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Offshore Floating Renewable Energy and the Future of Power to Fuel Technology

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Abstract

This paper reviews the state of the art in Power-to-Fuel (P2F) technology, and the effects such technology could have on the future energy mix. P2F is broadly defined as using electrical energy to produce a fuel from its component parts, often in the presence of a catalyst. The most familiar is the production of fuel using the hydrogen and carbon via the Fischer-Tropsch process.

The paper will determine the technical readiness, evaluate the projected economics, and present how incorporating it into an offshore renewable energy development scheme could make hereto uneconomic renewable energy development areas profitable.

As the offshore resources are much better than on land, and the environmental impacts less, it is anticipated that using offshore renewable energy to produce clean, carbon neutral, eco-fuels will provide massive global benefits, not least of which will be the preservation of the utility of trillions of dollars of existing equipment and infrastructure.

For example,offshore and onshore pipeline infrastructure can be re-purposed to move green-fuels to shore for further processing; producing green-plastics and even green carbon neutral car and jet fuel. These would be carbon neutral replacements for these hydrocarbon-based products, but at the same time leave the existing infrastructure for distribution and use unchanged. In gas form product can be transmitted much farther than even HVDC. In liquid form the export path could be through tankers, freeing the operators to sell to the best market rather than just to the local grid.

Keywords:carbon neutral; eco-fuels; landscape; solar energy

Introduction

The energy landscape is changing.For a century oil and gas have powered the world, and access to this cheap and transportable energy source provided a century of unprecedented improvements in the average person's life.But there are downsides to running our economies on this naturally occurring form of stored solar energy.Geopolitical tensions and instability caused by a global dependence on access to affordable energy has caused wars, allowed dictators to flourish, and destabilized large parts of the world.

Whether the cause or only a contributing factor the levels of CO_2 effect climate and the emissions from burning fossil fuels have had, and are having, a measurable effect on the world.One look at the clean skies that resulted from global COVID-19 lockdowns is proof of that.More importantly regardless of any personal view, or the uncertainties inherent in even good climate science, the world consensus is it is time to divorce ourselves from dependence on fossil fuels.

Given that is the case what is the best path to achieve that goal? Governments large and small, companies, and even wealthy individuals have stated very ambitious goals for reducing fossil fuel use but there is a decided lack of methodologies given on how to achieve these goals.

This paper is an exception to that paradigm.There is no focus on carbon footprint, instead the focus is on what would a practical path to reducing or eliminating the need for fossil fuels look like, and how could we minimize the economic impact on the world?As this paper will show when solid numbers are put forward to the scale of the problem shows itself to be a challenge that will rank in history alongside the European Conquest of the New World, Industrialization, the Great Depression, and World Wars I and II in terms of its effects on people and how we live.

A "cold turkey" switch from fossil fuels to electric and hydrogen as the primary energy sources by 2050, which is the basis of some proposals, would require retooling the global industrial economy. Imagine instead of having to rebuild the entire transportation grid and demolish and rebuild every petrochemical plant, we could convert to a carbon neutral/negative, renewable energy derived, hydrocarbon?You can effectively fill up your 1965 Mustang with wind and wave energy, drive to the airport and then fly to your destination in a jet powered by solar generated green-fuel!These fuels, not based on fossil mining, would have no particulates or trace toxins and therefore burn clean.

The simple fact is the technology to accomplish this exists, and the basic principles are simple.Split water into hydrogen and oxygen, pull carbon dioxide out of the environment, combine the carbon and the hydrogen and you get a hydrocarbon not based on fossil resources. Hydrocarbons made in this way have several advantages:

- They are pure in that they contain none of the common trace elements in oil-derived fuels.
- They can be used to replace mined hydrocarbons in petrochemical processes.
- The process can be tailored to produce hydrocarbons ranging from methane gas to heavy oils.
- They can be used to store and transport renewable energy from high resource, but unpopulated, areas to urban centers that need the energy; often using existing oil and gas transport networks [1].

The stumbling block has been the cost of these fuels could not compete with cheap natural gas and direct renewable electric power on a one to one basis.

This paper hopes to show that the cost dynamic is changing, that simple bbl-to-bbl cost comparisons that have been the focus of many papers ignores some key advantages of power to fuel systems, and that building offshore renewable energy powered industrial parks can be a near term and long term solution yielding a green energy future [2].

Lastly the paper looks at the advantages that these systems would have if installed in places where existing infrastructure like in the Gulf of Mexico, North Sea, Brazil, West Africa, Australia, or Indonesia can be repurposed instead of removed.

Defining the Market

Some of the significant stumbling blocks for shifting to a fossil fuel free, carbon neutral/negative economy are:

- Replacement of fossil fuel-based propulsion systems, especially for aviation.
- The societal costs of replacing trillions of dollars of infrastructure, equipment, and industries.
- The continuing need for hydrocarbons in the pharmaceutical and petrochemical industries.
- Limitations and negative environmental impacts of battery technologies.

How much fuel?

To put some numbers to, and get an idea of, the scale of the problem.Per the U.S. Energy Information Administration world consumption of oil is around 100 million barrels per day, and still growing at about 2% per year.The total global energy consumptions in 2017 14,500 MTOE and slated to grow to 18,400 MTOE by 2050. Currently 79% of all energy used is from fossil fuels [3].

Using US EIA Data in terms of use of fossil fuels the breakdown is almost evenly divided as follows [3]:

- Transportation 3600 MTOE
- Petrochemical 3800 MTOE
- Electrical Power 3700 MTOE
- Other (heating oil, coke production etc.) 345 MTOE

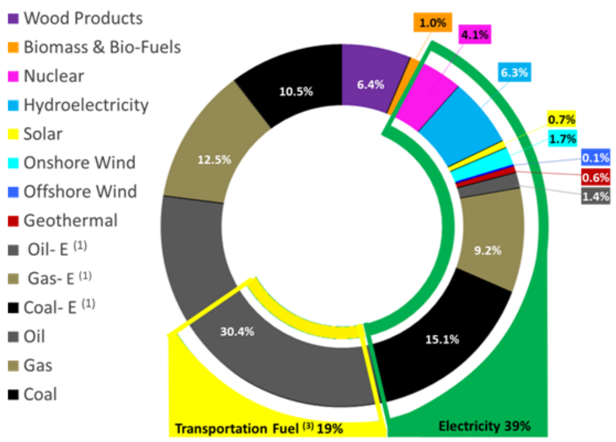
The total of 11,445 MTOE of fossil fuel is the energy equivalent of 100,000 TWh.Even at 100% efficiency that would mean more than 15,000 new 1 GW sized power plants.In fact, the number would be many times that, something we will address later in the paper.Figure 1 gives a breakdown of the global energy consumption in 2017 [4].

To replace the current global market for transportation fuel of 3600 MTOE will require 1.3 billion tonnes of hydrogen per year. That represents 11.3 billion tonnes of pure water per year, producing a further 13.8 billion tonnes of brine or wastewater.That's a total throughput of 25 billion tonnes. By comparison New York City uses 1.4 billion tonnes of fresh water per year [5].Over a typical 20 year design life of a fully renewable fuel economy that is equivalent to using the entirety of Lake Erie.

The hidden costs of replacing infrastructure

When accounting for the benefits of switching to renewable energy sources, particularly in transportation, the economic and social costs seem too often overlooked or ignored.To completely do away with hydrocarbon-based fuels means every car on the road will have to be replaced or undergo expensive retrofitting.Aircraft will require complete ground up redesign and because of decreased energy density will have less payload capacity [6].

The entire value chains that support internal combustion engines and turbines from the smallest weed-wacker to the largest gas turbine will need as a minimum retooling, or more likely replacement [7].The new plants are likely to be on average more automated than their legacy predecessors, not located in the same regions, and will require new skill sets.



Notes:
1. Oil-E, Gas-E, and Coal-E denote used to generate electrical power
2. MTOE = million tons of oil equivalent = 11.63 MWh
3. 95% of Transportation Fuel comes from oil and petroleum liquids, ~4% from Natural Gas, >1% Electricity
4. Sources, Ref 2 and 3.

Figure 1: 2017 Global energy use.

The distribution networks for oil and gas built up over 100 years will lose all utility and need replacement.

In short, the costs will be many trillions of dollars, the effects on job markets will be disruptive, and it is not clear that the proposed replacements will be better in the long term.Unless the governments of the world decide otherwise and give massive subsidies to average people to replace the existing equipment, the majority of the economic burden will fall on the lower end of the income scale as people are forced to pay for new hydrogen or battery powered transport [8].

Again, putting the scale of the problem in hard numbers, globally there are approximately:

- 30,000 commercial airliner and military planes [9]
- 500,000 private aircraft [10]
- 30,000 helicopters [10]
- 1.4 billion cars [11]
- 325 million commercial vehicles [12]

All of the above are designed to run on hydrocarbon fuels, just 3 of which make up 90% of the fuel use per the US Energy Information Agency:

1. Diesel
2. Gasoline
3. Kerosene/Jet Fuel

The good news is all the above can be made using power to fuel technology, the problem is that as a practical replacement for fossil fuels the Power-to-Fuel industry is in its infancy [13].

Using Renewable Energy for Transportation

There are five primary methods being considered for using the energy produced by renewable energy sources for transportation [14].

Batteries – Lithium Ion, Flow Batteries.

Burning hydrogen directly, stored and transported either as a liquid or high-pressure gas.

Using fuel cells power by hydrogen or methane.

Conversion of H_2 and N_2 to ammonia to be used as a fuel.

Conversion of CO_2 and H_2 to fuels, which is this paper's focus.

Batteries have limitations in their application, particularly for aircraft.Added to that the batteries currently used require rare earth metals that restricted in their supply, are difficult to recycle, can burn in the event of an accident, have a limited life span, and are slow to recharge when compared to filling a gas tank.

Burning hydrogen directly can be attractive, but it would require a complete re-tooling of the transportation infrastructure and the engines that run it.Hydrogen also has some costly material challenges and cannot, as is sometimes claimed, be used directly in most existing pipeline systems.Hydrogen also has a power density problem.While a kilogram of hydrogen has the heat energy of 1 gal of gasoline, even in liquid form a kilogram of hydrogen is only 70 kg/m^3, meaning you can put 3.5 to 4 times the energy of hydrogen into the same tank if you use gasoline.It is the main stumbling block in direct use of hydrogen for aviation.

Fuel cells are more promising than direct combustion, but to date is too expensive and very sensitive to the purity of the activation gases [15].

Ammonia has also been considered as a replacement fuel for hydrocarbon-based fuels.The drawbacks here are pure ammonia is a very volatile and caustic liquid and would require the same level of re-tooling as either batteries or pure hydrogen as fuels.In controlled environments like petrochemical plants, ammonia is used safely, but tanks of pure ammonia being driven around as today's cars are raises some serious safety concerns. Ammonia used as fuel is not like the ammonia used in cleaning your home.While less likely than gasoline to ignite, pure ammonia is much more dangerous than gasoline when you consider that it is the fumes and contact with the liquid ammonia that are the hazard.If the ammonia tank in a car ruptures the released ammonia will give off toxic fumes that can kill a person in just one or two breaths.If it comes in contact with skin, it literally dissolves the skin and flesh off the bones.

Lastly, we get to power-to-fuel.If it can be made to work efficiently at the very least it would ease the transition to a hydrogen-based economy, and it would more importantly allow the world to go carbon neutral much more quickly.It can also serve as a transition phase if going to a hydrogen-based economy remains the goal.It will allow the retirement and replacement of legacy hydrocarbon infrastructure as it wears out, rather than ripping out equipment still in its prime.One of the big attractions is the first step in the process is making hydrogen.This means that as the world changes to be more hydrogen based the equipment built to make green hydrocarbons can be used as is, simply bypassing the final process steps [16].

Onshore vs. Offshore

So, given that power-to-fuel is worth pursing, why would an offshore solution be preferable to an onshore one?Why not build a power-to-fuel plant attached to every onshore wind and solar farm that converts any excess energy (energy not sold to the grid) to fuel?

Water access and discharge

The first and most obvious point is access to water. To replace one years-worth of fuel consumed by the worlds current transportation needs would require more than 8 times the freshwater used by New York City in a year.Less obvious is the ability to dilute the discharge [17].The water that currently goes into an electrolzyer must be purified meaning that regardless of the source there will be a brine waste stream.Offshore for every 4.5 kg of water that goes into the hydrogen separation unit, 5.5 kg of brine are discharged.This is true even if the electrodes can use filtered seawater directly. Once the H_2 and O_2 are liberated the remaining liquid will be brine.

Likewise, other pollutants are concentrated. If for example an onshore plant was set up along the Mississippi river, then it is probable that the wastewater will require treatment before it would be allowed back into the river.Any waste products or chemicals in it would have been concentrated by the separation process to dangerous levels.

The brine discharge offshore would also be an environmental problem if discharged in large quantities from a single location, such as if an FPSO type processing vessel is used with power supplied by offshore energy [18].For this reason, among others the authors have assumed a distributed model, with each energy platform making its own freshwater and hydrogen.Only the CO_2 capture and reformation will take place at a central location.Ideally on legacy platforms and repurposed FPS, and FPSO vessels.

Size and efficiency

Onshore sites are more restricted in size than their offshore cousins and are becoming harder to permit near population centers. Onshore it is becoming more common to include solar power on the same site, but the energy density is still low compared to offshore.This is in part because the size of offshore wind turbines is on average larger than onshore [19].At sea, besides offshore wind, the possibility of capturing wave energy, tidal energy, or ocean thermal energy means the power per installation can be many times that of an onshore site.

Once the power is made and converted to hydrogen, transport offshore will be simpler and safer than it is onshore.While the capital cost of offshore pipelines is higher per mile than onshore pipelines, the permitting and routing are usually much simpler, with an overall economic advantage to the offshore solution.The installed lines are less likely to be damaged than onshore pipelines and if damaged the risk to people is much lower offshore.

While view shed (covered below) is an issue, most large urban centers are located near a coast. This means that the renewable energy sites, even if placed over the horizon can be within 25 miles of the final consumer.

Given a power to fuel solution, both onshore and offshore sites can transport the produced clean fuels using existing systems, but offshore systems (ships for liquids and long high-pressure pipelines for gas) are not open to onshore production.

Recent developments pushing offshore renewable to floating solutions will eventually lead to offshore turbines becoming even larger.Wind turbines to 25 MW are being designed, and these are not practical for current fixed wind designs.The authors are also of the opinion that very soon other offshore renewable sources will enter into the market at commercial scale, wave, tidal, and OTEC are all poised to leap from test tank to making fuel for gas tanks.

View shed

View Shed, defined as the visual impact on the local community, is a real issue in wind farm siting. Onshore and near shore this is often the issue that kills a potential permit. Installations out of sight of land effectively remove that as an issue.

Considering the speed at which the world must progress to meet its climate goals, and the quantity of power that will be required the only real answer to view shed issues is to move the energy farms far enough out to sea.

Wildlife impacts

The wildlife impacts of onshore renewables are more negative than offshore installations providing the offshore installations are located far enough offshore.Onshore bird kills and bat kills are concerns the industry is working hard to correct, and should not be seen as a reason not build a wind farm, but offshore the issue is reduced or eliminated [20].

Any sailor will tell you that one sign you are getting near shore is you start to see birds. In the open sea unless you are in a migration route there are no birds or bats.

Noise pollution is also an issue, and turbines make noise offshore and onshore, onshore the effects on local wildlife and domestic stock is under study, and offshore the noise impacts on marine mammals are likewise under study.

To date the position of groups such as the World Wildlife Federation are that the positives of clean carbon free energy outweigh and possible negative impacts that wind farms may have [6].

What is also clear is offshore there are real benefits to marine life caused by renewable energy facilities. Within the confines of the site commercial fishing is restricted?

The hulls and moorings of floating systems, and the legs and piles of fixed systems offer habitat locations.

Even oil and gas platforms act as artificial reefs in places like the Gulf of Mexico. At its peak there were 4500 platforms in the Gulf of Mexico (now down to 1700), but once offshore renewables go global and floating that number will be dwarfed.

To meet the 15,000 GW of installed power using offshore wind turbines would, allowing for a 50% capacity factor, and 15MW per turbines, mean more than 2 million installations worldwide.

Offshore that would create habitats on the scale of the Great Barrier Reef. Conversely onshore that many turbines would have a measurable impact on local bird and bat populations.

Multiple use

Unlike onshore renewable energy sites, one being used for offshore energy can host multiple technologies, often not related to energy [21].

This is especially true for floating facilities.Activities that can be added on the same facilities to increase the positive economics of an offshore renewable energy site are:

- Aquaculture
- Ocean Mining
- Blue-tourism/floating hotels
- Marine research
- Bio-fuel production
- Marine Rescue and Monitoring (coast guard)
- Weather stations
- Communications relays
- Big Data Storage

Summarizing Offshorevs.Onshore Advantages

Offshore

- Using a distributed solution ensures minimal environmental impact.
- Unlimited water supply.
- No view shed issues if placed more than 12 miles offshore.
- Overall impacts on wildlife populations are positive.
- Can often be located nearer to population centers.
- Can host other industries such as aquaculture or ocean mining.
- The amount of renewable energy per installation is much higher offshore than onshore.

Onshore

- Depletes local water supply.
- Potential pollution issues.
- Takes up useable land.
- Often far removed from population centers.
- View shed and local tourism issues.
- Bird and bat kills are a continuing problem.
- Noise pollution can be an issue depending on location.
- Would require new onshore pipelines, which are more difficult to permit than offshore.
- Distributed discharge solutions are not an option.

The Power to Fuel Cycle and Economics

The study of power-to-fuel has taken on a renewed interest since the signing of the Paris Accords. There are multiple studies underway and various national programs to encourage research into the technological components [22].

While the systems are very different the basic functions and objectives remain the same. Enough of an advance in the technology has occurred that the construction of offshore prototype facilities is already being proposed for power-to-hydrogen plants, and power-to-fuel will not be far behind.

Figure 2 below shows a basic cycle, mass, and energy balance.It is not tremendously efficient in terms of value, producing roughly 8.4 barrels of liquid fuel per day for every 1 MWh of power [1].

The interesting thing is even at that low output and ignoring allowance for things like carbon credits or tax incentives; the result is a nearly a break-even facility.

As the technology advances, offshore facilities based on a cycle like the one below will be profitable without subsidy within a few years.

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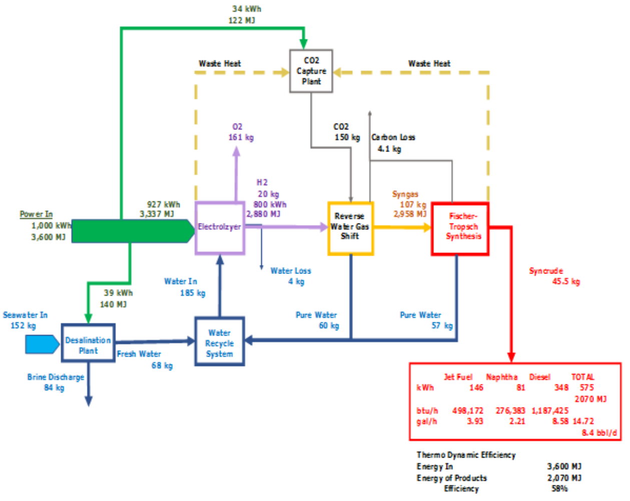

Figure 2: Energy and Mass Balance, Simplified from Reference 1.

The economic model is based on using a floating platform with multiple energy sources generating 30 MW of power, with the deck capacity to support the power to fuel process equipment shown in Figure 2 above. Many papers have gone into great and often misleading detail of how much a gallon of eco-diesel will cost to produce [23].There are many unknowns, and the technology is evolving at a pace that is astonishing, so predicting and exact break-even cost of production is at best a moving target with a very large diameter bulls eye.

This paper is not trying to justify the economic value of power to fuel, but neither can the economics be ignored. To that end a simplified model was run, using the following assumptions:

- Realized diesel price 1.5 times the current wholesale price ($1.95 per gallon, Ref) on the assumption there would be a market for premium carbon neutral fuel.
- No tax breaks or incentives, including carbon credits were applied.
- An assumed overnight cost of $100 Million for a 30 MW, floating, renewable energy, Power-To-Fuel plant was assumed. This is based on what would be possible if the plants are mass produced [24].
- A 30-year design life, and 1year fabrication and installation time were assumed.
- A Capacity Factor for the renewable energy of 65%, and a plant availability of 95%.
- A OPEX of $2 million per year.
- Decommissioning was assumed to be negligible.

Even at the low rate given in Figure 2 of 8.4 bbl/d/MW the IRR is 3%.A sensitivity using what we termed a Technology Factor, defined as the positive effect on production in terms of bbl/d/MWh of advancing technology gave the following result [25].It would require an improvement from the current thermodynamic efficiency of 58% to 95% (TF=1.64) and raising the price premium to 2 to achieve a marginal IRR of 13%.

In short it can be done, it can make money, but it will never be cheaper than mining fossil fuels. That, however, really is not the objective. For example, leather can be produced at 50% or less of the current cost of manufacture if discharge water in not treated, workers toil in unsafe conditions, child labor is used, and where the hides are sourced is ignored. As a society though people long ago chose to take the path that is better long term, even though it means that cowboy boots will cost more. Producing clean fuels instead of mining hydrocarbons is the same thing. As a society we must chose the sustainable path.

Is it Practical?

2050 is often taken as the date when the energy transition must be completed. What would it take to reduce the current level of 79% of all energy use sourced from fossil fuels to just 10%?One possible mix would be as shown [26].This is not to say that nuclear energy and bio-fuels won't also play a role, but as a thought experiment what would it take using the three commercially proven renewable energy technologies to replace these fuels on one to one energy basis?

The experts at Davos this year who stated that the world economy will have to take a significant hit to go Carbon Neutral have it wrong [19].The addition of 91,000 turbines a year is roughly 6 times the current global manufacturing capacity. Likewise adding 25,000 km^2 of solar is roughly 8 times the amount added in 2018.To achieve even a portion of this will have a positive effect on the world's economy. New construction on this scale will be an economic boost. Further the longer-term benefits of affordable, limitless, constant, and clean energy will boost the world's economy in ways we don't yet appreciate (Figure 3).

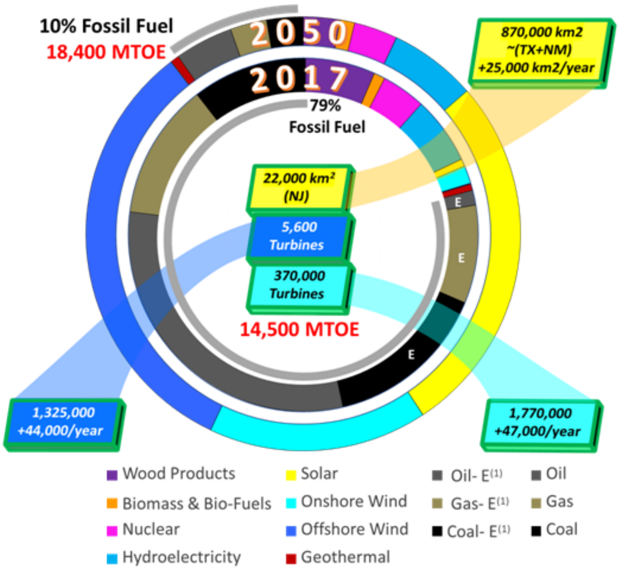

Figure 3: Reducing Fossil Fuels to 10% of the Energy Mix.

Is it Safe?

Safety and environmental concerns must always be compared to the status quo.In terms of safety a power to fuel platform would be much safer than comparable oil and gas platform. With a drilling or production platform your greatest risk is an uncontrolled release from the reservoir, such as occurred with Macando. When a power-to-fuel plant suffers a failure likewise its greatest exposure would be to the incoming power and hydrogen from the supporting platforms

[27].These would pose a safety risk, but virtually no environmental risk. The difference between the conventional oil and gas safety risk and the renewable energy risk is if the reservoir isolation fails you cannot "turn off" the reservoir pressure, whereas the renewable energy platforms feeding the power-to-fuel plant are fully under humane control.

Once the fuel is made its risks are the same as those of the transporting the fossil fuel-based version of the same fuel, be it a methane pipeline, LNG, liquid pipeline, or a tanker full of diesel.All are known and societally acceptable risks.

Legacy Oil and Gas Field Advantage

The market for renewable electrical power in regions where there is a large oil and gas presence is often not economically attractive. Easy access to low cost gas, onshore wind, and solar energy means that electricity prices are often low in these areas. Combine that with an offshore wind resource that is for the most part average in these areas and it is no surprise that developers have focused on high value markets in Europe and US the North East and West Coasts.

What these legacy oil and gas areas do have is a massive potential for developing a robust offshore renewable power to fuel market [28].There are several places in the world where offshore oil and gas has developed a robust infrastructure, the Gulf of Mexico, the North Sea, the coasts of Brazil, Australia, and Indonesia to name a few. There are thousands of platforms connected by many thousands of kilometers of subsea pipelines. These legacy platforms and pipelines could change the economics of producing power to fuel.

If this existing oil and gas infrastructure was repurposed as shown in Figure 4 below instead of decommissioned it would significantly reduce the capital expenditure needed which would translate into cheaper fuel [29].

Couple this with a local community that often welcomes offshore energy projects, local supply chains built to support offshore development, permitting processes that can be greatly simplified when compared to locations without existing development, and these areas become far more interesting as a renewable energy powerhouse.

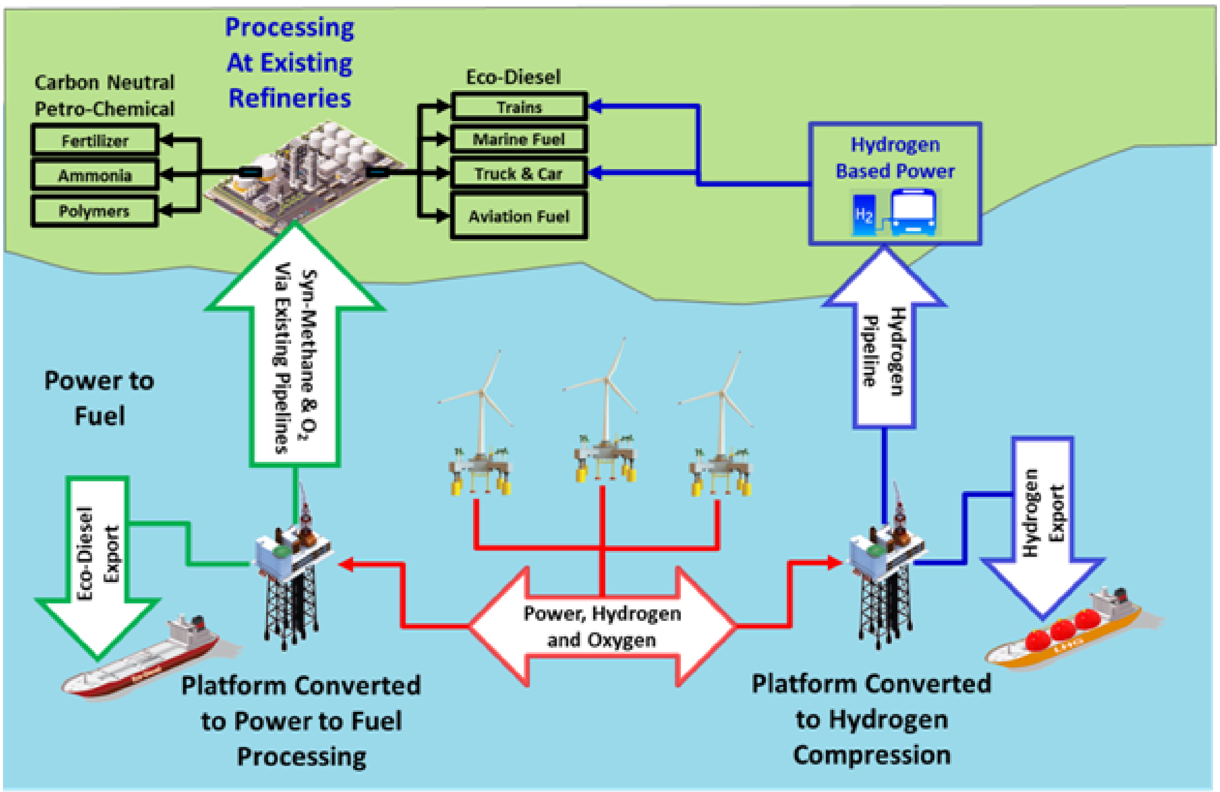

Figure 4: Legacy Oil and Gas AreaOffshore Renewables Value Chain.

Conclusion

While there are still technical and financial hurdles to overcome the obvious long-term benefits of offshore production of carbon neutral and carbon negative fuels using renewable energy has the potential to become the primary source of transportation fuels. No other solution offers the versatility, potential knock on benefits, and minimal societal disruption that offshore renewable based power-to-fuels does. In one technology the answers to energy storage, energy transport, and low-cost low impact production are found. The advantages of offshore renewables are increased further is locations where legacy oil and gas equipment and infrastructure can be repurposed.

The economics of power to fuel can be further improved by taking advantage of:

- Shared use activities such as aquaculture and ocean mining
- Sale of additional product gases such as oxygen
- Tax incentives
- Carbon Credits
- Improved power generation and
- Improvements in the power-to-fuel component technologies.

It may not be possible to make fuels generated using renewable energy as cheaply as we can from mined fossil fuels, but as a society we must chose the sustainable path. There are other options such as direct use of hydrogen that may be the long-term solution, but power-to-fuel is the sustainable option that will be the least disruptive and costly, while still meeting those sustainable goals. It will allow a transition to completely fossil carbon free economy as current infrastructure is replaced.

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