# The role of microalgae in the deployment of biofuels: contrasting algae and solar technologies

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**Abstract:** With this study, it is aimed to provide an integrated review of the likelihood of microalgae deployment in the framework of biofuels production, while confronting it with emerging technologies, namely solar power. In this framework, a comparison study between the evolution of solar energy and algae biofuels will be made to draw lessons for what could be a possible success path of microalgae biofuel technology. This paper presents a discussion of the ongoing development of policies to optimise production and to encourage emerging energy technologies. To provide insightful arguments, this paper builds upon the Strategic Energy Technology Plan (SET Plan) and the European Directives, 2010 scenarios made available by the International Energy Agency regarding energy technologies perspectives, among scientific state-of-the art literature.

**Keywords:** algae; biofuels; policies; economic barriers; renewables; emerging technologies; solar; strategic; directive; energy; emergent; scenario.

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## 1 Introduction

This study aims to provide an integrated review of the likelihood of microalgae deployment in the framework of biofuels production, while confronting it with emerging technologies, namely solar power.

Sustainability is a fundamental principle in natural resources management. Therefore, it is increasingly clearer to society that the continued use of fossil fuels for energetic purposes is unsustainable. Innovative technologies and sources of energy must be developed to replace fossil fuels and contribute to the reduction of emissions of greenhouse gases associated with their use. Biofuels are particularly important to decarbonise means of transportation that lack other fuel options (especially trucks, ships and aircraft). However, alternative sources of biofuel derived from terrestrial crops such as sugarcane, soybeans, maize, rapeseed, among others, inflict a lot of pressure on the global food markets, contribute to water scarcity and precipitate the destruction of forests. Furthermore, the use of biofuels will depend on the development of viable, sustainable, second-generation technologies that do not appear to be yet commercially viable.

In this context, algal biofuels are generating considerable interest around the world. In USA, they may represent a sustainable pathway for helping to meet the biofuel production targets set by the Energy Independence and Security Act of 2007. Similarly, in the European Union, they can contribute to the achievement of goals established in the recent Renewables Directive. The European industrial initiative on bioenergy intends, as part of its strategic objectives, to address technical-economic barriers to the further development and accelerated commercial deployment of bioenergy conversion technologies for widespread, sustainable exploitation of biomass resources. It is thus necessary to contribute with a study that incorporates biomass feedstock availability assessment, production, management and harvesting in support of the up-scaling of promising technologies, like micro-organism (algae)-based ones. Bio-energy has to bring to commercial maturity the most promising technologies, to permit large-scale, sustainable production of advanced biofuels and highly efficient combined heat and power from biomass. Different bio-energy pathways are at various stages of maturity. For many, the most pressing need is to demonstrate the technology at the appropriate scale – pilot plants, pre-commercial demonstration or full industrial scale. By 2020, the contribution to the EU energy mix from cost-competitive bio-energy used in accordance with the sustainability criteria of the new Renewable Energy Sources (RES) directive could be at least 14%.

The existing economic situation of large-scale production of algae biodiesel is not yet competitive when compared with other contemporary renewable technologies such as wind, solar or geothermal. In this framework, a comparison study between the evolution of solar energy and of algae biofuels will be made to draw lessons for what could be a possibly successful path for microalgae biofuel technology, among other emergent renewable energy technologies.

With the current demand for renewable fuels, mainly for use in the transport sector, there is a need to develop a range of resources for sustainable biofuels. Therefore, this paper presents a discussion of the ongoing development of policies to optimise production and to encourage emerging technologies in the USA and the European Union. Therefore, biofuel production needs to be set in place, and an efficient distribution system needs to be organised to bring biofuels to the market. At the end, to create a credible market, steady and with a growing demand, it needs to be stimulated. Many of the implementation stages can constitute limitations to the level of success of these emerging technologies. In this way, with adequate policy support and incentives, the algal biofuel industry is prone to develop, and assuming that this technology follows renewable energy cost trends, costs will decrease to eventual economic viability. To provide insightful arguments, this paper builds upon the Strategic Energy Technology Plan (SET Plan) and the European Directive 2009/28/EC of 2010 scenarios made available by the International Energy Agency regarding energy technologies perspectives, among scientific state-of-the art literature.

This paper is, thus, intended to provide a comprehensive state of technology summary for fuels and co-products from algal feedstock and to draw some insights upon the feasibility and techno-economic challenges associated with scaling up of processes. This work also seeks to explore economic, social and environmental impacts of deploying algal biomass production systems at a commercial scale, while contrasting it with other renewable technologies.

To achieve this, this paper is structured as follows. In the next section, an overview of algae biofuel technology is provided. In Section 2, a brief comparison of biofuel technologies and the pros and cons of microalgae are shown. Sections 3 and 4 present the biofuel policies that apply in the EU and the USA, followed by a summary of the evolution of the Photovoltaic (PV) energy technology, where some grounds for a comparison analysis between its path and the one likely to be made by algae biofuels technology are developed. Finally, conclusions are drawn.

### *1.1 Overview of current status*

Several studies have been conducted on the technical feasibility of growing algae for biofuel production in the laboratory (Tao and Aden, 2009; Chisti, 2007; Brennan and Owende, 2010; Carvalho et al., 2006; Hirano et al., 1997; Ono and Cuello, 2006; Pulz, 2001; Pulz and Gross, 2004; Sheehan et al., 1998; Spolaore et al., 2006; Terry and Raymond, 1985; Ugwu et al., 2008), which have proved absence of the major drawbacks associated with current biofuels. However, the costs of producing this new fuel are still too high compared with other biofuel sources.

This technology uses the oils from microalgae as the raw material to produce biofuel. Microalgae are microscopic photosynthetic organisms that are found in both marine and freshwater. These organisms use solar energy to combine water with carbon dioxide ($CO_2$) to create biomass (Sheehan et al., 1998).

The mechanism of photosynthesis in microalgae is similar to that of higher plants, with the difference that the conversion of solar energy is generally more efficient because of their simplified cellular structure and also because of more efficient access to water, $CO_2$ and other nutrients. For these reasons, microalgae are capable of producing 30 times as much oil per unit of land area as terrestrial oilseed (Sheehan et al., 1998).

Algae can be autotrophic or heterotrophic; the first requiring only inorganic compounds such as $CO_2$, salts and a source of light energy for their growth, while the latter are non-photosynthetic, therefore requiring an external source of organic compounds and nutrients as a source of energy (Brennan and Owende, 2010).

In microalgae cultivation, carbon dioxide must be fed constantly during daylight hours. Algae biodiesel production can potentially use some of the carbon dioxide that is released in power plants by burning fossil fuels. This $CO_2$ is often available at little or no cost (Chisti, 2007). However, the fixation of the waste $CO_2$ of other kinds of businesses could represent another source of income for the algae industry. This sort of fixation is already being made in some large algae companies on a trial basis; though at present there is a lack of public data on the results. Although this is a very promising future possibility, and some species have proved themselves to be capable of using flue gas as nutrients, there are few species that survive at the high concentrations of $NO_x$ and $SO_x$ present in these gases (Brown, 1996).

Ideally, microalgal biodiesel would be carbon neutral, as all the power needed for producing and processing the algae would come from biodiesel itself and from methane produced by anaerobic digestion of biomass residue left behind after the oils have been extracted. Although microalgal biodiesel can be carbon neutral, it will not result in any net reduction in carbon dioxide that is accumulating as a consequence of burning of fossil fuels (Chisti, 2007).

The nutrients for the cultivation of microalgae (mainly nitrogen and phosphorus) can be obtained from liquid effluent wastewater (sewer); therefore, besides providing its growth environment, there is the potential possibility of waste effluents treatment (Cantrell et al., 2008). This could be exploited in two ways by microalgae farms: as a source of income by providing the treatment of public wastewater, and by obtaining the nutrients the algae need.

After the process of extracting the oil from algae, the resulting product can be converted to biodiesel. Biodiesel produced from algal oil has physical and chemical properties similar to diesel from petroleum and to biodiesel produced from crops of the first generation, and compares favourably with the International Biodiesel Standard for Vehicles (EN14214) (Brennan and Owende, 2010).

Like with a refinery, it is still possible to obtain other products in the cultivation of microalgae, such as ethanol, methane and biohydrogen. Although they are possible processes and proven in the laboratory, they are still little studied on industrial scales.

As of today, it has been shown that it is scientifically and technically possible to derive the desired energy products from algae in the laboratory. The question lies, however, in whether it is a technology that merits the support and development to overcome existing scalability challenges and make it economically feasible (UNESCO, 2009). Economic viability is currently the main hurdle to overcome for this technology. Current costs associated with both the state of the science and technology are significant, and represent a major factor working against development.

Commercial algae production facilities employ both open and closed cultivation systems. Each of these has advantages and disadvantages, but both require high capital input. Closed photobioreactors are significantly more expensive to construct, but have not been engineered to the extent of other reactors in commercial practice, and so there may be opportunities for significant cost reductions. Neither open ponds nor closed photobioreactors are mature technologies. Therefore, until large-scale systems are built and operated over a number of years, many uncertainties will remain. Cultivation issues for both open and closed systems, such as reactor construction materials, mixing, optimal cultivation scale, heating/cooling, evaporation, $O_2$ build-up and $CO_2$ administration have been considered and explored to some degree, but more definitive answers await detailed and expansive scale-up evaluations (Pienkos and Darzins, 2009).

## 2 Comparing feedstock for biofuel

Biofuel production could be made from several sources. Among crops, it could be obtained from corn, sugar cane, switch grass, soybeans, rapeseed, canola, etc. Each crop has its own impact and land-use requirements, as stated in Table 1.

**Table 1** Comparison of biofuel feedstock environmental impacts for transportation fuels from various biofuel crops

| *Crop* | *Used to produce* | *GHG emissions** (kg *of $CO_2$ created per mega joule of energy produced*) | *Use of resources during growing, harvesting and refining of fuel* | | | | *Pros and cons* |
|---|---|---|---|---|---|---|---|
| | | | *Water* | *Fertiliser* | *Pesticide* | *Energy* | |
| Corn | Ethanol | 81–85 | High | High | High | High | Technology ready and relatively cheap; reduces food supply |
| Sugar cane | Ethanol | 4–12 | High | High | Med | Med | Technology ready; limited as to where it will grow; reduces food supply |
| Switch grass | Ethanol | –24 | Med-low | Low | Low | Low | It will not compete with food crops; technology not ready |
| Wood residue | Ethanol, biodiesel | N/A | Med | Low | Low | Low | Technology ready; reduces food supply |
| Soybeans | Biodiesel | 49 | High | Low-med | Med | Med-low | Technology ready; reduces food supply |
| Rapeseed, canola | Biodiesel | 37 | High | Med | Med | Med-low | Technology ready; reduces food supply |
| Algae | Biodiesel | –183 | Med | Low | Low | High | Potential for huge production levels; technology not fully ready for scale up |

*Emissions produced during growing, harvesting, refining and burning.
Gasoline is 94, diesel is 83.

*Source*: Data source: Adapted from Groom et al. (2008)

When the oil yields of different biofuel crops are compared, it becomes clear that microalgae biofuels are far more efficient, as demonstrated in Table 2.

**Table 2** Comparison of estimated production and land-use requirement from various biofuel crops

| *Crop* | *Oil yield* (L/ha) [a] | *Land area needed* (M ha) |
|---|---|---|
| Corn | 172 | 1540 |
| Soybean | 446 | 594 |
| Canola | 1190 | 223 |
| Jatropha | 1892 | 140 |
| Coconut | 2689 | 99 |
| Palm oil | 5950 | 45 |
| Microalgae[b] | 136.900 | 2 |
| Microalgae[c] | 58.700 | 4.5 |

[a]For meeting 50% of all transport fuel needs of the USA.

[b]70% oil (by weight) in biomass.

[c]30% oil (by weight) in biomass.

*Source*: Chisti (2007)

## *2.1 Advantages of algae-based biofuels*

Compared to other sources of feedstock for producing biofuels, algae-based biofuels have several advantages. These advantages are:

- microalgae are capable of producing oil all year long, therefore the oil productivity of microalgae is greater compared to the most efficient crops
- microalgae can be produced in brackish water and on land that is not arable (Searchinger et al., 2008); microalgae do not affect food supply or the use of soil for other purposes (Chisti, 2007)
- microalgae have a fast growing potential and several species have 20–50% of oil content by weight of dry biomass (Chisti, 2007)
- regarding air quality, production of microalgae biomass can fix carbon dioxide (1 kg of algal biomass fixes roughly 1.83 kg of $CO_2$) (Chisti, 2007)
- nutrients for the cultivation of microalgae (nitrogen and phosphorous mainly) can be obtained from sewage, and therefore, there is a possibility of assisting municipal wastewater treatment (Cantrell et al., 2008)
- growing algae do not need the use of herbicides or pesticides (Rodolfi et al., 2008)
- algae can also produce valuable co-products, such as proteins and biomass after oil extraction, that can be used as animal feed, medicines or fertilisers (Spolaore et al., 2006; Brennan and Owende, 2010), or fermented to produce ethanol or methane (Hirano et al., 1997)
- the biochemical composition of algal biomass can be modulated by different growth conditions, so the oil yield can be significantly improved (Qin, 2005)
- microalgae are capable of performing the photobiological production of 'biohydrogen' (Ghirardi et al., 2000).

The above combination of the potential for biofuel production, $CO_2$ fixation, wastewater treatment and the possibility of production of biohydrogen highlights the potential applications of microalgae cultivation.

Compared to other biofuel technologies, the most favourable factor for the cultivation of microalgae for the production of biofuels is that they can be grown in brackish (salt) water and on non-fertile land, and the oil yield production is far superior.

### 2.2 Challenges of algae-based biofuels

Despite its potential as a potential source of biofuels, many challenges have hindered the development of technologies for producing biofuels from microalgae to commercially viable levels. Among them, and based on recent literature, we elect as the most important:

- the selection of species must balance the requirements for biofuel production and extraction of valuable by-products (Ono and Cuello, 2006)
- achievement of greater photosynthetic efficiency through the continuous development of production systems (Pulz and Scheinbenbogan, 1998)
- development of techniques for growing a single species and reducing evaporation losses and diffusion of $CO_2$ (Ugwu et al., 2008)
- few commercial cultivating 'farms', so there is a lack of data on large-scale cultivation (Pulz, 2001)
- impossibility of introducing flue gas at high concentrations, due to the presence of toxic compounds such as $NO_x$ and $SO_x$ (Brown, 1996)
- choosing algae strains that require fresh water to grow can be unsustainable for operations on a large scale, and may exacerbate fresh water scarcity (UNESCO, 2009).

Although there are several challenges related to the development of microalgae biofuels technologies, many policies are being made regarding this new source of feedstock for biofuel, as is stated in the next chapter of this paper.

## 3 USA and EU biofuels policies efforts

In this section, special focus is devoted to biofuels policies, because they make for major drivers for biofuel technology deployment. Both the USA and Europe are the two regions most representative of algal biofuel producing companies around the world. The USA has 78% and the EU 13% of all algal biofuel producing companies around the world (Singh and Gu, 2010; Castanheira and Silva, 2010).

### 3.1 US policies in brief

The US Department of Energy published on May 2010 important information for the US policy trends in the "National Algal Biofuels Technology Roadmap". This document represents the output from the National Algal Biofuels Workshop held in

Maryland in 2008, and was intended to provide a comprehensive roadmap report that summarises the state of the algae biofuels technology and documents the techno-economic challenges that are likely to be met before algal biofuel can be produced commercially. This document also seeks to explain the economic and environmental impacts of using algal biomass for the production of liquid transportation fuels.

Afterwards, the US Environmental Protection Agency suggested revisions to the National Renewable Fuel Standard program (RFS). The proposed rules are intended to address changes to the RFS programme, as required by the Energy Independence and Security Act of 2007 (EISA). The revised statutory requirements establish new specific volume standards for cellulosic biofuel, biomass-based diesel, advanced biofuel, and total renewable fuel that must be used in transportation fuel each year. The regulatory requirements for RFS will apply to domestic and foreign producers and importers of renewable fuel (EPA, 2009).

This rule proposes to establish the revised annual Renewable Fuel Standard (RFS2), and to make necessary programme modifications, as set forth in EISA. Therefore, the required volume modifications made under RFS2 are shown in Table 3, eventually reaching 36 billion gallons by 2022.

**Table 3** US renewable fuel volume requirements for RFS2 (billion gallons)

| *Year* | *Cellulosic biofuel requirement* | *Biomass-based diesel requirement* | *Advanced biofuel requirement* | *Total renewable fuel requirement* |
|---|---|---|---|---|
| 2008 | n/a | n/a | n/a | 9.0 |
| 2009 | n/a | 0.5 | 0.6 | 11.1 |
| 2010 | 0.1 | 0.65 | 0.95 | 12.95 |
| 2011 | 0.25 | a | 1.35 | 13.95 |
| 2012 | 0.5 | a | 2.0 | 15.2 |
| 2013 | 1.0 | a | 2.75 | 16.55 |
| 2014 | 1.75 | a | 3.75 | 18.15 |
| 2015 | 3.0 | a | 5.5 | 20.5 |
| 2016 | 4.25 | a | 7.25 | 22.25 |
| 2017 | 5.5 | a | 9.0 | 24.0 |
| 2018 | 7.0 | a | 11.0 | 26.0 |
| 2019 | 8.5 | a | 13.0 | 28.0 |
| 2020 | 10.5 | a | 15.0 | 30.0 |
| 2021 | 13.5 | a | 18.0 | 33.0 |
| 2022 | 16.0 | a | 21.0 | 36.0 |
| 2023+ | B | b | b | b |

[a]To be determined by EPA through future rulemaking, but not less than 1.0 billion gallons.

[b]To be determined by EPA through future rulemaking.

*Source*: EPA (2009)

Therefore, based on the table above for all renewable fuel categories, the applicable standards for 2010 were proposed, each representing a fraction of a refiner's or importer's gasoline and diesel volume, which must be renewable fuel.

The proposed specific targets for 2010 in the USA include 0.06% from cellulosic biofuel, 0.71% from biomass-related diesel, 0.59% from advanced biofuel, and 8.01% from renewable fuel from other sources. Algae-based fuels could be considered under the advanced biofuel or bio-based diesel portion of the RFS, according to the proposed rule. The EPA is encouraging involvement of different stakeholders and requesting comments on the expanded RFS2 proposal that falls in line with congressional mandates (UNESCO, 2009).

While cellulosic ethanol is expected to play a large role in meeting the 2007 Energy Independence and Security Act (EISA) goals, a number of next generation biofuels, particularly those with higher-energy density than ethanol, show significant promise in helping to achieve the 21 billion gallon goal. Of these candidates, biofuels derived from algae, particularly microalgae, have the potential to help the USA meet the new RFS, while at the same time moving the nation ever closer to energy independence (US DOE, 2010).

To accelerate the deployment of biofuels produced from algae, President Obama and Secretary of Energy Steven Chu announced on 5th May 2009 the investment of US$ 800 million on new research on biofuels in the American Recovery and Renewal Act (ARRA). This announcement included funds for the Department of Energy Biomass Program to invest in the research, development and deployment of commercial algal biofuel processes (US DOE, 2010).

UNESCO (2009) states that these last events encourage leading scientists and engineers from universities, private industry, and government to collaborate and increase the rate of advancement towards economic viability and deployment of algae biofuel technologies. The funding will focus on algal biofuel research and development to make the fuel competitive with traditional fossil fuels, as on the creation of a smooth transition to advanced biofuels that use current infrastructure.

Meanwhile, the Algal Biomass Organisation (ABO) is focusing its efforts on achieving three main goals for the algae biofuels technology:

- *Financial parity*: Algae fuels must receive the same tax incentives, subsidies and other financial benefits that are currently accorded to other biofuel feedstock.
- *Regulatory parity*: Algae must be recognised as an effective medium for the 'beneficial reuse' of carbon dioxide, and a significant part of the solution to the American overall carbon reduction strategy. Federal agencies should develop regulations that treat algae growth and production as equal to other biofuel feedstock and carbon sequestering technologies.
- *RFS parity*: Because algae are not cellulosic, low-carbon algae-based fuels are not counted towards the 16 billion gallon cellulosic biofuel carve-out within the RFS's advanced biofuel mandate. Consequently, all non-cellulosic biofuels, including algae-based fuels, are left to compete among themselves to meet a five billion gallon threshold within the mandate (ABO, 2010).

The ABO's advocacy has also helped to enhance the prospects for several pieces of legislation being considered by Congress, including:

- *S 1250* – Renewable Fuels Act of 2009: This bill would expand the definition of cellulosic biofuel to include algae-based biofuels, and cover them under the cellulosic biofuel producer credit and under the special allowances for cellulosic biofuel plant property.
- *HR 3460*: This bill would amend the Clean Air Act to include algae-based biofuel in the Renewable Fuel Standard and algae-based biofuels in the cellulosic biofuel producer credit.
- *HR 4168* – Algae-based Renewable Fuel Promotion Act of 2009: A companion bill to S. 1250, this bill would similarly expand the definition of cellulosic biofuel to include algae-based fuel, giving algae-based fuel the same production tax credits and special allowances for biofuel plant property as cellulosic biofuels.

As the main region so far for algae biofuel production, the USA is leading policies concerning this technology. Many more advances in this field are expected from the USA in the next few years.

### *3.2 Europe policy standpoint*

To promote the use of energy from renewable sources, The European Parliament published on April 2009, the Directive 2009/28/EC which

> "Establishes a common framework for the promotion of energy from renewable sources. It sets mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy and for the share of energy from renewable sources in transport. It lays down rules relating to statistical transfers between Member States, joint projects between Member States and with third countries, guarantees of origin, administrative procedures, information and training, and access to the electricity grid for energy from renewable sources. It establishes sustainability criteria for biofuels and bioliquids." (EU, 2009a, p.27)

Directive 2009/28/EC also establishes in its Article 4 that each member state shall adopt a national renewable energy action plan. In a nutshell, the national renewable energy action plans shall set out member states' national targets for the share of energy from renewable sources consumed in 2020, and the policies and measures adopted to achieve those targets.

Concerning energy from biofuels, Directive 2009/28/EC establishes in its Article 17 the sustainability criteria for these fuels, stating that biofuels that do not fulfil the sustainability criteria set out in this article shall not be taken into account. The main criteria are:

- The greenhouse gas emission saving from the use of biofuels taken into account shall be at least 35%. From January 2017, the greenhouse gas emission saving shall be at least 50%, and from January 2018, at least 60%.
- Biofuels shall not be made from raw material obtained from land with high biodiversity value.
- From land with high carbon stock.

- From land that was peat land in January 2008, unless evidence is provided that the cultivation and harvesting of that raw material does not involve drainage of previously undrained soil.

At the end of 2010, a communication from the European Parliament set the strategy for competitive, sustainable and secure energy by 2020. The SET Plan sets out a medium-term strategy valid across all sectors. Yet development and demonstration projects for the main technologies (e.g., second generation biofuels) must be speeded up (EU, 2010).

Among the projects to be launched, the €9 billion European Industrial Bioenergy Initiative aims to ensure quick market uptake of sustainable second-generation biofuels, since implementing large-scale sustainable biofuel production is one of the targets to be achieved.

## 4 Lessons to be learnt from PV/solar technology

### *4.1 The path of solar energy*

In this section, a summary of the evolution of PV energy technology is presented to provide grounds for a comparison analysis between its path and the one that may possibly be run by the algae biofuels technology.

Of late, the use of PV technology for electricity generation has increased rapidly, and its demand has grown by an average of 30% per annum over the past 20 years (Solarbuzz, 2010). In 2009 alone, the global PV industry installed over 7 GW of modules, with a total module production of 8.95 GW, and cell production of 10.66 GW – a 51% increase over the 2008 cell production of 7.05 GW (Mehta, 2010). Most of this success is due to the increased efficiency in commercial applications of PV technology that can largely vary among the different technologies used in manufacturing the modules. Allied to these improvements in efficiency of PV systems, the production cost for PV modules has declined significantly.

However, it is still an immature technology, and will continue to require targeted support to drive early deployment. The same is most likely to apply to microalgae. By stimulating secure, long-term commercial opportunities for investors, policy makers harness the competitive power of companies operating throughout the supply chain to increase production capacity, gain valuable commercial experience, drive down costs and improve performance (ECF, 2010b).

In this context, government intervention is the main driver for the development of renewable energies. Investment will be made only if incentives are sufficient to guarantee a commercial return to power generators and biofuels producers. Estimates published in the recent Energy Outlook 2010 (IEA, 2010a) show that government support worldwide for both electricity from renewables and for biofuels totalled US$ 57 billion in 2009. Biofuels receive more government support than any other RES or carrier by itself. Total support in 2009 was US$ 20 billion, with the highest levels of support in the USA and the European Union. Renewables-based electricity generation reached US$ 37 billion of global support, of which PV exceeded US$ 7 billion in 2009 (IEA, 2010a). Just for comparison, fossil-fuel consumption subsidies totalled US$ 312 billion in 2009 (IEA, 2010a).

Therefore, policies for the development of solar energy and biofuels have a strong impact on the development of technologies, and are extremely important worldwide. In the next section, policies related to the development of solar energy are studied and the key points are discussed.

### *4.1.1 Solar policies*

In Europe, several roadmaps are proposed in the "SET-Plan Roadmap on Low Carbon Energy Technologies" initiative, of which one refers specifically to solar energy. These roadmaps put forward concrete action plans aimed at raising the maturity of the technologies to a level that will enable them to achieve large market shares during the period up to 2050 (EU, 2009b).

In this roadmap, the European Industrial Initiative on solar energy has set its strategic objective to improve the competitiveness and ensure the sustainability of the technology and to "facilitate its large-scale penetration in urban areas and as free-field production units, as well as its integration into the electricity grid". For that, an industrial sector objective was set so that solar energy will provide up to 15% of the European electricity demand by 2020 (EU, 2009b). However if imports of North African renewables are achieved (Desertec Industrial Initiative and the Mediterranean Solar Plan), the contribution of solar energy will probably be higher (ECF, 2010a).

Concerning solar energy, the Directive 2009/28/EC presented earlier also refers specifically to this class of technology. In the specific case of solar thermal energy, it is said that

> "Member States shall promote certified equipment and systems based on European standards where these exist, including eco-labels, energy labels and other technical reference systems established by the European standardisation bodies." (EU, 2009a)

It is also stated that member states shall ensure that certification schemes or equivalent qualification schemes are available by 31st December 2012 for installers of solar PV and solar thermal systems. Each member state shall recognise the certification awarded by other member states in accordance with criteria presented in the same directive. It also stipulates that solar PV and solar thermal installers shall be certified by an accredited training programme or training provider (EU, 2009a).

Directive 2002/28/EC, or the Energy Performance of Buildings Directive, aims at reducing energy consumption in buildings. The directive lays down certain requirements which member states must observe for the calculation of the energy performance of buildings, taking into account local situation and environment. Member states are required to set minimum energy performance requirements for buildings. The directive entered into force on 4th January 2003. It had to be transposed into national legislation by January 2006 (EU, 2002).

One of the concrete results of this directive was the creation of new legislation among member states regarding solar energy. In Portugal, for example, one of Europe's sunniest countries, it was established in 2006 through the "Decree-Law No. 80/2006", that the use of solar thermal systems for heating domestic water in buildings is mandatory whenever there is sufficient exposure to sunlight to all new residential buildings and all new service buildings without central acclimatisation systems. For all large remodelling, the same rules apply (PT, 2006).

As an alternative to the use of solar thermal collectors, the law established the possibility of using any other form of renewable energy that captures, on an annual basis, energy equivalent to that of solar collectors, such as PV technologies, for example. Therefore, the energy collected can be used for purposes other than heating water if it is more efficient or convenient (PT, 2006).

Another bill (PT, 2002) made it possible for micro power generators to deliver energy to the public grid, generating premium revenues for producers who used RES, like PV.

An outline of the range of PV support mechanisms in place in some countries during 2009 can be found in Table 4.

**Table 4** Outline of the measures applied

| | |
|---|---|
| Enhanced feed-in tariff | An explicit monetary reward is provided for producing PV electricity; paid (usually by the electricity utility) at a rate per kWh somewhat higher than the retail electricity rates being paid by the customer |
| Capital subsidies | Direct financial subsidies aimed at tackling the up-front cost barrier, either for specific equipment or total installed PV system cost |
| Green electricity schemes | Allows customers to purchase green electricity based on renewable energy from the electricity utility, usually at a premium price |
| PV-specific green electricity schemes | Allows customers to purchase green electricity based on PV electricity from the electricity utility, usually at a premium price |
| Renewable Portfolio Standards (RPS) | A mandated requirement that the electricity utility (often the electricity retailer) source a portion of their electricity supplies from renewable energies (usually characterised by a broad, least-cost approach favouring hydro, wind and biomass) |
| PV requirement in RPS | A mandated requirement that a portion of the RPS be met by PV electricity supplies (often called a set-aside) |
| Investment funds for PV | Share offerings in private PV investment funds plus other schemes that focus on wealth creation and business success using PV as a vehicle to achieve these ends |
| Income tax credits | Allows some or all expenses associated with PV installation to be deducted from taxable income streams |
| Net metering | In effect the system owner receives retail value for any excess electricity fed into the grid, as recorded by a bi-directional electricity meter and netted over the billing period |
| Net billing | The electricity taken from the grid and the electricity fed into the grid are tracked separately, and the electricity fed into the grid is valued at a given price |
| Commercial bank activities | Includes activities such as preferential home mortgage terms for houses including PV systems and preferential green loans for the installation of PV systems |
| Electricity utility activities | Includes ‘green power’ schemes allowing customers to purchase green electricity, large-scale utility PV plants, various PV ownership and financing options with select customers and PV electricity power purchase models |
| Sustainable building requirements | Includes requirements on new building developments (residential and commercial) and also in some cases on properties for sale, where the PV may be included as one option for reducing the building’s energy foot print or may be specifically mandated as an inclusion in the building development |

*Source*: IEA (2010b)

Feed-in Tariffs (FIT) is one of the most successful mechanisms for the expansion of PV electricity so far, since it was first introduced in Germany almost 20 years ago. Over the previous five years, the number of countries offering FIT has more than tripled. These tariffs can be national-scale, state-based or even operate at the local community level, such as the Swedish scheme announced in 2009 (IEA, 2010b).

Nonetheless, in practice, public support frequently involves a combination of measures. While fewer measures are expected to generate a lower administrative burden, on the other hand, more measures may mean greater flexibility to deal with unforeseen circumstances. Funding issues are significant, and continued financial support is critical to the success of any mechanism. Table 5 provides a broad overview of some of the key PV support measures (IEA, 2010b).

**Table 5** Characteristics of some key support measures

| | *Enhanced feed-in tariffs* | *Direct capital subsidies* | *Green electricity schemes* | *Renewable portfolio standards* | *Tax credits* | *Sustainable building requirements* |
|---|---|---|---|---|---|---|
| Target audience | Grid-connected PV customers with business cash flow requirements e.g., housing developers, investors, commercial entities | PV customers with limited access to capital, e.g., households, small businesses, public organisations | Residential and commercial electricity customers | Liable parties, typically the electricity retailing businesses | Any entity with a tax liability, such as salary earners and businesses. However, may not be relevant for many prime candidates for PV | New building developments (residential and commercial); also properties for sale |
| Countries reporting use of this support measure, or similar | Australia, Austria, Canada, Switzerland, Germany, Spain, France, Israel, Italy, Japan, Korea, Portugal, the Netherlands, Sweden, USA | Australia, Austria, Switzerland, Germany, France, Italy, Japan, Korea, Malaysia, Sweden, USA | Australia, Austria, Canada, Switzerland, Germany, Spain, Italy, Japan, USA | Australia, Japan, Korea, Sweden, USA | Canada, Switzerland, France, Japan, Malaysia, Portugal, USA | Australia, Canada, Switzerland, Denmark, Germany, Spain, Korea, Portugal, Turkey, USA |
| Implementation | Typically administered by the electricity industry billing entity | Requires considerable public administrative support to handle applications, approvals and disbursements | Commercial business operation of the electricity utility; some public administrative support for accreditation of projects | Public administrative support via a regulatory body | Administered by the existing taxation bodies | Typically administered by the local building consent authority |

**Table 5** Characteristics of some key support measures (continued)

| | *Enhanced feed-in tariffs* | *Direct capital subsidies* | *Green electricity schemes* | *Renewable portfolio standards* | *Tax credits* | *Sustainable building requirements* |
|---|---|---|---|---|---|---|
| Economic and political considerations | Method of internalising the externalities associated with traditional energy supply | Up-front capital cost is seen as the main economic barrier to the deployment of PV. Can be used for both off-grid and grid-connected support programmes | Government involvement in selective, customer-driven, electricity business commercial activities raises some interesting questions. However, utility projects may better realise the network benefits of PV | Can be seen as a distortion in the functioning of the electricity market, especially if overly prescriptive | Same benefits as the direct capital subsidies but without some of the negatives | Appeal largely depends upon the degree to which property prices are impacted and the cultural acceptance of prescriptive approaches |
| | There are varying political perceptions regarding the use of public funds or funds generated by the electricity industry | | | | | |

*Source*: IEA (2010b)

In the USA, the most significant recent development is the passage of the ARRA in February 2009. ARRA provides new funding at the federal level, loan guarantees and tax credits for renewables and for energy efficiency (IEA, 2010a).

The main support mechanism at the federal level is the investment tax credit (mainly for PV). These are complemented by federal loan programmes, such as loan guarantees or clean renewable energy bonds. Several states now have renewable portfolio standards (mandatory or not) and offer incentives (IEA, 2010a).

## *4.2 Similarity analysis*

It is clear that solar technologies are more mature than algae biofuels, although both are considered to be emerging energy technologies. Measures and policies are far more developed in the solar sector.

However, these two technologies have some similarities. New solar technologies are being developed that could increase potential and reduce costs (ECF, 2010a). The same is happening with algae biofuels, which are still an expensive solution (as is solar energy), but research is ongoing to turn it to a more economically feasible technology. In both technologies, several land-based technologies are being developed that are in demonstration or in an early commercial phase (ECF, 2010a).

As is happening with solar generation, the use of biofuels is expected to continue to increase rapidly over the next decades, thanks to rising oil prices and government support. Advanced biofuels, including those from algae feedstock, are assumed to enter the market by around 2020, mostly in OECD countries (IEA, 2010a).

To enhance this market penetration, governments should create policy frameworks that facilitate and reward clean tech entrepreneurship and facilitate an entrepreneurial environment to drive change, both in solar and algae technologies. We already can see some of these signals in the solar pathway, but not quite in algae biofuels. A flourishing business and research community that attracts talent and investors has proven to be a strong engine for change (ECF, 2010a). Overall, market efficiency and operational performance can be significantly reduced if investors and companies are insulated from risks that they are best placed to manage (ECF, 2010b).

## 5 Future of algae-based biofuels

The future pathway for algae-based biofuels is still unclear. Although several challenges remain in the path towards commercialisation and adoption of algae as a biofuel, as seen so far, an increasing number of companies and politicians now believe the rewards outweigh the risks.

Theoretically, microalgae have been shown to be a potential source to produce biodiesel because of their many advantages as a sustainable feedstock for biodiesel production compared to other feedstock (Ahmad et al., 2011). Nevertheless, not only are more innovations still needed for the development of technologies which reduce costs while increasing the yields of production (Singh and Gu, 2010), a comprehensive set of policies to assist the development of microalgae technology is also required.

In the managing area, it is extremely important in the early phases of this promising industry, to deliberate on new business models that look at the bioenergy potential of algae for the transportation fuels market, as well as production of other higher value products so as to make the economics practicable (Singh and Gu, 2010).

## 6 Conclusion

It is increasingly clearer to society that the continued use of fossil fuels for energetic purposes is unsustainable. Therefore, other sources of energy must be developed to replace fossil fuels. Alternative sources derived from terrestrial crops such as sugarcane, soybeans, maize, rapeseed, among others, inflict a lot of pressure on the global food markets, contribute to water scarcity and precipitate the destruction of forests. Besides that, many countries cannot grow most of the terrestrial crops due to climate factors or lack of fertile cultivation areas for energetic purposes.

The focus on using renewable energy in the transport sector leads to reduced dependence on oil, and consequently, a reduction in external trade deficit balances. It also results in a reduction of $CO_2$ emissions, thereby contributing to tackle climate change by reducing greenhouse gases emissions. Moreover, diversification of supply sources leads to more security of supply, essential for the transport sector, by the endogenous production of fuels that leads to greater control of its production and introduction into the market.

This is where algal biofuels can really make a contribution for world sustainability in the future, since most studies confirm the technical and biological feasibility of producing biofuels in large quantities from microalgae. Technological advances in cultivation, harvesting and extraction of oil from microalgae are scientifically well known, and should continue to move forward in the coming years with increasing investment in R&D in this area. However, policy frameworks have to be addressed to develop the market penetration of such emerging technology.

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