ADAPTIVE RENEWABLES:
ENERGY AT THE MITIGATION-ADAPTATION NEXUS

by
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A capstone submitted to Johns Hopkins University in conformity with the requirements for the degree of Masters of Science in Energy Policy and Climate

Baltimore, Maryland
December 2020

Abstract

As the clean energy transition accelerates, the challenges of climate impacts are being seen worldwide. Because energy is a leading source of carbon emissions, renewable power production offers a tremendous opportunity for climate mitigation. This paper examines the potential for advancing renewables deployment concurrently with climate adaptation, thereby achieving co-benefits at the nexus of mitigation and adaptation. A literature review is conducted; the feasibility for coastal protection from storms via offshore wind farms, wave erosion via floating breakwater, and multi-use planning within the blue energy space are explored. Additionally, opportunities to reduce the urban heat island effect and land use competition with solar panels are examined. Finally, various configurations of renewable hybrid energy generation are assessed, as well as implications for grid architecture, transmission planning, and equity within the field.

Mentor: Thomas Peterson

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Introduction

Climate mitigation efforts have not changed the trajectory of global carbon emissions substantively. The effects of climate change continue to be seen globally- catastrophic storms of increasing intensity, flooding, droughts, and rising seas (IPCC, 2014.) While natural sources of greenhouse gas (GHG) emissions have always existed, human activity has dramatically increased the emissions of carbon dioxide, methane, and other climate forcing gases over the past 200 years. Land use and agriculture have played a role in these emissions which must be addressed, but is not within the scope of this paper. Energy sourcing remains a primary source of emissions (EPA, 2020), with the fossil fuels used globally to power transportation and built environments as the primary culprit. With renewable energy and far-reaching opportunities for electrification increasingly coming on board, a clear opportunity to decarbonize exists, and is being vigorously pursued by some. In fact, modelling indicates the feasibility of entirely renewable energy sourcing in North America as early as 2030, should policy be advanced that allows for grid modernization and increased interconnections (Aghahosseini et al, 2017.)

As these renewable energy sources come online, society continues to grapple with major threats to infrastructure (European Commission, 2020,) the economy, and potentially even geopolitical stability brought about by our warming world. The energy sector is particularly at risk, due to sea level rise, unstable precipitation patterns, storms of increasing intensity, and higher average temperatures (Ebinger & Vergara, 2011.) From hyperlocal to international, efforts at many levels are underway to address the need for adaptation; the Paris Agreement's inclusion of adaptation and monitoring via the quinquennial global stock take highlights this focus at the international level (UNFCCC, 2020.)

Globally, nations are now faced with a unique, two-fold challenge: to decarbonize, and to adapt to an increasingly unstable climate in tandem, in real time. This presents a truly 'wicked' problem (Rittell & Webber, 1973,) particularly given other recent challenges like the Covid-19 pandemic. Siloing mitigation and adaptation will become increasingly problematic as both are impacted by the climate crisis.

A tremendous equity issue exists insofar as the developing world, responsible for less total carbon emissions, is hit ‘first and worst,’ and has less ability to fund adaptation efforts (Center for Global Development, 2020.) For these nations, leapfrogging economic advancement predicated on fossil fuel-based generation and instead advancing resiliency through power generation would be greatly advantageous both from an environmental and economic perspective. Given the large share of GHG emissions related to power production globally, rapid transition to zero carbon energy sourcing remains a keystone of decarbonization. Fortunately, power production is a sector in which this transition has been underway for some time.

Figure 1: Decarbonization Across Sectors (Victor et al, 2019)

Also of concern are the ramifications of focusing on mitigation to the detriment of adaptation; according to an analysis by Bahn et al (2019), pursuing both is likely to delay the transition to zero carbon energy systems. However, climate threats to the grid infrastructure are already large, under the current scenario. Additionally, the aging US grid presents a stumbling block, with many assets now still in use 50 years past their intended lifetime (U.S. GAO, 2014.)

The task of energy sector decarbonization presents many challenges, but also opportunities. This paper will analyze one: namely, the potential for renewable energy to both mitigate climate change, as well as support adaptation efforts.

Methods

A literature review was conducted to identify opportunities for the utilization of renewables within the climate adaptation space. A framework for performance criteria was established upon which to measure the available options based on need, cost, and ability to operationalize. Factors considered during the literature review are below. These factors provided a conceptual framework from which to approach the identification of opportunities to utilize renewables for adaptation.

Performance Criteria Framework for Adaptive Renewables	
Increased Resilience	Risk reduction from threats due to climate change: flooding, droughts, storms, etc.
	Cost reduction for damages
Disaster Risk Mitigation	Ensuring emergency power during disasters
	Increased independence/ability to ‘island’ critical resources
Equity	Increasing grid reach with low carbon power
Decarbonization	Potential for low carbon energy production
Feasibility	Ability to operationalize

Areas of adaptation work were considered in the development of this model; currently, these focused in the sectors of economic, social, physical, ecological, and technological work (Nyamwanza & Bhatasara, 2014.) Climate impacts of varying tempo and duration were considered, given that these factors are likely to greatly impact the adaptation response. Press (continuing and persistent) effects such as saltwater intrusion due to rising sea level will elicit a different response than short term events like storms (Gopalakrishnan et al, 2018.)

Figure 2: "Adaptation and Disaster Risk Management Approaches for a Changing Climate" (Field et al, 2012)

Results

Hurricane protection: Offshore Wind Farms

The threat of hurricanes and tropical cyclones continues to impact coastal communities; the tempo of the 2020 hurricane season drives home the need for addressing this issue. As technological advancements in offshore wind design increase globally (de Falani et al, 2020,), new opportunities for energy-based resilience are emerging. Jacobson et al (2014) has shown that offshore wind farms (OWFs) can act to reduce hurricane wind speed by as much as 92 mph, as well as storm surge by up to 79% for large wind farms (300 GW capacity.) While sea walls can also provide protection from damaging storm surges and winds, OWFs offer the additional benefit of renewable power generation. This could be a huge advantage to coastal communities, with a large wind farm situated between Washington, DC and

New York projected to have potentially reduced Hurricane Sandy's wind speeds by up to 87 mph (Jacobson et al, 2014.) Hurricane Harvey's onshore precipitation could have been reduced by as much as 20% had it passed over a large OWF (Archer et al, 2018.)

While there is little data on OWFs performance and potential for damage in hurricanes, a growing body of work seeks to model risks and establish parameters for reducing damage in high wind. Modelling indicates that additional support and stabilization of OWF monopiles are necessary for structural protection in the event large scale hurricanes (Yin et al, 2017; Kim & Manuel, 2019; Hallowell et al, 2018.) Large-eddy simulations offer a means by which to assess risk in different types of storms, and potential for damage in high wind scenarios; this area would benefit greatly from further research (Worsnop et al, 2017.)

Urban Heat Island protection: Solar

As temperatures rise around the globe, the Urban Heat Island (UHI) effect is becoming an increasingly prevalent issue in cities, with health and psychological impacts related to heat stress, including heat related morbidity and mortality (Giridharan et al, 2004). The modification of a variety of factors can feed into UHI mitigation, including urban planning, vegetation and green space, reductions in pavement (Gago et al, 2013,) and land use planning (Shandas et al, 2020.) The fact remains that cities use a greater share of the world's energy resources, particularly in the developed world (Madlener & Sunak, 2011). Therefore, they are an important opportunity for siting Distributed Energy Resources (DERs).

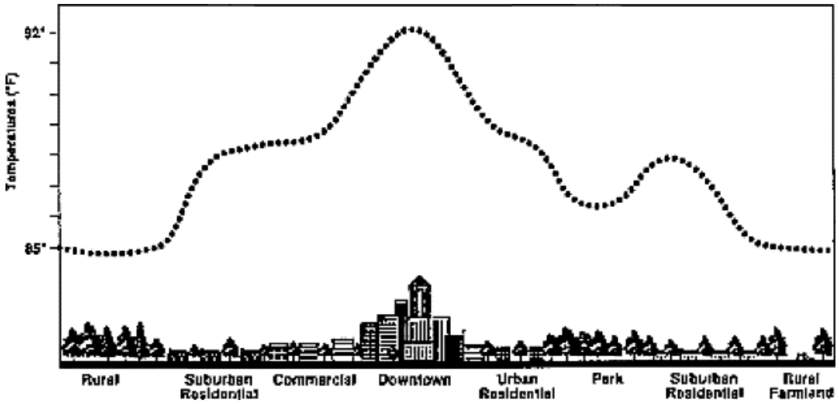


Figure 3: The Urban Heat Island Effect (Giridharan et al, 2004)

As a mature technology, rooftop solar offers an important mechanism for urban energy generation. Modelling indicates rooftop solar can both dampen UHI and reduce air conditioning demand, with ambient air cooling once solar conversion efficiency exceeds 20% (Taha, 2013.) This effect is shown to be stronger for inland cities not subject to coastal weather (Masson et al, 2014.)

As the climate warms, impacts to solar arrays will increasingly be seen. These include unpredictable cloud patterns, damage due to higher temperatures and hail, and reduced efficiency with higher average temperatures (Arent et al, 2014.) These impacts will need to be addressed going forward for wide scale deployment of solar.

Coastal Protection: WEC Breakwaters/Tidal Storm Barriers

As ocean temperatures warm, wave energy has increased at a rate of 0.4% annually since 1948 (Reguero et al, 2019.) This increase in kinetic energy translates to greater risk of erosion and flooding in coastal communities, particularly when coupled with ongoing sea level rise (Kousky, 2014.) As sea level rise and subsidence coalesce, flood risks will continue to intensify, with global projected losses of $60-63 billion annually in 2050 (Hallegette et al, 2013.) This increased kinetic energy also results in greater potential energy generation via Wave Energy Converters (WECs). Globally, wave energy has been estimated to have 2,000-4,000 TWh potentially available for generation (Lee et al, 2016.) While wave energy is deployed less than other renewables at present, due both to cost challenges and unproven designs relative to other more established sources, the potential for shoreline protection in light of increased wave energy is large (Iglesias & Abanades, 2016; Zanuttigh & Angelelli, 2013.) Christensen et al (2013) have shown that the lee side of wave farms can experience reduced wave energy by as much as 10%.

Coastal adaptation measures for wave attenuation are receiving increasing attention as part of local adaptation plans, including New York City, which plans to increase the use of breakwaters and other floodgate systems following damages from Hurricane Sandy (City of New York, 2013.) The addition of WECs to existing breakwaters can help reduce long term maintenance with reduction in kinetic energy, while providing power generation with little downside (UNFCCC, 2019.) Companies like Australian firm Wave Swell, which uses oscillating water column technology in its Uniwave WEC, are advancing this narrative (Wave Swell, 2020.) Recently, efforts have been made to successfully implement a proof of concept for a floating breakwater/WEC, thereby providing a clean energy-adaptation solution (Howe et al, 2020; He et al, 2013.)

WEC farms have also been shown to provide protection for aquaculture sites; research indicates that wave energy reaching both the aquaculture site and the shoreline is reduced (Silva et al, 2018.) Fixed bottom WEC breakwaters have been under development for some time, and offer a less scalable, though also viable solution (Arena et al, 2013; Torre-Enciso et al, 2009.) Finally, Resonant Wave Energy Converters offer potential shoreline protection as well as generation (Mattiazzo, 2019.)

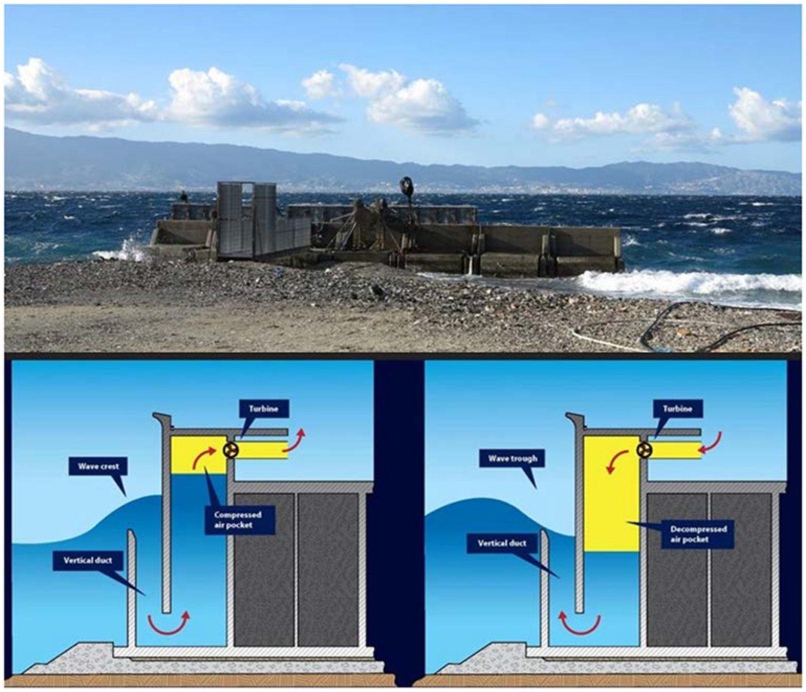


Figure 4: Resonant Wave Energy Converter (Mattiazzo, 2019.)

Another important area of protection exists in the deployment of tidal power integration into storm surge barriers, as has been done at Oosterscheldekering in the Netherlands. The installation, owned currently by Tocardo, includes 5 turbines with a 1.25 MW capacity in one portion of the storm surge barrier, with potential additional capacity to be added in the future (Ajdin, 2020.) These types of projects, seeking to expand tidal deployments to sites closer to shore and of less depth, increase the accessibility of tidal generation to more areas (Roberts et al, 2016.)

Resilient Urban Water Management

As precipitation patterns change in the context of climate change, sometimes at a high rate (Kunkel, 2020,) the importance of water management, particularly in urban areas with high levels of impervious surfaces, will become increasingly important (Henstra et al, 2019.) An estimated 10% of total global electricity use is utilized for water management, whether through pumping potable water (3%), or urban water management (7%) (Rana et al, 2016.) As precipitation patterns change, maintaining resilient power generation for these critical infrastructure services can be accomplished through increased renewables deployment at water management facilities (Knezovi & Rozić, 2020.) Leveraging distributed generation at local facilities will allow for greater levels of independence and make islanding in the case of grid instability more accessible.

Flood Protection: Siphon Pipe Hydro

As the cryosphere warms, glaciers are melting while glacial lakes rapidly expand worldwide (Zemp et al, 2017.). Should the terminal moraine often holding glacial lakes in place destabilize or collapse due to changing temperatures, seismic or avalanche activity (Yamada, 1992), the resulting flooding can be catastrophic. One method for mitigating these glacial lake outburst floods (GLOFs) is to insert siphon pipes into the moraine to draw down the lake levels. The addition of small-scale hydropower turbines into these siphon pipes could provide a reliable source of downstream communities, which often exist beyond the grid edge (Holzknecht et al, 2020.)

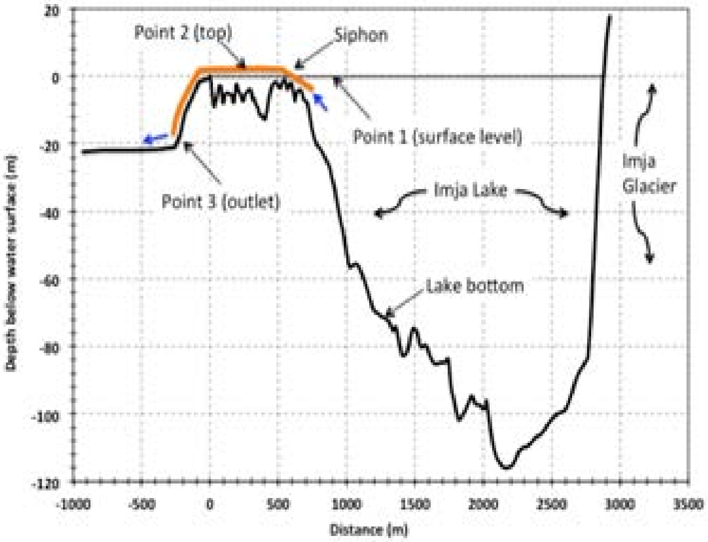


Figure 5: Siphon Pipes at Imja Tsho (Somos-Valenzuela et al, 2014)

Hybrids:

As competing land use needs intensify with sea level rise, changes in agricultural suitability, and population growth, a particularly promising area for renewables to advance climate adaptation is in hybrid and multi-use models, that increase the output for the footprint of a given installation. Hybrid energy models, where multiple renewable generation are deployed simultaneously, can dramatically increase the capacity factor for the installation. Multi-use models, which co-locate energy generation with other functions, such as agriculture or aquaculture, also provide an important increase in total spatial output. Additionally, in both cases, co-location results in other benefits, including increased generation and better crop production.

Renewable energy has long posed an issue for grid stability in terms of dispatchability; as nations seek to meet carbon reductions goals in line with their Nationally Determined Contributions (NDCs) to the Paris Agreement, the growing share of renewables in the energy marketplace will increase this problem (UNFCCC, 2015.) The variable nature of these generation methods will result in increased load balancing challenges, including energy production and supply droughts (Raynaud et al, 2018.) Hybrid models offer a way to mitigate these issues, with a smaller footprint.

Hydropower/Solar: "Floatavoltaics"

As precipitation and temperature patterns change globally, hydropower generation capacity is likely to be negatively affected, due to the potential for drought and greater evaporative losses (Aaheim et al, 2009; Hamududu & Killingtveit, 2012.) Additionally, resource competition in the water sector is likely to increase, as hydropower must compete with agricultural and municipal water needs (Ebinger & Vergara, 2011.) Floating photovoltaic (PV) installations offer tremendous potential for electricity generation, providing 10% of US energy needs with only 12% of inland water area used (Spencer et al, 2018.) Global floating PV installations have reached 2 GW of generation capacity, with high likelihood for further expansion, particularly in China. While locating PV on water has higher initial costs, the temperature reduction due to their proximity to the water results in a longer lifespan, and increased output (Doyle, 2020.)

Co-locating PV plants in floating (FPV) installations on existing hydropower reservoirs has the potential to convey substantial benefits in terms of reducing evaporation (Perez et al, 2018). Global estimates are as high as 74 billion m^3 conserved, resulting in the potential addition 142.5 TWh of production to existing hydropower installations (Farfan & Breyer, 2018.) The National Renewable

Energy Laboratory (NREL) estimates that floating solar has the potential to provide up to 40% of global energy (Lee et al, 2020.) Given shifting and often increasingly unpredictable weather patterns, this benefit extends beyond FPV hydropower hybrids to irrigation reservoirs, where the reduction in algal growth resulting in improved water quality adds to system benefits (Santafe et al, 2014; Haas et al, 2020.) Parameters exist for suitability of this application, including water depth (due to needs for anchoring and concerns over beaching) and seasonal water availability (Lee et al, 2020.)

In many cases, the addition of FPV can reduce the need for future spending on build out of new hydropower projects to increase generation as power needs grow (Sulaeman et al, 2021.) Hybridizing these two energy sources also increases the functionality of an off-grid or micro-grid setup (Guezgouz et al, 2019,) and helps buffer against potential future generation losses on the hydro side as changing precipitation patterns affect water resources (Arent et al, 2014.)

Figure 6: Floatavoltaics (Cazzaniga et al, 2018)

Adding floating solar arrays to existing hydropower reservoirs also offers other benefits, including increased output of the PV panels due to cooling from the water below and a decrease in wave activity (Rosa-Clot et al, 2017.) Additionally, variations in generation can be minimized by optimizing hydropower output for times when the PV plant is not producing power, or when addition generation is needed (Cazzaniga et al, 2019.) Submerging PV systems can both protect them from weather on the surface, and potentially also increase system output, depending on depth and temperature (Cazzaniga et al, 2018.)

Figure 7: Submerged PV (Cazzaniga et al, 2018)

Energy storage, another critical factor in energy decarbonization can also be integrated into the system, in the form of micro compressed air energy storage (Cazzaniga et al, 2018), or by way of pumped storage hydropower. Using FPV in a pumped storage hydropower scenario offers tangible benefits as well; FPV power can be utilized during off-peak hours to move water back to the upper reservoir for use during times of high demand (Lee et al, 2020; Liu et al, 2019.) FPV in a pumped storage application is not without its challenges; mooring for the panels must be able to adapt to continual changes in water levels. Also, many naturally ideal locations for pumped hydro (i.e. a valley that is suitable for upstream damming for the upper reservoir) will present issues with shading of the panels at certain times of day, if valley ridges are significantly higher than the reservoir (Barnard, 2019.) However, this application is being deployed currently by the German firm Vattenfall, with initial plans for 5 MW of installed PV capacity in its hydropower reservoirs, and plans for future expansion (Casey, 2020.)

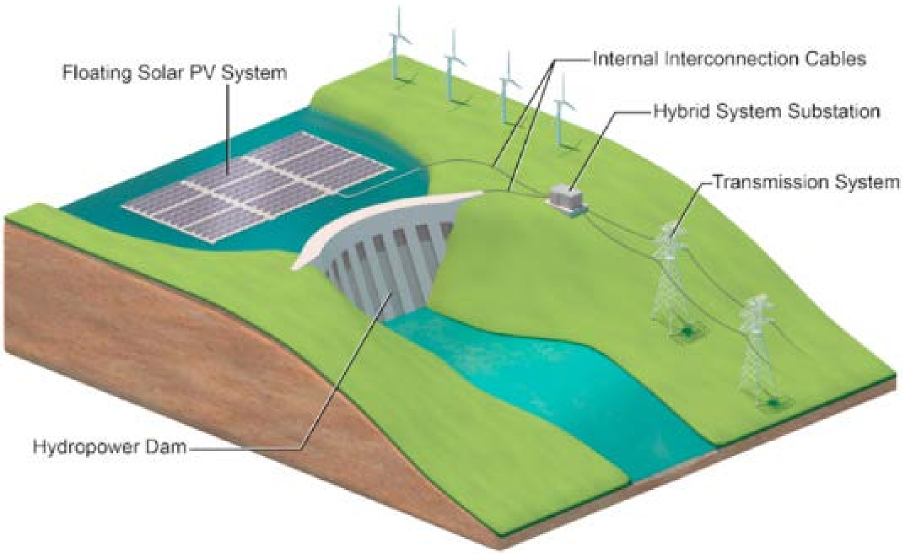
Additionally, great potential exists for utilizing existing transmission infrastructure in place for dams already with the addition of PV arrays installed on the faces of the dams themselves.

Figure 8: Japanese PV installation on dam face (Kougias et al, 2015)

Given the propensity for these assets to be located far from load centers, lowering costs of infrastructure construction and maintenance through usage of lines for multiple generation sources should be prioritized where possible (Balser et al, 2012.) This could increase total energy output for hydropower installations, and offer a power source for pumped storage during off peak hours to return water to the upper reservoir (Kougias et al, 2015.) This model could also be advantageous coupled with a wind farm, which during periods of excess production could provide energy for pumping to the upper reservoir (Nikolaou et al, 2020.)

Drilling down to increased granularity of power fluctuations, hybrid PV/hydropower deployment can smooth variability at the hourly level, with adjustments to far more dispatchable hydro output serving to balance fluctuations on the PV side caused by weather (Lee et al, 2020.) This hybrid model is beginning to be deployed at scale, with 30MW of floating solar to be deployed at the Batalha hydropower facility on the São Marcos River in Brazil (Bellini, 2020.) The U.S. Military is also planning to build a 1.1MW project at Fort Bragg in North Carolina, in the interests of eventually creating a micro-grid (Foehringer Merchant, 2020.)

Figure 9: Hybrid solar-hydro system (Lee et al, 2020)



Solar/Wind

Hybridizing wind power generation with other generation sources can be extremely beneficial in terms of reducing fluctuations in energy supply; it is expected to become more so as time goes on, due to increased seasonal variance in the context of the changing climate (Weber et al, 2018; Arent et al, 2014; Solaun & Cerda, 2020.)

Hybrid models involving solar and wind generation offer the obvious advantage of balancing variable production, both seasonally and on a more granular level (Jervery, 2016.) This balancing of fluctuation is especially valuable for micro-grids and where the option for islanding is needed. For urban areas, hybrid wind-solar arrangements can provide greater balancing between power supply and demand, by as much as 35% when compared with standalone wind (Lopez-Rey et al, 2019.) This hybrid model can result from actual physical co-location, or via virtual hybridization- that is, utilizing wind generated at distance from the location with a solar array, as the U.S. Department of Defense has done at Fort Hood. Onsite solar is complemented by wind power from several hundred miles away, with the goal of eventually having the option to operate as a micro-grid when needed (Luciano, 2018.)

Wind/Wave

The co-location of offshore wind and wave energy converters (WECs) also holds tremendous potential for leveraging transmission infrastructure and sharing construction costs of structural elements, with additional co-benefits to both generation sources. Clustering generation from different renewable sources increases spatial output, reducing the likelihood of crowding in the marine environment, and advancing conservation objectives as smaller generation footprints are required. The uniform generation of wave energy converters also serves to decrease fluctuations in energy production

(Perez-Collazo et al, 2014.) Finally, and perhaps most exciting, building wave converters in offshore wind installations could reduce wave energy, thereby protecting wind farms (Astariz & Iglesias, 2015.)

Floating breakwaters with WECs incorporated could also provide a source of protection and energy generation, though this remains in the early stages of development (Howe et al, 2020.) Finally, floating wind turbines with WECs built into their bases are under development, and offer potential efficiency increases with a minimal footprint (Muliawan et al, 2013.) These combinations can be grouped via mere co-location, as a truly hybrid system, or as part of an “energy island” (Astariz & Iglesias, 2015.)

Figure 10: Offshore Wind Energy Potential (Astariz & Iglesias, 2015)

As with many other hybrid technologies mentioned here, this type of hybrid has not been widely deployed, and lacks the appeal of proven renewables technologies (Perez-Collazo et al, 2014.) Astariz et al found dramatically reduced costs for co-located wind-wave installations, by as much as 50% overall, 14% in maintenance, and 25% reduction in capital costs (Astariz et al, 2015.)

Agrivoltaics/biomass

Land use competition is likely to intensify due to a decline in viable crop land with changing temperatures, and the changing climate will reduce crop yield in some areas (Gammans et al, 2017.)

Meeting the growing global population's nutritional needs will require reliance on many potential adaptation strategies in the agriculture space, including double cropping (Kawasaki, 2019). Meanwhile, land use competition between agriculture and renewable energy may result in further competition within the food-energy-water nexus; already 6% of viable agricultural land has shifted to wind power generation in the province of Ontario, for example (Morris & Blekkenhorst, 2017.)

The integration of PV arrays into cropland is another important strategy for increasing land productivity (Marrou et al, 2013a, Barron-Gafford et al, 2014.) Ideal locations for crop production are often ideal locations for solar energy production as well (Adeh et al, 2019,) and for this reason, there has long been competition between PV and biomass production (Calvert & Mabee, 2015.) Combining biomass cultivation with PV in an agrivoltaics format, therefore, is a promising way of addressing land use issues. Biomass is also capable of production on less fertile croplands that have been subject to agriculture related degradation, and these marginal growing areas could offer an important spatial resource (Zumkehr & Campbell, 2013.)

Livestock grazing can also be combined with PV arrays, offering shade in arid climates and potentially similar benefits to livestock feed as with agricultural crops (Hanley, 2020.) This sector can be grown with the aid of industry groups such as the American Solar Grazing Association (Charles, 2020). Grazing animals on agrivoltaics land is also likely to increase biosequestration, and should be considered part of the suite of regenerative agriculture practices that can provide a tremendous, natural carbon sink (Colley et al, 2019.) Co-location of solar panels with agricultural crops or “agrivoltaics” provides numerous benefits, with modelling indicating potential increases in crop yields of up to 70% (Dupraz et al, 2011) and 30% for lettuce (Dinesh & Pearce, 2016.). Agrivoltaics result in an increase in soil moisture retention and biomass (Hassanpour et al, 2018; Marrou et al, 2013b), as well as potentially creation of a greenhouse effect for crops located below the panels, resulting in warmer temperatures in the winter months (Armstrong et al, 2016.) Alternately, the panels can reduce heat stress in arid climates (Barron-Gafford et al, 2019.)

The increase in potential power generation could be substantial; Dinesh & Pearce (2016), found that agrivoltaics being used in US lettuce cultivation alone would result in additional generation of between 40 and 70 GW. Opportunities to further optimize agrivoltaics practice continue to come to light, including introducing tinted semi-transparent panels that allow the plants and PV panels to 'selectively harness different portions of the electromagnetic spectrum' (Thompson et al, 2020.) Changes to the panel's density could also increase solar radiation received by crops (Dupraz et al, 2011.) This scenario results in greater financial yield, as well as higher protein crops; this could be an important effect considering recent research indicating rising carbohydrate levels in crops linked to higher levels of atmospheric CO2 (Zhu et al, 2018.)

Figure 11: Agrivoltaics (Dinesh & Pearce, 2016.)

Policy flexibility around land use zoning and regulation will be key to ensuring adaptability in land markets (Anderson et al, 2018.) Funding and acceptance by the agricultural community also represent key hurdles to deploying agrivoltaics at scale. Recent developments, such as the partnership between Sun'Agri and RGreen Invest, aimed at constructing 300 agrivoltaic farms in France (Spaes, 2020) offer a model for future public-private work. As an emerging field, maintaining a full understanding of the environmental impacts inherent in scaling agivoltaics is key; given the sharing of both physical space and solar radiation, it may become necessary to explore new ways of determining productivity (Leon & Ishihara, 2018.)

Multi-Use Models: Blue Energy/Aquaculture

As the blue economy grows, unique opportunities exist to leverage marine spatial planning for multiple uses within the food-energy nexus. The 'Blue Revolution' long predicted presents tremendous potential to address the growing global needs for food and power (Sachs, 2007.) For example, offshore wind farms (OWFs), which have often in the past been closed to fishing, could provide ideal locations for aquaculture, should issues of antibiotic use, waste, and the introduction of non-native species be addressed (Craig, 2018.) These multi-use models offer potential additional efficiencies for common personnel, weather forecasting, and other benefits in terms of resource consolidation (Christie et al, 2014.) Offshore food production presents a number of benefits as well, including lessened spatial competition, reduced conflict among 'user groups, and optimal environmental conditions for a wide variety of marine species' (Buck & Langan, 2017.)

As mentioned above, deployment of WEC breakwaters can help protect coastlines from increased wave activity (Howe et al, 2020) and mitigate the need for choosing another means of protection, such as hard armoring or beach nourishment (Gopalakrishnan et al, 2016.) Large floating multi-use platforms, suitable for a variety of uses including aquaculture, floating airports, and other facilities can benefit from having WECs incorporated into their design as well (Nguyen et al, 2020.) These platforms can potentially incorporate multiple elements, and provide important square footage for a variety of applications. They have not been widely researched (Abhinav et al, 2020,) though early results are promising (Zanuttigh et al, 2016.)

Encouraging developments continue to come from collaborations between the public and private sector, including ongoing work between the US National Renewable Energy Laboratory, Wave

Venture, and others seeking to advance WEC technology (Weber & Roberts, 2019.) Having onsite power generation broadens the scope of possibilities for platforms potential uses. Concrete pontoons, as have been used successfully in the 7,710-foot Evergreen Point Floating Bridge outside Seattle since 2016, and a similar scenario may be useful in the future, though the impacts of saltwater on concrete structures built at scale are relatively unknown (Abrams, 2020.) However, concrete seawalls dating back to the time of Ancient Roman empire have been found to have hardened over time due to the addition of aluminum tobermite to the concrete (Jackson et al, 2017); this is perhaps worthy of further research in the context of blue energy.

Figure 11: Multi-Use/Blue Energy Concept (Abrams, 2020)

Aquaculture itself has also been shown to provide protection for coastal communities in reducing wave energy (Zhu et al, 2020;) hybrid blue energy/aquaculture models could conceivably be utilized as protection for both coastal communities as well as important areas for blue carbon/biosequestration, such as mangroves. This could help support initiatives such as Because the Ocean Initiative, which highlights the high potential for impact in the marine environment (Because the Ocean, 2019.) Additionally, significant cost reductions have been found to exist for co-located resources, with wave-wind installations having a reduced Levelized Cost of Energy (LCOE) of as much as 50% (Astariz et al, 2015.) Algae production for use as biofuels offers another potential area of energy sourcing within the blue economy. Repurposing offshore oil and gas infrastructure for this use could reduce cost for build out of aquaculture setups (Sedlar et al, 2019.)

From a conservation standpoint, the environmental impacts of offshore wind appear to result in a net gain to marine habitats following installation, including protection of the benthic zone from wave scouring (Wilson & Elliott, 2009,) and habitat creation on wave energy substructures (Langhamer & Wilhelmsson, 2009.) Given ongoing negative impacts to the marine ecosystem by ocean acidification, this may serve an important function in increasing resilience for the benthic community. Scour protection constructed for use with OWFs has been shown to have positive impacts on the marine environment, and can function as an artificial reef (Glarou et al, 2020,) though these benefits may extend to species unequally (Lu e tal, 2019.)

Coral reefs have been found to decrease wave energy by up to 97% (Ferrario et al, 2014); it is possible, though as yet unexplored, that artificial reefs could dissipate wave energy in a similar way, thereby protecting the onshore environment from increased wave energy. Innovative solutions such as artificial reef cubes, made by UK-based Arc Marine utilize mining byproducts and can remain in place, even after wind turbines may be disassembled, continuing to provide habitat and scour protection (Broom, 2020.)

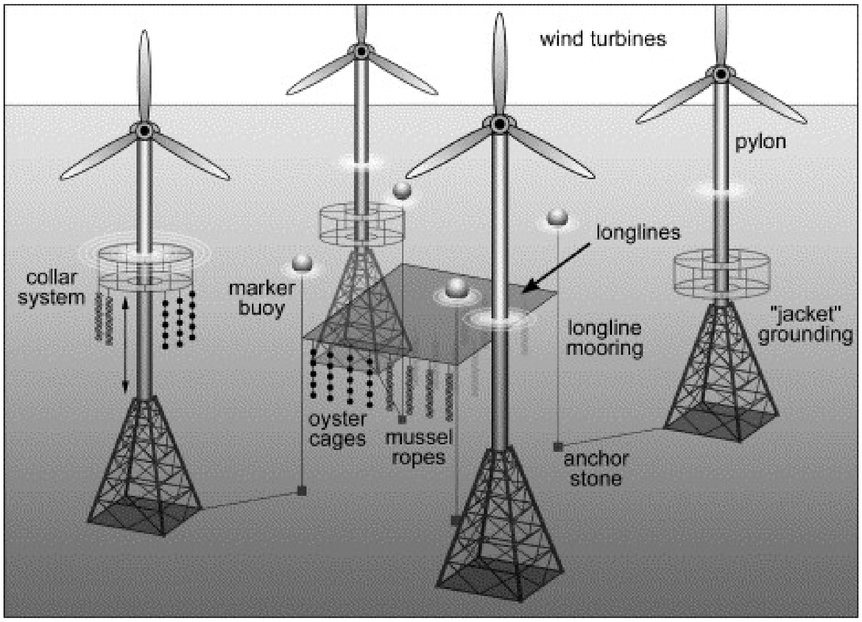


Figure 12: Multi-Use Wind/Aquaculture Concept (Buck et al, 2004)

Ocean Thermal Energy Conversion (OTEC) is another blue energy sector in nascent stages, though its high potential for energy delivery should become scalable. For ocean resources available to Taiwan, for example, potential generation has been gauged at 2.8 GW (Lin & Chen, 2016.)

Significant work must be done in the policy realm to signal to potential players in the developing blue multi-use space that sufficient regulatory stability exists to allow for projects to move forward in the shorter term (Onyango et al, 2020.) Regional partnerships, such as the recent formation of the Southeast and Mid-Atlantic Regional Transformative Partnership for Offshore Wind Energy Resources (SMART-POWER), offer advantages for joint policy making that translates across municipal boundaries (Condon, 2020.) If these challenges can be successfully addressed, the potential for food production as well as biofuel harvests of algae is great. Offshore wind turbine bases can provide an ideal structure for anchoring equipment for raising a variety of mollusks (Buck et al, 2004,) though a knowledge gap exists in terms of impacts from electromagnetic fields and sound from the turbines to marine life (Hooper & Austen, 2014.)

Development of multi-use projects should occur with each use being under consideration in tandem, and ideally, from project outset to encourage stakeholder interests be represented and accounted for (Christie et al, 2014; Jansen et al, 2016.) Also, there is potential for administrative issues to arise between US states, which have authority over the first 3 miles of coastal waters, and the Federal government's Bureau of Ocean Energy Management (BOEM), whose jurisdiction extends from 3 miles to 200 miles, in the Exclusive Economic Zone (EEZ). Adding to this the jurisdictional challenges of the Regional Fishery Management Councils (RFMCs) and the National Marine Fisheries Services (NMFS), the need for inter-agency collaboration and collaboration in the area of marine spatial planning is paramount. Ensuring that inter-agency cooperation is prioritized will remain critical, both for adaptation (Golpalakrishnan et al, 2017) and blue energy development. Identifying potential zones of conflict between fisheries and OWFs, considering advancing aquaculture in these areas, and protecting Important, Sensitive and Unique Areas (ISUs) for conservation has been done in the Washington State Marine Spatial Plan should be prioritized in future years (Craig, 2017.)

As the marine environment becomes more crowded, combining multi-use models with emerging technologies such as floating OWFs, which allow for installation at a much deeper water (Li & Zhang, 2020,) offer a pathway towards management conservation of critical marine habitat. However, combining multiple young industries in a multi-use model presents a high degree of uncertainty, and coupled with the high capital expenditure required for construction of these projects, a stable regulatory environment is critical to encouraging growth (Dalton et al, 2019.) Additionally, there is a strong case to be made for robust Marine Spatial Planning, in the interest of identifying critical ecosystems and ideal blue energy sites (Weiss et al, 2018.) 'Ocean Energy Clusters,' in which a variety of blue energy fields work together at a common location, may provide the quickest path forward toward innovation and stabilization of these young industries (European Commission, 2017.)

Advances in tidal power, including optimization of suitable turbines for lower current environments, allow for increased deployment of this technology in a variety of settings (Moammadi et al, 2020.) Early investigations into multi-use models for tidal energy/aquaculture indicate potential increases in power generation for power generation of as much as 19% when long-line mussel cultivation was used to optimize tidal kinetic energy (O'Donncha et al, 2017.) Flow rates were observed to be decreased around the mussel canopies, and when tidal devices where located below the canopies, the increased flow there resulted in greater energy production.

Areas of Further Research: Waste-to-Energy and Thermal Power

While technology continues to advance in the waste-to-energy sector, no applications for use in the adaptation space were identified. Biochemical, thermo-chemical, and chemical waste-to-energy technologies each involve significant environmental challenges, including disposal of the toxic fly ash produced for high temperature processes, air pollution and greenhouse gas emissions resulting from use of end products. Biological hydrogen production processes (BHPPs) and microbial fuel cells (MFCs) offer perhaps the best opportunity to address waste disposal with low byproducts, but are not yet scalable (Bishoge et al, 2019). There is a clear need to address the issue of emissions from municipal waste itself, as well as the handling of waste generally given problems of plastics and other products off-gassing as a result of photo degradation (Royer et al, 2018.) The argument has been made that biogas offers a transitional energy source away from fossil fuels, and reduction in GHG emissions (Thrän et al, 2020,) but no adaptation opportunities were identified from this source.

No adaptation opportunities were identified for thermal power at this time. This generation source will certainly be affected by the changing climate in the future (Arent et al, 2014), and should be a topic of further research as well.

Discussion

The adaptation field will continue to evolve with changing global needs. This paper has sought to address one potential area for advancement. However, any advancement must come as part of a comprehensive suite of solutions. For example, though opportunities may exist for shoreline protection from wave energy, as detailed previously, with wave energy and aquaculture, the establishment of rolling easements will still likely become a necessity (Titus, 2011) as sea level rise couples with subsidence, particularly on the US Atlantic coast. Pursuing adaptation and mitigation simultaneously is likely to result in lower total cost long term and can be done in ways that are complementary to both approaches (Bosello et al, 2013). Lastly, advancing clean energy in this way: through the use of 'adaptive renewables' mitigates the risk of reduced generation by current sources due to climate impacts (Jorgenson et al, 2004.)

Equity

The inequity between developed nations responsible for the bulk of emissions, having benefited economically for decades from a fossil fuel-based economy, and the developing nations who have been responsible for far less global emissions, and yet are much less well-resourced to respond to the climate crisis is palpable (Althor et al, 2016; Warner, 2020.) This has led to a greater focus on adaptation in the developing world, and mitigation in the better resourced developed world (Ayers & Huq, 2009.) In the face of constrained, finite resources, countries will be met with the choice between prioritizing adaptation or mitigation. As a unilateral effort, adaptation is generally more attractive, due to the potential for cross border emissions leakage (Auerswald et al, 2017.) Bridging the gap between adaptation and mitigation, or 'adaptigation' (Göpfert et al, 2019) will be crucial to avoiding a global focus on adaptation that allows mitigation efforts to stagnate.

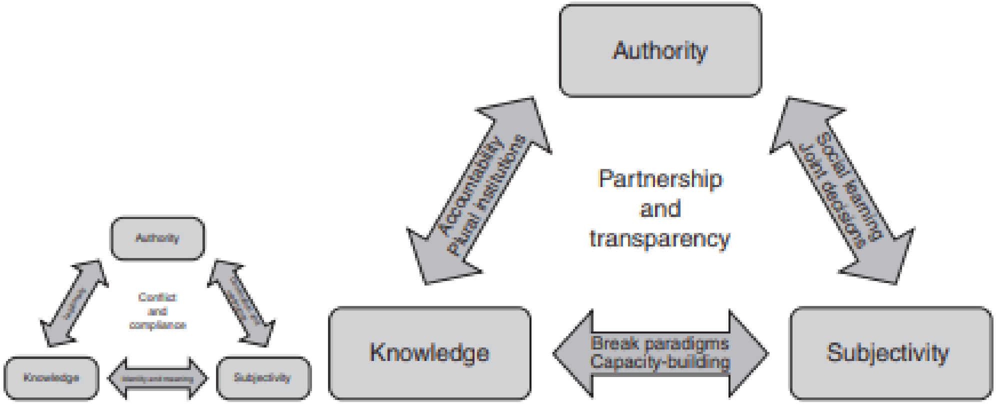
As energy infrastructure siting decisions are made going forward, it is critical to gather stakeholder input, and carefully consider local impacts, which can include reduced home and land value, noise, and the disruptive impacts of construction wind farms. Worker retraining should also be an area of focus as the transition away from fossil fuel generation continues (Dorrell & Lee, 2020.) Additionally, capacity building remains a critical area of priority, with the United Nations Framework Convention on Climate Change focusing particularly on this area as it relates to gender (UNFCCC, 2019.)

Presently, 34% of initial connections to the grid are supplied by clean energy (IEA, 2017); the potential for ongoing decarbonization should that number be increased is large. The correlation of poverty and lessened likelihood of accessibility to clean energy has been shown (Pachauri et al, 2004.) For the developing world, the potential for providing energy with renewable sources such as solar and micro hydro is great, particularly in areas not yet touched by the grid where a micro-grid could be created. As adaptation propels development forward to a greater degree over time (Chavez-Rodriguez & Klepp, 2018; Paavola & Adger, 2005), sensitivity to the ramifications of this linkage is needed. It will become increasingly important for adaptation to take a more holistic approach, including livelihoods (Tanner et al, 2014) and socio-political processes (Eriksen et al, 2015), and not merely physical infrastructure, to maintain geo-political stability.

Additionally, with the adaptation field favoring western, developed knowledge sources, much local knowledge (Chavez-Rodriguez & Klepp, 2018), often so crucial to successful adaptation, is at risk of being overlooked or discounted. Indigenous knowledge, which provides a deep, hyperlocal understanding of local ecosystems, should not be discounted (Green & Minchin, 2014.) The strongest adaptation planning would include scientific knowledge and traditional ecological knowledge (Lebel, 2013) and long-term relationships that facilitate dialogue among partners and across sectors (Conway & Mustelin, 2014.)

Renewables development in the developing world will be affected by policy making, though this is less tied to the ‘quality of governance’ (Mengova, 2019.) Utilizing technology such as tinted semi-transparent PV in an agrivoltaics format has the potential to offset protein deficiencies caused by shifting CO2 levels affecting crops, which will be especially detrimental to developing world subsistence farmers (Zhu et al, 2018.) The addition of hydropower into siphon pipes as a way to mitigate GLOFs could provide clean, baseload power to the most remote alpine villages, often hugely economically disadvantaged (Holzknecht et al, 2020.)

Figure 14: Empowerment-Focused Adaptation Framework (Eriksen et al, 2015)



Given the highly localized decision-making inherent in adaptation planning, a high degree of stakeholder engagement is crucial for project success. From this standpoint, applying a postmodernist perspective to adaptation offers unique advantages for building a participatory process that yields results most helpful to the communities affected (Nyamwanza & Bhatasara, 2014.) A framework that involves stakeholders at the greatest possible level, including education and feedback, will help create adaptive capacity across individuals, groups, and institutions (Tabara et al, 2010.) While the adaptation space must continue to move towards greater collaboration between those working in 'science and practice' (Moser et al, 2017), collaboration between stakeholders and those in both of these fields is critical as well.

Figure 15: The Climate Learning Ladder (Tabara et al, 2010)

Adoption/Funding Adaptation

As renewable energy develops globally, adoption is likely to be influenced by geographic location and adoption by others in the region, and exposure to clean tech through commerce (Fadly & Fontes, 2019.) Using renewables towards adaptation could also help address the current funding gap for adaptation efforts (Moser et al, 2017), offering a resiliency pathway with economic co-benefits, i.e., low carbon power generation. Given resource constraints, particularly at the local level, coordination and knowledge sharing would be extremely beneficial (Fu et al, 2017.)

A rapid transition to a zero-carbon economy is vital to staving off the worst effects of climate change; however, this transition will come at great cost. Funding climate adaptation at the scale needed globally will be extremely expensive, and funding sources should be diversified to include public and private funding at the state, local, and federal level (Coffee et al, 2020.) Long publicly supported systems, tied to the fossil fuel industry, and even the industry itself, must pivot. Substantial funding must be invested to build out renewable generation and storage at grid scale. Smart adaptation that leverages available knowledge and makes efficient use of resources can provide extensive cost savings as well (Field, 2018.)

Grid Architecture

A nimble, modern grid is required to support the complexity of a system that relies on broadly distributed generation and storage, within an electrified society. Much of renewables' future success relies on a robust transmission and distribution system being in place, and a utility marketplace that offers entry points for new technologies as they emerge. For fluctuations in demand to be continually met and baseload power provided to an ever-broader network of electric vehicles and smart homes, reliability hinges on the system being capable of drawing from many energy storage options, balancing fluctuations across regions, and being ready to isolate or ‘island’ problems as they arise.

As power generation shifts increasingly to DERs, grid architecture needs to be fundamentally addressed. Restructuring the grid in a decentralized way will allow for islanding of generation and transmission issues, and increase flexibility (Ebinger & Vergara, 2011.) A shift away from the centralized model currently in place, and likely to a Layered Decentralized Optimization (LDO) model is highly plausible (Kristov et al, 2016.) FERC has taken an important step toward encouraging DER adoption with order 2222. A variety of technological advancements will play a role in this shift; for example, synchronous condensers, which are hastening the transition off gas generation, as has been happening recently in Australia. The Australian Energy Market Operator is installing 4 synchronous condensers to address ‘system strength’ deficits, and thereby shift generation off gas and towards renewables (Parkinson, 2020.) Other innovative solutions for addressing shifts in dispatchable generation, such as vehicle-to-grid technology, could provide tremendous storage capacity (McMahon, 2019) and dramatically change the grid landscape. Increasing flexibility on the demand side will also play a critical role in achieving zero carbon generation (Palm & Ellegard, 2017), potentially through smart home technology and mechanisms such as time-of-use pricing.

Threats to the grid due to climate change include storm damage to infrastructure, overheating causing transformers to ‘trip off’ and line loss as temperatures increase (Arent et al, 2014.) As planning proceeds for advancement in the energy sector, it will become increasingly important to take into account this and other risks on both the supply and demand side (Cronin et al, 2018.) Power production forecasting will remain a critical component of maintaining grid stability, and may require new methodologies as demand shifts and storage is added (Kazi, 2011.) As temperatures rise, less demand will be placed on heating sources, including fossil fuels, and more demand will be placed on cooling, and therefore, the grid (USGCRP, 2014.)

Transmission

Transmission presents an ongoing challenge to the growing DER grid share; under the US's current scenario, in which project developers must shoulder the cost of transmission from projects often far afield from load centers, this addition to already high CAPEX costs comes at a detriment to industry expansion. For example, for the 28.5 GW of offshore wind development on the US East coast, fully one fifth of the total $100 billion cost is projected to go towards transmission (Burke et al, 2020.) Should this model shift to regional planning and construction of transmission to support DER expansion, long term cost reductions could be substantial, with projected savings of as much as $500 million in New England alone. (Pfeifenberger et al, 2020.) The distance at which blue energy projects are often sited from load centers represents a key logistical hurdle, increasing timelines for project build out substantially (European Commission, 2019.) In 2015, 40% of adaptation funding was allocated towards infrastructure; however, only $5 million of the total $121 million was for renewable energy (Nakhooda et al, 2015.) This proportion will need to be increased dramatically for needed grid modernization, including transmission build out to occur.

Government investment in infrastructure is another major factor in transitional speed and success. For example, the US Interstate Highway System was 90% funded through the federal government for 1956-1992; a similar investment in infrastructure would be tremendously impactful in scaling existing technology, developing new technology, and employing both (Victor et al, 2019.)

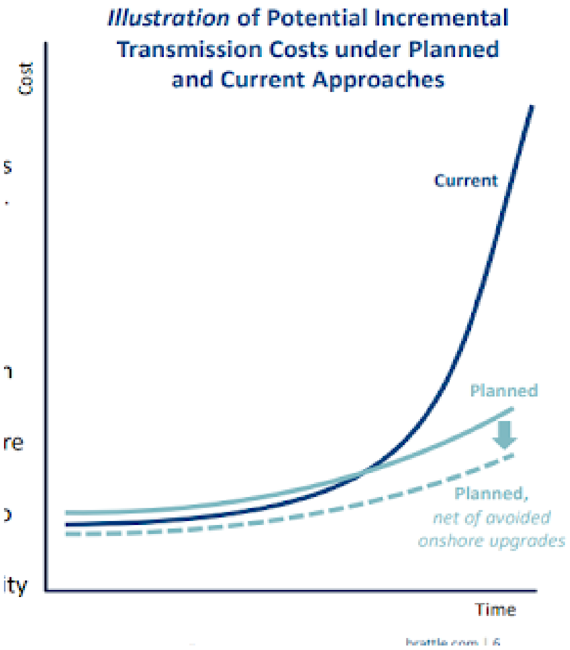


Figure 16: Transmission Cost Projections (Pfeifenberger et al, 2020)

One of the major obstacles for increasing transmission capacity in the US is community and landowner opposition. This could dramatically hinder a project's ability to proceed, and should be addressed early in, if not before regulatory permitting is underway. A careful analysis of impacts to local communities must be undertaken, and communicated to stakeholders. Driving trust in both the technologies and entities involved is critical to positive public perception and avoiding NIMBY (not in my backyard) dynamics. Those who are more familiar with a given form of renewable energy generation will tend to be more accepting of the source being located in their community; advocacy campaigns can therefore be crucial to public acceptance (Schumacher, 2019.)

In light of high costs and long lead times for permitting, existing transmission infrastructure should be leveraged in the siting of utility scale renewables deployment where possible. This can help address the issue of asset stranding for fossil fuel-based generation, which is likely to be an increasingly widespread problem in the coming years (Green & Newman, 2016.)

Summary Findings

A review of available literature identified 5 areas of high opportunity for application of renewables to climate adaptation. Further, 5 hybrid renewables scenarios were identified that would increase low-carbon power production with minimal footprint. The 10 areas were then assessed against the performance criteria framework to determine key areas of opportunity and priority for future build out. Summary findings including areas of greatest strength for each energy source are outlined below.

Table 2: Adaptive Renewables: Opportunities Summary

	Increased Resilience	Disaster Risk Mitigation	Equity	Decarbonization	Feasibility
Hurricane Protection: OWF	●	●		●	
UHI Protection: Solar	●		●		●
Coastal Protection: WEC	●	●	●	●	
Urban Water Management	●	●			●
GLOF protection: Siphon Pipe Hydropower	●	●	●		
Hydropower/Solar	●			●	●
Solar/Wind	●			●	●
Wind/Wave	●			●	
Agrivoltaics/Biomass	●				●
Blue Energy/Aquaculture	●		●		

Transformational Change: A Path Forward

With a high number of sectors requiring synchronous, large scale shifts, often on a short timescale, high level transformational change is needed to meet the coming challenges of providing for quality of life of the world's growing population, as well as transitioning to clean energy in a resilient way (Moser et al, 2019.) With a majority of adaptation practice in the US being phased, stepwise, and building on current practices (Kates et al, 2012), a shift of several orders of magnitude is likely to be extremely disruptive to this nascent field. This will require "work to examine interactions between activity spheres—the places of flows through which politics and power act, including that derived from knowledge and science" (Pelling et al, 2015) on an ongoing basis. Simultaneously advancing mitigation could provide aid where adaptation measures fall short, depending on the situation, but should be advanced in tandem (De Bruin & Dellink, 2011.)

Enhancing synergies between climate mitigation and adaptation wherever possible achieves significant gains in future ability to respond to climate events, while working to achieve carbon drawdown. As uncertainty remains an ongoing component in planning and decision making, frameworks to address these concerns should continue to evolve in order to avoid maladaptive projects, and 'no regrets' solutions be pursued wherever possible (Ebinger & Vergara, 2011.) While adaptation projects that restore ecosystems can ultimately result in increased green and blue carbon sinks, the opposite could also be true (Locatelli, 2011). Great care should be taken to avoid additional emissions due to adaptation efforts.

Figure 17: Conditions of System Change (Moser et al, 2019)

From a policy perspective, governments must create clear, stable standards for technologies and "credible commitments around the rate of phase-out" to encourage rapid change (Victor et al, 2019.)

With careful decision making around siting of power sources, energy production can support climate resiliency, food production, and protect communities from the worst impacts of the storms that will come. For a long time, energy has been a known source of carbon emissions; the solutions needed to address this issue are now here. Smart deployment of those solutions could provide the much-needed momentum to decarbonize, as well as advancing collective resilience. Advancing mitigation in a way that moves climate resilience forward is a worthy goal to build towards in future years.

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Curriculum Vitae/Biographic Statement

Sara Holzknecht holds a Bachelors of Business Administration from the University of Washington, Bothell. She is a Campaign Organizer with ocean conservation NGO Oceana, where she works to maintain sustainable fisheries, stop offshore drilling, and reduce plastics pollution in Washington State. She is also the co-founder and President of the local climate advocacy group 350 Eastside, which seeks to stop fossil fuel infrastructure expansion, encourage building electrification, and educate the community on how to get involved in. Through her work with 350 Eastside, she co-directed the short film, Yehow, which tells the story of two women coming together to fight a pipeline expansion project and the environmental impacts involved. Yehow has been selected for the Toronto Women's Film Festival and the McMinnville Short Film Festival, where it has been nominated for the Shawash Ilihi award for indigenous centered films.

Finally, she is part of the leadership team of an effort to create a new Public Utility District in East King County to replace the current for-profit utilities' fossil fuel-based energy mix with clean, publicly owned power. She is a 3-year student member of the American Society of Adaptation Professionals (ASAP), and completed ASAP's mentorship program in 2020.

Prior to her work in climate advocacy, Sara owned and operated a small winery near Seattle for 10 years. Growing evidence of the severity of the climate crisis caused her to close the business and shift gears to focus on decarbonization at home and abroad.