Preliminary Report

Hydrogen Scotland: A Route to Export Powerhouse

Boosting Productivity with Existing, Emerging, and Future Renewable Energy Technologies

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1. Ammonia as Store of Renewable Energy

The Australian CSIRO breakthrough technology, projected to lower markedly the cost of producing hydrogen from ammonia, has greatly enlivened the prospects of using ammonia as a means of storing and transporting renewable energy.

BOC to collaborate with CSIRO on revolutionary $3.4m hydrogen project

Link to video presentation…

This is likely to accelerate the pace of efforts to improve the cost-effectiveness of **existing technologies** using renewable energy to manufacture ammonia and to incentivise the **emergence of lower-cost prototype technologies** and extremely promising lab-based **future technologies**.

The ammonia market at a glance:

- At 180 million tonnes pa ammonia is the second most produced chemical in the world
- Predominant uses: fertilisers, explosives, industrial processes and refrigeration
- Food production would only meet the needs of 4 billion without ammonia products
- Prices have ranged between $US500 and US$900 per tonne since 2012
- Consumption is growing at about 3% pa
- Dominant producers are China, Russia and the USA

At present about 95% of the power for ammonia production is from fossil fuels with attendant pollution amounting to about 3% of global greenhouse gas emissions. Most production uses the 100-years old Haber-Bosch (H-B) chemical process in which methane from natural gas or coal gas and oxygen form ammonia under extreme pressure and temperature, requiring massive energy inputs. Natural gas prices and availability greatly affect the cost of production and the capacity for certain countries to be ammonia independent.

That's the present. What about the medium term, 2020-2030? For a glimpse, consider the South Korean Government's plan to replace the country's approximately 26,000 compressed natural gas (CNG) buses with hydrogen-powered vehicles, reported THE CHOSUNILBO. The government will allow existing filling and gas stations to set up hydrogen fuel pumps and encourage companies to develop major parts for hydrogen vehicles such as measurement sensors and hydrogen storage tanks.

And that's just South Korean buses. In addition, hydrogen fuel-cells could well find increasing use in powering:

a) **Trucks** – moving goods around the Port of LA

b) **Trains** – world's first orders in Germany

c) **Planes** – replacing jet fuels with liquid hydrogen

d) **Ships** – recent hydrogen fuel-cell systems for maritime applications, first cruise ship scheduled

e) **Rockets** – NASA has used hydrogen as rocket fuel for decades but for interstellar travel have commissioned a 2017 study of fusion rockets.

This 2017 study of electric bus technologies compares the performance of **diesel buses** with **hybrid electric buses** (generating electricity on board using a diesel engine), **fuel-cell electric buses** (generating electricity on board using hydrogen fuel-cells) and **battery electric buses** (store electricity on-board, charged overnight or intermittently *en route*). The study concludes:

> "Today, electric buses (EBs) hold a clear advantage over diesel buses in several performance categories, particularly the reduction (or elimination) of tailpipe and greenhouse gas emissions. Electric buses may also deliver benefits in terms of energy efficiency, environmental impact, passenger comfort, and integration with renewable energy sources. EBs are already becoming the bus of choice for a number of cities and public transport providers worldwide. While EBs still suffer from increased vehicle kerb weight and higher total costs of ownership, ongoing technology development and increased production volumes should reduce these obstacles in coming years."

However, in contrast to the prospects for hydrogen fuel-cell buses, trucks, trains, ships and planes there are competing commercial interests for and against the development of hydrogen fuel-cell cars. While it makes sense for the fossil fuel and car manufacturing industries to lobby for the hydrogen car, essentially a product line extension for them, former US DOE Secretary Steven Chu was quoted in the article "Toyota vs Tesla: Can hydrogen fuel-cell cars compete with EVs: "We asked ourselves, 'Is it likely in the next 10, 15, 20 years that we will convert to a hydrogen car economy?' The answer was no." A compelling contrary view from Washington State University concludes:

> "The entire problem is that folks view this 'race' as a competition in the first place. That creates an unnecessary race to the bottom. We need all of our clean energy solutions to be substantially successful — and fast. What I've shown here is that in many, if not every way, hydrogen fuel-cell vehicle technologies are synergistic with battery electric vehicles. Our goal should be the best of both worlds."

This is reinforced by Shell in hedging their bets by buying the retail fuel network First Utility to provide a comprehensive network of renewable energy super-chargers for electric vehicles throughout the UK and Germany as well as the ongoing delivery of oil, diesel and natural gas. At the same time Shell is also part of several initiatives to encourage the adoption and role of hydrogen in the future of transport. A three-way bet from the corporate with a world-leading scenario planning capacity.

Also relevant is the suit filed by New York City against BP, Chevron, Conoco-Phillips, ExxonMobil and Royal Dutch Shell, the world's five largest publicly traded oil companies, seeking to hold them responsible for present and future damages to the city from climate change, through the oil and gas products they have sold over the years. It also charges that the companies and the industry of which they are part have known for some time about the consequences but sought to obscure them. As of late January 2018, nine US cities have done likewise.

Will this increasingly compel these majors to consider implementing initiatives such as the development of the renewable ammonia-hydrogen fuel cycle on a massive scale? Would this be an opportunity for BP to do more than tout themselves as the "Beyond Petroleum" company with vastly less costly environmental risk than offshore oil & gas exploration and production just as Trump's offshore oil drilling plans ignore the lessons of BP Deepwater Horizon.

2. Scale of Ammonia-Hydrogen Opportunity

Providing renewable ammonia-hydrogen fuel for a 26K bus fleet would require the construction of renewable (wind/solar/wave) energy farms generating about 8,700MW with an estimated capital requirement of £8.4bn[1]. This could be achieved through the installations at, say, 25 locations across the Highlands & Islands (HI) each generating an average of 368MW.

To put this in context, a further 15MW-16MW would deliver the power for a population of about 10,000 residents in the region of each location. If we assume that the availability of increasingly economic renewable power would deliver a capacity to manufacture high value-added products for export markets drawing mainly on local natural resources, then a further 116MW would bring the renewable energy farm capacity to about 500MW at each location, increasing the estimated capital requirement to £12bn for a total of 12,500MW, more than twice Scotland's installed wind power capacity of 5,328MW as of March 2015.

Beyond this can we envisage renewable hydrogen energy stored in ammonia for export on a scale 100 times Scotland's energy needs or greater than the maximum annual production of energy from oil & gas sourced from the North Sea in the past 50 years? Would we catch Dutch disease or take the Norwegian sovereign wealth route?

Renewable energy to ammonia production technologies – existing, emerging, future – are outlined in the next three sections of this paper. The final section identifies a wide range of opportunities for Scotland to benefit from contributing to and adopting advances in existing, emerging and future renewable energy technologies to meet growing global demands for energy on the one hand and disrupting the supply modes of energy on the other.

In other papers the authors are conducting further investigations of:

a) *Innovation in Building Social Capital to Maximise Well-Being*

b) *Investment in Demonstrations of Hydrogen Scotland Technologies*

c) *Investment in the Deployment of Hydrogen Scotland Technologies and Advances*

d) *Scoping the Extent of Eco-Industrialising*[2] *the Highlands and Islands: Proposed eco-industrialisation of the Highlands and Islands would focus on the manufacture of high value-added products for export markets drawing mainly on local natural resources, including seaweed, peat and bog iron.*

e) *Crofting as a Catalyst for the Hydrogen Scotland Development and Eco-Industrialisation*

f) *Greenprint for a Lead Community on the Isle of Skye: The attraction of investment in prototype demonstrations of the existing/emerging/future ammonia production technologies and a model eco-industrial park*[3] *(EIP) in Skye as a leading demonstration supporting the attraction of the massive investment in renewable energy generation foreshadowed.*

g) *Evaluation of the National Socio-Economic and Environmental Impacts of Multiple Communities: Articulation and depiction of a model community of 10,000 residents operating a 500MW renewable energy farm to meet local power needs, a major ammonia-hydrogen export enterprise and the operation of a major eco-industrial park followed by the development and application of a computable general equilibrium model (CGEM) to assess the national/regional/multisector economic and environmental impacts of 25 such communities throughout the Highlands and Islands.*

h) *Appraisal of Manufacturing and Service Export Opportunities from Implementing Hydrogen Scotland*

i) *A Business Case for Operating an Implementation Capacity on the Isle of Skye*

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[1] South Australian Green Hydrogen Study: A report for the Government of South Australia (page 6). By way of comparison as reported in The Times, Dec 2017: Planned expenditure on Heathrow T5 now reduced to about £14 billion about £2 billion more than the estimated potentially massive productivity-boosting investment in 25x500MW wind farms.

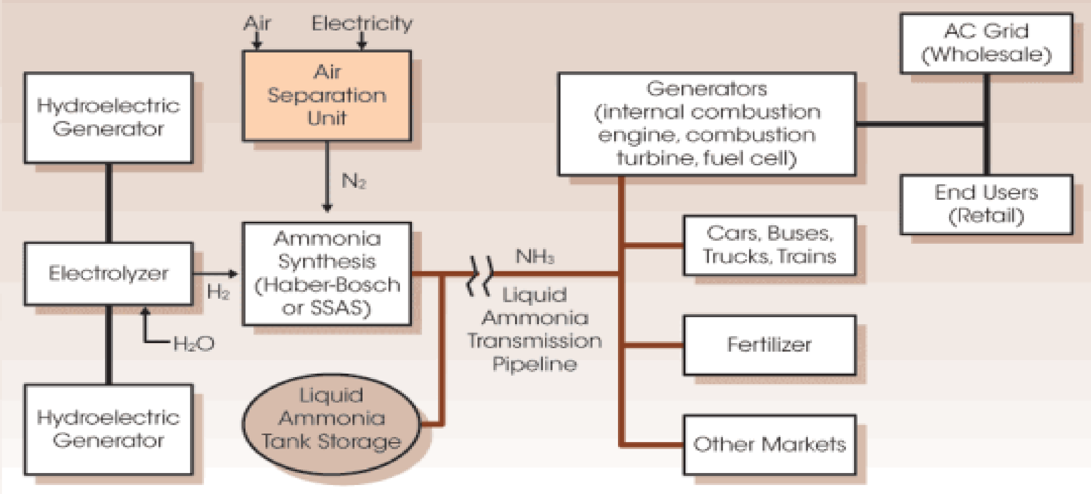
[2] Eco-industrialisation or Industrial Symbiosis is a closed loop production cycle continuously improving environmental and economic outcomes. Mutually beneficial connections among industry, natural systems, energy, material and local communities become central factors in designing eco-industrial production processes.

[3] Delivers inter-business cooperation with the local community to reduce waste and pollution, efficiently sharing resources (such as information, materials, water, energy, infrastructure, and natural resources) to achieve sustainable development by increasing economic gains and improving environmental quality.

3. Existing Technologies to Produce Ammonia from Renewable Energy

Renewable energy accounts for only about 5% of so called "green" ammonia production, chiefly from hydroelectricity as reported and depicted in the figure below from the HydroWorld.com paper *Renewable Fuels: Manufacturing Ammonia from Hydropower*.

FIGURE 2 Ammonia Manufacturing Process



The process of manufacturing ammonia from a hydro facility varies from the natural gas process in the method of delivering the hydrogen. With hydro, hydrogen is produced by cracking water with electrolyzers; with natural gas, hydrogen is produced using steam methane reforming.

To be viable ammonia synthesis by the Haber-Bosch (H-B) process or Solid-State Ammonia Synthesis (SSAS) process (discussed in the next section) requires steady flows of cheap electricity. Rapid advances in lowering the costs of battery storage technologies to handle wind, wave and solar power intermittency together with rapidly decreasing costs of generating wind and solar power is likely to provide near term solutions that will surpass markedly the financial viability of hydro and without its adverse externalities.

Many countries are either investigating ammonia-hydrogen production or funding prototype operations to gain experience in using abundant, low cost renewable energy to produce ammonia for local farm-based and other uses or in some cases for exporting on large to massive scales.

In Scotland, the 2006 report of the Hydrogen Energy Group noted that renewable energy resources are primarily located in the Highlands and Islands (paragraph 42, page 13). Among other things, this has led to projects designed to gain experience in the application of fuel cell technologies to convert renewable energy generated hydrogen to power for transportation purposes at the local level:

a) HI-Energy funded Hebridean Hydrogen Park in which hydrogen is produced by electrolysis then stored for use by postal delivery vehicles.

b) HIE funded Orkney Surf'n'Turf project to produce hydrogen from tidal power then transport to Kirkwall for fuel cell conversion back into electricity for use as auxiliary power for ferries.

c) Public and private partnership funded Aberdeen Hydrogen Bus Project using hydrogen produced from a 1MW electrolyser to power a 10 fuel-cell bus fleet operating in public revenue service.

In 2014 Scottish Enterprise funded the report "Rural study onto ammonia-hydrogen production", which recommended "that in order to test the feasibility of this concept, a small-scale device (100-300kW hydrogen facility) should be taken forward in order to evaluate its practicality, at an estimated total capital cost of around £2 million".

A case is currently being developed for the Isle of Skye to be used as a location for such a test using renewable energy as well as a prototype plant for the emerging SSAS technology and the potentially game-changing, lab-based technology being developed at Glasgow University considered in the following sections.

Given the technology advances since 2014, it may be worth conducting a further study to evaluate the economics of producing ammonia by drawing power from an existing major hydroelectric installation.

One possibility would be comparing the economics of using the Lochaber hydroelectric power facility to produce ammonia for export instead of current plans to upgrade the existing smelting plant and planned downstream operations to extend aluminium ingot production to the manufacture of aluminium rolled products and auto parts.   One the one hand, the former requires air, water, cheap electricity and a short pipeline to tanker distribution and/or local production of a wide range of ammonia-based products for local use and export. On the other, there is a need to import alumina, use massive amounts of "cheap" hydroelectric power for:

(a) aluminium smelting with its adverse externalities;

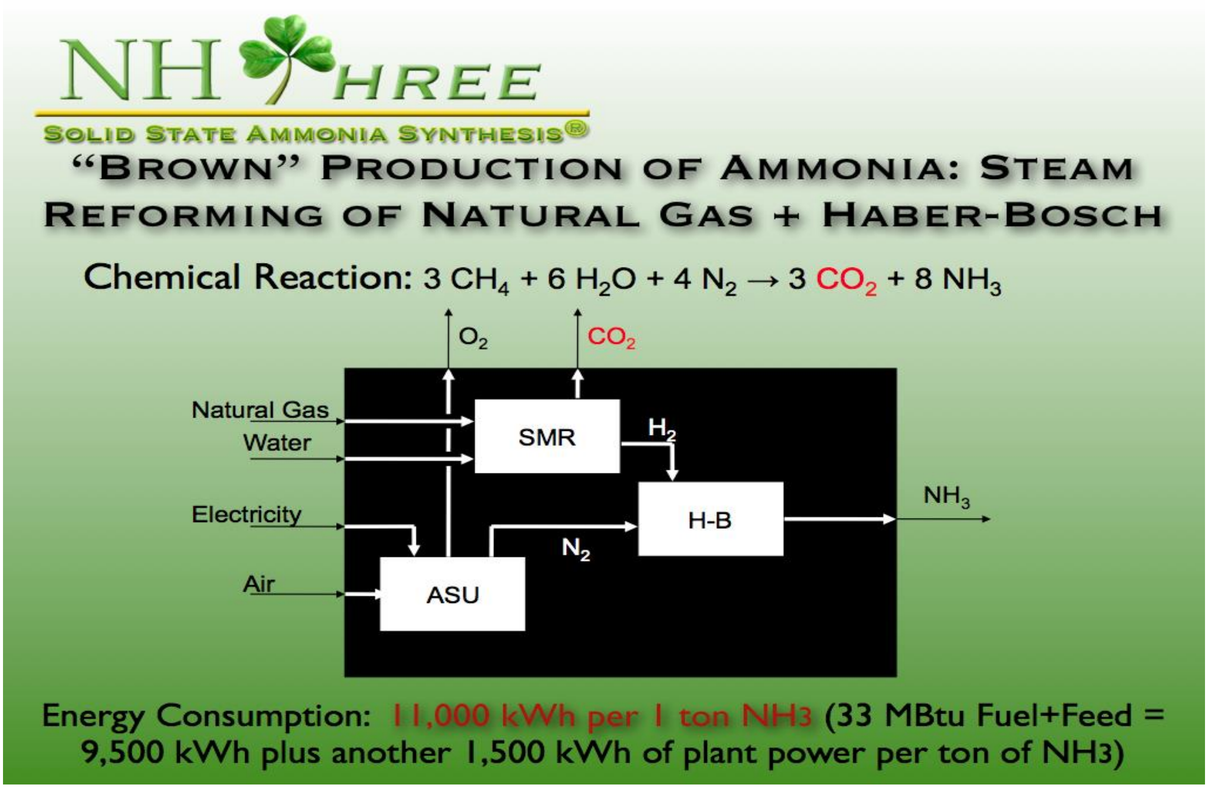
(b) convert aluminium ingots to rolling stock; and

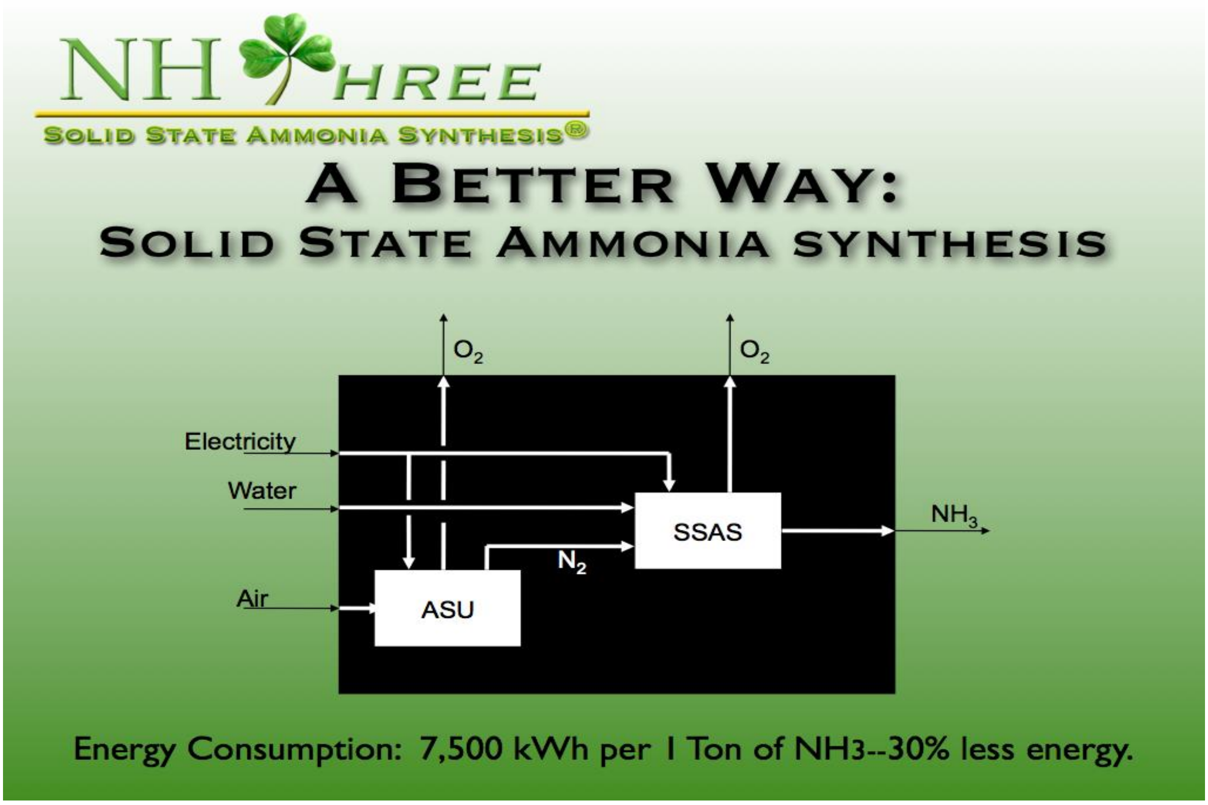
(c) subsequent manufacture of auto parts, and finally export these various products.

In Australia, ammonia-hydrogen is being viewed as "our next great export":

4. Emerging Technologies to Produce Ammonia from Renewable Energy

A comparison of the power requirements of the electrolysis and H-B process with the Solid State Ammonia Synthesis (SSAS) process for the production of ammonia is shown in the diagrams below from USA based company NHThree LLc (NHThree).





NHThree have developed and patented an SSAS technology to produce ammonia at a lower cost than the H-B process, and with the obvious environmental advantage of not using fossil fuel feedstock. The key processes in SSAS are:

a) dissociating gaseous H_2O into gaseous O_2 and adsorbed H+
b) transporting H+ through a proton conducting membrane
c) reacting H+ with adsorbed N_2 to make NH_3.

SSAS plants will differ from renewable energy configured H-B plants through:

a) reduced capital and operating costs
b) design flexibility enhancing plug & play features, remote monitoring to increase suitability for operating in remote locations
c) lessening pressures on the environment.

SSAS could solve problems associated with renewable electrical energy:

a) load levelling, inter alia, postponing investments in new generating capacity
b) night-time production of electricity
c) conversion of stranded (generated at locations remote from the grid) electricity into transportation fuel.

NHThree: "SSAS could be the "killer app" that will allow clean-nuclear, hydro, solar, and wind power generation to reduce the world's dependence on fossil fuels."

In Australia, technology company Alchemy of Air Pty (AOA) Ltd has secured exclusive rights to manufacture and roll out the NHThree technology in a territory that includes Australasia, the majority of Asia and the Middle East including Israel. The publicly listed Australian company Authorised Investment Fund Limited (ASX: AIY) has agreed to purchase 30% of AOA.

Note the oxygen produced as a by-product can be used for other chemical processes within eco-industrial parks (EIPs) or exported as a relatively valuable product.

Move quickly and an opportunity may exist for a Scottish Highlands' concern to secure the rights to manufacture the technology for the European market, initially testing the technology then rolling it out throughout the Highlands in partnership with appropriate communities, including the possibility of active involvement by crofting communities in the establishment and operation of EIPs.

As noted above, a case is being made for the Isle of Skye to test this technology and to take a lead in rolling out the process throughout the Highlands.

5. Future Technologies to Produce Ammonia from Renewable Energy

A research group at Glasgow University have lab-tested a process that produces hydrogen 30 times faster than the leading commercial electrolysers which need catalysts made of precious metal, high pressures and as noted above massive inputs of electricity from renewable energy sources. Writing in the journal Science in 2014, the group claims their process will increase hydrogen production with lower power loads at normal atmospheric pressure. Instead of remaining a gas, requiring storage at high pressures and low temperatures, their process will store hydrogen in a carbon-free liquid.

Speaking to BBC Scotland, the group leader Prof Cronin says it'll take time and money to achieve the scale of an industrial process: "I think for making something that's going to get into a really large system, it's going to take up to ten years. Hopefully we'll inspire a company to get started and put the technology in that company."

The process has already been patented through financial support from Scottish Enterprise.

As noted above, a case is being made for the Isle of Skye to provide a location for testing this technology once sufficiently developed.

6. Boosting the Scottish Economy by Advancing Renewable Energy Technologies

6.1 Existing Demand

6.1.1 Replacement of Fossil Fuel Imports

As reported in The Times (13 December 2017), "Britain has met just under half of its winter gas needs in recent years from North Sea production and domestic storage sites. The remainder has come by pipeline from Norway and the Continent, and through imports of liquefied natural gas (LNG) by ship from countries such as Qatar."

And that's just Britain among most nations that will seek to replace such fossil fuel imports with power generated at home, increasingly via renewables with surplus production converted to storable and transportable ammonia. While the ammonia exports from 25x500MW wind farms across the Highlands would scarcely make a dent in this demand, it holds the potential to power an immensely productive sub-economy capable of boosting the whole Scottish economy as outlined below.

6.1.2 Robotics and Drones in Agriculture

As reported by Compute Scotland robotic and drone technologies are playing increasing roles in raising the productivity of agriculture in Scotland. Robot machinery and drones are likely to become mainstream as renewable energy becomes the lowest cost option. At the same time sensors/drones and "big data" applications will reduce the need for skilled drivers of tractors and a wide range of agricultural machinery. The use of drones to applying pesticides at the point of need rather than aerial spraying will lead to less pollution of waterways. The same applies to increasingly effective application of fertilisers, including ammonia-based and seaweed-based fertilisers.

Conceivably each HI-EIP could house an enterprise with the capacity to apply these technologies to crofting, farming and seaweed harvesting.

6.1.3 Vertical Farming: 390 Times More Productive Than Field Farms?

AeroFarms

VertiCrop: Vertical Farming

AeroFarms' headquarters in Newark, New Jersey, is a former steel factory that's been converted into the world's largest vertical farm. Throughout the 6,410m^2 of growing space, plant beds are stacked on top of each other in 12 layers between floor and ceiling. LEDs provide lighting and the roots of leafy greens, herbs and salads are kept nourished using an "aeroponic" mist claimed to use 95% less water than outdoor agriculture. "This is game-changing in terms of productivity," explains Marc Oshima, AeroFarms' co-founder. "We can take the same seed that might take 30-35 days to grow outside, and it will have a 12-16 day crop-cycle in our system, so we can have 20 crop cycles a year."

AeroFarms' agricultural optimisation relies on algorithms that continually monitor nutrients and lighting at different points in the plants' growth cycles. By optimising light wavelengths and the nutrient-filled mist, operators can endow plants with different tastes, textures, colours and yield. "For example, we can make watercress spicier and lettuce sweeter," he says. The flagship facility, in partnership with RBH, Prudential and Goldman Sachs will be able to produce 900,000kg of vegetables -- which will be distributed to local buyers -- annually when it reaches full capacity, predicted for midway through 2016.

Also depicted is the vertical farming venture VertiCrop using a hydroponic technology with the claim of 20 times more yield than open field agriculture.

Clearly an assessment of the foregoing productivity/yield claims would precede serious investigation of these technologies, for example, as a core business facility within each of the projected 25 HI eco-industrial parks (HI-EIPs), distributing their products in kelp-based biodegradable packaging - produced by select HI-EIPs for general EIP usage and as an export product – as dry foods for export, as fresh foods for local and regional consumption and as an input to high-value added food products - for cold storage for gourmet markets, cook chill for gourmet markets and hospitals and sous vide for leading restaurants. The capital cost of land acquisition and buildings would be very different from the AeroFarms' case unless fit-for-purpose solutions are offered by any of the 173 buildings on the Buildings at Risk Register across the Highlands or other structures.

6.2 Emerging Demand

6.2.1 Transportation

The demand for wind power and all renewable forms of power generation is going nowhere but up if we add the ever-increasing electrification of transportation systems globally:

a) **Trucks** – starting with electric tractors over 20 years ago, all types of electric trucks are being built. Hybrid diesel-electric trucks have been in operation for over 10 years.

b) **Trains** – Railway electrification has constantly increased since the world's first orders in Germany in the late nineteenth century accounting by 2012 for nearly one third of total tracks globally, with Scotland adding the Glasgow to Edinburgh route by 2018 and HS2 coming on stream the late 2020s, about 20 years after HS1.

c) **Planes** – Boeing backed hybrid jetfuel-electric planes and Easy Jet lead development of all electric planes in the next decade.

d) **Ships** – Perhaps the day is coming when all containers will arrive dockside on electric trucks or (preferably) trains for transporting by electric ships.

e) **Rockets** – "Instead of fuel, plasma jet engines use electricity to generate electromagnetic fields, compressing and exciting a gas, such as air or argon, into a plasma – a hot, dense ionised state similar to that inside a fusion reactor or star."

6.2.2 Molten Metal Batteries

Further, add the surges in demand that will arise from the use of renewable electricity in the pollution-free production of metals (beyond the "congealed" electricity already used in converting alumina to aluminium), often from hydro sources such as the Lochaber operation noted above. As an example, MIT research has led to the prototype development of molten metal batteries for potentially cheap, long-lasting storage of renewable energy to overcome the problem of intermittency, in competition with the rapid development and use of lithium-ion batteries for the storage of renewable power. The recent start-up company, Ambri, aims to accelerate the development of this technology.

6.2.3 Renewable Electrification of Metal Production

A variation of this MIT technology is also being developed to renewably electrify the production of "green" iron, steel and other metals through "a new anode material for oxygen evolution in molten oxide electrolysis" published in Nature and subsequently reported by MIT Press. It is anticipated that the pollution-free steel production process will be commercially viable at the scale of a few thousand tonnes per annum, an order of magnitude less than current viable steelmaking operations and **conjuring the image of reopening the bog iron ore mines of the northern Highlands to produce "green" steel at a number EIPs in this region.** These and many other mines are described in the publication *Economic minerals of Scotland – bedrock of Scotland's economic development*. As this recent McKinsey article claims, small metal and mining projects can operate profitably.

6.2.4 Hydrogen and Graphite Production from Onshore Natural Gas or Biomethane and Bog Iron

Jobs by the thousands and pounds by the billions if only Scotland would bow to the pressure of exploiting its onshore oil and gas reserves. Even in areas where there would be minimal environmental impacts there is still the environmental downside of transporting, refining and polluting uses of the extractions. But what if the natural gas extracted could be used on site to achieve **carbon neutral** outcomes. This is the prospect offered by the developers of the Hazer Process to enable the effective conversion of natural gas, and similar feedstocks, into hydrogen and high-quality graphite to meet burgeoning global demand, using very cheap iron ore rather than precious metals as a process catalyst.

Question is whether there are multiple locations throughout the Highlands and Islands that could co-locate bog iron and natural gas extraction for efficient operation of this process. Or could the hydrogen produced be used to transport the bog iron to the production site as well as to transport the processed graphite and the hydrogen to end users?

The developers of the Hazer Process are also bettering **carbon neutral** outcomes by using biomethane for **carbon negative** outcomes. Scotland is already replete with biomethane production facilities with more in development. What prospects are there for several of the proposed EIPs producing biomethane from local "waste" materials for hydrogen-graphite production? How feasible would it be to co-locate these operations with the production of lithium-graphite batteries for the rapid growing electrical vehicle market, sourcing and shipping the lithium from UK mining operations being developed by Cornish Lithium? How feasible would it be to further co-locate with a plant for the production of graphene from graphite for more efficient lithium-graphene batteries and for the emerging myriad applications of the super strength properties of graphene. Talking of advanced materials, The Scottish company CelluComp with the mission "material change for good" is producing a range of advanced "sustainable" materials from waste or as they put it "nano cellulose fibres of root vegetables". Does this portend scope for further symbiotic synergies for co-location in EIPs with abundant cheap renewable energy on tap?

The prospects are endless. A forthcoming paper on HI-EIPs will survey a wide range of prospects in depth and provide the views of proponents and specialists on their feasibility.

6.3 Future Demand

6.3.1 Distributed Ledger Technology

It is anticipated that overwhelming electrical energy will be required to operate distributed ledger technologies (DLTs) services. For example, in the case of France matching or exceeding some 15% of the national electricity consumption is presently accounted for by digital technology. DLT services will include the application of blockchain and variant technologies and associated energy-intensive "mining" efforts underpinning over 1,000 cryptocurrencies led by Bitcoin and a myriad of envisaged smart contract services led by Ethereum. This rapid growth in energy demand is leading to the creation of "energy-light" algorithms such as that underpinning the cryptocurrency provided by Litecoin. Conceivably regulation will require algorithms to enact the imperative: use only renewable power in a bid to decarbonise the environmental impact of DLTs. Or the commercial imperative as reported in the Times (Jan. 2018): "At Google's Deepmind in London, algorithms are preparing to save the search engine company a fortune in energy bills by rethinking its electricity distribution system." Roll on quantum computing….

A further controlling prospect is to balance the burgeoning energy demand of DLTs with the use of smart contracts to optimise efficiencies in the retail energy markets, whereby distributed ledgers can act as "a new driver to enhance the level of integration and development of the energy retail market delivering benefits"[1] such as: (a) maximising the returns to consumers who generate their own power and sell their excess to the grid – producing consumers or prosumers; and (b) consumers enter into an energy contract ledger system that facilitates a change in energy supplier at the click of a few buttons on a mobile device.

6.3.2 Hyperloop and the Boring Company

Hyperloop: "Hyperloop is a new mode of transportation that moves freight and people quickly, safely, on-demand and direct from origin to destination. Passengers or cargo are loaded into the Hyperloop vehicle and accelerate gradually via electric propulsion through a low-pressure tube. The vehicle floats above the track using magnetic levitation and glides at airline speeds for long distances due to ultra-low aerodynamic drag. Hyperloop One systems will be built on columns or tunnelled below ground to avoid dangerous grade crossings and wildlife. It's fully autonomous and enclosed, eliminating pilot error and weather hazards. It's safe and clean, with no direct carbon emissions. Watch this video to get an idea of how Hyperloop works."

Boring Company: "To solve the problem of soul-destroying traffic, roads must go 3D, which means either flying cars or tunnels. Unlike flying cars, tunnels are weatherproof, out of sight and won't fall on your head. A large network of tunnels many levels deep would fix congestion in any city, no matter how large it grew (just keep adding levels). The key to making this work is increasing tunnelling speed and dropping costs by a factor of 10 or more – a goal of **The Boring Company**. Fast to dig, low cost tunnels would also make Hyperloop adoption viable and enable rapid transit across densely populated regions, enabling travel from New York to Washington DC in less than 30 minutes."

6.3.3 Wireless Electricity Transmission

Recent advances in wireless electricity transmission (first demonstrated by Nicola Tesla nearly 130 years ago) have led Stanford scientists reporting in Nature on advances in powering electric vehicles:

> "In theory, one could drive for an unlimited amount of time without having to stop to recharge. The hope is that you'll be able to charge your electric car while you're driving down the highway. A coil in the bottom of the vehicle could receive electricity from a series of coils connected to an electric current embedded in the road."

The distant future:

a) Solar energy electrical transmission from stations on the Moon to space craft orbiting the Earth or on a course to the planets or will harnessing fusion obviate?

b) Redirecting comets or asteroids on a predicted collision course with Earth from transmission stations on the Moon targeting massive coils installed on the comets or asteroids or a fusion directed missile?

6.4 Existing Disruption of Supply

6.4.1 Step decrease in price of wind power

In addition to the emerging massive demand for renewable energy from the technologically disrupting electrification of metal production and molten metal batteries noted above, an increasingly compelling case to replace fossil fuel imports globally with renewable ammonia-hydrogen may arise as the price of renewable energy falls. As an example of a potentially disrupting existing technology, anticipated positive developments in wind energy plant technology have led to predicted **onshore wind power prices (at a November 2017 auction) in Germany falling to about a third of the price of energy from the new Hinkley nuclear power plant in the UK.**[2] Is this likely to lead to a marked decrease in the estimated £12bn cost of the 25x500MW wind farms?

[1] Distributed Ledger Technology: beyond block chain (pp 76-77), UK Government Office for Science, Jan 2016 and the Video.
[2] Wind power prices have plummeted again in Germany, RenewEconomy, Nov 2017.

6.4.2 Stored solar and geo-thermal power – road energy and air-conditioning

In the past 30 years all manner of solar and geothermal technologies has been developed and applied in Scotland and worldwide for road heating (ice-free in winter) and cooling (of overheated tarmac in summer). The same energy storage systems used to achieve these outcomes are also being used with heat pumps to power the air-conditioning of buildings. In the main these are one-off applications, customised for specific situations such as low-cost harnessing of solar and geothermal energy.

As yet no "game-changing" technologies have been developed in this space. In as far as these technologies can be utilised cost-effectively in HI-EIPs, it's worth noting that the Ullapool-based firm Invisible Heat is well placed to provide advice on applications.

6.4.3 Misty Solar

Solar panels generate the most electricity on clear sunny days, typically dropping on cloudy days by 10-25% of their rated capacity depending on the density of the clouds and their diffuse light receptivity. Panels engineered to capture a broader range of the solar spectrum generate more electricity even when it's overcast, with the payback period for the Misty Isle only about 20% longer than the best UK location.

Solar Panel Generation in the UK by Location

Location	Solar Energy Generation (kWh/1kWp)	Approx. Payback Terms on a 4kWp
Plymouth	2.61	6 years & 2 months
Brighton	2.48	6 years & 5 months
Bristol	2.46	6 years & 5 months
Norwich	2.44	6 years & 10 months
Birmingham, Hull & Liverpool	2.31	7 years
Newcastle	2.29	7 years & 1 month
Carlisle	2.23	7 years & 3 months
Dumfries & Aberdeen	2.21	7 years & 5 months
Glasgow	2.13	7 years & 8 months
Isles of Skye	2.10	7 years & 9 months
Thurso	2.04	7 years & 10 months

And this from R K Joinery, Portree-based installer of solar panels and air/ground source heat pumps:

> "Solar energy panels are by far one of the most popular renewable energy solutions invested in by home owners in the Skye and Lochalsh area. The panels capture direct energy from the sun which is then converted to electricity to heat and power your home. The panels function in daylight and cloud cover is not an issue. As you are generating your own energy this offers a significant saving on your utility bills."

6.5 Emerging Disruption of Supply

6.5.1 Types of Solar Panel

There are a wide range of different solar panels available including tiles, slates, and lightweight films that all have their benefits and disadvantages when it comes to choosing the right solar energy system. Solar slates and tiles are becoming more popular because they are aesthetically pleasing, economical and durable. Add to this thin film, flexible solar panels that can be integrated into any shape which means that they have a wider range of uses, including on caravans and tents.

6.5.2 Game Changing Potential in Optoelectronics Devices Including Solar PVs

As reported in Nature (September 2017), perovskite materials have become very promising candidates for a new generation of potentially printable and efficient optoelectronic devices including solar panels using photovoltaics:

> "As of 2017, innovative preparation methods give access to ever higher material quality and tunability; perovskite-based photovoltaics research is now moving beyond pure efficiency improvements and is exploring scale-up, tandems and stability issues; and applications in light emission and detection continue to soar, thanks to a deeper understanding of the perovskites intriguing physical properties."

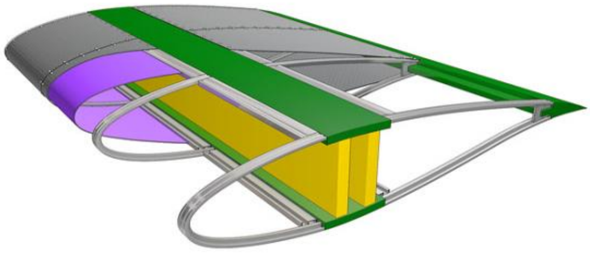
6.5.3 Revolutionising Wind Turbines and Blades

Materials for Wind Turbine Blades: An Overview: This recent review covers the use of advanced materials for incremental improvements in blade effectiveness. What follows are proposals for major improvements. While building at ever-larger scales has reduced wind power costs, further deployment continues to be hindered by the manufacturing and transportation of large blades, expensive operations and maintenance, and siting and transmission limitations. R&D is in the pipeline to make further marked reductions in the costs and noise of wind power even as the technology facilitates faster blade rotation:

1. GE is developing fabric-based blades tension wrapped around a lightweight, easily altered, metal structures to reduce their weight and production costs by 70% while maintaining conventional wind turbine performance.
2. The production of leather from kelp and jellyfish (noted earlier) leads to the query whether it could be used to produce the blade fabric at several of the conjectured 25 HI-EIPs.
3. And from left field or Phys.Org, Nov. 2016 "Owl-inspired wing design reduces wind turbine noise by 10 decibels", while having no negative impact on the blades aerodynamics.

An assessment will be made of the prospects for a number of the HI-EIPs manufacturing the components for the fabric-based blades (depicted below) for assembly onsite at the 25x500MW wind farms, referred to earlier, and beyond this to assembly at the sites of wind farms worldwide as a major export initiative. Lochaber aluminium smelter for metallic components and/or composites using EIP produced super-strength graphene (section 6.2.4) or bog iron steel (also section 6.2.3)?

Fabric Covered Blades Could Make Wind Turbines Cheaper & More Efficient



Illustrated is a section of a wind blade depicting a new manufacturing concept that would entail covering the blade with a tensioned fabric, significantly reducing production costs and making wind power more economical. Image by GE.

This would enable the construction worldwide of much larger wind turbines (operating within much cheaper to build tower structures) that can capture more wind with significantly lower production and transportation costs.

6.5.4 Wave and Tidal Energy

Scotland has tremendous wave and tidal energy resources and as such has been at the forefront of global marine energy developments for the past decade. The Orkney based wave and tidal test facility, the European Marine Energy Centre (EMEC), with over a decade of real-sea experience has deployed more grid-connected marine energy converters than at any other single site in the world and the centre remains the world's only accredited marine energy laboratory.[1] The potential exists to generate more electricity than is currently needed from the waters around the Scottish coast. As noted earlier, the Orkney Surf'n'Turf project to produce hydrogen from tidal power is a leading-edge development, foreshadowing a capacity to generate hydrogen locally for local transportation purposes.

Wave Energy Scotland (WES) was formed in 2014 at the request of the Scottish Government as a subsidiary of Highlands and Islands Enterprise. Its aim is to ensure that Scotland maintains a leading role in the development of marine energy. So far WES has awarded £25.4m to 61 projects, working with 171 separate organisations, across 11 different countries.[2]

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[1] The wave and tidal resource of Scotland, Science Direct, Dec 2017

[2] Wave Energy Scotland

6.5.5 Floating Wind Farms: Renewable Energy, Ammonia Production and Seaweed Harvesting

The first floating wind turbine in the US started operations in 2014 as recorded in this Ted Talk.

Norwegian company Statoil has made the final investment decision to build the world's first floating wind farm: The Hywind pilot park offshore Peterhead in Aberdeenshire, Scotland. Statoil has installed a 30 MW wind turbine farm on floating structures at Buchan Deep, 25 km offshore Peterhead, harnessing Scottish wind resources to provide renewable energy to the mainland. The wind farm will power around 20,000 households. Production start is expected in late 2017. Irene Rummelhoff, Statoil's executive vice president for New Energy Solutions says:

> "We are very pleased to develop this project in Scotland, in a region with a huge wind resource and an experienced supply chain from oil and gas. Through industry and supportive policies, the UK and Scotland is taking a position at the forefront of developing offshore wind as a competitive new energy source."[1]

Masdar and Statoil recently announced a collaborative agreement to analyse data from the "batwind" storage facility connected to the Hywind wind farm.

As old rigs come to the end of their use for oil and gas extraction would it make sense for them to continue operations as hubs for fixed and floating wind farms? In contrast to the Hywinds' development the Beatrice Offshore Wind Farm will extend the operation of the two wind towers installed adjoining the closing down of the Beatrice Oil Field operations. Should the Beatrice oil rigs be decommissioned and removed as planned or used not only as a hub for this wind farm but also as a facility to house a plant for the production of ammonia? How feasible would it be to use Scotland's many aging rigs as wind farm hubs for this purpose, including the three currently stranded in the Cromarty Firth? Could existing pipelines from old rigs be used to transfer wind energy produced ammonia to onshore storage and tanker transportation to export markets in preference to the dissipation losses from long distance electrical-cable transfer of wind energy to the onshore grid? As it happens, this has been assessed by means of a simulation model developed as part of a doctoral dissertation.[2] How would water for the ammonia production process be produced?

a) On rig rainwater harvesting (limited supply)?

b) Reverse osmosis desalination using wind energy or OTEC (page 5)?

c) Using their own specially designed form of graphene, 'Graphair', CSIRO scientists have supercharged water purification, making it simpler, more effective and quicker. The new filtering technique is so effective, water samples from Sydney Harbour were safe to drink after passing through the filter. Could Graphair be produced from proposed production of HI graphite-graphene considered in section 6.2.4?

d) Drilling and extraction from water table below the seabed using existing oil & gas drilling equipment?

e) Reverse pipeline (ammonia pumped to onshore from rigs for storage/shipping and water pumped from onshore to rig?

The economic feasibility is likely to be dependent on ultra-cheap renewable energy and/or increasing robotisation of material transfers, production and maintenance operations (including onshore storage/loading of ammonia - and possibly oxygen - to shipping tankers for export). Increasing robotisation would also reduce on-rig human demands for water consumption.

Beyond renewable energy storage for export, could the steel cables strung between wind turbine mountings and disused oil rigs provide an ideal seaweed growing and harvesting (shipping free) zone? The Dutch enterprise Ecofys has actively pursued the opportunity of large scale offshore biomass cultivation, culminating with the launch of a pilot test project for seaweed cultivation in the Dutch North Sea. Could members of crofting families be trained to perform maintenance works on onshore and offshore wind turbines as well as year-round seaweed growth tending and harvesting?

And from left field could old rigs be deployed for the operation of utility level wind energy generation from wind kites? The Scottish firm KPS have extensively tested and developed a twin-kite system for this purpose

[1] First power 8 September October 2017 as per this YouTube video uploaded by Statoil.
[2] A Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind

that uses 85% less materials than wind turbine systems. Left field? Not when you consider that it is backed by Shell, E.ON[1] and Schlumberger[2].

6.5.6 Collecting and Converting Ocean and Sea Borne Plastic Waste to Bioenergy

Nature takes millions of years to create fossil oil. Licella's Catalytic Hydrothermal Reactor (Cat-HTR™) takes 20-30 minutes to create a renewable biocrude oil. Using water at or near supercritical temperatures, the Cat-HTR™ converts a wide variety of low-cost, waste feedstocks and residues into high-value products. The Cat-HTR™ platform has been extensively tested, and conservatively scaled up, over the past ten years to its current commercial-ready module, located on the NSW Central Coast, Australia.

Unlike techniques such as pyrolysis, hydrothermal upgrading with Licella's Cat-HTR™ platform produces a stable biocrude which can be easily shipped, is not acidic and is miscible (blendable) with conventional oil. Licella and its partner Armstrong are planning to build a 20,000 tpa terrestrial plant shortly in the UK.

Licella's Chief Scientist, Dr Bill Rowlands, responded in the affirmative to our query as to whether it would be possible to develop a portable scale operation of the Cat-HTR™ platform for operation on very large ships (say aircraft carrier size) designed to collect plastic waste at sea, convert the plastic to crude biofuel, refine the biofuel at sea and use this to power the ship in a continuous operation? His response: "Yes, it would certainly be possible to develop a unit with a footprint that would fit on a large ship. The non-optimized footprint of a unit capable of processing 20,000 tpa of plastic would be around 3500 m^2, producing about 14,000 tpa of fuel. With a large ship burning say, 200 tonnes per day (my guess) then it would seem feasible for such a ship to be more than self-sufficient."

Issues in customising a sea-based plant would need to deal with the particular issues of sodium chloride contamination of the plastic recovered from the ocean, the integration of the technology with the ships' systems and the fact that nearly half the waste in the plastic garbage patches is nylon fishing nets as reported in this recent ABC Science News article. In relation to the first two, Bill Rowlands considered neither as "show-stoppers in my view".

Water purity solutions include distillation of seawater and/or subsequent reverse osmosis or application of the 'Graphair' (noted above) to supercharge water purification, making it simpler, more effective and quicker, any of which could be powered by refined biocrude produced onboard.

In relation to Cat-HTR™ processing of nylon, Dr Rowlands responded: "We would need to investigate the fate of the nitrogen in the nylon, if it is a substantial component of the mix. It depends what fuel specifications are attached to the fuels for the ship's engines and for other combustion purposes. One can burn pretty much anything in a slow stroke diesel, but that doesn't mean that an OEM will warrant it."

Planned efforts to clean up the oceans of plastics and fishing net debris — The Ocean Cleanup (plastics) and the Healthy Seas Initiative (nylon) — involve processes of concentrating the seaborne waste into dense clumps for hauling on board then returning to shore (using polluting diesel unless a renewable hydrogen to electricity powered shipping is used) to sort and convert the waste to various products including diesel and recycled nylon fibres. Neither of these processes would appear to be nearly as cost effective as the Cat-HTR™ solution. However, the technology for waste concentration and hauling on board may be appropriate technologies.

The proposal here is that following benefit-cost analysis based on quick and ready engineering assessments of the feasibility that funding is sought to build a prototype (substantially autonomous) ship that integrates all the processes foreshadowed in the foregoing.

6.5.7 Pulp and Paper Industry Waste to Bioenergy

"The Cat-HTR™ process is a strong technical fit for the kraft process. The opportunity to directly produce advanced biofuels from our existing systems could transition Canfor from being strictly a pulp and paper manufacturer to a bio-energy producer as well. The Licella™ technology has significant similarities to our existing processes which make this partnership a natural fit." Brett Robinson, President, Canfor Pulp.

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[1] E.ON UK is an English energy company and a subsidiary of E.ON, the world's largest investor-owned power and gas company.
[2] Schlumberger Limited is the world's largest oilfield services company, employing about 100,000 in more than 85 countries.

An opportunity for the Scottish pulp and paper industry to regrow to its former scale and do so more economically and environmentally?

6.6 Future Disruption of Supply

6.6.1 Integration of Renewable Resources and Infrastructure

Of high relevance is the recent report from the Siemens' Intelligent Infrastructure programme: **"**The Business Case for Smart City Infrastructure: Aberdeen**": "**A city seeking to diversify its economy around the future of energy demonstrates how harbours play a such an important role in that economic diversity and how this economic generator can play its part in the energy economy and transport systems development."

In considering the Challenges of Constant Growth, Siemens consider that:

> "Digitalization is changing our world. Today the number of connected devices has surpassed the number of humans on the planet. These intelligent devices generate massive amounts of data transforming life and business across all sectors. However, much infrastructure has yet to be transformed by the information age. Instead, in most places, trains, power systems, buildings, buses, and roads have hardly changed in nature. Some digital systems have been incorporated but we have only just begun to unlock the potential of fully digitized, electrified, information-enabled, intelligent infrastructure. Doing so will be key to meeting the world's present and future sustainable development challenges."

6.6.2 3D Housing in Highlands & Islands and Developing Country Sister Communities

The Overview paper refers to 3D printing of houses for less than $10K using locally produced concrete as depicted in this video and described in this article. Then consider making these houses autonomous with a larger flat roof surface serving as a water tank to catch rainwater and providing additional outdoor living space. Add to this 3D printed ultra-low cost, high efficiency solar panels on the flat roof and the external walls clad with sheets of 3D printed solar cells, using seaweed extracts. The 3D printed versions of these roof mounted wind turbines (perhaps adapting this 3D printing process for large blades) would then generate more than sufficient supplies of energy regardless of the weather, especially if the cost of battery storage continues to plummet, possibly with this seaweed-based advance. Provide a 5G service and the occupants can interact at ever more advancing levels of communication/data-sharing/computation with any groups anywhere and elder citizen occupants can be supported by an ever-increasing efficacy of telehealth monitoring and supporting drone services

Consideration could be given to 3D printing of houses (as considered above) on crofts to house:

a) young family members;

b) working visitors;

c) developing country students/farmers receiving an education & training in farming/crofting/permaculture/afforest, perhaps obtaining the University of the Highlands and Islands (UHI) certificate in crofting;

d) small communities of elderly citizens moving from acute hospital beds to community care and the therapy of participating in permaculture and afforest activities.

Another prospect could be UHI based research on 3D to produce designs for 3D house printing machinery (for central belt manufacturing) and software drivers and leverage this into a significant R&D 3D printing program.

This Ted Talk describes how one young woman frustrated by her lack of self-determination in the housing market created a computer game that allows home buyers to design a house and have it delivered to them in modular components that can be assembled on-site. She refers to the how the advances in 3D printing is accelerating progress towards this outcome by markedly cutting costs, protecting the environment and helping provide homes for those in need. She calls for a way of mirroring the provision of such housing in developed countries with an equivalent build in a developing country. A possibility in our case could be to ask each developing country student to use the computer game to design a 3D house for a member or family of her or his community back home. If the students in a given crofting community are all from the same "sister" community back home then in time that community will have a substantial quality housing stock. Funding for this endeavour could be sought from the appropriate international training entities (e.g. UNITAR supported by

UNDP) with NGOs funded to operate the 3D printing facilities in developing countries. The rapport and relationships between a crofting community and their developing country "sister" community could lead to many opportunities and benefits for all concerned. Extend this across all crofting communities and Scotland could make a profound and globally significant difference in this "trade not aid" space.

6.6.3 Integration of Renewable Resources and Purposeful Built Environments

The integration of renewable resources in buildings is a fundamental aspect of the 21st-century architecture in order to achieve zero energy buildings (ZEB), reduce the consumption of fossil energy and cut carbon emissions in urban areas[1]. Advances include small vertical axis turbines on the roofs buildings, between buildings and internal corridors in buildings. Solar PV panels are already widely used and integrated into building structures. Increasingly the same is likely to apply to tiles on roofs and walls and even to the capacity of windows to capture energy, especially if perovskites greatly enhance the current low efficiency of current applications. Of particular interest is a prospective nano-technology to integrate wind energy capture into solar panels referred to as "Nano Vent-Skin Micro-Turbines".

Perhaps this development possibility for Glasgow-based small wind turbine manufacturer Gaia-Wind through their partnership with Danish company Vestas, the world's largest manufacturer of wind turbines.

The authors recently produced a discussion paper on improving the tourism infrastructure of the Isle of Skye which outlined a case for a multipurpose building referred to as Skye IDEA (page 34), featuring: among other things, a world-class climbing wall; capacities for attracting entrepreneurs and innovative enterprises; a business incubation centre; research activities supporting EIP initiatives, in particular processes for reaching agreement on the governance arrangements for the proposed 25 x HI settlements drawing on sources such as the Highland Council, the Crofting Commission, the Scottish Crofters' Federation and the Institute for Innovation and Public Purpose (IIAPP)[2].

The IIAPP's "ambitious agenda aims to inform public policy; innovations in public services including health and social care; green innovation and sustainable development". IT is relevant to the design and built environment issues facing the proposed 25 Windfarms/HI settlements/EIPs and a highly innovative and energy-efficient building for Skye IDEA that the IIAPP operates from The Barlett, University College London's "global faculty of the built environment." So also is the Jeanne Gang's practice of designing relationships of trust through architecture inspired and driven by communities and governance populating each other's minds. Add to this the recent study on public policy to maximise wellbeing creation rather than wealth creation, *The Origins of Happiness:*

> What makes people happy? Why should governments care about people's well-being? How would policy change if well-being was the main objective? *The Origins of Happiness* seeks to revolutionize how we think about human priorities and to promote public policy changes that are based on what really matters to people. Drawing on a uniquely comprehensive range of evidence from longitudinal data on over one hundred thousand individuals in Britain, the United States, Australia, and Germany, the authors consider the key factors that affect human well-being.

Can institutional and ownership arrangements reduce costs further and lead to ever improving productivity? In this respect, the Isle of Skye Renewables Co-operative (established in 2007 for the purpose of owning a share in the Ben Aketil wind farm located near Dunvegan) provides one such ownership arrangement worth assessing.

The same applies to the *Low Carbon Hub* and their recently published *Community Energy Manifesto* setting on why community energy is a vitally important driver of the UK's national energy transition. As a precursor, they envisage the whole of Oxfordshire powered by an interconnected series of smart micro-grids centred around multiple small-scale, community-controlled renewable energy schemes.

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[1] Small Vertical Axis Wind Turbines for Energy Efficiency of Buildings, *Journal of Clean Energy Technologies, Vol. 4, No. 1, January 2016*

[2] IIAPP's founding director, Mariana Mazzucato, is Professor in the Economics of Innovation and Public Value, author of *The Entrepreneurial State*, winner of the 2018 Leontief Economic Prize, a member of the Scottish Government's Council of Economic Advisors, and a member of the World Economic Forum's Council on the Economics of Innovation.

And this from *Wired*: “Microgrids and the blockchain are powering our energy future”. As the “bell tolls” for the era of large-scale power plants many are heralding and championing the ascension of grid networks of super-smart and super-clean energy systems embodying the rise of microgrids linked to localised power sources, and often referred to as “distributed generation” sources. For example, a handful of buildings in a town with their own solar panels might be connected to nearby residences. People with their own solar panels can sell surplus electricity to their neighbours: a peer-to-peer network for electricity. DLT is being used to ensure that accurate records of these transactions are shared by everyone on the network.

The productivity boosting prospects for this being utilised by microgrids controlled by each of the proposed 25 x HI community developments and their attendant EIPs would be markedly enhanced by the gains envisaged for applications optimising the interconnectivity of the microgrids. Conceivably advances in such DLT-enabling software (for not only the optimisation of energy microgrids but also the envisaged myriad export-based production activities within and between HI communities) would be within the provenance of residents operating within and between these communities. As the prospects and realities for decentralised (trust-based, well-being focussed) communities are increasingly enhanced worldwide, HI communities in the vanguard would be well placed to deliver Software-as-a-Service (SaaS) at a significant industrial scale of effort. Why not shepherd SaaS and sheep?