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## **PHYSICAL CONSTRAINTS AND OPTIONS IN ENERGY POLICY**

### **RESEARCH REPORT 78**

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## EXECUTIVE SUMMARY

Overall energy flow in a societal energy system has three stages: primary source to secondary fuel media to tertiary services production. The secondary stage is comprised of fuel media: electrical, chemical, mechanical and thermal. These have a systematic ('diamond') inter-conversion structure with conversion inefficiencies attached to each connecting pathway. Each energy technology is located at one of these stages and corresponds to a pathway down into or out of, and/or around, the conversion diamond, characterised by its combined inefficiencies and consequent waste streams. The Basic Energy Problem [BEP] is to align the 3 stages so that services demand is effectively met by source supply. This overall framework provides the physical constraints on choices for designing an adequate system.

It also provides the physical options/contingencies to be considered. Each source with more than one primary technology route converting it 'down' to fuels creates an adaptive option (a 'supply vertex' or fork on the flow graph), similarly each tertiary service supplied by more than one secondary fuel creates an adaptive option (a 'demand vertex' ) and each pair of inter-fuel conversion pathways between nodes in the fuel diamond creates further such vertices. Together these define the basic physical adaptive options available.

When designing energy scenarios, the first decision is that concerning the scale of demand modification initiatives, with large heating/cooling demand being especially responsive to management tools. There follow 3 decisions concerning the roles of the four fuel forms: (I) how transport and essential chemical energy demands are to be met, (II) how decentralised will be the meeting of the residual demand for stationary heating and cooling, and (III) what will be the relation of stationary energy technology to that of transport technology.

*Example of decision (I): provision of transport energy.* Though taking several forms, there are foreseeably just two alternative tertiary drive technologies that convert stored energy into linear motion: gas expansion (GE, e.g. internal combustion engine) and electromotive (EM, e.g. electric motor). For each of these the same design options for fuel storage and utilisation apply. In consequence, for each drive technology there are essentially only three available fuels, a drive-dedicated fuel – hydrocarbons for GE, electricity for EM – plus hydrogen and compressed air for each (used directly in GE and making electricity for EM via fuel cells, resp. microturbines). *Basic transport dilemma:* Each available fuel presently faces significant limitations, especially for supplying heavy transport.

There are three key policy choice points for transport fuel and drive technology: C1) that between F1a) hydrocarbons and F1b) electricity, hydrogen or compressed air as fuel, C2) within F1b) that between F1bi) electricity with battery storage, F1bii) electricity with hydrogen or compressed air storage and F1biii) hydrogen or compressed air used directly, and C3) within each of F1bii) and F1biii) that between hydrogen and compressed air. These choices involve five key bottleneck technologies: 1) hydrocarbon production by industrial photosynthesis; 2) high capacity, transportable electricity storage; 3) hydrogen from carbon-sequestered coal using heat, 4) hydrogen from water using photolysis or thermolysis; and 5) high capacity, transportable compressed air storage. (A 6<sup>th</sup> technology, carbon sequestration at on-board exhaust, should be included as a monitored possibility because of the access it would give to fossil hydrocarbon use.)

## Physical Options in, and Constraints on, Energy Structure

### *I. Orientation*

#### *Kinds of constraints on energy policy*

There are four principal classes of requirements (‘constraints’) that we place on good energy policy, respectively concerning 1) the physical nature of energy, 2) our current historical circumstances, 3) the way we prefer to run our society and 4) the requirements of acting rationally. In this report we focus on bringing order into 1), the complex array of physical constraints that circumscribe any adequate energy provision system, because this must provide the basis of energy scenario formation.

#### *This report*

This report lays out the basic physical structure of energy systems. From this can be derived both the physical options/contingencies to be considered, and the physical constraints on choices, when designing an adequate energy system. For completeness, the report concludes with a brief overview of the categories of all other constraints on adequate energy policy – Appendix 1.

#### *Why do this?*

It turns out that the inherent structure of energy and energy technologies makes for a complex but specific set of constraints on the adequate provision of energy fuels. These constraints are much tighter for provision of transport fuels than they are for satisfying stationary energy demands. The addition of a carbon-neutrality constraint raises serious challenges for the future provision of energy fuels, especially for transport, challenges that have a specific structure and offer specific opportunities and adaptive options.

The examination to follow is essential preparation to systematically characterising the nature of energy options, in turn required for systematically structuring the energy scenarios required by the backcasting method. This will enable the suite of alternative basic energy scenarios to be constructed as the starting point for scenario backcasting, adaptive analysis, and development of an adaptive energy policy.<sup>1</sup>

### *II. Basic Structure of Energy Transformation and Utilization in Human Society*

The Laws of Thermodynamics may be summarised as: energy is conserved, but in every process it loses quality, that is, some of its capacity to do work. (The range of tasks for which it can be used narrows, a loss of adaptiveness.)

First consequence: it is not energy per se, but energy of high work capacity, that may become scarce.

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<sup>1</sup> For scenario construction see the Research Report *A Framework for Energy Policy Scenario Construction*; for backcasting see Discussion Paper #8, *Adaptive backcasting - the method of possibility and design for planning the future*; for adaptive analysis see Discussion Paper #9, *Adaptive Analysis for Energy Policy*; all available at [www.ccsd.biz](http://www.ccsd.biz).

Second consequence: each time energy is used its loss of work capacity creates an unavoidable waste stream of energy that can no longer be used for the original task. This leads to two distinct conceptions of energy efficiency, quantity (1st Law) and quality (2nd Law) efficiency, the proportions of available energy, respectively useful work, actually utilised in the desired task.<sup>2</sup>

Third consequence: the overall energy flow through an ecosystem or society is ultimately unidirectional, from various natural sources of relatively high work capacity, such as coal and sunlight, through primary production devices (power stations, etc.), to secondary fuels (electrical, chemical, mechanical and thermal) and their inter-conversions (e.g. heat to electricity), to tertiary devices such as washing machines and automobiles delivering the desired services (cleaning, transport, etc.). See Figure 1 below.

Fourth consequence: avoidable wastage of quantity of energy is minimised by ‘patching leaks’, increasing 1<sup>st</sup> Law efficiency; avoidable wastage of work capacity is minimised by matching the work capacity of the energy input to that minimally required by the work to be done, increasing 2<sup>nd</sup> Law efficiency. Whence, these two efficiencies may vary somewhat independently.

Fifth consequence: matching a waste stream to a further useful task demanding lower work capacity, called co-generation<sup>3</sup>, reduces the total quantity of primary input energy required to perform both tasks, increasing 1<sup>st</sup> and 2<sup>nd</sup> Law efficiencies. Matching each waste stream in turn to its next most useful task forms a systematic co-generation cascade from high capacity primary source input to low capacity tertiary output (as in a mature ecosystem and now partially in some industrial systems). This minimises the total quantity of primary energy input required to perform these given tasks, maximising 1<sup>st</sup> and 2<sup>nd</sup> Law efficiencies (within the existing system design). In addition, processes can sometimes be fundamentally re-designed so as to produce the same or similar output but reduce both quantity and work capacity wastage, increasing 1<sup>st</sup> and 2<sup>nd</sup> Law efficiencies; e.g. substituting recyclable single-use plastic hypodermic needles for re-usable sterilisable glass needles.

Sixth consequence: pursuing all of these measures as their scopes permit, maximises 1<sup>st</sup> and 2<sup>nd</sup> Law efficiencies and minimises the total input demand for both quantity of energy and capacity for work. In current human industrial systems, 1<sup>st</sup> Law efficiencies tend to be near their maximum theoretical values (not always high, e.g. ~40% maximum coal-to-electricity conversion efficiency in steam turbines) while 2<sup>nd</sup> Law efficiencies tend to be far below their maximum allowed values (e.g. a bar radiator is < 10% 2<sup>nd</sup> Law efficient, but use of a 25<sup>o</sup>C waste stream is 100% efficient).

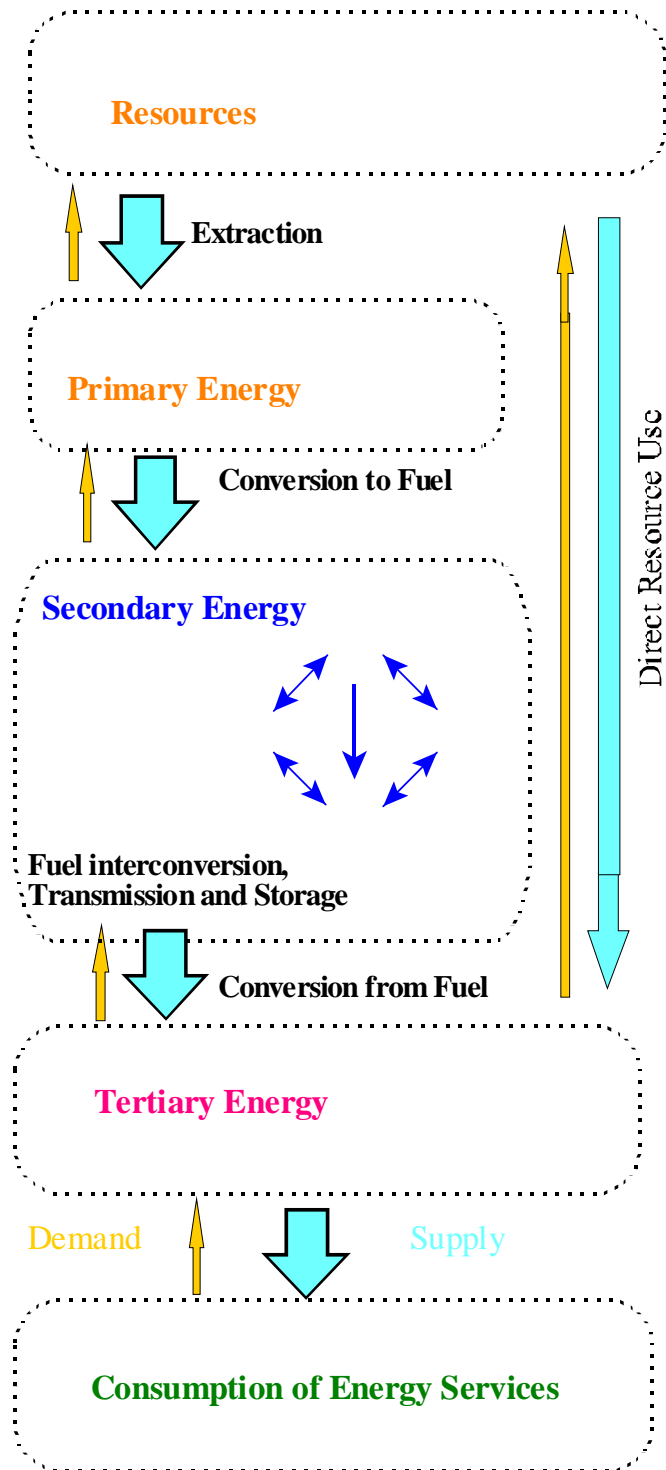
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<sup>2</sup> General note: efficiency is simply any (useful output)/ (total input) ratio for some system. Efficiency remains ill-defined until the following is specified: a system, its useful outputs and corresponding inputs, their measurement, the measurement time interval. A system can have indefinitely many incommensurable efficiencies defined on it by varying the other defining factors. And system efficiency is distinct from sub-system efficiency and often optimising one of these requires sub-optimality for the other. All this is true of economic and any other societal efficiencies as well as of physical efficiencies.

<sup>3</sup> The term is often reserved for the generation of electricity off a thermal waste stream, but here it is generalised to the extraction of any type of useful work from any waste stream.

**The basic energy problem [BEP]:**

Given a particular terrestrial endowment of primary resources, find suites of feasible primary, secondary and tertiary energy technologies that will match primary resource exploitation to tertiary demand in a manner that is adaptively sustainable and welfare enhancing.



**Figure 1: Human Energy System Flow**

### ***III. Key Role of Secondary Energy Media***

*Fuels and Adaptability: single fuels.* In bridging the primary/ tertiary energy gap, energy resources are often converted from their naturally occurring primary physical forms into other physical forms, e.g. in turbine electricity generators coal is converted first into heat, then into pressurised steam, then into mechanical rotation and finally into electricity. Major motives for conversion are to facilitate trans-location (= transportation or transmission) of energy from source to consumption locations, and to facilitate energy storage for power modulation to meet local time-varying tertiary demand requirements. The conversion of heat to electricity has been favoured historically for all these reasons. For convenience we refer to these four features as aspects of energy transformation. How adaptable an energy form is, is measured not only by available capacity and the efficiency of its transformation, that is, of its conversion, trans-location, storage and modulation, but also the ease of regulating (measuring, observing, shaping) those transformations - resolution accuracy, reliability, and responsiveness, on freely specifiable demands for arbitrary desirable purposes.

The dominant secondary energy fuels that currently act as intermediaries between primary and tertiary energy forms are hydrocarbons (chemical) and electricity. Their ubiquity is not accidental: they are marked out by their relatively high adaptability, that is, by their transformative capacities as above. Two other energy forms currently play as ubiquitous secondary conversion and modulation roles: rotation and heat (cf. their place in turbine electricity production above).

The adaptability of each of these four fuels, in each of the four aspects (conversion, etc.), is a matter of degree. It is constrained by thermodynamics but also by available technology . Historically only hydrocarbons have been easy to store on a large scale and only hydrocarbons and electricity have been easy to trans-locate. But technology is currently developing toward a condition where, on a large scale, heat will become easily storable and moderately easily trans-locatable, electrical and rotational (mechanical) energy will become moderately storable, although mechanical energy will remain difficult to trans-locate. However, the remaining limitations can be circumvented by making use of fuel conversion adaptability to convert the fuel into a more amenable form, e.g. for storage purposes electricity can be converted into gravitational potential energy through pumping water uphill.

*Fuels and Adaptability: fuel systems.* Between them, these four fuels exemplify the four generic forms of fuel energy in widespread use: electrical, chemical, coherent mechanical and incoherent (random) mechanical, ie thermal. If, e.g., use of compressed air grows as a transport fuel, as seems likely, it can be added to rotation as another form of coherent mechanical energy and hydrogen can similarly be added to hydrocarbons as another form of chemical energy. Gravitational potential is expressed as mechanical energy (raised water - river flow, pumped storage, tides) and can be annexed to that node.

The four energy forms identified above represent a natural physical categorisation, and among them they form a completely connected fuel inter-conversion system. Currently, there is no useful technology for directly converting between mechanical and chemical energy fuels, in either direction, and only small-scale specialised semiconductor technology for direct (thermo-electric) conversion of heat into electricity (e.g. cooling in spacecraft and submarines). Each of these three inter-conversions proceeds at large-scale via intermediate fuels (although sometimes at the cost of significant conversion losses). The four fuel forms

together permit any given energy fuel to be generated from any other at societal scales, perhaps passing through several intermediary fuels on the way. So each fuel is in consequence essential as well as ubiquitous to the functionality, and adaptability, of an energy system.

Specifically, in consequence of their inter- conversion capacities, each of these four fuels could in principle play the role of a universal energy currency in the presence of the others: each can be derived from every primary resource (conversion into energy currency) and each can satisfy every tertiary demand (use of energy currency to generate services). To remind of this we refer to them collectively as energy media. (Not included in the media at this stage are radiation and nuclear energy forms, even though they play particular, often important, roles in our energy economy.<sup>4</sup> They are not included because each of these has a significantly lower adaptability than the others: it is currently much harder to integrate them into an enlarged, controllable, complete fuel inter-conversion system.)

*Fuels: efficiency versus adaptability.* In sum, each fuel medium is adaptable and together the four media form a maximally adaptable (because completely connected) fuels network. To the extent one fuel comes to dominate an energy system (e.g. an all-electric society) then 1<sup>st</sup> Law efficiency may increase (from both conversion reduction and scale increase), and prices correlatively decrease, but adaptability is also reduced. Efficiency may also be lost in these circumstances if resources in a form already suited to demand requirements are needlessly first converted into the dominant medium (e.g. domestic rooftop solar energy converted photovoltaically to electricity before being used to heat water).

*Fuel media conversion diamond.* Each inter-conversion has a characteristic conversion technology associated with it. Technologies may combine more than one conversion in the same process (cf. turbine electricity production), and technologies may operate in sequence to effect several conversions (e.g. a fuel cell converting hydrogen to electricity followed by an electromagnetic drive converting electricity to motion). In consequence, each conversion, and conversion sequence, has a particular 1<sup>st</sup> Law and 2<sup>nd</sup> Law thermodynamic efficiency associated with it (though usually only the 1<sup>st</sup> Law efficiency is discussed and calculated). This translates into economic cost differences among them and, because of the specific waste streams produced, also into environmental cost differences among them.

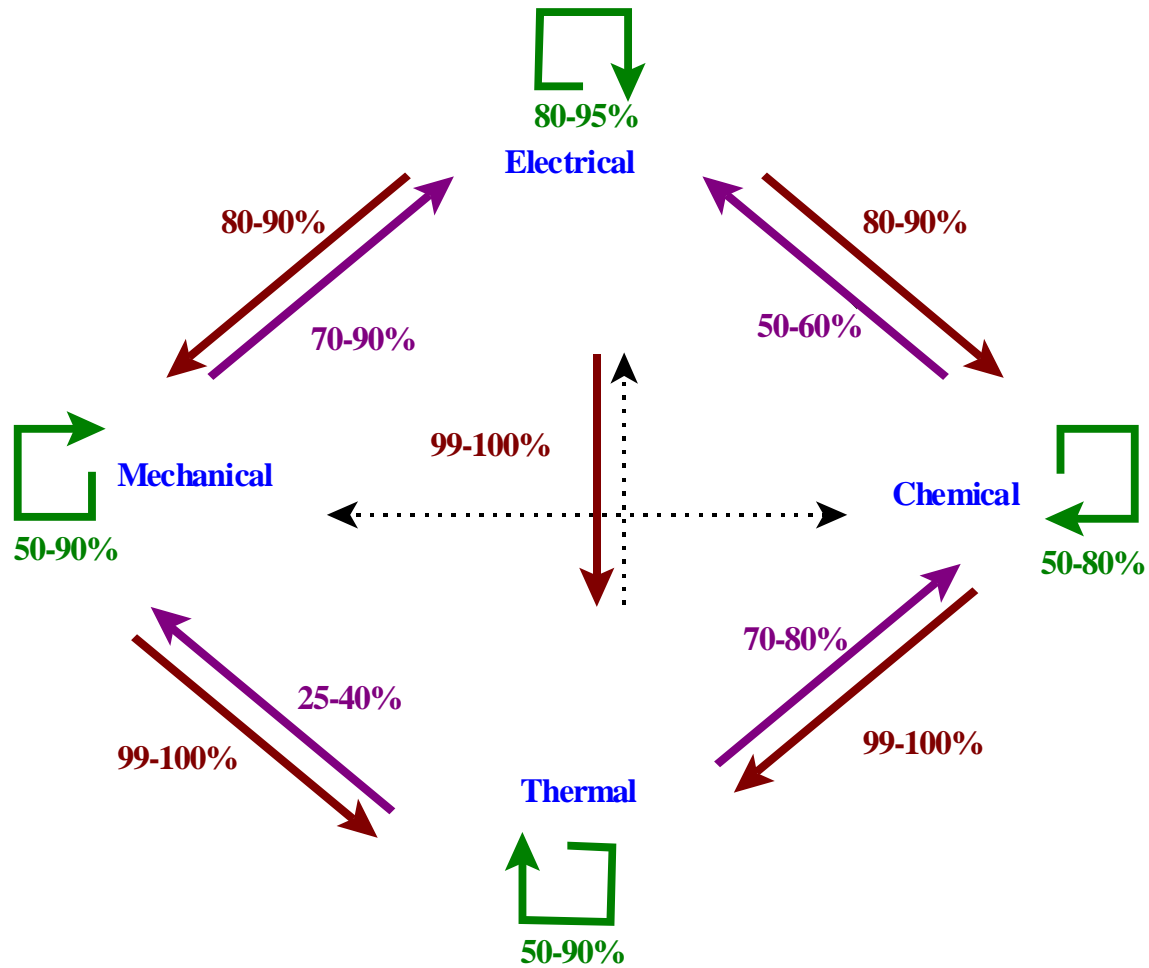
Fuel conversion losses have a systematic structure: i) for any pair of fuels there is typically one direction in which conversion is substantially more efficient and ii) these relationships are systematic among (they aggregate multiplicatively across) the fuel kinds. When the four fuels are arranged by conversion efficiency the result is the media conversion diamond, where the more efficient conversions run vertically downwards and the less efficient upwards – see Figure 2.

Every practical conversion corresponds to a trip around the diamond, e.g. coal turbine electricity forms the trip from chemical to thermal to mechanical to electrical energy, while a direct carbon fuel cell moves in the other direction from chemical directly to electrical, not

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<sup>4</sup> Nuclear media, which are energy dense and solid, so storable, are ruled out by safety considerations stemming from both the nature of the radiation they emit and from their high energy densities, which make their processes hard to reliably control - we manage it at present only for large power stations and military submarine transport.

surprisingly achieving much higher (about double) efficiencies. Similarly, the trip in electrical wind power is from mechanical to electrical. The ‘distance’ of a conversion can be crudely measured as the number of steps in the corresponding trip; it is a rough measure of the overall loss incurred by the conversion, and hence of the overall size of the conversion waste streams. (In a trip the overall efficiency is the product of the component efficiencies.)



**Figure 2: Energy Media Transformation Pathway Efficiencies**

*Fuel conversion: efficiency principles.* The foregoing observations about fuels lead to the following general recommendations. [Media Matching] for any given tertiary task, prefer a primary resource that delivers energy already in the medium required by the task because this obviates media conversion. If it is also quality matched it also obviates quality conversion. Otherwise, [Quality Bias] Prefer higher over lower quality primary supply media and lower over higher tertiary supply media because this saves conversion 'quality upgrade' costs and maximises supply adaptability. The application of both principles to tertiary supply minimises use of the most convertible (adaptable) primary resources. Elsewhere, these two principles offer opposite policies for the primary-tertiary supply difference; in practice their partial application - e.g. by lowering the primary medium toward tertiary matching - is best traded off against the capacity to drive valuable co-generation from the resulting waste streams.

For instance, electricity is thermodynamically preferred to hydrogen generated by electrolysis, and certainly to electricity generated from that hydrogen by fuel cell. Electricity becomes the 'thermodynamic default' here, unless hydrogen can be generated directly by photolysis. Similarly, hydrocarbons directly delivered from bacterial or algal photosynthesis - industrial photosynthesis technology - is preferred to hydrogen from electrolysis, though not to hydrogen from photolysis. Photolysis and industrial photosynthesis thus become important 'bottleneck' technologies for future hydrogen use. Again, sources of mechanical energy (wind, wave, water flow) can directly deliver compressed air without media conversion losses, making it a bottleneck technology for this fuel since it is preferred to producing compressed air from heat or electricity and of equal preference to hydrogen produced from photolysis or industrial photosynthesis. (Here limitations in the extractable primary mechanical resources and in effective in-vehicle storage make these technologies the focus of this bottleneck.)

Since heat suffices to deliver food processing and space heating/cooling then a special argument will be needed to use electricity instead for this purpose. Further, locally produced and quality matched heat becomes the 'thermodynamic default' here, as in local ground or ocean/lake heat exchange or solar local solar thermal collection for delivering space heating and cooling. Conversely, if tertiary technologies can be chosen so as to be supplied by such heat sources then there is a prima facie case for preferring them. A large proportion (perhaps 70%) of stationary tertiary demand is for heat at various temperatures. Thus there is considerable flexibility in the choice of resources and technologies to meet the demand, highlighting the use of these principles above in designing the most effective system for doing so.

However, these principles are ultimately only guides to designing an energy system, other considerations, from costs, safety and security to sheer lack of appropriate feasible technologies can lead to their suspension. More subtly, the conditional benefit of using an already-provided energy medium may outweigh the resulting violation of these principles. For instance, once grid electricity is connected to a site for some specific use (say electric motors) it may prove less expensive at the margin to also use it for space heating and cooling than would be direct local heat production - further entrenching electricity's advantage in other marginal uses. However, in general the further the energy system departs from these thermodynamic efficiency principles the greater will be its thermodynamic, and eventually environmental and economic, burden, and the less adaptability it will have to change its ways.

#### ***IV. Primary Resources - Energetic Form***

There are three key questions concerning each primary resource:

(Q1) What is the resource capacity relative to human global and local Australian demands?

(Q2) What energy media are most directly derivable from it, and then next derivable?

(Q3) What is its natural net greenhouse gas emission profile when utilised as per (Q2)?

Answering the first question tells us how important a quantitative role the resource could play in satisfying energy demand. In each case a well-defined answer requires also specifying the technological method of exploitation and transformation into an energy medium, because these determine what proportion is recoverable and how much wastage occurs in doing so.

Answering the second question tells us where the primary resource first enters the media interconversion diamond (Figure 2), and hence the technologies that are required to satisfy various demand tasks, and the thermodynamic costs that must be paid to do so. Answering the third question then identifies the carbon penalties that must be paid for the use of that resource by those primary technologies.

The qualification to *net* emissions is to capture the difference between use of *carbon-additive* fossil fuels which increase net atmospheric carbon when used (they re-emit once-sequestered carbon) and *carbon-neutral* uses that emit zero net atmospheric carbon.

Carbon neutral uses include (i) fossil fuels with carbon capture and (re-)sequestration, (ii) bio-fuels that only re-emit captured atmospheric carbon when used, that is, re-cycle atmospheric carbon, and (iii) energy production that is *carbon-free*, such as geothermal, wind and solar energy.

The answers to these key questions for the resources above are summarised in Table 1 below. Entries indicating large global capacities or low net emissions are green, their respective opposites are red. The table supports the following:

(R1) [Long-term abundance] Only 8 of the 19 resources identified are of high or moderate/high capacity - that is, are long-term abundant - in relation to global demand: coal, industrial photosynthesis, nuclear (breeder, fusion), solar radiant (photovoltaic, thermal, photolysis), and geothermal.

(R2) [Common media production] All 8 long-term abundant resources produce heat, 6 directly and 2 as the next available conversion, with 4 producing only heat; 1 of the 8 produces electricity directly and 7 of the 8 can produce electricity as the next available conversion; 7 of the 8 produce mechanical energy as the next available conversion (and none directly).

(R3) [Rare media production] Of the 8 long-term abundant resources, only photovoltaics directly produces electricity. Outside of hydrocarbon processing, only photolysis directly produces hydrogen and only photovoltaics and nuclear-temperature thermolysis produce hydrogen as the next available conversion.

(R4) [Carbon-neutral abundance] Assuming fossil carbon sequestered, all abundant sources are carbon-neutral, and all except coal and industrial photosynthesis are carbon-free.

(R5) [Carbon-neutral restricted] All the direct mechanical sources are of low capacity, though carbon-free.

(R6) [Use adaptability] Among the 8 long-term abundant resources, the chemical media: coal and industrial photosynthesis, are the most versatile, producing all the major energy media either directly or as the next available conversion.

These conclusions in turn point toward useful lessons for policy formation:

(PR1) If greenhouse emissions constraints are operative in post-2050 scenarios, the carbon-free long-term abundant resources must form the major resource basis.

(PR2) Carbon sequestration technology is essential for use of coal in the intermediate term to 2050 and because coal (and other fossil fuels) are such versatile resources, its use should be extended as far as feasible through improving use efficiency and sequestration technology. There is considerable scope in principle for improvement in efficiency – about doubling, to 75-85% – through utilising direct injection coal engines (slow diesels) and direct coal fuel cells.<sup>5</sup> Achieving these efficiency increases would increase the capacity to use coal and hence extend its contribution horizon. But even this plus use of sequestration will not prevent a long-term phasing down if demand growth compounds, driving up emissions losses from capture inefficiencies to the agreed emissions cap. In transport, any use of fossil fuels is constrained by the present difficulty of on-vehicle capture of the resulting carbon emissions.

(PR3) There are prima facie cases for heat, electricity and mechanical energy to remain important energy media in long-term future scenarios, viz. that heat is the largest demand, electricity and mechanical energy are versatile, and all are ubiquitous. However, since at present heat and mechanical energy cannot be easily stored or transported in quantity by current technologies, these latter form bottleneck technologies for these media.

(PR4) Production in quantity of carbon-neutral hydrocarbons, especially attractive for heavy transport, is limited to industrial photosynthesis, the bottleneck technology for this medium. Biomass can supplement with limited quantities of hydrocarbons.<sup>6</sup>

(PR5) The availability of directly produced carbon-free hydrogen depends on the successful development of photolysis technology, the bottleneck technology for this medium, otherwise it is produced at second conversion from photovoltaic electrolysis of water (or at third conversion from thermal electricity).<sup>7</sup>

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<sup>5</sup> L. Wibberley, 2007, 'Alternative Paths to Low Emission Electricity', Coal21 Conference, Hunter Valley, Australia, September 2007.

<sup>6</sup> Note that sequestration at exhaust is not foreseeably applicable on-vehicle, especially not to jet engines, which must then be served with biomass or industrial photosynthesis hydrocarbons. While carbon-free hydrogen is not limited (in principle) and could be converted into a hydrocarbon, that requires a carbon-neutral source of carbon - suggesting that, whatever it is, it instead be utilised directly - and will suffer from the inefficiencies of three transformations; which suggests that instead hydrogen be used directly or to generate electricity via fuel cells.

<sup>7</sup> The option of generating hydrogen from thermolysis of water using very high temperature heat (~3,000 °C) from nuclear reactors is presently unproven and thermodynamically uncompetitive with photolysis, although it could become a more attractive alternative were nuclear power generation to be developed.

(PR6) Individual coherent mechanical resources are restricted to supporting roles in scenarios; however, bundled together, they may provide a substantial carbon-free energy resource and, supported by heat generation, even a preferred one for transport.

Natural Energy Resources: Key Characteristics						
Resource	Primary Tech.	Relative Capacity		Media Production		GHG Emissions
		Global	Australian	First	Second	Intensity
<b>Chemical</b>						
Oil		Low	Low	HC, Heat, H	Elec., Mech.	High
Nat. Gas		Mod.	High	HC, Heat, H	Elec., Mech.	Mod./High
Coal		High	High	Heat, HC, H	Elec., Mech.	Mod/High
Biomass	Natural	Low	Low	HC, Heat, H	Elec., Mech.	Low/Mod.
Industrial photosynthesis	Concen.	Mod/High	Mod.	HC, Heat, H	Elec., Mech.	Low
<b>Electromagnetic</b>						
Solar radiant	Thermal	High	High	Heat	Elec., Mech.	Low
	Photo-voltaic	High	High	Elec.	H, Heat , Mech.	Low
	Photo-lysis	High	High	H	HC, Heat Elec.	Low
<b>Nuclear</b>						
Uranium	Burner	Low/Mod.	High	Heat	Elec., Mech., H	Low
	Breeder	Mod./High	High	Heat	Elec., Mech., H	Low
Thorium	Burner	Low/Mod.	High	Heat	Elec., Mech., H	Low
Hydrogen	Fusion	High	High	Heat	Elec., Mech., H	Low
<b>Thermal</b>						
Geo		Mod./High	High	Heat	Elec., Mech.	Low
Marine		Low	Low	Heat	Elec., Mech.	Low
<b>Mechanical</b>						
Hydro		Low	Low	Mech.	Elec., Heat	Low
Wind		Low/Mod.	Low	Mech.	Elec., Heat	Low
Tidal		Low	Low	Mech.	Elec., Heat	Low
Wave		Low	Low	Mech.	Elec., Heat	Low
Currents		Low	Low	Mech.	Elec., Heat	Low

**Table 1: Natural Energy Resources: Key Characteristics**

Table 1 entries largely reflect general knowledge. However because some areas are more complex and/or controversial than others, we note the following in their partial support. (a) Any hydrocarbon input can in principle be used to produce the same three distinct media products and these can shift in directness of production and mutual proportions as technology and overall industrial design shifts. (Biomass and industrial photosynthesis entries are discussed further below.) (b) At 1-2.5 GigaWatts per 10 square kilometres there is abundant solar radiant energy. (c) Current proven commercial uranium and thorium stocks are small compared to global electricity demand, let alone for other stationary uses and transport as well. Though stocks increase substantially as ore grades are lowered, so too do energy and environmental costs of extraction, lowering

competitiveness. (d) Each of the mechanical sources might on average comfortably contribute 5-15% of total energy demand, depending on natural endowments, after which further extensions require increasingly strenuous and expensive means, such constructing large ocean platforms or accessing atmospheric jet streams to expand wind power.

### ***V. Tertiary Services - Energetic Form***

The following lists human final energy demand in rough order of current quantitative scale of importance, with their current predominant supply media:

1. heat - low temperature (15-35 °C) space heating and cooling, refrigeration (-20-0 °C) and hot water (35-65 °C), industrial process steam (65-200 °C); supply: electricity + (fossil) liquid hydrocarbons;
2. transport - light and heavy; supply: (fossil) liquid hydrocarbons;
3. industrial processing, including energy transformation - high temperature heating (500-3500 °C) and chemical reduction; supply: (fossil) hydrocarbons (solid + liquid) + electricity;
4. stationary mechanical motion; supply: electricity + (fossil) liquid hydrocarbons;
5. lighting; supply: electricity;
6. signal processing and transmission - for information processing, regulation and communications; supply: electricity;
7. other non-photosynthesis agricultural demands; supply: liquid hydrocarbons + electricity.

Swamping all these together but usually unaccounted, is solar energy for natural photosynthesis in agriculture, passive heating/ cooling and lighting in buildings and passive drying.

The following observations about tertiary demand stand out:

(D1) The largest demand is for low to moderate temperature heat, which can most (thermodynamically) efficiently be met either from multiple direct sources and/or from co-generation applied to waste streams from other energy generation or industrial processes. The least efficient uses of electricity and hydrocarbons are for low to moderate temperature heat. Heat is at present not easily transported in quantity, so it needs to either be produced locally or converted to electricity for transmission; however this constraint may be relaxed in future.

(D2) Heat provision excepted, the use of electricity is effectively essential for all categories of its present use and unlikely to be displaced therein, however these roles represent only a small proportion of final demand.<sup>8</sup>

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<sup>8</sup> Essential electrical uses include nocturnal and some indoor lighting, controllably reliable small scale mechanical motion, information and signal processing and long distance real-time communication, and extremely high temperature heating (e.g. arc welding). Hooker et al. *Energy and the Quality of Life* (Toronto: University of Toronto Press, 1980) estimated essential electricity for a modern economy at ~10% tertiary demand and this figure will not have changed much except for an increase in the demand for information processing. In principle, energy for final mechanical demand could be provided by direct mechanical primary sources, but these lack the subtlety of integration and control that use of electrical motors provide. (However, power regulation and efficiency in compressed air engines is evidently becoming comparable to that of carburetors with liquid hydrocarbons.)

(D3) The use of hydrocarbons is convenient, but not currently essential, in any category except transport, where they will likely become increasingly also non-essential (see below).

(D4) Solar radiation input for agricultural photosynthesis is essential (electrically powered artificial lighting is both thermodynamically and economically inefficient).

These conclusions in turn point toward some useful lessons for policy formation:

(PD1) Given carbon emission constraints, the replacement of fossil hydrocarbons will increasingly be required as tertiary energy demand expands, but need not in itself force restructuring of services.

(PD2) Attention should be given to expanding the satisfaction of heat demand (i) through the expansion of passive acquisition, (ii) development of technology for local, quality-matched sources, and especially for co-generation, and (iii) through the removal of non-technology barriers (building standards and financing, fuels pricing, etc.).

(PD3) The provision of a carbon-neutral transport fuel medium to replace existing fossil hydrocarbons will become increasingly essential, but is the largest and most difficult issue because of the tight demands on a successful transport medium (see ‘Transport’ below).

(PD4) The generation of essential electricity must also become increasingly carbon-neutral. This challenge will be compounded should either (PD2) fail to relieve the use of electricity for heat and/or (PD3) lead to the adoption of electricity, or of electrolytic hydrogen, as an important transport medium.

There are two classes of measures in addition to those above that contribute to a successful resolution of the BEP: (I) the substitution of, and/or reduction in, tertiary services and (II) improvements in process transformation efficiencies, especially through deep re-design of processes (see 5<sup>th</sup> consequence, p.2). These are the distinct strategies for energy system modification that together constitute demand shaping.

*An elaborated BEP:*

*Given a particular terrestrial endowment of primary resources, make use of the 3-stage techno-thermodynamic analysis of energy constraints above to find suites of feasible primary, secondary and tertiary energy technologies that will match primary resource exploitation to tertiary demand in a manner that is adaptively sustainable and welfare enhancing.*

This structure also provides the physical options/contingencies to be considered. Each source with more than one primary technology route converting it to fuels creates an adaptive option (a ‘supply vertex’ or fork on the flow graph), similarly each tertiary service supplied by more than one secondary fuel creates an adaptive option (a ‘demand vertex’) and each pair of inter-fuel conversion pathways between nodes in the fuel diamond creates further such vertices. Together these define the basic physical adaptive options available (see figures 3 and 4 below).

## *VI. Transport - Options and Possibilities*

Energy use technologies divide conveniently into transport and stationary applications. For the purposes of energy policy analysis, transport applications are distinctive, not merely because they are a significant contributor to economic adaptiveness (essential for enabling markets in materials and manual labour), but even more importantly because they have particularly stringent energy technology requirements over and above that required of other applications. Because energy resource requirements for transport are more highly constrained, it makes sense to investigate them first – how transport energy demands are met will then further constrain possibilities available to meet stationary demands.

Arguably the evaluation criteria dominating transport choices are adaptability (underlies convenience, individuality), safety and cost (time, finance - includes reliability).<sup>9</sup> It turns out that the inherent structure of transport design technologies makes for a subtly tight set of constraints on the adequate provision of transport fuel media, much tighter than that on satisfying stationary energy demands (see below), due to the need for an energy resource that is continuously accessible wherever the vehicle moves. In consequence, the addition of a carbon-neutrality constraint raises serious challenges for the future provision of transport fuels.

*Transport drive design.* A transport drive technology is a device that converts some energy medium into mechanical energy of vehicular motion. The conversion may be direct, as in linear electromagnetic drives and jet propulsion, or via rotational energy (wheels, propellers) acting against a resistance (rail, road, water or air). There are only two basic types of on-board drive technology available, those that rely on the forced expansion of a gas (internal and external combustion engines – respectively, petrol/diesel and steam, compressed air, and jet engines), forming gas expansion [GE] drive technology, and those that use electromagnetic motors to create torque (centrally or at each wheel), forming electromagnetic [EM] drive technology. This provides the beginning of the design structure - see Figure 3 below, read from bottom up.

A moving vehicle requires an energy supply. The two basic ways to provide this are **A**) continuous delivery and **B**) on-board storage, with each of these taking one of two basic designs. **A**) The two basic alternatives for continuous delivery are via a fixed energy supply network – e.g. electrified trains for EM, or via on-board capture – e.g. photovoltaic generation for EM. There is no feasible technology for continuous fuel delivery to GE drives.<sup>10</sup> (Use of wind, river and ocean currents is a drive-less on-board capture alternative in limited, but sometimes useful, circumstances.) Continuous energy delivery from a supply network is effective but the design severely reduces route flexibility – that is, reduces travel route adaptability; it has useful application in sufficiently dense urban areas – with computerised small, light rail vehicles promising to significantly relax both adaptability and population density requirement constraints, a bottleneck technology for this option.

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<sup>9</sup> That is, excluding environmental, aesthetic and other social components. Most individual consumers might rank the text components in the order stated, many firms would reverse the ranking; all might place floors under each component value.

<sup>10</sup> The only feasible technology for continuous fuel delivery to GE drives is electricity converted on-board to compressed and/or heated air, but this is not competitive with its direct EM use. It is possible that the emergence of compressed air drive technologies may change this.

Continuous delivery is currently ineffective because feasible supplies are either too sparse (solar radiation) and/or too dangerous (microwave, laser beams).<sup>11</sup>

**B)** The two basic alternatives for on-board storage are B1) two storages, a dynamic energy storage available for immediate injection into the drive engine (e.g. a steam head for GE, a high-current, low-capacity battery for EM) and a static storage that can be converted into the working form as required (e.g. coal for a steam GE, a low-current, high-capacity battery for EM) and B2) a single storage performing both functions (e.g. a petrol tank for GE, an all-purpose battery for EM). The capacity to use coal – a high energy density, stably storable and transportable fuel – and steam – also high energy density but not easily statically storable – as specialised storage technologies under B1 illustrates dual storage design, while the success of petrol in effectively providing both functions explains its attractiveness as a transport fuel. Conversely, the difficulty of finding a satisfactory all-purpose battery for EM under B2 technology illustrates the attraction of fuel cell technologies for EM transport (combined with dynamic super capacitors of the CSIRO type): by efficiently converting chemicals to electricity, fuel cells make static chemical storage available to EM drive technologies. The use of micro-turbines would make compressed air storage similarly EM available, currently a less attractive alternative. Both are bottleneck technologies for this EM storage strategy. The range of hybrid technologies is accounted for by just two alternative drive technologies, but many alternative dynamic and static storage fuels and all vehicles have to find some way of conversion among static store, dynamic store and motion; many combinations are possible.

Summarising Figure 3 below, for each drive technology (GE, EM) there are essentially only three available fuels, a drive-dedicated fuel – hydrocarbons for GE, electricity for EM – plus hydrogen and compressed air for each. Three of the four fuel media are involved while heat, the fourth medium, is the final working form of GE.

*Basic transport dilemma.* Assuming future transport fuel supply must be carbon-neutral and adequately support vehicle requirements, each available fuel presently faces significant limitations, especially for heavy transport (includes trucking, shipping and aircraft, where demand is most insistent and the weight of transport vehicles demands high energy density storage).

*Transport fuel constraints.* The major constraints on transport fuel are that it must be:

- (a) energy dense (by weight and volume),
- (b) easily transportable,
- (c) easily storable and replenished,
- (d) abundant to meet demand,
- (e) clean or cleanable of waste products (including net carbon emissions),
- (f) consistent with water and land use constraints in production, and
- (g) economical.

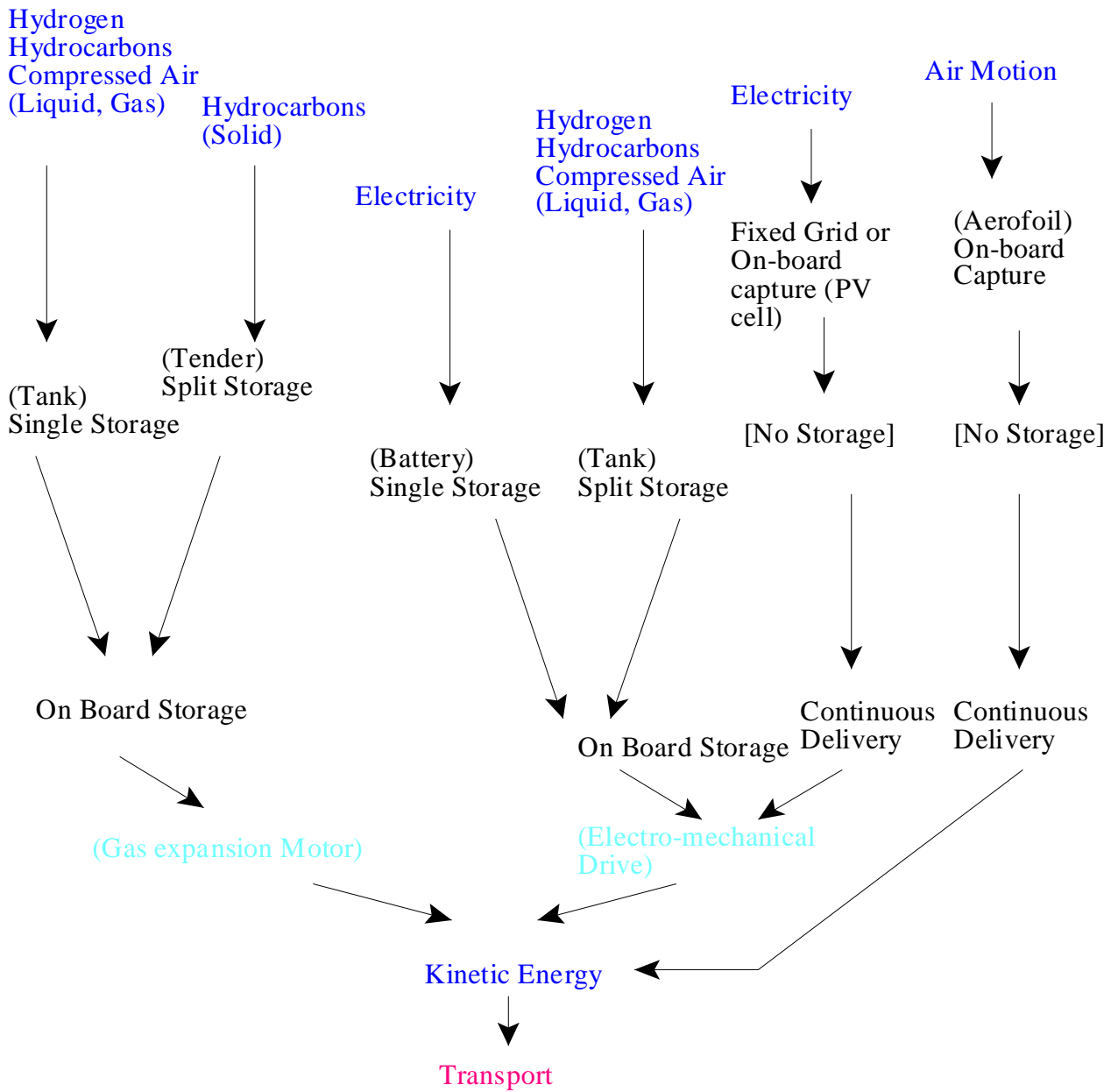
All but (e) and (f) are inherent to transport functionality. (e) reflects health and climate change constraints, (f) reflects the growing nexus between energy provision and water demand: water use in coal mining (+ pollution) and electricity generation and, conversely,

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<sup>11</sup> These are bottleneck technologies for this option, but there is at present no serious prospect of them becoming effective. However should recent (2007) US military arguments for safe yet effective microwave transmission of power from space prove workable, this option might later become real.

large electricity demands by water desalination plants, plus large demands by traditionally farmed biofuel crops.

The current and/or likely future energy media that could supply GE and EM technologies are summarised in Table 2 below and then each option is discussed in turn. Although contemporary technological developments are aimed at overcoming, or ameliorating, the main disadvantages, none of these at present clearly meets all the criteria above.



**Figure 3: Transport Technology Design Structure**

Satisfying Desiderata for Transport Fuels							
Desiderata	Hydrocarbon - fossil	hydrocarbon - biomass	hydrocarbon - photosynthesis	Hydrogen - non-carbon compounds	Hydrogen	Mechanical - compressed air	Electricity
Dense	Y	Y	Y	Y/N	N	Y/N^	Y/N^
Storable <sup>+</sup>	Y	Y	Y	Y	Y	Y/N^	Y/N^
Transmissible <sup>+</sup>	Y	Y	Y	Y	N	Y/N^	N
Abundant	Y	N	Y/N*	Y	Y	Y	Y
Clean	N	Y	Y	Y <sup>+</sup>	Y <sup>+</sup>	Y <sup>+</sup>	Y <sup>+</sup>
Water efficient	Y	N	Y	Y <sup>+</sup>	Y/N <sup>#</sup>	Y	Y/N <sup>#</sup>
Economic	Y/N <sup>~</sup>	Y/N*	Y/N*	Y/N*	Y/N*	Y/N^	Y/N^

**Table 2: Satisfying Desiderata for Transport Fuels**

**N** Potential efficiency increases (carbon fuel cells) and exhaust capture technology may reduce this constraint to carbon sequestration

**^** Derives from current storage/transport limitations.

**+** All improperly used fuels can do harm.

**+ Carbon-neutral and water-demand status = status of source technology.**

**\*** Determined by capacity, efficiency and cost of source technology.

**~** Depends on carbon price

Chief constraints of transport fuels:

*Hydrocarbons* presently cannot easily be cleaned of carbon at their vehicular point of use. While this constraint holds fossil sources cannot be used to supply carbon-neutral hydrocarbons for transport. Even were it relaxed<sup>12</sup>, carbon capture inefficiencies would place severe long term constraints on its use.

*Biomass hydrocarbons* are limited in abundance by the solar insolation density and the inefficiency of photosynthesis – together determining land demand/ unit energy produced – in relation to land availability, where it competes with other agricultural and environmental uses. Biofuel production is also limited in energy efficiency and constrained by water demand because growing biomass requires large water throughputs and undried biomass is primarily water, whence biofuel production makes large transport energy and infrastructure demands to transport the biomass to centralised processing centres (since water is heavy) and transport congestion may prove a further constraint. Finally, there are the ecological impacts of the large mono-crop cultures involved.

*Industrial photosynthesis* hydrocarbons would use mirror-concentrated sunlight, high density enclosed photo-reactive vessels, water fertilised with carbon-neutral, carbon-rich emissions (e.g. sewage methane), and genetically engineered high efficiency photosynthesis species (e.g. algae or cyanobacteria) that directly produce biofuels (e.g. ethanol, bio-diesel). The result is solar driven recycling of atmospheric carbon and independent solar driven recycling of water that offers large reductions in land use and in water, haulage and process energy required compared to current farmed biofuel production. However this bottleneck technology is still under development; the pathways involved seem technically feasible, but the ultimate costs and constraints are not yet clear.

*Hydrogenous non-carbon compounds* (such as ammonia) promise higher energy density and simpler storage requirements than hydrogen, but production is subject to the same constraints

<sup>12</sup> Either via increased efficiency through direct coal fuel cells (note 3) or on-board sequestration (there has recently emerged a claim by a UK group to have invented a process to capture exhaust emissions on-board, see Reuters, July 17, 2007); but at this stage both processes remain theoretical possibilities.

as hydrogen (see below) and adequate on-board storage, combustion and waste management technologies are all yet to be developed for most or all of the many potential compounds.

*Hydrogen* is the smallest molecule and forms a quasi-perfect gas, whence liquefaction is infeasibly expensive and leak-free gaseous storage and transport, especially at sufficient pressure for required gas energy densities, is difficult, expensive and potentially more dangerous.<sup>13</sup> Carbon-neutral hydrogen for transport must be produced from water either

1) directly by photolysis or

2) indirectly by

a) electrolysis using carbon-neutral electricity,

b) high temperature thermolysis, or

c) from i) inherently limited biomass or ii) industrial photosynthesis. The supply, cost and constraints of hydrogen production and storage depend upon the corresponding properties of these technologies. There is at present no prospect of hydrogen technology sufficing for heavy transport.

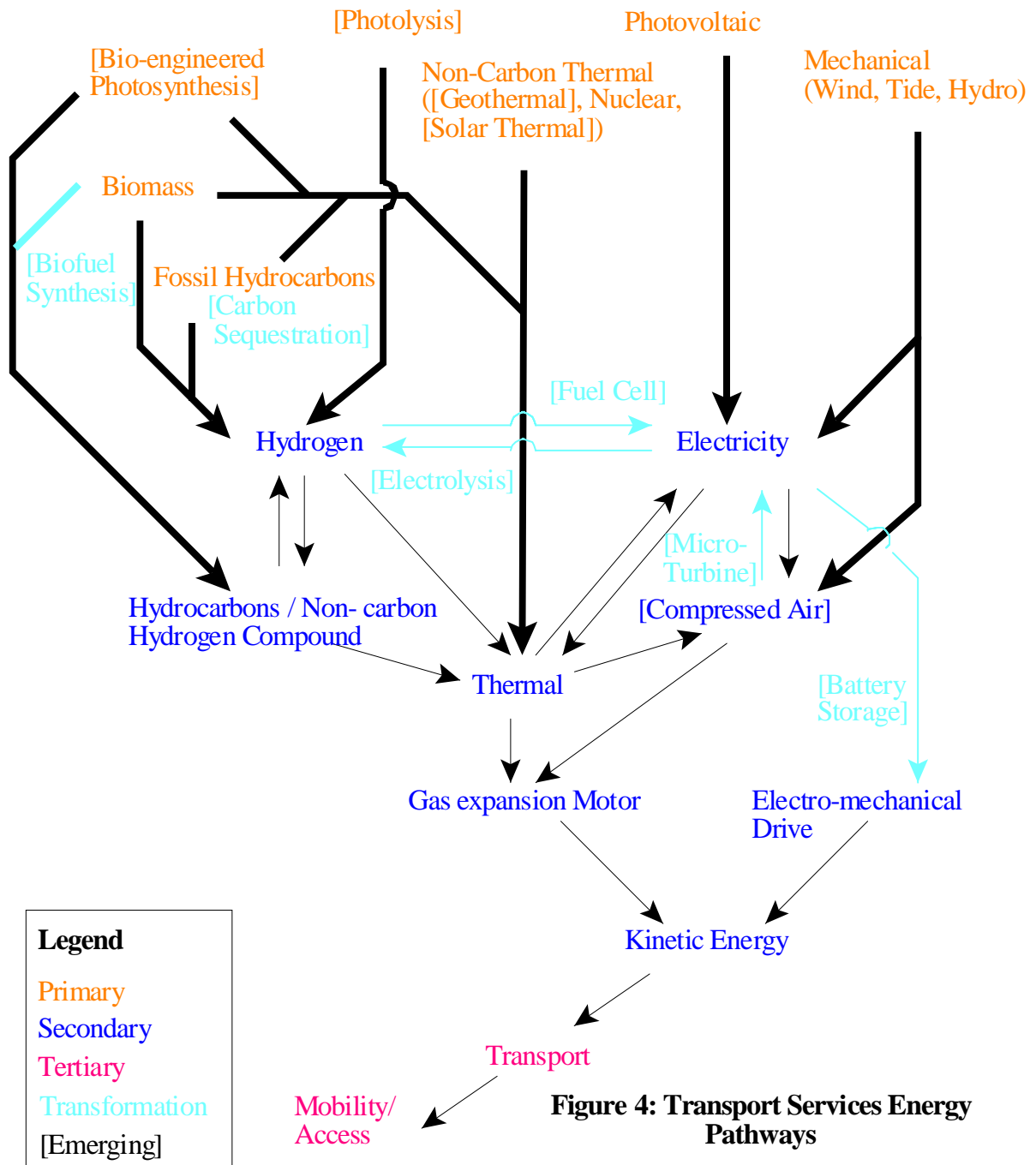
*Compressed air* drive technology is just entering mass production (India). With liquefaction infeasibly expensive, high pressures and/or temperatures are required for practical energy densities, making storage and transport expensive and potentially dangerous. Nevertheless, compressed air can easily be produced from any other energy medium, and hence from all sources; its supply, cost and constraints depend upon the corresponding properties of these technologies. There is at present no prospect of compressed air technology sufficing for heavy transport.

*Electricity* is not easily storable and mobile battery storage of electricity is weak, weighty and expensive. The life-cycle costs of batteries and the negative impact of their weight on performance, especially in hilly terrain (both EM and EM/GE hybrid), in relation to their storage capacity, are the primary current constraints on direct-use EM transport technology. However, several new battery storage technologies are under development that may change this situation in the mid term. Even so, there is at present no prospect of battery technology sufficing for heavy transport. The alternative is to shift static storage media by adding a transportable conversion technology, e.g. a compressed air turbine or a fuel cell.

The resulting structure to carbon-neutral transport fuel production pathways is given in Figure 4 below. The fossil pathway re-sequesters once-sequestered carbon, the biomass and photosynthesis pathways recycle atmospheric carbon and the remaining pathways are carbon-free. As noted earlier, each additional conversion step lowers the inherent achievable efficiency and adds to the conversion infrastructure required.

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<sup>13</sup> Safety is an issue where leakage occurs, but note that hydrogen burns at a substantially lower temperature than do hydrocarbons and that gaseous hydrogen burns upwards and hence generally away from humans, in contrast to liquid hydrocarbons.



These fuel pathways marry with the fuel demand options in Figure 3 to provide the design possibility space for transport energy. The redundancies in Figures 3 and 4 identify the basic options for future transport provision, and range from the macro redundancy between GE and EM drive designs, which represent two significantly different industrial structures, to micro redundancies such as that between primary technologies to supply thermal energy. These redundancies provide the basis of adaptive options.

Here we note two pragmatic features of this analysis approach. On the one hand, several redundancies can be pared from the structure on the grounds that they are strongly uncompetitive with their rivals and hence unlikely ever to become of practical relevance. For instance, the possible pathway from hydrocarbon (however produced) via heat to hydrogenous compounds for GE has been ignored as a redundant alternative to direct feed of industrial photosynthesis biofuel to GE because it has neither thermodynamics nor storage technology to recommend it. (The scarcity and cost of hydrocarbon bio-fuels will also strongly mitigate against using them to generate heat.)

On the other hand, the natural thermodynamic and economic efficiency advantages enjoyed by direct pathways do not automatically ensure their policy support since, as noted earlier, they may be offset by adaptiveness, water limitation, pollution, opportunity cost, location, employment, abundance and other countervailing considerations. For instance the photolysis-hydrogen-(via fuel cell)-electricity-EM pathway may become preferred to that of the shorter photovoltaic-electricity-EM pathway because the decentralised battery storage the latter requires is too expensive and/or impractical compared with the decentralised chemical storage the former offers and/or because fuel cells become so widespread that their collateral advantages (maintenance convenience, use elsewhere in the business, etc.) outweigh their energy inefficiencies.<sup>14</sup> The non-carbon thermal-heat-electricity and photovoltaic-electricity pathways will compete on storage capacities to provide reliability and load-following (respectively using heat, electricity media), on integration of the stored medium into the energy matrix, and on costs more generally. Both examples highlight the importance of showing all the conversion technologies involved in a pathway. Also note that even if an indirect production pathway is less efficient, it nevertheless provides an adaptive option to exploit the intermediate, instead of the final, products if required (e.g. other uses for, and export of, fuel cells), and this may prove decisive.

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<sup>14</sup> For discussion of energy system features of this kind see Brinsmead and Hooker *Industrial Networks*, Discussion Paper #6, available at [www.ccsd.biz](http://www.ccsd.biz).

## ***VII. Stationary Energy - Options and Possibilities***

Having identified the tight constraints on transport energy provision and the key technologies involved, it is now appropriate to consider the remainder of demand. Stationary final demands are primarily for heat and electricity, irrespective of their primary sources (currently predominantly electricity). In industrialised economies, transport demand can be assumed to be roughly 25% of final demand and stationary demand to be roughly 75%, = heat (55%), essential electricity (15%) and essential hydrocarbons (5%).<sup>15</sup> The key issues for the stationary sector are how these three components are to be supplied and how those supply paths interact with one another.

Tertiary demand for hydrocarbons or hydrogen is almost wholly confined to metals smelting (principally iron) and chemical feedstock (including for plastics, paint, lubricants and fertilizer). In smelting, the demand is primarily for heat, not a chemical medium per se. Carbon is also used as a reductant, a quite specific use of energy – in principle replaceable by hydrogen - and (in steel making) in small quantities as an additive. Call the non-thermal uses the essential uses for hydrogen/hydrocarbons.

*Heat.* As noted earlier, currently most of fossil hydrocarbon use eventually supplies heat (either directly or via electricity generation ) and the largest new additions to supply technologies all generate heat: geothermal, solar thermal and nuclear. Though geothermal and nuclear generation are normally centralised and turbine-configured to use the heat to generate electricity, heat may also be extracted directly for local uses near the plant and, as storage densities improve, more distantly. On the other hand solar thermal technology, including mirror-concentrating technologies, may be decentralised and its heat used directly and locally, as may heat extracted on-site as co-generation from other processes.<sup>16</sup> Thus the two key subsidiary issues here are: (Q1) what are to be the relative contributions of hydrocarbons and electricity to supplying heat? and (Q2) how decentralised are the heat generating technologies to be?

*Hydrocarbons.* In a carbon-constrained world, with inefficiency constraints on sequestration plus physical and economic constraints on biomass/industrial photosynthesis production and with many alternative ways to generate heat, the default response is to not use hydrocarbons for heat generation. It is reasonable to assume instead that in the mid to longer term all carbon-neutral hydrocarbons produced are absorbed by the stationary essential-uses and transport sectors where various of their unique properties are exploited.

*Electricity.* The essential uses for electricity create a minimal demand for it. However, the large new heat-generating technologies are configured for electricity generation, not only to serve historical habit, but because heat is currently more difficult to transport, and less elegantly adaptable, than electricity. This raises the issue of trading-off such advantages of electricity against its non-essential, thermodynamically mis-matched use. In principle, the

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<sup>15</sup> The potential for mechanical energy, specifically compressed air, to compete with electricity on many essential tasks, e.g. driving lathes or communications (as once occurred), is ignored here on grounds of the superior controllability and energy efficiency of electricity.

<sup>16</sup> Smaller, somewhat decentralisable nuclear power plants may also become available using pebble bed reactor design, now under development (and of uncertain cost), but the degree of decentralisation is likely ultimately to be circumscribed by safety and security considerations.

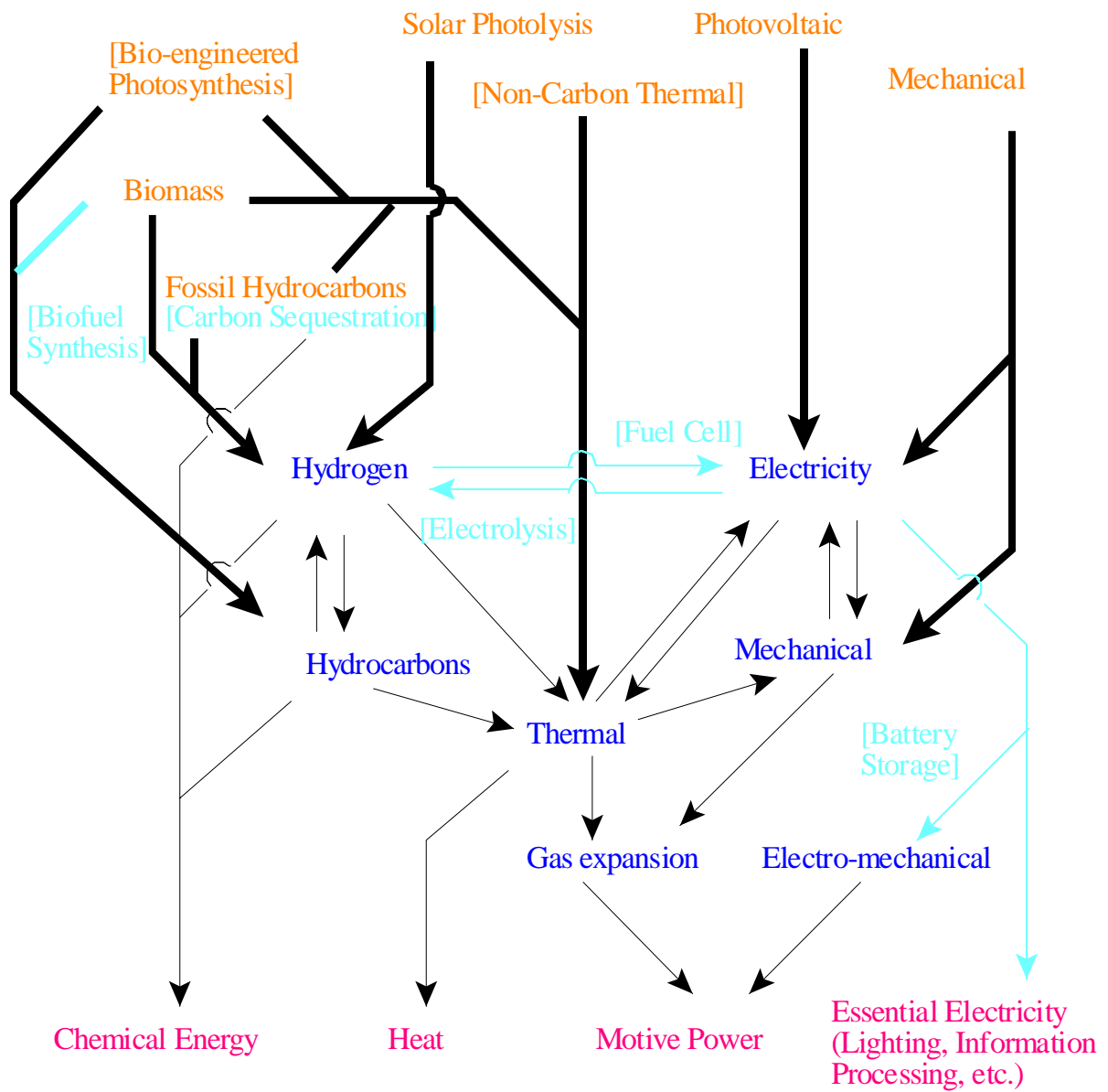
quantity of electricity required may occur anywhere between the roughly 15% of final demand needed for essential uses up to that additionally required for all non-essential stationary hydrocarbon roles plus all transport energy (maximal use, roughly 85% of total demand). No matter what the demand turns out to be within this enormous range, above some point near to the minimal use extreme, meeting overall energy demand will also require access to the new heat-generating technologies (above) in significant quantities.

A modification of Figure 4, drawn for transport, captures the possibilities for meeting stationary demand, by separating off the biofuels pathway and feeding it into a generalised mechanical tertiary demand (e.g. including diesel electric generators as well as transport) and by making heat a final medium with others. This yields Figure 5 below. Similar pathway redundancies occur as for the transport sector, with similar conclusions.

*Demand management* - reducing and shaping demand through re-design of the energy infrastructure - stands as an important complement to the foregoing analysis because it eases transitional stress in the shorter term and contributes to satisfying ecological constraints in the long term, and because it is well recognised (International Energy Agency 2006 *Energy Technology Perspectives, Scenarios and Strategies to 2050*, ISBN: 92-64-10982 ) as one of the most cost effective means of reducing greenhouse emissions, in many cases resulting in a net economic benefit. Secondary media demand management includes a) tertiary demand reduction – from improved building insulation to lifestyle changes, b) conversion efficiency improvements – from patching leaks through increasing thermodynamic quality matching and co-generation, to radical process re-design, and c) secondary media shaping – from substituting media lower on the media transformation diamond so as to reduce 2<sup>nd</sup> Law inefficiencies and increase flexibility of provision, e.g. choosing heat pumps to satisfy space heating demand, to improved use of natural energy flows, e.g. increasing the use of sunlight for lighting (e.g. through windows and light ducts), solar heat and wind for drying, solar heat and/or ground/ocean/lake source heat pumps for heating and cooling, mechanical power from wind or water flows and local biomass combustion.<sup>17</sup> Between them this range of initiatives represents at least a potential 30-50% reduction in tertiary demand on specifically industrially produced energy. It becomes a particularly important strategy if emissions from heavy transport and air travel cannot be reduced, given the absence of applicable alternative fuels.

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<sup>17</sup> Replacing industrially supplied media with natural alternatives that currently fall outside our formal energy accounting can be called demand management only because 'demand' is restricted to demand for resources over which humans have legal and economic rights. In a fully accounted energy system, where all natural energy flows were included from the beginning, substitution measures would be legitimately considered management of supply. On the other hand, because unaccounted resources are natural and local, they typically require only basic, passive re-design to exploit, hence many of the changes are of the same kind as other demand management strategies: individually of relatively small scope and scale, with diverse physical principles underlying their mechanisms, their wide spatial distribution and sometimes deep design embeddedness within the energy system, their proximity to consumers and interaction with wider social cultural norms, and the correspondingly longer times scales required to effect substantial change.



**Figure 5: Stationary Energy Services Pathways**

Legend		
Primary	Secondary	Tertiary
Transformation		[Emerging]

### ***VIII. The Structure of Energy Policy Decisions***

To resolve the BEP, tertiary demands are to be assigned among the four energy media in such a manner as to have them satisfiable from available primary resources by efficient and economically competitive primary technologies so that the whole energy infrastructure is adaptively sustainable and welfare enhancing. A schematic decision structure appropriate for this is given in Figure 6 below.

Clearly the first issue to be decided are the sizes of the component demands. Thus the first policy decision is that concerning the scale of demand modification to be achieved and thus the consequent scope, vigour and cost of the demand management programme to be enacted. The large heating/cooling demand is especially responsive to management modification measures (physical, backed by incentives) up to around 70% demand reductions, with light transport fuel demand similarly modifiable (via vehicle performance and transport mode, not necessarily movement per se) up to around 40% demand reductions.

Then with respect to the roles of the four media, the leading issues are: (I) how transport and essential hydrocarbon demands are to be met, (II) how decentralised will be the meeting of the demand for stationary heating and cooling, and (III) what will be the relation of its technology to that of transport technology. Brief discussions of these issues follow.

I. There are three choice points currently structuring transport fuel and drive technology policy: C1) the choice between F1a) hydrocarbons and F1b) electricity, hydrogen or compressed air as fuel, C2) within F1b) the choice between F1bi) electricity with battery storage, F1bii) electricity with hydrogen or compressed air storage and F1biii) hydrogen or compressed air used directly, and C3) within each of F1bii) and F1biii) the choice between hydrogen and compressed air.

These choices involve five key bottleneck technologies: 1) hydrocarbon production by industrial photosynthesis; 2) high capacity, transportable electricity storage; 3) hydrogen from carbon-sequestered coal using heat, 4) hydrogen from water using photolysis or thermolysis and 5) high capacity, transportable compressed air storage. A 6<sup>th</sup> technology, direct carbon fuel cells, especially with carbon sequestration at on-board exhaust, should be included as a monitored possibility because of the access it would give to fossil hydrocarbon use.

The preceding three choices will be significantly influenced by the manner and speed with which (various versions of) these six technologies develop and their unfolding wider ramifications for employment, innovation, rural employment and similar considerations. Inevitably, dominance by any one of them will strongly encourage the wider use of its fuel and utilisation technologies, including for electricity generation for stationary uses. Thus how the choices among them are decided places important constraints on the rest of the energy infrastructure design.

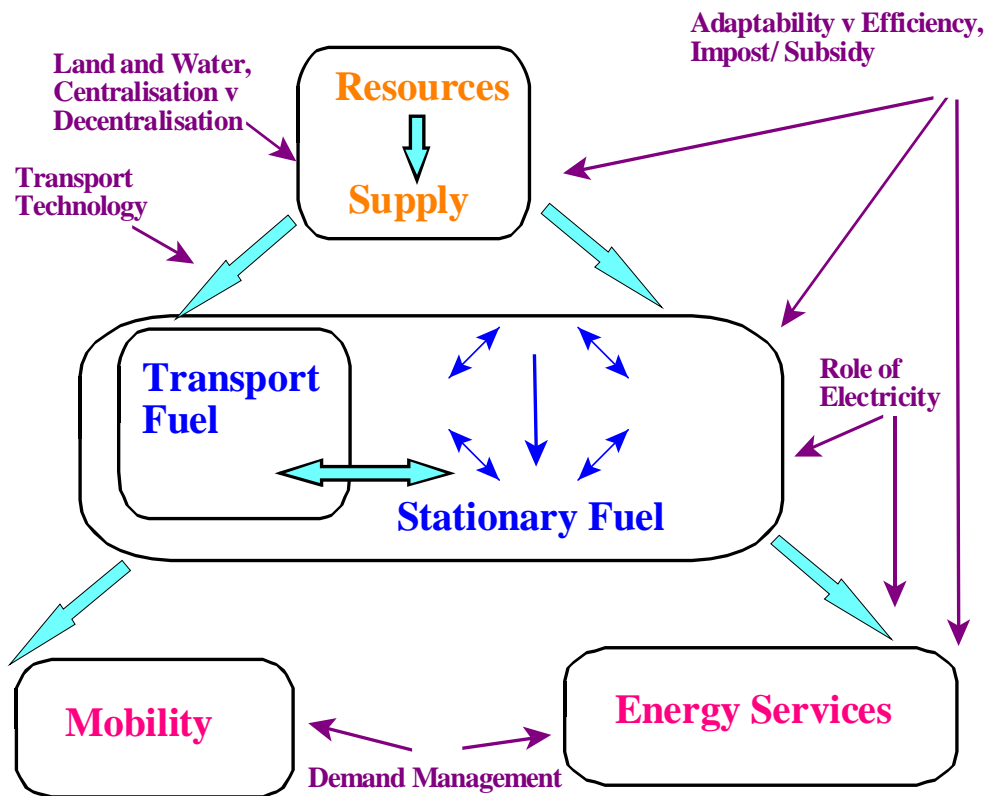


Figure 6: Energy Provision: Principle Decision Structure

II. A primary factor in determining the broad character of energy infrastructure is how centrally stationary heat demand is met. If it is largely met in a centralised manner (as it is now, primarily through supply from large fossil-fuelled electrical generators), then the technology must be electrical and/or hydrogen/ compressed air generation, with corresponding attraction to using related transport technology. Since geothermal and nuclear technology must take centralised forms, then unless decentralised solar technology is widely used, a centralised option may be forced (at least in the medium term). Suppose, on the other hand, that heat demand is largely or wholly met in a decentralised manner, through exploitation of distributed shallow ground-source, concentrating solar or solar-derived resources. Then the demand can be met consistently with quality-matched primary technology design, while leaving greater freedom to select transport energy (in particular hydrocarbon use).

III. The underlying issue here is the trade-off between efficiency and adaptability. Reflecting on the overall energy structure, Figures 3-5 we observe that if a large role is assigned to centralised electrical generation, or if distributed local electrical generation technology becomes flexible and efficient then, except for stationary essential-uses of hydrocarbons, the prospect of an all-electric medium society opens up, where economies of scale in generation also tip the balance for transport technology in favour of EM drives. By contrast, there are no similar prospects of an all-heat future or an all-mechanical (including compressed air) future because of the inherent limitations of these media, though each must play an important

tertiary services role in any energy economy. This, allied to the large prima facie inefficiencies of an all-electric system and its sacrifice of technological adaptability, makes it unlikely to be fully realised. And because of the constraint to carbon-neutral operation there is now no real prospect of the similar all-hydrocarbon future (bar essential electricity) that once there might have been. Finally, because of the indirectness of hydrogen production, unless direct photolytic (or thermolytic) production in quantity becomes competitive there is little prospect of an all-hydrogen future, even supplemented with hydrogenous compound transport fuels. In short, the most technically and economically attractive future is an adaptable, opportunistic mixture of all significant source and media kinds, and of the salient technological alternatives within each kind, evolving to suit all the evolving constraints.

The adaptability of the system as a whole has various aspects.

- The richness of the mix of technologies and media involved provide a basic underlying adaptability: new technological developments, e.g. an increase in efficiency in the photolytic production of hydrogen, can be opportunistically taken up because the basic technical, skills and infrastructural arrangements will be already in place.
- The many conversion interrelations among media production processes within the energy infrastructure, which allows it to internally adapt to shifting demand and to develop new local industrial opportunities as wider industrial economics allows.,
- The adaptive synergies among technologies that increase the capacity for adaptive response. For instance, there can be useful mirror-concentrated solar thermal boosting of all manner of primary energy production processes, from preheating input to steam turbine electrical generators to speeding up reactions through warming in industrial photosynthesis bioreactors and hydrogen photolysis, and of a range of waste cleanup processes from carbon dioxide separation for sequestration, to hydrogen separation in photolysis. There are similarly many co-generation opportunities within energy conversion processes, some of which can usefully contribute to the process of infrastructural design, e.g. to the preceding input and waste cleanup processes. By contrast, an all-electric future would have few or none of these adaptive advantages, a disadvantage in a highly uncertain domain like energy.

## Appendix 1: Non-physical Constraints on Energy Policy

In addition to constraints imposed by the physical properties of energy, there are three other categories of constraint on energy policy. A. Timing constraints represent further practical considerations regarding what is materially possible, whereas B. functional policy constraints and C. principled constraints are normative considerations concerning satisfactory energy system performance and policy making rationality requirements.

### A. *Timing constraints*

Ideally, the energy system that satisfies the BEP is also *adaptively resilient* (see IDP#1), which is the capacity to adapt to risk realisations so as to preserve functionality intact. Adaptive resilience competes with adaptation efficiency but 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. An adaptive policy (see IDP#8) is one that changes with changing circumstances to realise adaptive resilience. It is inherently concerned with timing, because it is concerned with constructing contingency plans for responding to a variety of events, and these will often be sensitive to their temporal sequencing and duration. In our circumstances, 2 classes of timing constraints play significant roles, process time constants and the timing of advances in technological development:

#### A.1. *Process time constants*

Each of the following are timing constraints that will play an important role in adaptive planning: time to peak oil, the time for atmospheric carbon to build up to various climate impact severities, the time for economic growth to cause energy demand to double. In consequence, planning cannot be solely concerned with physical outcomes, a-temporally specified, but must also take into account the timing of adaptive preparations.

Typically adaptive policy response will be structured by ratios of process rates, e.g. the rate at which climate changes occur compared to the rates of adaptation of key systems like coral reefs and coastal cities, or the rate at which energy conservation can reduce demand proportionately against the rate of economic growth. This latter is especially important for the future role of fossil hydrocarbons in energy supply as it determines the rate at which economic growth pushes up the volume of inevitable fugitive carbon emissions. Its ratio to that of the rate of natural global sequestration of atmospheric carbon then determines the time to the forced abandonment of further use of fossil carbon sources, even with successful sequestration.

#### A.2. *Timing of Technology Development*

The timing of technological availability can be crucial to the developmental direction of energy infrastructure. Each bottleneck technology, e.g., represents a still-developing technology whose arrival at the commercially exploitable threshold would create a large-scale alteration of the adaptive possibilities - engineered large scale photosynthetic production of liquid hydrocarbon fuel, e.g., would radically alter the prospects for Integrated Combustion Engine (ICE) transport technology, competing alike with compressed air and

electromotive drives, while the similar transition for photovoltaic electricity, or for effective transport electric battery storage, would radically alter the prospects for electromotive drives.

These two classes of constraints inter-leave with each other in complex ways - not least because the latter can modify the former. Adaptive policy planning must ultimately take place within the time-structured landscape made by these constraints.

### ***B. Functional Policy Constraints***

We now consider normative constraints that must be satisfied before an energy policy is considered fully satisfactory. The commonest ones are briefly listed here:

#### Traditional Energy Policy Requirements

1. continuously satisfy rising demand for energy services, including base and peak loadings;
2. minimise risk of disruption to energy supply;
3. competent to achieve the atmospheric carbon emissions reduction target;
4. minimise disruptive socio-economic changes;
5. minimise the cost increases to energy budgets, respecting plant investment lead times;
6. maximise the useful life of existing and future plant;

#### Social and Economic Requirements

7. preserve or enhance national security;
8. preserve or enhance consumer choice (maximizes range of support for consumer lifestyle preferences);
9. maximise the opportunities for social and economic (including export) development;
10. enhance industrial skills development and employment;
11. preserve or enhance rural development, including employment;
12. preserve or enhance potential for effective democratic participation in steering energy policy objectives;

#### Risk Amelioration Requirements

13. maximise risk amelioration (by optimising weighted satisfaction of risk ameliorative portfolio(s) of technologies and supporting infrastructure);
14. preserve or enhance potential to flexibly re-prioritise energy policy objectives;
15. minimise disruption to ecological diversity and other support bases for ecological adaptive resilience;
16. preserve or enhance support for an adaptively sustainable culture.

The first six constraints are traditional and broadly concern operational effectiveness, the next six are among the more important aspects of policy for one of the largest and deeply skilled infrastructural investments of a modern economy, and the last four are appropriate for risky (and uncertain) contexts - but are also constitutive of achieving adaptive sustainability. In practice they all represent goals toward which policy design strives, but will in general only imperfectly achieve.

### *C. Principled Constraints*

We finally note principled constraints arising from the inherent normative nature of policy making in general and energy policy making in particular. They concern inherent tensions among relevant normative requirements. Consider, e.g., the goals of safety and cost minimisation; there will be some opportunity to simultaneously improve both, but after a certain point movement toward either one (more safety, less money) will typically require moving away from the other (increased safety equipment also requires more expenditure, and vice versa). Such practical conflicts among goals are widespread in practice and include that between pursuing efficiency and adaptability, the key functional trade-off for any ecosystem, individual, firm or nation. In each case their resolution calls for intelligent compromise.

Adding the physical constraints to these 3 classes of constraints completes the constraints landscape for adaptive energy policy planning.