Energy Policy 38 (2010) 4897–4902

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Viewpoint

An integrated renewable energy park approach for algal biofuel production in United States

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ARTICLE INFO

Article history:
Received 26 August 2009
Accepted 20 April 2010
Available online 10 May 2010

Keywords:
Algae biofuel
Renewable energy
Integrated renewable energy park

ABSTRACT

Algal biomass provides viable third generation feedstock for liquid transportation fuel that does not compete with food crops for cropland. However, fossil energy inputs and intensive water usage diminishes the positive aspects of algal energy production. An integrated renewable energy park (IREP) approach is proposed for aligning renewable energy industries in resource-specific regions in United States for synergistic electricity and liquid biofuel production from algal biomass with net zero carbon emissions. The benefits, challenges and policy needs of this approach are discussed.

1. Introduction

Global warming, shortage of fossil fuels and energy security have pushed several countries to pass legislation to meet the growing demand for liquid transportation fuel with biofuels (Jacobson, 2009). Corn and sugarcane based bioethanol constitutes 90% of the commercial-level biofuel that exists in the market today (REN 21, 2009).

Although fuel ethanol and biodiesel production increased in 2008, the assessments of production potential, environmental impact of biomass facility production and carbon sequestration have thus far revealed that biofuels based on these feedstocks comply marginally with various sustainability criteria (Hoekman, 2009). Increased corn acreage for biofuel production has raised concerns regarding fertilizer and pesticide pollution, greenhouse gas (GHG) emissions, soil erosion, disruption of global food supply, reduced crop biodiversity, and biocontrol ecosystem service losses (Donner and Kucharik, 2008; Fargione et al., 2008; Hill et al., 2009; Landis et al., 2008; Searchinger et al., 2008; Tilman et al., 2006).

Conversion of ecologically vulnerable wetlands, rainforests, peatlands, savannas, and grasslands into new croplands creates enormous biofuel carbon debts by releasing several magnitudes more CO_2 than the annual GHG reduction that these biofuel would provide by displacing fossil fuel (Sawyer, 2008). Biofuel production using corn grain, soybean, and wood biomass required more fossil energy than the energy content of the biofuel. Furthermore, even if all US corn and soybean are converted to fuel, only 12% of gasoline and 6% of the diesel demand would be met (Hill et al., 2006; Patzek, 2004; Pimental and Patzek, 2005, 2007; Tilman et al., 2009). No credible studies show a positive energy balance or ecological footprint from traditional feedstock-based biofuels. A strong global biofuel industry will not emerge unless these critical environmental and social concerns are addressed (Henry and Devereaux, 2009).

2. Opportunities and challenges of algae as an advanced feedstock

The many biofuel mandates already in place indicate a need for rapid development of advanced feedstock-based biofuel. Advanced biofuels, defined as those that yield a net lifecycle reduction of at least 50% in GHG emissions compared with fossil fuels, offer particular advantages for the environment as well as for local economies. Biodiesel made from fast-growing algae, enzyme hydrolysis of forest waste and switch grasses, thermal depolymerization of organic waste to form ‘biocrude’, and direct biological synthesis of more complex biofuels, each have such potential (BRDi, 2007; US DOE, 2009). Of the many possible advanced feedstocks, algae-based biofuel stands out as the most promising for faster development (US DOE, 2009).

Extensive research was conducted to investigate the utilization of microalgae as an advanced energy feedstock, with applications being developed for biodiesel, bioethanol, and biohydrogen gas production (Huntley and Redalje, 2007; Margolis and Kammen, 1999; Rosenberg et al., 2008). Algae have higher photon conversion efficiency and can synthesize and accumulate large quantities of neutral lipids (biodiesel) and carbohydrates (bioethanol) along with other valuable co-products (e.g. astaxanthin, omega 3

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0301-4215/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2010.04.036

fatty acids, etc.) from abundant and inexpensive raw materials (e.g., sunlight, CO_2, inorganic nutrients found in wastewater). They can be grown on saline/coastal seawater and on non-crop lands (desert, arid and semi-arid land), resources for which there are no competing demands (Hu et al., 2008; Melis and Happe, 2001). Algae can utilize growth nutrients such as nitrogen and phosphorous from a variety of wastewater sources (agricultural run-off, concentrated animal feed operations, and industrial and municipal wastewater), thus providing a sustainable bioremediation of these waste water for economic benefits (Shilton et al., 2008). They can also couple CO_2—neutral fuel production with CO_2 sequestration from other power industries, in turn generating carbon credits (Dismukes et al., 2008).

Compared to other advanced feedstocks based on cellulosic ethanol, algal genomics and basic research are more advanced and gaining in momentum. Investors have already shown particular interest in algae-based biofuel, for example, in United States on a combined basis, the combination of biodiesel and algae venture capital investments totaled $320 M in 2008—up from the $307 M invested in 2007 (Cleantech Investment Monitor, 2008). Most recently, industry leaders such as Shell, ExxonMobil, and British Petroleum have also invested substantial resources in developing algae-based biofuels.

So what are the bottlenecks in utilizing algal biomass? Although several algal biofuel based companies have boomed in the last few years, most are still grappling with the non-trivial technology hurdles needed for cost effective production and extraction of biofuel from algal biomass. A defined set of technology breakthroughs will be required to develop for the optimum utilization of algal biomass for commercial production of biofuel (US DOE, 2009). As no biofuel is carbon-neutral in the current scenario, significant fossil fuel input is needed for growing, processing, and extracting the oil which might offset the positive aspects of the algal biofuel. Further, energy production using algal biomass may use large amounts of freshwater, which would compete with crops and cities (US DOE, 2006). Globally, commercial bioenergy production is projected to consume 18–46% of the current use of water by the year 2050. Already, the agricultural sector in the United States uses roughly 80% of the available freshwater and several regions face serious water shortages (US DOE, 2006).

3. Integrated renewable energy park (IREP): a novel approach for algal-based biofuel production

What would be a better comprehensive renewable biofuel energy vision? The renewable energy and related resources information in the United States indicate the major renewable energy sources such as solar, wind, and geothermal, are aggregated in a "corridor" primarily comprising regions of New Mexico, Arizona, and Colorado as well as parts of Utah, Texas and Nevada (Fig. 1 A–C). Further, substantial saline ground-water resources ($\sim$15 billion acre-feet of brine water) that cannot be used for traditional agriculture or for drinking water, but that can be used for algal culture, are contained within several huge aquifers in this proposed corridor (Fig. 1D) (Goldstein, 1990; Huff, 2004; Maxwell et al., 1985). Most of these states also possess vast stretches of under-developed semi-arid land suitable for large-scale biomass production from feedstocks such as algae and switch grass (Fig. 1E). The arid climatic conditions coupled with plentiful sunlight and saline water in the region can support a diversified and strong algal biofuel industry.

As most of these regions possess multiple energy sources, they are highly suitable for consideration as "integrated renewable energy parks" (IREP) (Fig. 2). The notion is to use multiple sources of renewable energy (e.g. solar, wind, geothermal) to create a "smart green grid" while at the same time the energy/heat generated from any renewable source is used for algal biomass production. IREPs complement and optimize integrated energy production process with no or minimal fossil fuel input creating environmental-friendly, emission-free energy parks.

The growing, harvesting and processing of any feedstock including algal biomass requires considerable energy. The use of fossil-based energy sources for these actions would reduce the net carbon gain in a life cycle assessment for this new fuel pathway. However, if algal energy production uses non-fossil, renewable energy sources such as wind and solar energy, the process will show a substantial net carbon gain.

One of the challenges in the algal biomass is the year round production of biomass in United States. In colder months (3–5 months) outdoor algal growing facilities and photobioreactors need to be controlled for optimum algal growth. Green house-based algal production may need heat to sustain high productivity. Greenhouses with solar panels to harvest solar energy or greenhouses to operate with the heat from geothermal would substantially contribute to the sustainability issue. Indoor production capability would be particularly important in the future emission constrained situation.

One unique aspect of algae compared to other advanced feedstocks is the spectrum of species available for amenability for biofuel production. Various species may be selected to optimize the production of different biofuels. Algae offer a diverse spectrum of valuable products and pollution solutions such as food, nutritional compounds, omega 3 fatty acids, animal feed, energy sources (including jet fuel, aviation gas, biodiesel, gasoline, and bioethanol), organic fertilizers, biodegradable plastics, recombinant proteins, pigments, medicines, pharmaceuticals, and vaccines (Pienkos and Darzins, 2009).

The multi-product paradigm from algae becomes particularly important in the present scenario and makes it a perfect candidate feedstock for biorefinery concept. A biorefinery integrates biomass conversion processes and equipments to produce fuels, power, and value added chemicals from biomass, a facility analogous to modern petroleum refineries, which produce multiple fuels and products from crude petroleum (Taylor, 2008). By producing multiple products, a biorefinery takes advantage of the various components in biomass raw material and their intermediates therefore maximizing the value derived from the biomass feedstock.

Several of the algal biomass co-products such as omega 3 fatty acids and recombinant proteins have high demand and market value. The biorefinery approach can be a viable option for the algal biofuel sector to attain financial sustainability. Using renewable energy in the biomass generation and processing may give firms incentives and offset the fossil fuel inputs. The concept of low carbon fuel is getting increased attention due to indirect land use and other sustainability issues related to other advanced feedstock such as lignocellulosic based biofuel (Ponti, 2009). By limiting the input of fossil fuel into energy production and processing facility, firms can qualify for two types of incentives: generating renewable energy and reducing emission.

Although from a resource standpoint, IREPs can be considered as centralized facilities, it is not a single central facility, like giant petroleum refineries operated by a single firm. Major firms can be a part of IREPs and might play an important role in the development of this concept. However, other small scale renewable energy (wind, solar, geothermal, and biomass) firms, working as a consortium, may also be an integral component of IREPs. Together these firms can cross feed power, heat, raw materials, and products with the shared goal of minimizing emissions to the atmosphere and optimizing the utilization of natural resources

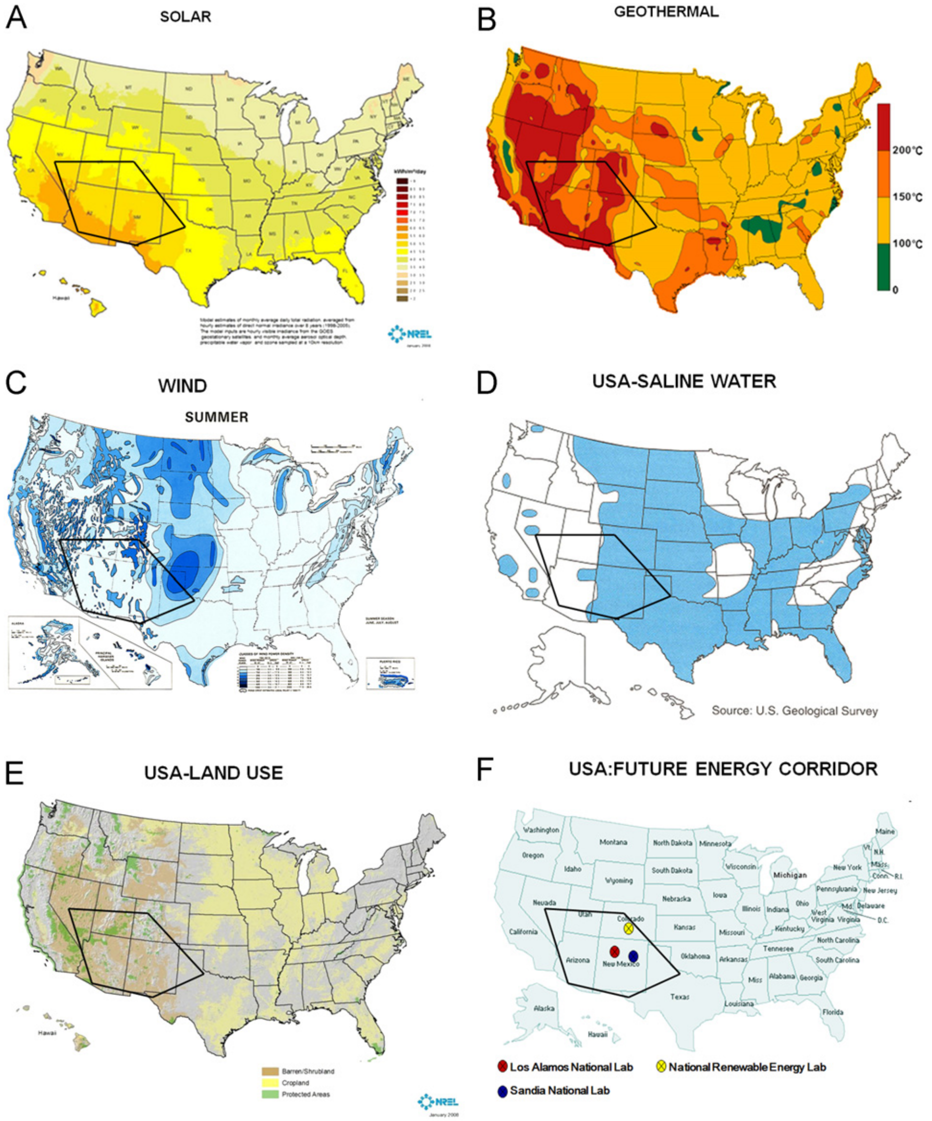
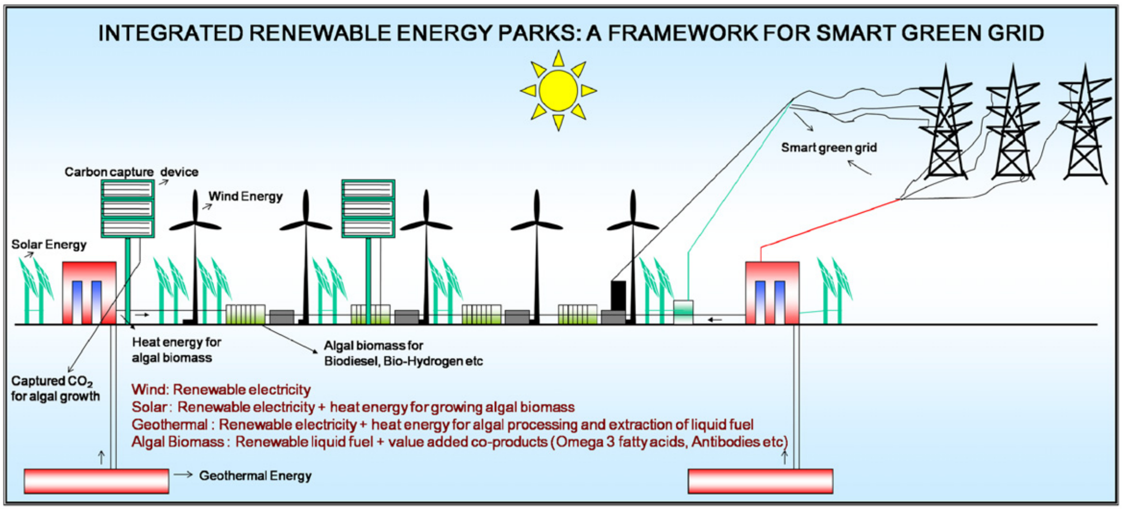


Fig. 1. The renewable energy resources of USA show a future "Renewable Energy Corridor". The resource map of solar (A), geothermal (B), and wind (C). Ancillary resource for IREPs saline water (D) and land use (E) and prestigious national research institutions (F) in the proposed corridor. Some images courtesy of Department of Energy/ National Renewable Energy Laboratory and US Geological Survey.



Wind: Renewable electricity
Solar: Renewable electricity + heat energy for growing algal biomass
Geothermal: Renewable electricity + heat energy for algal processing and extraction of liquid fuel
Algal Biomass: Renewable liquid fuel + value added co-products (Omega 3 fatty acids, Antibodies etc)

Fig. 2. Integrated renewable energy parks: a frame work for a "smart green grid" with net zero carbon emission.

such as land, water and fossil fuels and fossil agricultural chemicals.

4. IREPs in a cap and trade scenario

The current political and policy debates on energy, climate, and GHG emissions ultimately focused on three basic premises: (i) strong requirement for cleaner energy production and conservation technologies on a global scale; (ii) the need for future mandates on emission reduction to be aligned with the clean energy production and energy conservation policies; (iii) the need to act with urgency. The US energy sector in will undergo a major transformation and the nature and magnitude of the shift will be mainly geared by key legislation and enforcement by various governmental agencies. The current Waxman–Markey Bill, 2009 (American Clean Energy and Security bill, 2009) which passed in House of Representatives, have provision for a 17% emission reduction below 2005. Further, it mandates a cap and trade to be fully phased in 2016 with extensive terms for emission permits. It also has provision that regulated industries would be allowed to purchase carbon offsets to meet a portion of their required emission reductions. This provision means they could fund clean energy projects elsewhere instead of cutting their own emissions. The bill also has a number of provisions to help develop "smart grid" technologies and build better transmission infrastructure.

An emission-restriction scheme is highly likely to be implemented in future. Although it is not possible to anticipate the full market response of the carbon trading, one foreseeable outcome is that there will be legislative and regulatory certainty to limit emission with a mandatory trading scheme (e.g. cap and trade (emission certainty but price uncertainty) or carbon pricing (emission uncertainty but price certainty)). Consequently, the investment portfolio of major energy and other energy intensive companies will be mainly aligned with clean energy technologies. In a cap and trade regulatory environment, new business and investment models for adapting to emission will evolve quickly. Unlike the older business models where big firms obstruct the development of smaller firms, the bigger firms would leverage small firms and might even invest substantially in startups and small units aligned to them for carbon permits and offsets. Hence, the framework of IREPs will be enhanced by a cap and trade regulations.

Carbon capture will be inevitable component in industries such as coal-fired power and manufacturing plants. Cap and trade will provide strong incentives for firms to invest in technologies to capture and use this carbon for productive use. Similarly, companies will have incentives to invest in clean energy for carbon offsets for at least to another decade. Eventually, commercial carbon capture and economically feasible clean coal technologies may emerge. Carbon capture and the productive use of CO_2 in algal biofuel will act as a natural driver in the markets, increasing investments in IREPs.

Algae capture two pounds of CO_2 in each pound of algae produced. One of the positive environmental impact will be algae-based biofuel production that captures significant amounts of CO_2 released by the power plants in the proposed region. Four Corners Power Plant, located on Navajo land in Fruitland, N.M., is one of the largest coal-fired generating stations in the United States, generating 2040 MW. Existing CO_2 emissions in the Four Corners region include 15.6 million tons per year (tpy) from the Four Corners and 13.4 million tpy from the San Juan plants for a total of 29 million tpy of CO_2. The negative impacts of such emission could be offset by capturing the CO_2 for algal production. Although a daunting task, CO_2 storage and distribution will be an inevitable part of future power plant design and investment plans in our carbon constrained planet. As such, an extensive CO_2 grid for storage and distribution should be envisioned to reduce the negative impacts of the GHG without totally hindering the operation of traditional coal-based power plants.

A federal policy initiative for development of this infrastructure should be planned with an active interaction with power plant companies. Substantial subsidies and loans should be given to companies that interconnect the CO_2 grid, which will substantially reduce GHG. This interconnection will make a significant reduction of GHGs and power plant pollution. Without a comprehensive plan it is unlikely the industry will curb substantial amounts of GHG (Patrinos and Bradley, 2009; Quadrelli and Peterson, 2007). Infrastructure development requires billions of dollars, but these are critically needed investments in the sector for the sustainable production of biofuel in an environmental friendly manner. Incorporating some of these plans into the new American Clean Energy and Security bill (2009) would be a first meaningful step towards this infrastructure development.

The integration of established prototype carbon capture devices which feed algal cultures should also be examined (Fig. 2). Several novel green technologies such as geothermal heat pumps (Dickenson et al., 2009), dual fuel (bivalent) ground source heat pumps (Ozgener and Hepbasil, 2007), solar assisted heat pump systems (Benli and Durmus, 2009), solarwind turbine (which harvest wind and sun energy in one element) are receiving increased attention because of their potential to reduce primary energy consumption and thus reduce GHG emission. Further, newer energy conservation and utilization concepts such as bioheat from wood (Ohlrogge et al., 2009), bioelectricity from biomass (deB Richter et al., 2009), and hybrid hydrogen–carbon process for the production of liquid hydrocarbon fuels (Agrawal et al., 2007) can also be envisioned into the broader design concept of IREPs. Together, these technologies and concepts can maximize the ecological and environmental benefits of energy production from IREPs. The green electricity from these IREPs may flow into the existing grid. The IREPs in this corridor may also be developed into a hub to thoroughly connect the three main US national grids: Western, Eastern, and Texas.

This proposed renewable energy "corridor" is also home to key high-tech federal research institutions such as Los Alamos National Labs (LANL), Air Force Research Laboratory (AFRL), Sandia National Labs (SNL), and National Renewable Energy Labs (NREL) (Fig. 1F). These federal laboratories are significant developers of disruptive technologies, especially those of importance to national security and have some of the world's finest expertise in energy research and development. Much needed new technologies for renewable energy in general and algal biofuel in particular (such as optimum commercial-scale harvesting and extraction of biofuel from algae) can be developed at these institutions. Small and entrepreneurial firms are best equipped to transfer novel technologies that lead to discontinuous innovations (Brown et al., 2007; Kassicieh and Rahal, 2007) from national laboratories to firms with federal, state, and private entrepreneurial support.

The United States Department of Energy (DOE) has invested in the Bioenergy Research Centers and Advanced Research Projects Agency—Energy (ARPA-E) that are pursuing cutting-edge technologies in advanced feedstock such as algal biomass would lead the country into a "new frontier" of clean energy research. These major research investments will result in technological breakthroughs and innovative solutions.

The algal biofuel technologies are still in developmental phase. Innovative startup companies and small business units can play a major role in developing some of these key technologies into practical and viable market solutions thereby significantly contribute to the success of this sector. For the example, one startup algal biofuel company developed quantum disruption of algal cells to extract oil without a multistage oil separation scheme. These kinds of innovative technologies need to be tested for large-scale commercial utility, which can be done by small business units. A multitude of technological challenges need to be addressed by entrepreneurial companies to develop a mature, and diverse algal biofuel sector. As the algal biofuel sector evolves into mature industry, a myriad of ancillary and service based technologies (such as algal monitoring devices, algal process control) need to be developed for large scale commercial processing plants. Small business units and firms may play a role in the development of these ancillary industry needs.

Key environmental policies are needed to facilitate a vibrant small business sector willing to take these innovations to the market. Fortunately, the Waxman and Markey bill has a provision to create a federally owned, not for profit 'Green Bank' – formally called the Clean Energy Deployment Administration – with the key mission to encourage an integrated and strategic approach to clean-energy innovation, efficiency, and deployment (American Clean Energy and Security bill, 2009). This Green Bank will open credit markets, motivate private business to invest, and create good, clean-energy jobs in the US. A Green Bank capitalized with \$10 billion can leverage capital at the standard 10–1 ratio to provide loan guarantees in support of \$100 billion in private-sector investment in clean energy. These types of initiatives will safeguard the small business sector and contribute positively to the whole energy security and regional economic sustainability equation. Indeed, a trickledown effect due to IREP deployment may also be anticipated because of the existence of regional industrial consortiums. Using entrepreneurial firms this way will greatly help the IREP approach to succeed.

Universities and colleges can be identified as key energy grant universities, (Falkowski and Goodman, 2009) in order to gather and train the much-needed "brain power" in green energy technologies. Ironically, similar steps such as sun grant initiatives were hugely underrepresented in this corridor. Prioritizing some of these universities for long term research funding under the recently US-Congress enacted Advanced Research Projects Agency—Energy (ARPA-E) would be of immense importance. Together, universities and federal labs can be the leading network of "discovery–innovation–training" institutes for the next generation of energy challenges.

The leadership and state legislation environment in some of these "corridor" states are already quite vibrant and favorable towards renewable energy sector. For example, the state of New Mexico, home to two national labs and vast natural resources, ranks top in the US in Ph.D.s per capita and is poised to become a central player in the US race for energy independence. Similarly, Colorado and Arizona are also brimming with alternative-energy laboratories, businesses and job potential.

5. Conclusion

Integrated Renewable Energy Parks are highly relevant in a future "carbon constrained" business world. The annual renewable energy, comprising solar, wind, geothermal, and biomass, investment has increased fourfold to reach 120 billion in 2008 (REN 21, 2009), which are largely independent from each other. A strategic policy plan to integrate these industries together in the form of IREPs will have far reaching economic as well as environmental benefits. The proper development of marginal lands into productive use in these relatively under-developed regions will stimulate the small business sector which will in turn create both high-tech and low-tech jobs for local residents. Development may also provide "stepping stone" effects such as the extension of transportation networks, increased infrastructure, and rural development. Stepping stones are vital ingredients for regional development and economic sustainability (Henry and Devereaux, 2009).

The buildout of IREPs will create an integrated approach to sustainable and ecologically sensitive liquid transportation fuels. There are enormous economic and policy barriers that need to be addressed to maximize the success of this integrated approach to clean energy production. Cooperative engagement by federal and state governments coupled with the active participation of academia, national labs and private industry/investors will accelerate the establishment of IREPs. Science-based policy support from top administration (e.g., the Secretaries of Energy, Agriculture, Environment, and Homeland Security) can provide the valuable catalyst for these initiatives and collaborations. A meaningful marriage between regional industrial consortia and research groups designed to address technological and innovative challenges and an integrated renewable energy policy framework, may be the key for the success of our "energy independence".

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