WHITE PAPER

PETROSYNTHESIS

The Completion of the Industrial Revolution

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ABSTRACT

All biological processes on earth have their foundation in organic chemistry within which photosynthesis and respiration act in balance to respectively manufacture and consume organic compounds (principally hydrocarbons) in exchange for inorganic molecules (water, oxygen and carbon-dioxide) – the so-called "carbon cycle". These organic compounds provide unique benefits in energy storage, distribution and deployment (work, heat) and construction (materials) for both plants and animals. In relatively recent history (200-300 years) humans have created an industrialised society, adopting the same unique advantages of organic compounds for energy and construction as well as for a vast range of chemistries required for goods and services for comfort, health and leisure. The machines in this industrial system deploy combustion of hydrocarbons (work, heat) in equivalence and with identical macro-chemistry to respiration in animals. The system is however incomplete – depending for source material on the linear consumption of legacy photosynthesis from fossil fuel stores (petroleum, gas and coal). There is no industrial equivalent of photosynthesis to balance consumption and corresponding emissions (carbon-dioxide, water) in a circular manner. This is certainly unsustainable if industrial society is to survive. The new term petrosynthesis is proposed to describe the industrial equivalent of photosynthesis producing organic chemicals and oxygen from non-biological energy sources (the *forest in a factory*). Petrosynthesis acting in balance with combustion and other petrochemical consumption will provide the completion of the Industrial Revolution for a balanced, circular and sustainable future of indefinite timescale – the industrial version of the "carbon cycle". Within this system new paradigms emerge – for example the concept of waste - the curse of linear systems - falls away and has no meaning, just as it has no absolute in biology.

Petrosynthesis

noun

> the artificial creation of organic compounds (synthetic petroleum/petrochemicals) and oxygen from inorganic precursors (principally water and carbon-dioxide) using non-biological energy (such as hydro, wind, solar, tidal, nuclear, geothermal); the industrial equivalent of photosynthesis, using neither energy nor material produced by either concurrent photosynthesis (plants) or legacy photosynthesis (fossil fuels).

1. SYNOPSIS

A broad overview of historical and future world energy models is presented.

Present-day industrialised society has a total dependence on petroleum for energy and material. The current linear supply model using fossil deposits is unsustainable in terms of quantity (finite resource) and emissions (atmospheric carbon-dioxide causing global warming).

Clean and renewable industrial energy sources are available (hydro, wind, solar, tidal, geothermal) and will scale. Fusion power gives promise of even greater density and scale.

These energy generators are all electrical in delivery and can be distributed as direct electricity (direct work) or within the emerging hydrogen economy (first level chemical energy). A wide range of energy consumers require higher density of energy distribution and storage as provided by petroleum liquid fuels (gasoline, diesel, kerosene). Petrochemicals remain the basis for many critical industrial materials and also require a fossil-free solution.

Biological substitutes to petroleum (direct, or from waste) will offer niche benefits but for reasons of poor efficiency and biodiversity risk they simply cannot scale to meet the necessary global demand, and indeed will put further pressure on the natural world which is already highly stressed.

Carbon sequestration alongside "business as usual" in fossil fuel consumption offers a transitionary solution to the global warming aspect only, and generates, in effect, even more industrial waste.

The only circular and scalable substitute to fossil petroleum is synthetic petroleum, manufactured using renewable energy sources. The term "petrosynthesis" has been defined to generically describe this manufacturing process. Petrosynthesis is the industrial equivalent of photosynthesis in biology, and in combination with combustion has the same macro-chemistry and the same circularity and balance as photosynthesis and respiration in nature. As an industrial process, petrosynthesis has the same benefits relative to photosynthesis (single-purpose, efficiency, density, reliability, control) as an engine has relative to the horse. In this context, petrosynthesis can be seen as the second and completing step of the Industrial Revolution: taking a linear system of consumption into a circular and indefinitely sustainable domain.

Petrosynthesis may be combined in parallel with electrical and hydrogen energy layers to create a three-layer, symbiotic Circular Energy Economy. These three layers provide the necessary range of energy media to meet all the requirements of an industrialised society, with indefinite sustainability.

Petrosynthesis provides a new paradigm in energy and material consumption. Indeed, within a fully circular system, the concept of "consumption" (and associated "waste") falls away. There is simply "circulation". Circulation has only utility and cost, without durable consequence. Circularity of petroleum energy and material allows new perspectives and approaches to materials policy and consequent reductions in agricultural demand and stress on nature and deforestation in particular. Meanwhile the energy and material independence of nations reduces geopolitical tension.

2. ENERGY PROCESSES IN BIOLOGY

Biology, the basis of all life on earth, employs carbon, oxygen and hydrogen as the primary chemical elements to capture, store and distribute energy and construction material for use by plants and animals. Plants capture solar energy by photosynthesis, converting atmospheric carbon-dioxide and water into hydrocarbons (such as oil, fat, sugar, starch, protein, wood, fibre) whilst releasing oxygen; animals consume these hydrocarbons by respiration with oxygen, within an equal and opposite molecular chemistry. Decomposition of these energy sources can be immediate (food energy) or delayed (material energy).

The composition of the earth's atmosphere remains broadly balanced within this circular process, the so-called "carbon cycle". A very marginal imbalance over the long term (hundreds of millions of years) has provided hydrocarbon deposits – legacy photosynthesis – as fossil fuels, with a corresponding gradual reduction in atmospheric carbon-dioxide.

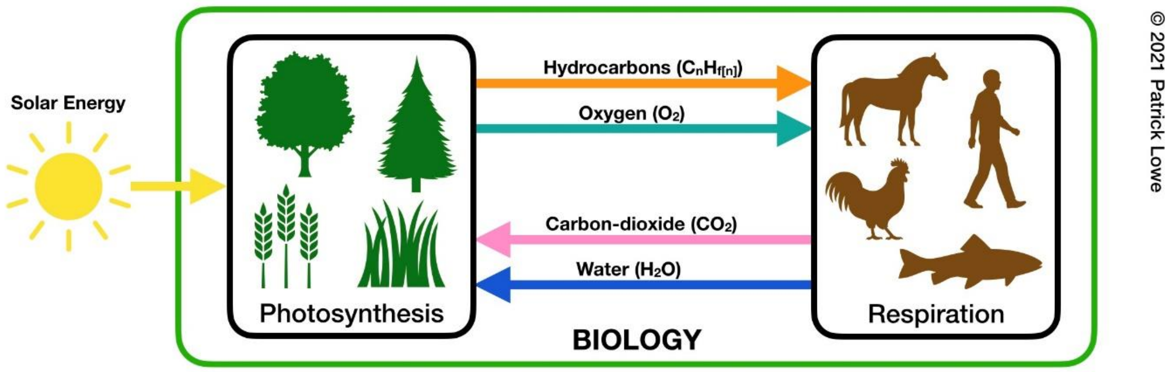

Figure 1: Energy Processes in Biology

3. PRE-INDUSTRIAL ENERGY SYSTEM

Pre-industrial societies deployed technologies based on bioenergy (for fire) and significant use of biological material (for construction of buildings, tools and fabrics). Combustion has an identical macro-chemistry to respiration. When not combusted, biological materials used by humans for construction return to nature and decay by biological respiration.

The scale of human populations and their rate of development in the pre-industrial period was limited by access to biological energy and material resources and never sufficient to create measurable imbalance on a global level even though discrete activity caused localised bio-stress and even desertification. This system essentially preserved circularity and was hence sustained for many thousands of years prior to the Industrial Revolution.

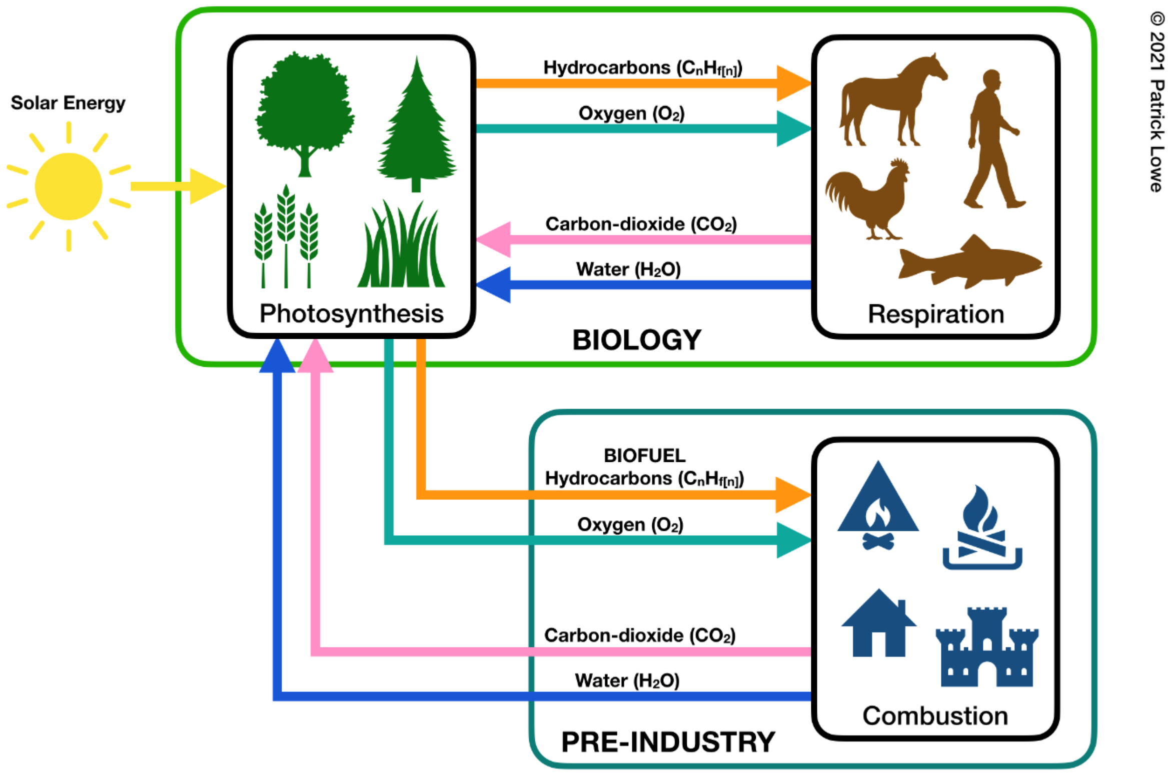

Figure 2: Bioenergy Model (Pre-Industrial)

4. THE INDUSTRIAL REVOLUTION

Access to fossil fuels in combination with high-energy technologies unlocked the ability for human society to leverage its own development at an exponential rate, creating the Industrial Revolution. Heat at scale enables production of industrial materials at scale (such as iron, steel, aluminium, brick, plastics); high-density energy stores in combination with combustion engines enable faster, heavier and longer-range excavation and transportation (for raw materials, goods and services) and highly efficient cultivation (allowing labour to leave the land). The benefits of fossil-fuel-based chemistries to modern society are immeasurable - including health, mobility and human comforts and extending to education, art, leisure and arguably societal advances such as democracy. These benefits are achieved by the leverage of dense and plentiful energy resources to generate *human capacity* that is not consumed by the basics of living and which can instead be deployed for further accelerated growth and development of technology and elevated social values. The rate of energy consumption enabling this advanced society far exceeds the capacity of terrestrial biology.

Industrial combustion has again the same the macro-chemistry as respiration. The significant difference to the pre-industrial bioenergy model is the consumption of hydrocarbon deposits which are the product of legacy photosynthesis and not the product of contemporaneous photosynthesis. This is a “linear” system – unbalanced and unsustainable. Fossil fuel deposits are finite and will expire; the imbalance of atmospheric carbon-dioxide causing global warming has become an issue of even greater and more immediate concern.

Within this linear system energy and material are finite resources and therefore the terms “consumption” and “waste” are more durable and attract moral evaluations within industrial societies that did not apply in the circular, pre-industrial context.

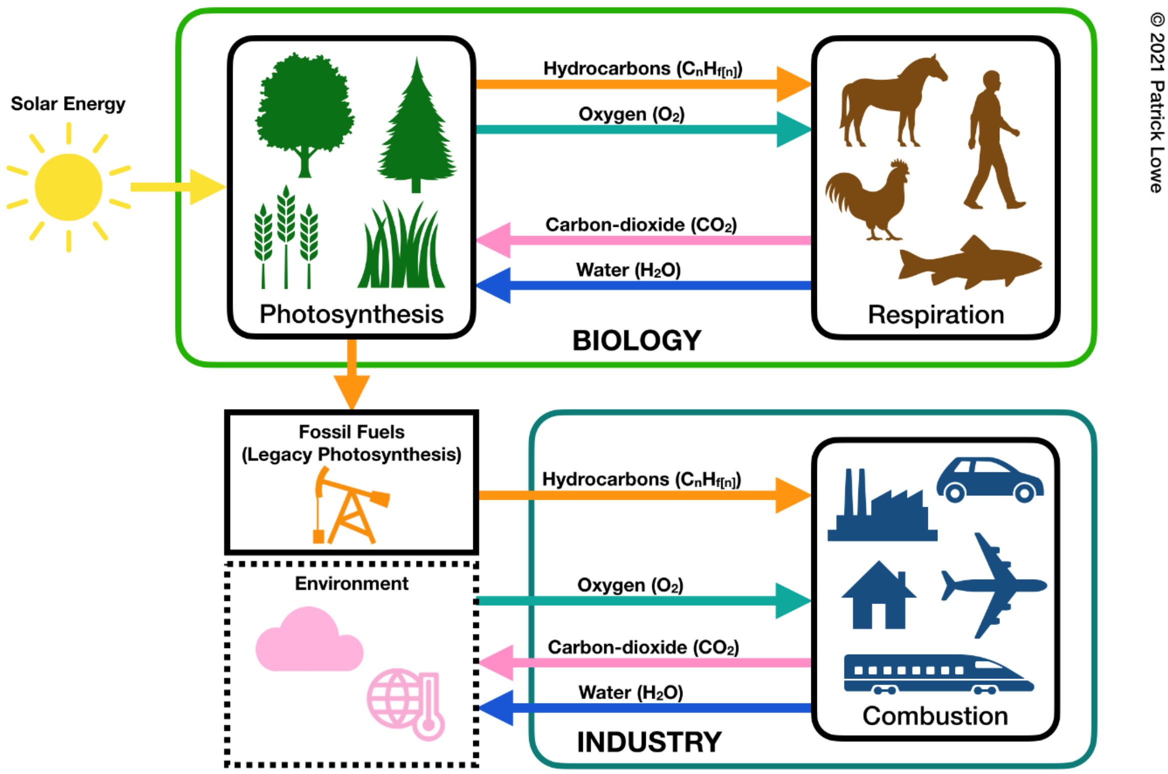

Figure 3: Fossil Fuel Model

5. RENEWABLE POWER

Energy generation from non-fossil-fuel sources has been developed in the form of hydro, solar, wind, tidal, geothermal and nuclear power. Of these, hydro, solar and wind power capture different forms of real time solar energy which itself derives from the solar nuclear fusion reaction. Geothermal and nuclear power (only when generated by fusion processes) also consume atomic material which is practically limitless. Tidal power consumes mechanical energy from planetary motion and is also practically limitless.

All of these energy sources are emission-free and classified as renewable. They are also industrial processes – inorganic, fully controlled, single-purposed and efficient in performance and size – and therefore scalable. They are suitable to displace the linear fossil fuel energy model as the source components of a circular energy system. They all generate electricity, either directly or indirectly from heat, and are typically unsuited to the generation of power directly at the point of use.

6. ELECTRIFICATION

Applications which can make direct use of distributed electrical energy from these remote renewable sources (either, directly or indirectly by use of batteries) can benefit from the most efficient energy deployment since energy losses in distribution (power conversion and grid transport) are relatively low. Furthermore, electrical machines are highly efficient to deliver work energy which can be deployed for prime motion or to leverage higher heating efficiency by the use of heat pumps.

The principal problem with electrification is the cost and density of energy storage. Most renewable power generators are intermittent and do not supply on a demand basis. This creates an even larger electrical energy storage demand than applies for a fossil-fuel-based generation system in which energy is stored upstream in fossil fuel buffers and electricity is generated in response to real time demand. Moreover, mobile consumers (transport applications) cannot connect to a static electricity grid and require integrated electrical storage solutions. Electrical energy storage methods include mechanical systems suitable for large scale (such as pumped storage hydro) and electrochemical systems (batteries) suitable for vehicles.

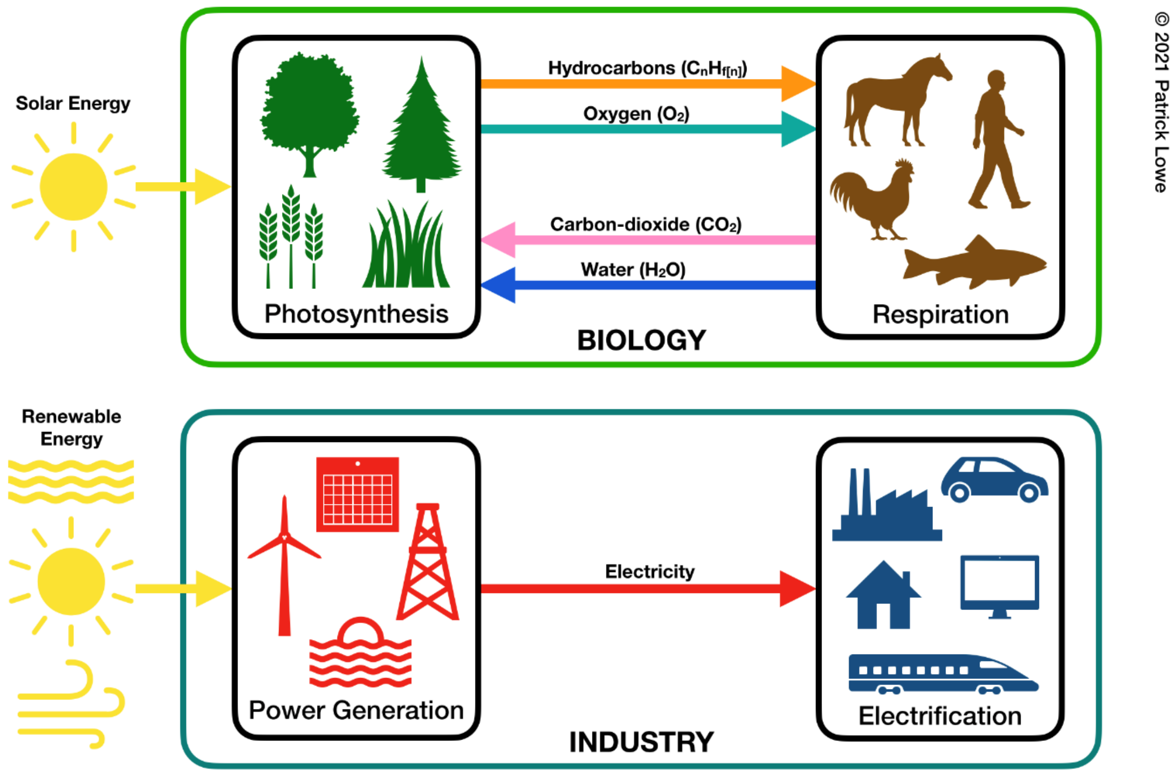

Figure 4: Electrification Model

7. THE HYDROGEN ECONOMY

The hydrogen economy has emerged as a solution for the storage and distribution of renewable energy in a chemical format where electricity is not a suitable medium. This can be in direct chemical processes (such as reduction for steel and cement manufacture), heating (where distribution and storage of hydrogen is more practical than electricity) or as an alternative to electrification for transport (in cases where weight and volume are not critical, but energy quantum is more demanding – such as trains and ships). Hydrogen fuel cell technology permits the reconversion of hydrogen chemical energy back to electrical energy at point of use.

Synthesised hydrogen is a perfectly clean chemical format, being produced from water using electrolysis from renewable power, and returning to water once combusted or otherwise reacted by redox processes.

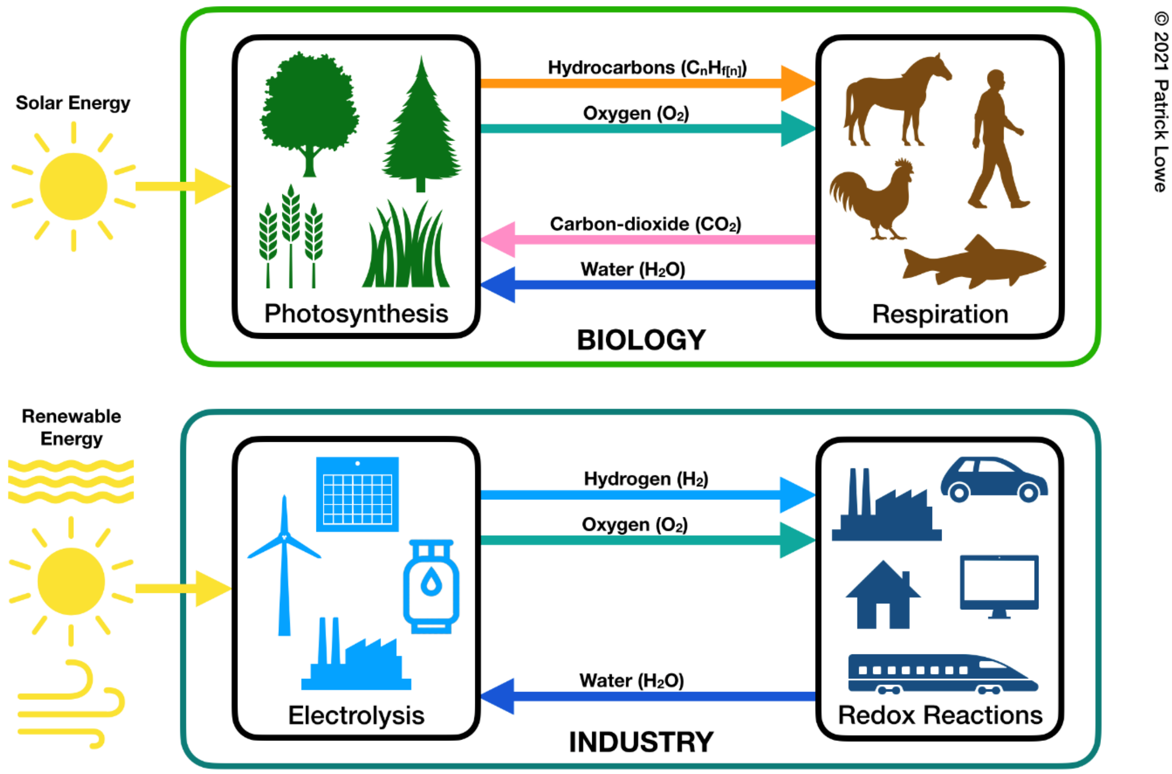

Figure 5: Hydrogen Model

8. UNIQUE BENEFITS OF ORGANIC CHEMICALS

A wide range of energy applications exist which are neither suitable for electrification (as first choice) nor hydrogen (as second choice). These applications are typically in the transport sector, in any vehicles for which the weight and/or the size of the mobile energy store is a performance-limiting parameter. This will also be a function of the quantum of energy required (for range and/or endurance). The energy density of batteries is typically 50 times lower (mass basis) and 15 times lower (volume basis) than typical liquid fossil fuels (hydrocarbons), net of the differing efficiencies of electrical and combustion motors. The energy density of hydrogen (once contained in a tank) is better than a battery but still typically 4 times lower (mass basis) and 5 times lower (volume basis) than fossil fuels. These factors leave a performance gap which remains critical for a huge range of common and vital assets to the industrial system – such as aeroplanes, any military vehicle, helicopters, fast boats and high-performance cars. Perhaps surprisingly, agricultural machinery lies within this list: a combine harvester is weight-limited (soil compaction) and endurance-limited (intense working when active) and is itself arguably the single most important machine to have enabled humankind's release from a fully agrarian society. For all of these machines, high density energy stores – such as those currently provided by gasoline, kerosene and diesel - are not optional. These vehicles will simply not function with the weight and volume penalties presented by battery or hydrogen tanks of equivalent energy. At the same time, the mass and volume deficiencies of electrical and hydrogen energy stores will not be closed by technical development – these gaps are a function of fundamental chemical and electro-chemical constraints.

It is interesting to revisit biology at this point. Not by accident, nature has also chosen hydrocarbons (organic chemicals) for the distribution and storage of energy in the form of oil, fat, sugar and starch. These are nature's equivalent of gasoline, kerosene and diesel fuels in industrial systems. The chemical step necessary is the addition of carbon to the hydrogen molecule – converting a high energy gas into a dense and portable liquid form.

9. INDUSTRIAL BIOENERGY

Humans have an affinity with nature – plants and animals – and so despite the accessories of modern life there is an ever-present desire to "return to nature". So biology is a popular destination to seek replacements for fossil fuels. A huge range of biofuels have been developed over several decades including bioethanol and biodiesel. First Generation biofuels use directly cultivated products such as cane and maize (converting sugar and starch respectively). Developing concerns over land competition and displacement of food production have created pressure to migrate to Second Generation biofuels which use agricultural waste as feedstock (converting, more typically, cellulose).

The macro-chemistry for this bioenergy model appears attractive and fully sustainable. However, the cultivation and conversion processes are intensive in energy overhead and water consumption. Plants are not efficient solar energy converters relative to industrial machines (a typical field crop is 22 times less efficient than a solar panel). Many biofuels are marginal if not negative in net-energy after cultivation and processing. Biodiversity is a risk (disease, for example) in the event that biofuels are adopted at scale, and, being a partly biological, non-industrial process (and therefore not fully controlled) the security of supply is poor. Land competition is the killer-blow to the adoption of bioenergy as a source for the required liquid hydrocarbon fuels as it will require an unrealistic fertile land mass and pressure for further massive deforestation. Indeed, it is wholly unreasonable to expect biology to now compensate for the enormous energy demands of the modern industrial system when nature is already under catastrophic pressure from that same system.

Whilst there are some special cases where bioenergy has positive environmental benefits, it must remain a niche solution within a future sustainable energy model.

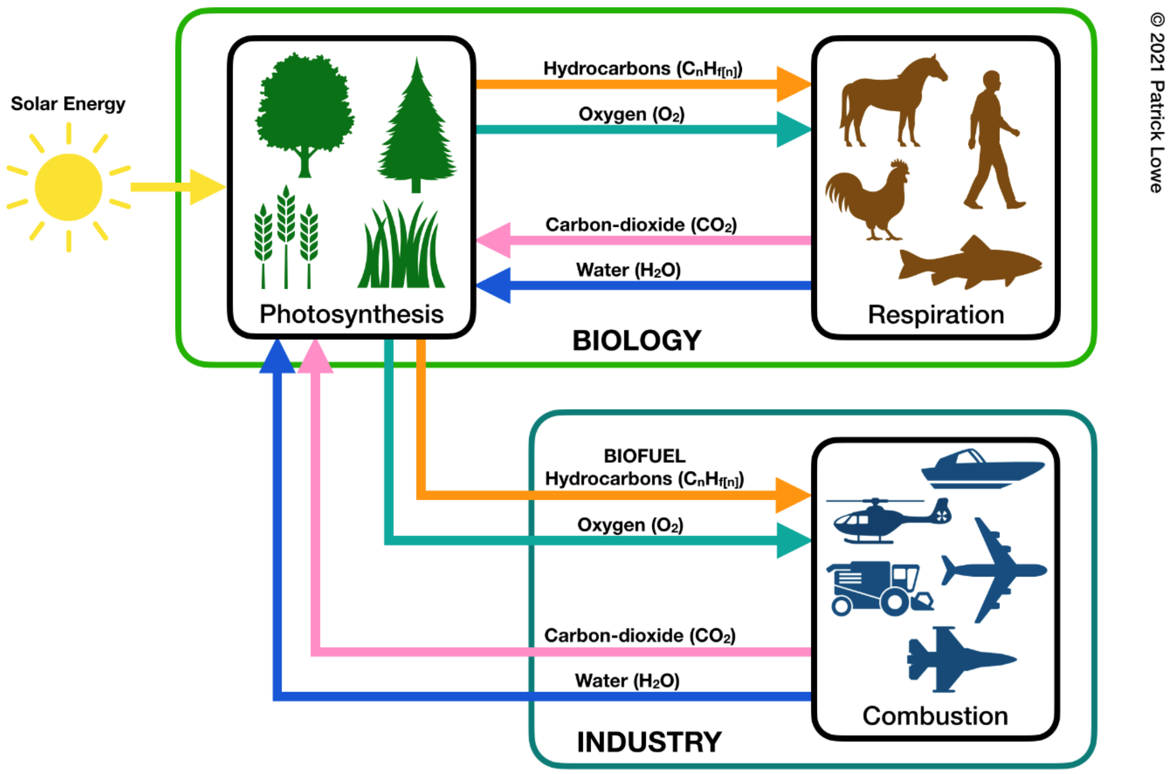

Figure 6: Bioenergy Model (Post-Industrial)

10. FUELS FROM WASTE

Many organic products including hydrocarbon fuels can be produced from waste.

These fit broadly into two categories: biological waste and petrochemical waste.

Biological waste includes a wide range of source material – ranging from agricultural by-products (such as straw), waste biomass (such as forest residues, construction timber) and municipal waste (such as food, oil). There is great merit in taking further benefit from energy already captured in organic material provided the processing energy (especially fossil-based energy) and other resource consumption (especially water) are appropriately accounted. Side benefit exists in any reductions to alternative waste disposal impacts such as landfill. Products derived from biological waste are in effect a specialised sub-set of industrial bioenergy and suffer from the same limitations especially in respect to scale.

Petrochemical waste includes plastics waste and non-biological industrial waste. The primary merit in recycling these wastes comes from the benefit of consuming existing or avoiding further contamination to the environment (such as ocean plastics, landfill). From a global warming perspective, fuel products derived from petrochemical waste which was originally manufactured from fossil-based petroleum precursors are simply a deferred version of conventional fossil fuels with identical macro-chemistry including equivalent carbon-dioxide emissions. In the absence of any associated carbon capture process, these products remain classified within the unsustainable fossil fuel energy model.

As will be discussed later, fuel products derived from petrochemical waste which was not manufactured from fossil-based petroleum precursors, but manufactured from synthetic petroleum precursors (products of petrosynthesis) may legitimately be combusted and are classified within the sustainable and circular petrosynthesis energy model.

In all of the above categories, security and quality of supply present additional challenges to direct fuel production (biofuel, fossil fuel or synthetic fuel respectively), since the source waste material is, by definition, a by-product of upstream activity that is dictated by others in composition and quantity.

11. FOSSIL FUELS WITH SEQUESTRATION

An extension to the fossil fuel energy model has been proposed in which carbon-dioxide is sequestered in a corresponding quantity to that which has been emitted by fossil fuel combustion. This involves capturing carbon-dioxide from the atmosphere in a process called Direct Air Capture (DAC). Carbon-dioxide sequestration techniques include storage in underground cavities or by conversion to carbonate minerals, or, to displace fossil fuel itself within oil wells. If properly transacted, taking account of DAC and sequestration carbon overheads, the approach can be net-zero in carbon-dioxide and therefore prevent global warming. Nevertheless it remains a linear, non-circular and unsustainable solution since fossil fuels and the corresponding capacity for carbon-dioxide sequestration will both eventually expire.

The sequestration model is attractive to oil companies as they own huge fossil fuel deposits which remain to be monetised, and it does indeed have a role to play within a transitionary energy solution.

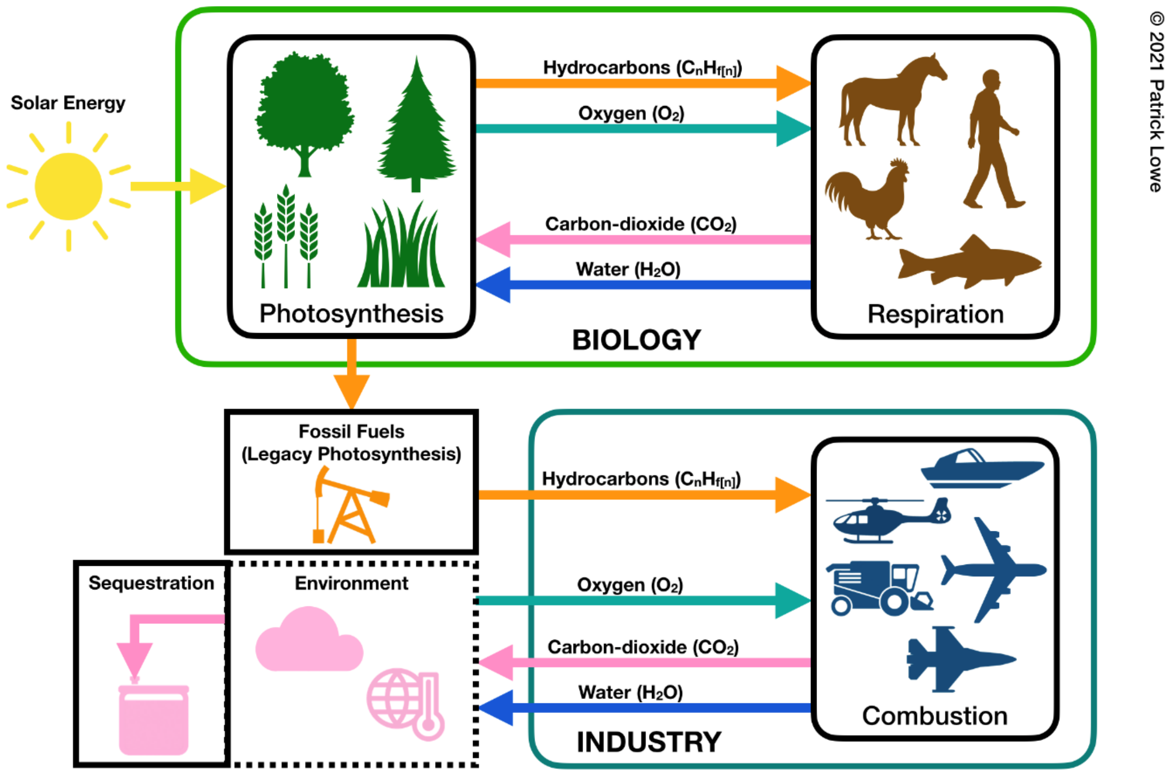

Figure 7: Fossil Fuel Model (with Sequestration)

12. PETROSYNTHESIS

Petroleum is defined as a set of chemicals – typically hydrocarbons – which are found within crude oil and further processed to produce fossil fuels (including gasoline, diesel, kerosene, butane and propane) and petrochemicals (for use as precursors for plastics and a huge range of modern products including pharmaceuticals). Custom and habit based on a fixed production history has associated petroleum and fossil fuel as one and the same material. But petroleum is not the same as fossil fuel. Petroleum is the basis of a vast range of fuels as well as incredible chemistries and resultant products which enhance the quality of life in modern society. The principal problem with petroleum is its current production model, being derived in a linear manner from finite fossil reserves and with linear impacts on the earth's climate through carbon-dioxide emissions, as well as huge geopolitical disturbance including military conflict associated with strategic control of oil and its wealth.

The petroleum we need can be manufactured rather than consumed from historical reserves. This manufacturing process is equivalent within the industrial system to the photosynthesis process within the biological system. We propose to define this industrial process as ***petrosynthesis***.

The macro-chemistry of petrosynthesis is identical to photosynthesis so that petrosynthesis can be considered a "forest in a factory" – generating petroleum and oxygen. As an industrial process it is single-purposed, fully controlled, highly efficient and scalable. In the same way, an engine is the industrial equivalent of a horse. The biological equivalents are less efficient but multi-purpose, diverse and highly complex including their ability to reproduce and evolve – an ability which has not yet been achieved by industrial machines.

With these parallels in mind, the author believes that humanity will look back at the current period in history (1750 – 2050) as a transitionary period of linear consumption of material, most particularly including petrochemicals, which provided a bootstrap to the completion of a fully circular and balanced infrastructure, as exists in biology. "Part 2" of the Industrial Revolution is the provision of the supply-side of high-utility energy and petrochemicals by construction of petrosynthesis capacity to match and fully balance the consumption-side created during "Part 1". This system will function indefinitely, in harmony with nature and the planet.

Petrosynthesis may generically employ a range of pathways to produce petrochemicals from renewable energy sources. These pathways include direct solar heat processes (such as Concentrated Solar Power), solar photochemical processes (such as artificial photosynthesis) and electrochemical processes using renewable electricity (such as eFuels/electrofuels). All pathways require some form of atmospheric carbon-dioxide capture such as Direct Air Capture (DAC).

Fusion power (electricity generated from nuclear fusion) is seen as the holy grail of clean and sustainable energy. One day soon this technology will be delivered. Petrosynthesis is wholly compatible with fusion power since it will allow even more efficient scaling with reduced dependence on wind and solar power generation, whilst enabling the distribution and storage of this vast quantum of centrally generated energy and materials to decentralised applications, just as happens today within the fossil fuel model.

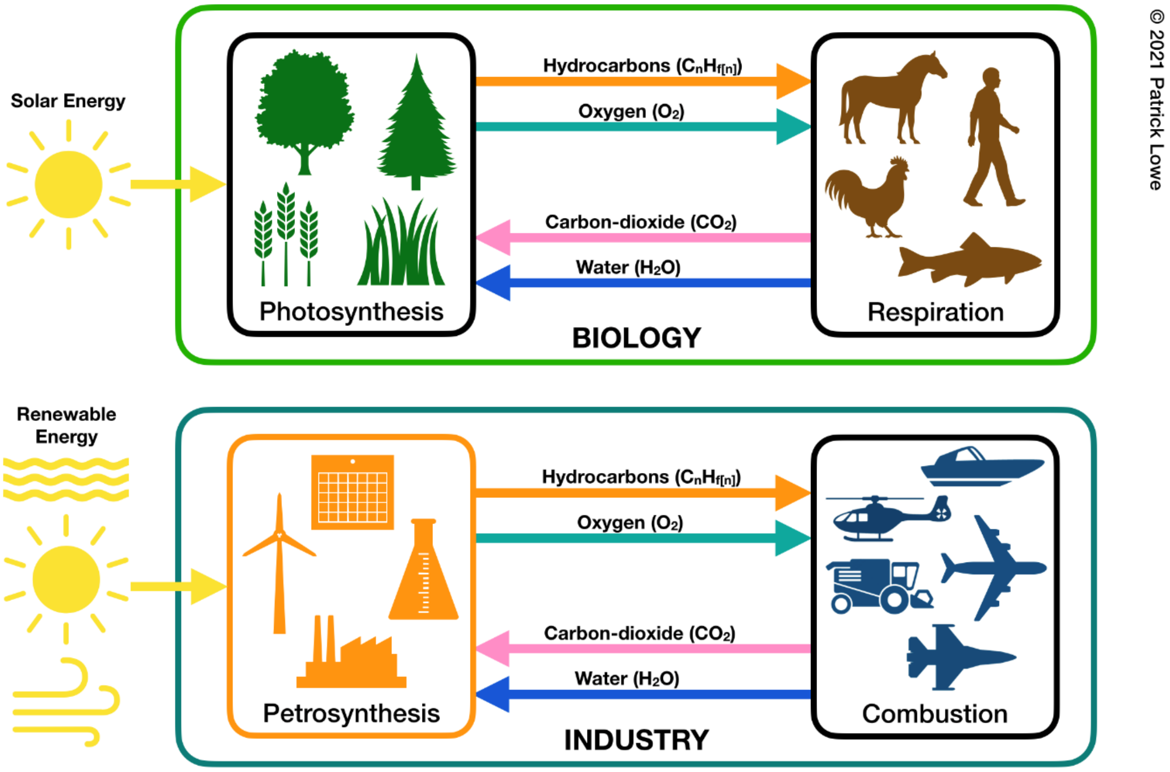

Figure 8: Petrosynthesis Model

13. PETROSYNTHESIS – A NEW PARADIGM

Petrosynthesis provides a new paradigm for geopolitics and industrial policy.

Unlike fossil petroleum, synthetic petroleum can be generated by the consumer. Local supply provides control, independence and security to the nation state – dispensing with the international friction associated with crude oil reserves. Sea transportation is avoided and hence the systemic ecological catastrophes of marine oil spills - a constant companion of the fossil-fuel age - are eliminated.

Modern military operations have historically succeeded or failed on the basis of logistics, and energy logistics in particular. Petrosynthesis alongside portable fusion power will in the future enable energy independence and unlimited mobility in military operations.

New approaches can be taken to industrial policies, many of which are counter-intuitive and counter-cultural. Recycling in particular can be considered at a macro-scale (via combustion and atmospheric carbon-dioxide), just as happens in biology. Use of natural materials should be reduced not increased, by substitution with synthetic materials derived from petrosynthesis, as this reduces pressure on finite agricultural capacity and hence reduces deforestation. Examples:

- Clothing/fabrics: no need to recycle complex fibre mixtures, simply combust waste material (for energy) and make all new material by petrosynthesis.
- Single-use plastics: plastics, if properly disposed (by combustion for energy) reduce pressure on agricultural capacity for paper and card.
- Plastics vs. natural materials: further increases in plastics deployment (recycled by combustion for energy at end-of-life) reduce pressure on agricultural capacity for paper, wood and natural fibres.
- Landfill vs. combustion of plastics waste: whilst combustion of plastics derived from fossil petroleum is of mixed benefit (reduces landfill but increases greenhouse gas and hence global warming), combustion of waste plastics derived from petrosynthesis is fully legitimate within a macro-scale carbon recycling process.
- Biodegradable plastics: degradation of plastics derived from fossil petroleum is of mixed benefit (reduces contamination but increases greenhouse gas and hence global warming), degradation of waste plastics derived from petrosynthesis is fully legitimate within a macro-scale carbon recycling process.
- Bioplastics: problems with plastics waste have motivated increased use of bioplastics but these create increased pressure on agricultural capacity; synthetic plastics, combusted for energy at end-of-life are a superior solution.

The implementation of circularity permits a new perspective on consumption and waste. These terms have no meaning and fall away, just as they do in biology. A plant or an animal cannot “consume” or “waste”; it lives and circulates. This will now apply in an industrial context. There is no consumption, there is only “circulation”. Circulation has utility and cost, but is absent of any durable consequence or damaging legacy to the planet.

14. CIRCULAR ENERGY ECONOMY

The three renewable, circular and scalable energy systems that have been described (Electrification Model, Hydrogen Model and Petrosynthesis Model) may be combined into one holistic energy system: the Circular Energy Economy (CEE). The CEE is net-zero in macro-chemistry. The CEE consists of three layers of energy supply and consumption: electricity, hydrogen and petroleum (gasoline, diesel, kerosene and LPG). Each layer has relative merits and will be adopted by application according to performance imperative and/or economics:

- Electricity layer:
  cleanest, most efficient, highest utility
  most difficult to store (heaviest, largest), most difficult to distribute
- Hydrogen layer:
  medium rating on all factors
- Petroleum layer:
  easiest to store (lightest, smallest), easiest to distribute
  least clean, least efficient

Generation of these three energy layers can work symbiotically. Renewable power sources are typically intermittent. Intermittency creates large storage demands, especially long span (seasonal) intermittency. Storage is the worst feature of electrical energy. Batteries can be used for short span balancing, excess (stored) hydrogen for long span balancing by use of hydrogen gas-fired power stations. Hydrogen electrolysis and petrosynthesis can make use of excess electrical generation during peak production periods (high wind, sun). Without the balancing hydrogen and petroleum layers it is difficult to contemplate a renewable power system of sufficient power and storage capacity to supply all required energies by electricity alone and without the use of fossil fuels in reserve.

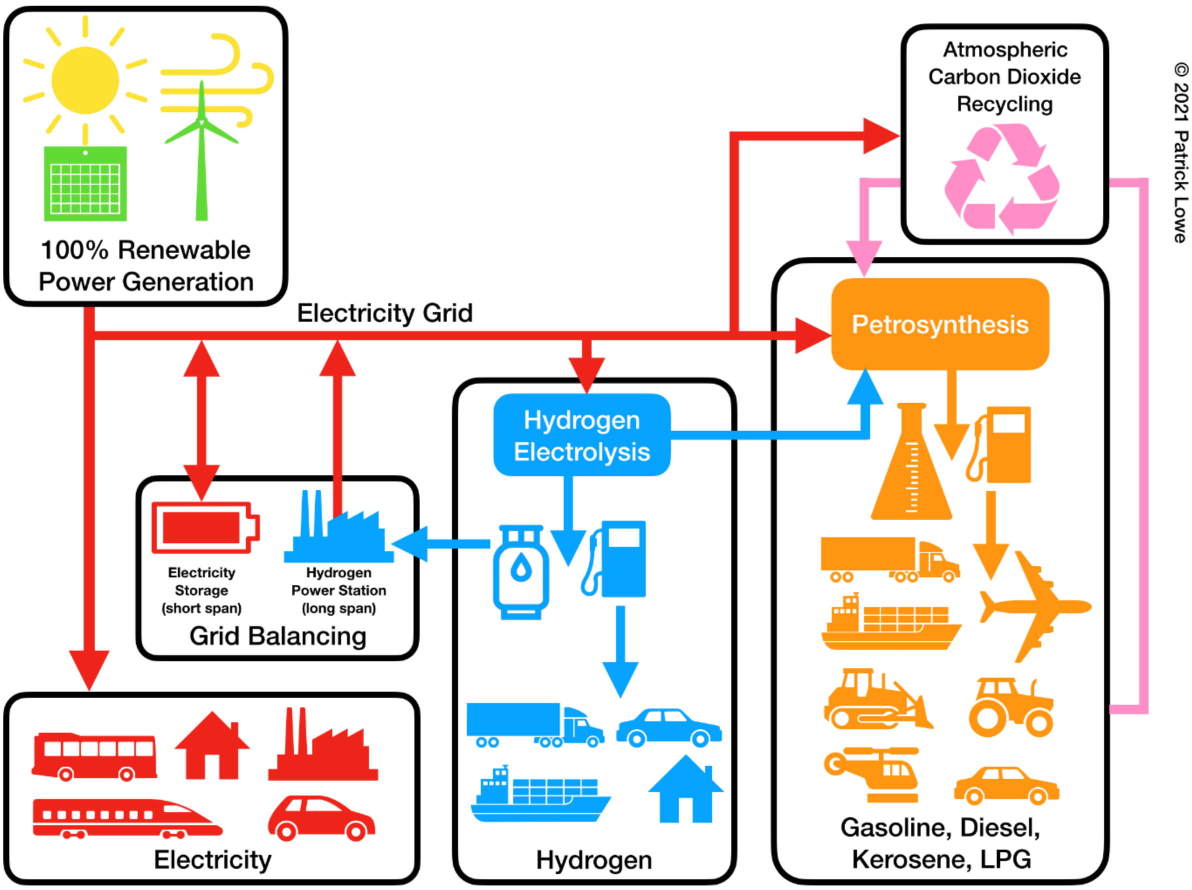

Figure 9: Circular Energy Economy

15. PROPOSED DEFINITION OF PETROSYNTHESIS

A range of products, processes and technologies that can be classified as elements or examples of petrosynthesis have been developed and named, for example,

Carbon Capture and Utilisation (CCU)
Renewable Energy (RE)
Electrofuels or eFuels
Concentrated Solar Power (CSP)
Artificial Photosynthesis
Direct Air Capture (DAC)
Hydrogen Electrolysis
Fischer-Tropsch (FT)
Power-to-Liquids (PtL)

However, are as far as the author is aware there is no generic name or descriptor for the high-level end-to-end process of petrosynthesis. A definition is proposed below.

Petrosynthesis

noun

> the artificial creation of organic compounds (synthetic petroleum/petrochemicals) and oxygen from inorganic precursors (principally water and carbon-dioxide) using non-biological energy (such as hydro, wind, solar, tidal, nuclear, geothermal); the industrial equivalent of photosynthesis, using neither energy nor material produced by either concurrent photosynthesis (plants) or legacy photosynthesis (fossil fuels).