements. If all this were completed it would provide a map of the basic adaptive options for the scenario along with their policy triggers and consequences, that is, it would provide a contingent or adaptive strategy.

Two time frames for option analysis. The focus of adaptive option analysis sketched above can take two different time frames, (I) long-term scenario analysis, providing *infrastructural adaptability*, the primary focus of diagram analysis here, and (II) short term analysis of adaptive support of services on a daily or seasonal basis, providing *services adaptability*. Both require adaptive options and in both cases these must be provided from the same physical options, though exercised over very different timescales for very different strategic reasons.

The short term reasons will concern response to daily or seasonal variations in demand or resource availability and responses to the temporary removal of technologies from active service for maintenance or because of breakdown. Responses must consist of varying the energy flows along the subset of pathways supported by established commercial technologies at the time. Once energy infrastructure of sufficient adaptive capacity is in place, the particular energy transformation pathways that are selected to meet short term demands can change relatively rapidly. Decisions regarding the details of how these flows change over time can be typically responsibly left to market forces, provided only that the market boundary conditions are suitably regulated (for instance, with respect to carbon constraints, black start requirements, infrastructure pricing regulations, and industrial development incentives). Pathway adaptability provides the energy system with the capacity to resiliently meet variable demand from variable resources at reasonable cost (energy supply reliability). While these short term pathway decisions are not to be resolved *within* strategic energy policy, one role of such policy is to ensure the existence of the adaptive capacity that makes those decision alternatives available.

The long term reasons, by contrast, have to do with the increasing bite of carbon constraints, the rise of new technologies, shifting economic strategies and the like. The result will be expressed in the waxing of some pathways, including from zero flow (previously unused pathways), and waning of others, including to zero flow (pathway elimination). In short, infrastructural adaptability treats the diagram pathways themselves as variable, in addition to their flow magnitudes. Over the long term, technologies will shift in status from R&D to demonstration to commercial pilot to fully commercialised and pathways will alter their flow magnitudes accordingly, along with shifting skills, regulatory activities and corresponding economic spill-overs. And even among commercialised technologies, pathways may be allowed to shift their flow capacities and temporal flow profiles, some even withering away. In fact, technological learning and changes in flow will tend to be mutually reinforcing as technical improvements attract increased flows and vice versa. These kinds of structural adaptabilities are enabled by having a range of technological options, associated with sufficiently mature industries and skills bases, and sufficient customer sophistication, to support alternatives. The long-term energy system development options that are kept open have the deepest economic implications because they will structure the future possibilities for employment, environmental impacts, exports, and general quality of life. Conversely, such infrastructural shifts are easier if supported by existing industrial capacity and workforce skills.

In general, the energy system will realise greater adaptability, both short and long term, the more alternative demand satisfaction pathways there are and hence the greater the number of actual, and potential, alternative routes there are into and out of each node in the energy network diagram. For example, major adaptive options for the generation of hydrogen in the Figure 8 scenario include gasification of either coal and/or woody biomass and, as a minor alternative, de-carbonising natural gas, but there are also background possibilities to generate it from industrial photosynthesis, photolysis or electrolysis should circumstances prove favourable. Concentrating solar thermal technology may be used not only to generate electricity directly, but also to produce thermal energy for industrial processes, including the provision of an energy boost to carbon capture (for storage), and/ or boosting gasification processes. Interconnections and hence pathways increase non-linearly; adding a single new connection to an already richly interconnected network will in general add many new pathways often involving parts of the network distant from the addition. The more pathways there are among a range of technologies the wider the range of conditions across which the pathway exploitation possibilities will leave the resulting system robustly resilient.

Importantly, development of a new pathway is in general easier if supported by existing pathways and nodes. For example, the technology cluster of this scenario provides reasonably good support for the production of hydrogen from photolysis, or via industrial photosynthesis, because of the existing demands for hydrogen. This support would not be as strong if there were a greater focus on biofuels for use in the internal combustion engine. There is also industrial development support for biomass combustion for thermal electricity production, given the likely smaller scale and distributed nature of solar thermal electricity generation, and existing familiarity with woody biomass agriculture. In contrast, this technological configuration offers less support for a nuclear industry due to the industry’s specialised technological nature. These are subtler but important aspects of considering vertices in their larger pathway, and ultimately system/diagram, contexts.

Conversely, energy technologies should not be considered in isolation, they should instead be identified in terms of their pathway roles. For example, the fuel cell may be thought of as a new electricity generation technology and hence as a stand-alone source. In fact, its pathway role is to permit chemical storage to substitute for electrical storage, particularly in transport technology. This means that it cannot be considered as stand-alone; unless it is supported on the primary side by a source of chemical fuel (hydrogen or hydrogen compound) and on the tertiary side by a suitable electric vehicle, it is impotent. Similar pathway considerations (though different in detail) would apply to the consideration of fuel cells for use in stationary industrial energy provision, for example as direct injection carbon engines for electricity generation (n. 3). In short, the relevant policy is a coherent policy for the entire pathway.

As for Figure 1, the pathways of Figure 2 enable the identification of some of the more structurally important choices. For example, the choice between bio-oil and bio-ethanol, both of which exploit agricultural photosynthesis for production and are to be used in the internal combustion engine, is less significant than the choice between these biofuels and hydrogen from gasified woody biomass or coal. This is because the latter significantly opens up the prospect of hydrogen fuel-cell vehicles. And, as the diagram shows, opening this prospect may support the emergence of photolysis and/or industrial photosynthesis, both important prospective hydrogen generation options because they are in principle far less quantitatively limited than the alternative pathways (that is, by carbon capture and storage constrained fossil fuel gasification and land and water limited agricultural photosynthesis).

Again, we learn from observing the right hand side of the diagram that the production of hydrogen by electrolysis provides a valuable storage option for electricity, which may be required if thermal storage and large scale compressed air energy storage are not realised. This is because the alternative electricity stores - vehicle batteries, decentralised vehicle compressed air storage, and (pre-electricity generation) coal – are small in magnitude. However, where solar thermal energy is used for stationary applications, whether it is exploited directly or via electricity has only moderate economic structural implications (direct use requires a more decentralised operations and maintenance regime), although it does have important implications for overall energetic efficiency.

In contrast, strong uptake of battery electric or compressed air vehicles would be a structurally significant development, providing a significant storage option for electricity at the same time as increasing electricity demand while reducing pressure on the need for chemical fuels. Particularly in this context, the option provided by integrated gasification combined cycle technology, to switch the energy medium generated by coal between hydrogen to electricity, is important because it enables this greater adaptive flexibility in the transport vehicle market. This allows customers to choose between the simplicity of batteries, including the convenience of recharging their vehicles from their own homes, and the range offered by fuel cells when combined with filling up at commercial hydrogen supply outlets. This technology additionally enables the generation of liquid fuels by further chemical processing which would prove valuable if improvements in on-board reformation of hydrogen from liquid fuels tip the vehicle fuel cell technology balance in favour of storing hydrogen chemically in liquid fuel form.

Of course any of these structural changes would have consequential implications for employment and general quality of life, plus wider environmental impacts. Industrial photosynthesis would have significant implications for rural industries, depending on its particular manifestation, either transforming the practice of biomass agriculture or reducing the need for it, while increasing the requirement for biochemistry and chemical processing skills. If viable at small production scales, photolysis hydrogen might result in a significant decentralisation of transport fuel generation, and provide more employment for the building industry.

The organisationally most important choices in the exercise of adaptive options are those that affect the overall pathway organisation of the energy system by introducing or removing significant pathways. The introduction of hydrogen and fuel cells, we saw, is much more important than the choice between bio-oil and bio-ethanol because the latter introduces a new transport pathway, with the possibility of many more connections to stationary energy, while the latter simply introduces a partial pathway variant. Least important adaptively are changes in single technologies within the same pathway role, such as an efficiency improvement. Indeed, the root conflict between adaptability and efficiency is that between more pathways, requiring more investment in fixed capital and maintenance, and hence lower overall efficiency, and fewer but more efficient pathways, requiring reduced adaptive pathway choices. This is resolvable only by compromise fitted to the prevailing circumstances.

The next step in the choice of pathway options is their evaluation. We will not explore this complex issue in any depth here in order to stay focused on adaptiveness identification. There will be little controversy in including the following among the evaluative factors: (i) the real options value of introducing, or increasing access to, an option by investing in the relevant technologies of, and/or balancing up flows among, its arms or, conversely, the options cost of exercising an option currently open by favouring one of its pathways over others, (ii) the direct costs and benefits of these actions, (iii) the equity value of the decision, for example its impact on rural amenity access, and (iv) its wider economic impact (on skills, innovation, etc.). Some combination of such factors will make up an option creation/exercise (destruction) evaluation function. Among them these factors capture the relative organisational importance of options.

The collection of all adaptive pathway alterations, organised by value and inter-dependencies upon one another, forms the within-scenario adaptive options space. It informs policy decision makers about how to exercise adaptive options within a given scenario as the arrival of new information on larger conditions, such as technological and economic changes, impinges upon choices within it.

These decisions may end up changing the qualitative orientation of the configurations in the ensuing trajectory. As they have been described earlier, the end-state energy configuration of a backcast scenario is enabled in advance through a set of sequential timed actions (e.g. to invest in R&D for technology A or create an incentive scheme for switching to fuel B) such that each successive system configuration retains the same general qualitative orientation throughout, e.g. to be fossil fuels oriented or nuclear electricity oriented. Identifying these preparatory decisions is the purpose of backcasting analysis. However we have seen that an adequately adaptive energy configuration will typically also contain within itself many options to act in response to changing conditions, e.g. by shifting flows among pathways – see Figure 3. Many ways of exercising these options will simply lead to energy configurations that are variations within the same overall qualitative orientation, e.g. shifting flow proportions between wind- and photovoltaic- generated electricity within an all-solar scenario. Some of these decisions, however, may impact on the developmental direction itself, ‘morphing’ the configuration trajectory in a significantly different developmental direction that diverges increasingly from the original orientation. E.g. the original scenario may have called for the development of IGCC thermal electric capacity with carbon sequestration as part of a carbon-sequestered all-coal scenario with transport energy supplied by coal liquefaction. The decision to use an increasing proportion of the IGCC plants to instead generate hydrogen in pursuit of an all-hydrogen scenario represents an increasing divergence from the all-coal orientation.

Such decisions must be incompatible at some point with the preparatory decisions for the original scenario. They amount to a decision, presumably taken in the light of changing circumstances, to no longer keep open some or all of the adaptive options kept open by pursuing that qualitative orientation. Acting in this way is not always necessary, but adaptive options were set up to provide for such decisions as well as for the more conservative ones that maintain the original qualitative orientation. Assuming that the original collection of satisfactory end-states from which backcasting was done was qualitatively complete, then the new trajectory will either now lie on that of some other scenario (in the example, on the scenario for hydrogen orientation) or terminate in an unsatisfactory end-state. If these conditions fail then either the morphing decision was in fact unacceptable, or the original collection needs to be augmented by a qualitatively new and satisfactory end-state that backcasts on to the newly identified configuration.

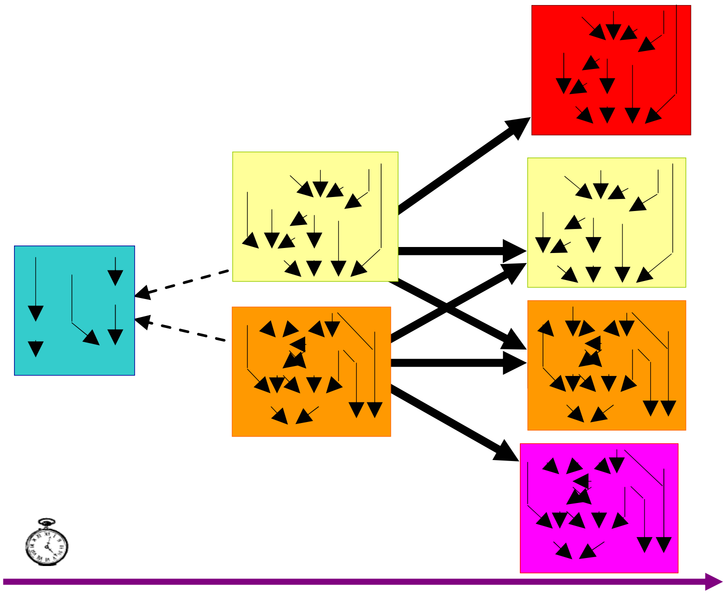


Figure 3: Morphing Scenarios

III. Portfolio analysis.

Beyond this within-scenario analysis, a portfolio of scenarios represents a still broader range of adaptive options, since in principle it keeps open all the adaptive options that appear anywhere within its member scenarios. As a first, simplified example, suppose each scenario in the portfolio were comprised of just a single energy technology, and the technologies were mutually independent of each other; then the portfolio holding these scenarios as members would provide the options of pursuing any mix of the corresponding technologies – see Figure 4. Any given technology mix could be determined by assigning support weights to each component scenario, hence technology, such that the sum of weights = 1. Weights may include 0, eliminating a technology from consideration, and of course new technologies can be introduced as they are invented, re-distributing the weights. Over time weights can be expected to vary as circumstances unfold. In this artificial example no scenario has any within-scenario options, so all the policy adaptiveness lies in the choice of portfolio weights. The choice and modification of the weighted mix provides the systematic basis for adaptive policy formation and decision making.

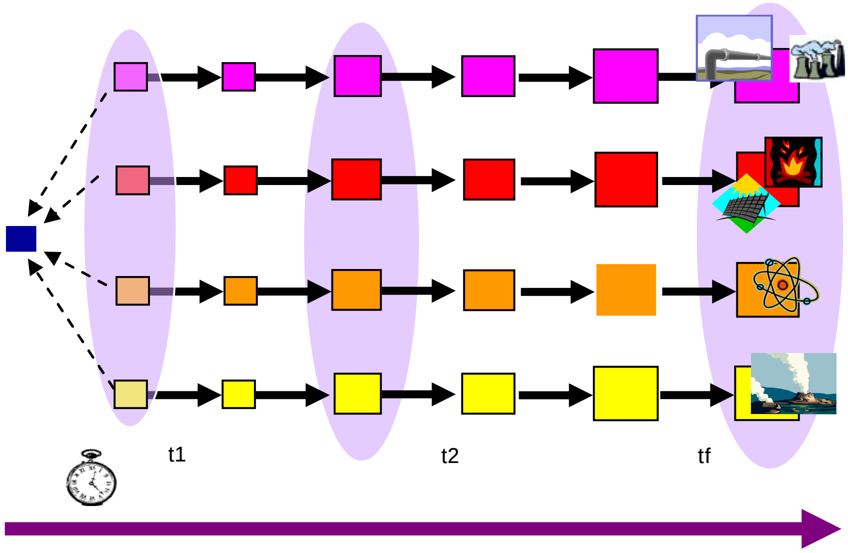


Figure 4: Simple Portfolio Backcasting

However, we have seen that individual BEP-satisfying scenarios are comprised of energy configurations that are in general more complex than those in this artificially simple case, especially if selected to promote within-scenario adaptive options. In that case the scenario portfolio holds these more complex scenarios and the portfolio content evolves along with evolving scenario content – Figure 5. A desirable adaptive scenario portfolio is one holding the widest feasible class of the most satisfactory scenarios for achieving all of a selected range of physically plausible and societally desirable end-states. The member scenarios could also be weighted to reflect a variety of development priorities.

A portfolio is constructed over its member scenarios snapshot by snapshot – see Figures 4, 5 allowing them to evolve with their member scenarios and with incoming new information. Call a portfolio at any given time, a portfolio snapshot at that time, and the configuration states of each of its member scenarios at any given time, scenario snapshots at that time. At each time the portfolio snapshot is essentially obtained by aggregating all the corresponding scenario snapshots of its member scenarios. But a mere aggregate is unordered, it will contain both repeated and competing configuration fragments and thus it will not be clear how the snapshot relates to an operating societal energy system at that time, that is, how it is to satisfy the BEP.

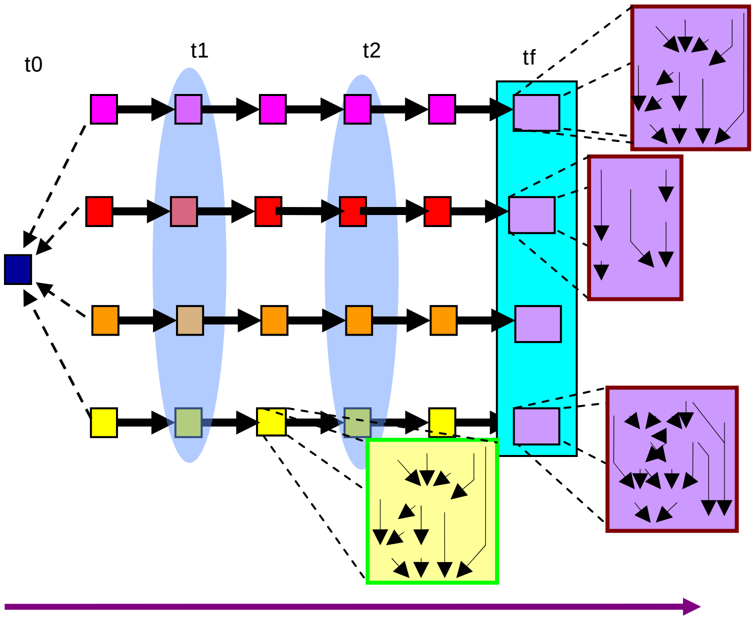


Figure 5: Portfolio Backcasting

To obtain a more intelligibly ordered structure from the scenario snapshot aggregate, follow these steps:

1. label each element by its developmental stage – say, R&D, pilot, commercial demonstration, commercial;
2. identify all redundant configuration fragments and remove the redundant copies;
3. retain those remaining and labelled commercial as an operating core configuration;
4. incorporate the non-redundant commercial elements into the configuration, minimising the additional energy flow pathways to do so;
5. repeat the step 4 successively for each of the less developed stages, so that all these technological advancement options are added into the configuration.

The options kept open in this configuration – let us call it the minimal portfolio configuration (at time t) – will be all those kept open among the scenario snapshots making up the portfolio at that time. It comprises a commoner core configuration enriched by an inner 'belt' of commercialised energy technologies and their additional pathways and two outer belts (say) comprised respectively of R&D, and pilot/ commercial demonstration, of particular energy technologies and their additional pathways. If, in addition, the member scenarios of a portfolio snapshot are weighted to reflect developmental priorities then notional flows can be assigned to the component pathways of the outcome portfolio configuration in a variety of ways.[2] The aim is not to reconstruct some uniquely correct 'shadow' flow, but simply to track development priority in the outcome snapshot, providing a waypoint in the overall process of construction of an adaptive strategy.

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[2] The simplest way to do it, is to assign flows to all pathways in each scenario snapshot as if it alone satisfied the BEP at that time then, in the simple aggregate configuration, change step 2 to calculating, for each element (redundant or not), the sum of the individual flows weighted by their respective priorities. (If unassigned, commercial demonstration could be assigned 2.5% of the flow assigned to the relevant sub-sector, pilot 1% and R&D 1%.) Then continue with steps 3-5. The flows in the resulting minimal portfolio configuration will then reflect developmental priority.

The analysis of within-scenario pathway options and decision inter-dependencies, and decision trigger points for a scenario snapshot, can now be incorporated into the corresponding portfolio snapshot decision ‘landscape’ that indicates the key contingent strategies for modifying the minimal portfolio configuration. A strategic policy will consist in a policy for supporting and modifying the portfolio snapshot that spans the widest set of most satisfactory scenarios, using the portfolio decision landscape. As the discussion will have made clear, there will be no mechanical procedure for deciding what to do, simply an enhanced and systematic awareness of potentialities, triggers and consequences for the energy system. This adaptiveness analysis is an aid, perhaps at times a crucial aid, to judicious decision making, not a substitute for it.

This minimal portfolio configuration can be retained as an abstract construct for strategic planning purposes, but in practice some actually realised configuration must also be the basis for supplying energy for the time being, and preferably at minimal additional cost. Even setting aside the non-commercial elements, so long as substantial options among commercialised technologies are being kept open, the resulting commercialised configuration will contain more capacity than is required for satisfying the BEP. A redistribution of energy flows among these technologies will have to be made, (i) sufficient to maintain each in a condition to be expanded should future developments dictate (that is, to maintain each as a real developable option), and (ii) while minimising wastes and consumer costs. These requirements may partly conflict; in that case a judicious minimax compromise will have to be reached. Similar considerations apply to retaining the pre-commercial options as real options while maintaining the cost of doing so within reasonable bounds.

At the close of Section *I* above we noted that information entering the system may cause various options to be exercised in ways that will morph a scenario over into some other one. There is a special case of this worth noting. Figure 6 illustrates how two hitherto distinct scenarios with significant infrastructural commonality can each be morphed into a single common hybrid scenario. Here the two original scenarios are lost and replaced by a single new one. As before, the original collection of end-states originally identified needs to be augmented by a qualitatively new and satisfactory end-state that backcasts on to the newly created configuration. Hybridisation might be contemplated if, for example, there were already sufficient natural commonality between the two scenarios or an adaptation due to new information was contemplated that would morph the system configuration trajectory from one scenario toward the other, and new information changed developmental priorities so as to emphasise the commonalities.

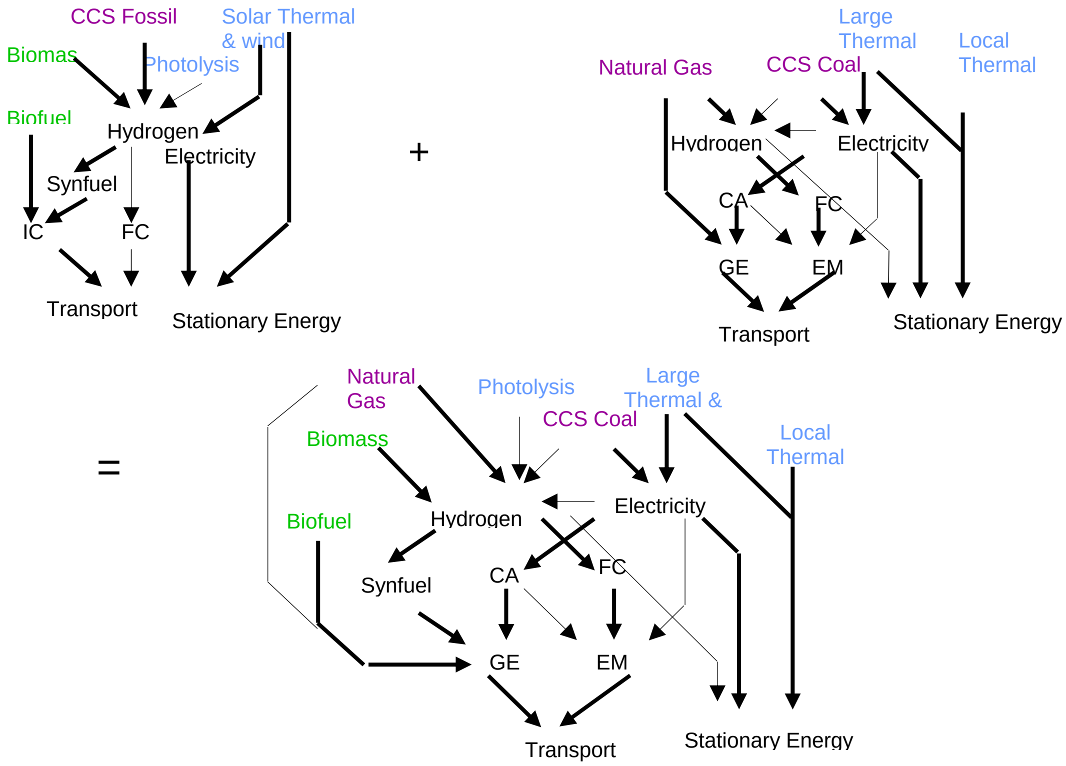

Figure 6: Scenario Hybridisation

A portfolio snapshot will change over time through three influences: (I) The component scenario snapshots already anticipate change over time as the scenarios develop; most obviously, pre-commercial energy technologies will mature toward commercialization. These changes may actually happen as time unfolds, in which case the technologies and their pathways will increase in capacity and some earlier dominant technologies and their pathways will decline or disappear – see Figure 7, third lineage . (II) Other information entering the system, e.g. that some technology had failed to live up to expectations, or reversely that it was successful and with unexpectedly wide applications, and such information may cause various options to be exercised in ways that will remove a scenario from consideration in favour of some other one – see Figure 7, bottom lineage. The portfolio then changes its composition. (III) If developmental priority weights have been used, these may also be altered in the light of either of the preceding developments. When the scenario mix has changed, as (I) and (II) contemplate, then generally scenarios will be re-weighted to reflect their new developmental priorities among the new ‘basket’ of scenarios held in the portfolio.

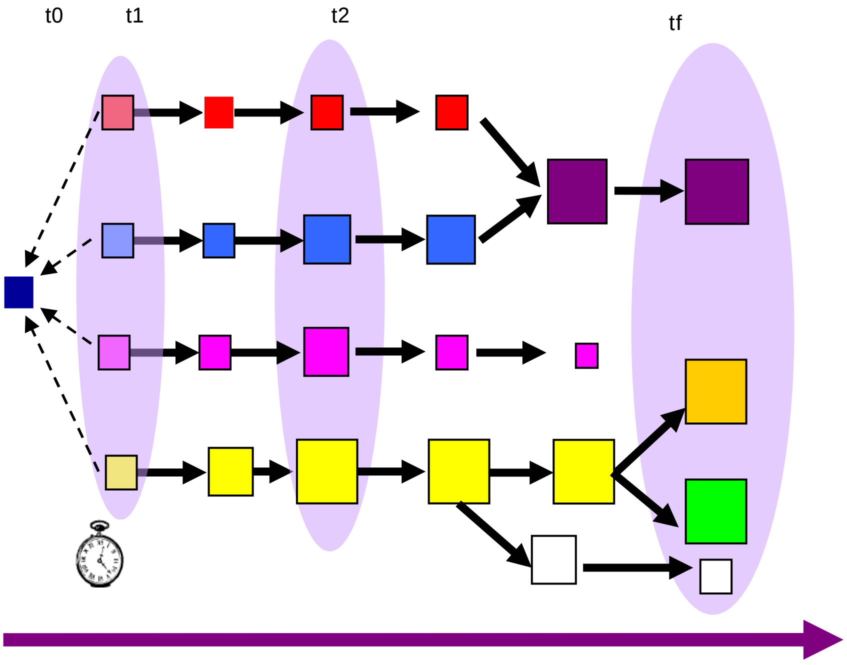

Figure 7: Portfolio Adaptation

What remains before action is the policy design problem: for a chosen adaptive initiative, design a policy that will simultaneously (A) be a rational solution for the future provision of energy, (B) be publicly supported, (C) attract the required capital, (D) be effectively manageable, and (E) be politically viable, and all of these on terms consistent with the public interest. As stated the problem is unsolvable, since the divergence of interests of the public, business, bureaucrats and politicians that respectively lie behind these conditions is typically too large to find substantial, let alone complete, common ground.

Of many contemporary energy examples, the following two illustrate the difficulties. Many states have imposed a Mandatory Renewable Energy Target [MRET], but while this stimulates some investment in renewables, in isolation it also has the effect of channelling investment into the lowest cost technologies at the time, driving out the technological diversity sought for future adaptiveness. Again, wise energy investment is currently a highly capitalised, highly skilled and risky venture; on the one side societal choices have left public institutions that are typically too budget constrained, risk averse and bureaucratic to cope effectively while, on the other side, private capital requires compensating investor confidence that can often only be provided by political market-shaping policies, such as a committed carbon tax regime, that are themselves of uncertain effect and effectiveness (witness the initial European experience with carbon trading). For example, a present danger is that poorly designed and too severe 2020 carbon emissions reduction targets (as opposed to 2050 targets), set under joint public and private pressure, will so constrain available investment capital as to again drive out investment in required adaptiveness.

Furthermore market-shaping policies invariably have significant redistributive impacts by the creation and elimination of rights, particularly property rights. This has the undesirable consequence that the most politically feasible public policy choices are invariably those where any uncompensated negative impacts are disproportionately borne by the most marginalised.

However, prudent energy policy requires the development of public institutions that are capable of responsibly making adaptive decisions, that is, that do not follow any pre-specified prescription, while maintaining both coherence over time and distributive justice, and this is itself a challenging design problem.

Responding to risk in the public interest is ultimately the proper responsibility of government. While substantial components of doing this can be assigned to private enterprise operating in the economic market, there are limits to this strategy. Since keeping industrial development options open generally requires substantial economic investments in diverse areas from physical infrastructure to employable skills, with uncertain payoffs to uncertain beneficiaries at uncertain times in the future, not all development options that are nevertheless socially prudent will be adequately maintained by either the unshaped economic market or the unshaped public bureaucracy. Developing an appropriate distribution of responsibilities is a wise art that is itself part of prudent public risk management - and so should be done in a way that is itself adaptively resilient to changing needs.

Appendix 1: Backcast Sketch of Scenario End-state ‘Decentralised Renewables and Hydrogen’

By 2050 electricity generation is provided predominantly by a combination of solar thermal and natural gas plant and individually limited resources: wind, hydro, with some photovoltaic, wave and tidal resources. Transport is highly energy efficient and provided predominantly by electric rail and hydrogen fuel cell vehicles, which are supplied by the gasification of coal and biomass, and by biofuels produced by emerging industrial photosynthetic processes. Thermal energy by-product from gasification technology is exploited for direct industrial use or electricity cogeneration. Some vehicles also run on natural gas refined from coal seam methane. Areas suited to forestry cultivation but not harvesting, including land regeneration, are exploited as carbon sequestration sinks. Energy storage is provided by pumped hydro-electric, compressed air and electrolysis hydrogen. The electricity grid is decentralised. Due to the relative scarcity and high cost of energy, demand management measures are also strongly implemented.

Decentralised Renewables and Hydrogen: Second intermediate term - 2025-2050

In coastal areas, the construction of solar thermal electricity generators complements the existing generation network. The construction of solar thermal electricity generators (at inland locations that best trade-off transmission costs against increased coastal cloud cover) complements the network providing electricity to predominantly coastal areas. The wind market is mature. After decades of development, wind turbines are much larger and more powerful, but also capable of producing power in lighter breezes. Bulk compressed air storage is now being developed to integrate with gas turbine electricity generators. Many of the larger gas turbines are fitted with carbon capture and storage processes, which are hybridised with solar thermal input. After several decades of technological development, the bandwidth and efficiency of photovoltaic generation has increased, and its total cost has decreased, significantly. Most firms and households are able to afford their own panels, and favourable sites for concentrating solar photovoltaic electricity generation are developed as aging coal fired power stations are retired. Urban solar property rights legislation is implemented on a wider scale towards the second half of the term. Wave and tidal resources also supply electricity in places where it is cost effective.

Industrial processes are transitioned to electrification as much as possible, although some use hydrogen as a fuel, when industrial processes are located sufficiently close to gasification plant. Extensive use is made of cogeneration of electricity and heat wherever possible. Some electricity load management storage is achieved by the production of electrolysis hydrogen for transport fuels.

In this period there is a major transition (from internal combustion engine and natural gas fuel cell vehicles) to a majority hydrogen fuel cell electric vehicles plus a significant minority of light battery electric or compressed air vehicles (some supplied from local photovoltaic or wind sources). Existing integrated gasification combined cycle electricity generators are fueled with increasing biomass ratios and produce less of their output as electricity and more as hydrogen. Solar thermal energy is increasingly used to provide energetic input to the chemical synthesis process. More gasification plants, but at slightly smaller scales, are built in areas close to forestry (and some agricultural) biomass energy resources and major regional centres experience significant growth in population and economic activity. Major hydrogen distribution networks are developed, scaffolding on existing natural gas and petroleum networks where possible. Freight transport is served by hybrid electric/ fuel cell rail for some routes and by hydrogen fuel cell road transport on others.

Decentralised Renewables and Hydrogen: First intermediate term - 2013-2024

Integrated coal gasification combined cycle [IGCC] electricity generators are constructed to meet increases in electricity demand. These are fitted with carbon capture processes, and are suitable for up to 100% biomass substitution. Biomass fuel is increasingly substituted for coal as biomass agriculture develops, and IGCC technology and operational management increasingly focuses on the efficient production of syngas and hydrogen rather than electricity. Agricultural, industrial and other sequestration of carbon captured by plants from the atmosphere now generates a cash flow through sale of the corresponding carbon credits accrued. There is extensive demonstration of solar thermal plant, in particular including hybridisation with carbon capture and storage for coal based electricity generation.

Windmills are constructed on high quality wind sites. There is some energy storage by electric batteries, and electrolysis hydrogen for vehicles is increasingly required towards the end of the period. A small number of centralised concentrating solar photovoltaic farms are demonstrated taking advantage of local manufacturing capacity in solar concentrator technology. Newly installed industrial processes are constructed with the potential for electrification and/or use of co-generated heat, existing industrial processes are investigated for their retrofit potential. Medium scale, direct current, electricity networks - which are isolated from the main grid - support local low energy residential and commercial communities in some areas, especially where appropriate storage (compressed air, pumped hydro, batteries for electric vehicles) is readily available. These communities are connected to regional destinations by light electrical rail, and eventually prove to be quite popular. Aided by the awareness created by new solar-access regulations, and the demonstration of new low energy communities, there is substantial uptake of one or more of photovoltaic electricity generation, solar thermal water heating, passive solar lighting and solar climate control (passive heating, air conditioning). Energy efficient building regulations and the rising cost of electricity reinforce the trends.

Natural gas is used as a transport fuel, first for internal combustion engine vehicles and later for natural gas fuel cell vehicles. Natural gas distribution networks for transport develop, and a few new gas turbine electricity generators are installed. There is a small uptake of electric vehicles, mostly light vehicles, which in addition to natural gas fuel cells create a demand for electric drive technology. Developments in power electronics lead to improvements in generators, drives and inverters also supporting developments in motor vehicle technologies. Speed limited light vehicles up to 400kg (including motorised bicycles) are permitted on cycleways enlarged to separate these from bicycles, and they are granted exclusive access rights to some urban roads. The popularity of more fuel efficient light vehicles is further increased by the high cost of petrol. Diesel road transport remains the mode of choice for freight, with some moves towards natural gas. The economic and technical feasibility of intermodal (road and rail) freight articulation is investigated.

Effective hydrogen storage methods for transport applications are developed and demonstrated. These storage methods provide high energy densities by mass and by volume, and are designed for safety in the event of high speed collisions. A small number of hydrogen fuel cell vehicles in the "light" classification are produced, initially fueled by electrolysis hydrogen, but these are initially restricted in speed and not permitted to travel with heavy vehicles due to safety concerns. Towards the end of the period, as confidence in the safety of hydrogen fuel storage increases, a small number of heavier hydrogen fuel vehicles are introduced to urban centres where there is currently high particulate air pollution and where the market for hydrogen fuel is large enough to justify investment in transmission infrastructure. Hydrogen production is primarily from coal gasification, but there is some commercial experimentation with efficient electrolysis. Carbon capture and storage is demonstrated, with trialling continuing on variants; a few fully commercial plants appear toward the end of the period. Biomass gasification for hydrogen production in existing coal gasification plants is demonstrated.

Decentralised Renewables and Hydrogen: Short intermediate term - 2007-2012

IGCC electricity generation suitable for biomass fueling is demonstrated. Small quantities of biomass are substituted for coal in traditional boiler generators, mainly in order to stimulate bio-energy agriculture. In addition, efficient methods of pre-drying biomass are explored. The suitability of alternative dedicated bio-energy crops for combustion and/or gasification in various regional areas are investigated. There is the first construction of an IGCC plant suitable for hydrogen production, and trial of carbon capture and storage. A good understanding of the suitability and retrofit potential of using existing petroleum pipelines for the transmission of hydrogen is developed, and cost-effective materials are identified for constructing pipelines for hydrogen transmission. Research into effective mechanisms for hydrogen storage continues.

No regrets energy efficiency improvement measures are introduced to forestall the need for the construction of significant new electrical generation plant while developments in wind powered generation and photovoltaics continue. Natural gas and wind supply fill any remaining shortfall. There are some significant breakthroughs in concentrating solar photovoltaics that promise moderate cost solar electricity in the foreseeable future. A small number of residential developments explore the potential for low consumption demonstration communities.