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Energy plants in the coastal zone of China: Category, distribution and development

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ABSTRACT

Fossil fuel is running out day by day and wide plantation of energy plants is very promising to solve future energy crisis. However, China has to feed 22% of the world population but occupies less than 10% global arable lands. Therefore exploiting 2,000,000 ha of non-agricultural coastal land is imperative. This article shows the category and unbalanced distribution of terrestrial and marine energy plants in the coastal zone, and points out five ways (biodiesel, bioethanol, methane, direct combustion and cell fuel) to utilize them. Also the development and progress made in each way is illustrated. At last, several practical suggestions are offered for the future exploitation of coastal energy plants for the globe.

Contents

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1. Introduction

Nowadays the development of global economy depends heavily on fossil fuel like petroleum, coal and methane. Excessive dependence upon fuel energy not only seriously pollutes our planet but also causes local wars and conflicts for the purpose of occupying energy resources since the storage and distribution of fossil fuel varies among countries [1]. As the world's third largest economy, China is consuming more and more fossil resources. In 2008 petroleum consumption of China reached 365 million tons, 200 tons of which were imported from other countries at a high price. What's worse, in 2008 CO_2 emission of China exceeds America and becomes the biggest discharger of both CO_2 and SO_2 [1,2]. Therefore developing new source of energy is highly imperative both economically and environmentally.

The energy plants refer to plants whose biomass can be used directly as an energy source. In a broad definition, this term designates any land-base or maritime plants since energy stored in any kind of life. Since China is of great biodiversity, the study of energy plants is feasible and promising. For example, 1554 species of oil plant have been found in China whose oil can be converted into biodiesel. Oil content of 154 species is greater than 40% in seed and 30 kinds of arbors or shrubs plants produce combustible components of biofuel richly [1].

Because of the large population and limited areas of arable farmland in China, it is impossible to grow energy plants in fertile inland farms extensively, which would cause nationwide famine. However, China has more than 2,000,000 ha of non-agricultural coastal land with extreme salinity and other adverse factors where normal crops cannot grow. And this number is rocketing in a rate of 13,300–20,000 ha per year. Therefore growing energy plants in these regions is a very practical approach, since it would not take any agricultural land and, if properly exploited, would partly solve energy crisis. To date, many kinds of coastal energy plants have been identified and improved, which grow not only on land but also in the sea. Alga is perhaps one of the most potential alternatives because of its astronomical amount, large specific surface area and amazing growth rate.

Exploitation of these energy plants is mainly in forms of biodiesel, bioethanol, methane, direct combustion and microbial cell fuel. The cell fuel is an unconventional way of directly utilizing energy stored inside energy plants, and deserves more attention and investigation.

2. Category of main coastal zone plants

2.1. Terrestrial plants

2.1.1. Hydrocarbon-rich species

This kind of plants is rich in hydrocarbons, which is easily converted into biodiesel or can be directly used as biofuel without any processes. Representative species of this type is listed as follows:

Euphorbia tirucalli Linn: Growing well in tropic coastal sand, *E. tirucalli Linn* usually have a trunk of 2.0–6.0 m and reach 10.0–25.0 cm in diameter. Its milky sap, rich in combustible hydrocarbon, can be used to produce biodiesel in the process of abstraction and conversion [2]. Besides liquid fuel, *E. tirucalli Linn* are also utilized to produce methane, and its output of CH_4 is 5–10 times more than normal plants. Belonging to the same genus with *E. tirucalli Linn*, another species, *E. 1athyrus* grow not only in coastal zone but also barren inland. Its sap contains a great amount of hydrocarbons resembling petroleum and produces 10–50 barrels of fuel per hectare per year.

Calotropis gigantean: This species grows in arid or semiarid coastal zone with milk-like but poisonous sap in its stem, branch and leaf. Ethane extractive of this sap contains high concentration of liquid hydrocarbon mixtures, whose carbon–hydrogen ratio is similar to petroleum [2]. As a new source of hydrocarbons energy, this fuel is expected to substitute petroleum in the future. Reportedly, in Australia one subspecies of *C. gigantean* can produce 10.64 thousand liters of light petroleum per hectare per year. In southern China, the perspective of *C. gigantean* is very bright because of its amazing growth rate of 30 cm per week and because of its ability to retain sand.

Sindora glabra: Nicknamed by local citizen as diesel-trees, *S. glabra* flow out yellowish or amber liquid when wounded. This kind of liquid owns a similar combustibility with diesel and thus is widely used by the local as kerosene. Typically, a plant with diameter of 30–50 cm can produce 2–4 kg biofuel each time [2].

2.1.2. Carbohydrate-rich species

This type of plants is mainly used to produce bioethanol. Carbohydrates mainly refer to sugar, stark and cellulose, and the former two can be converted into bioethanol more easily than cellulose.

2.1.2.1. Sugar-rich plants. *Helianthus tuberous L*: Belonging to Compositae family and Helianthus genus, this perennial herb evolves strong ability to resist salinity, cold, malnutrition and drought. Experiments have shown that irrigating *H. tuberous L* with salt seawater would not negatively affect its growth and sugar content. Typically 70% of its carbohydrate is synanthrin and fructose content is also high.

Sorghum dochna var. dochna: This annual herb also shows its ability to resist salt, drought and flood. Since people no longer eat its crop, its planting area shrinks dramatically.

Sugar beet: This is a very common sugar plant in the world which belongs to Chenopodiaceae family and Beta genus. It tolerates high level of salinity and alkalinity, but is sensitive to acid soil. So not only inland fertile farm but also coastal zone can be used for beet plantation.

Sugarcanes: Although some are planted near the sea, sugarcanes cannot strongly resist salinity as effectively as the above species such as sugar beet and *H. tuberous* [3]. As perennial C4 plants, sugarcanes have strong ability to absorb and fix CO_2 and can be harvested for more than 7 times a year. In the second largest bioethanol-producing country—Brazil, sugarcanes are widely grown and utilized to produce biofuel.

2.1.2.2. Stark-rich plants. Corn: Traditionally corns cannot tolerate salt effectively, and growing corn nearby coastal zone is risky for the future yield may drop dramatically. But some species of corn are more tolerant towards salt than others and technology such as cell engineering and genetic engineering has been employed to create new species that is suitable in coastal zone [17].

Potato: Like corns, traditional potatoes are not salt-tolerant, but some special species shows satisfying tolerance towards negative conditions in coastal zone. Investigations conducted by Liang et al.

have identified several tolerant species [18]. In fact stark content of potato is less than 20%. Compared with other energy plant, this number is not satisfactory.

2.1.2.3. Cellulose-rich plants. Spartina alterniflora: Belonging to Gramineae family SpartinaSchreber genus, this perennial herb has developed strong ability to resist salt and flood and can even live underwater. As C4 plants, *S. alterniflora* have a big biomass, good fiber quality, a wide range of distribution and high tolerance to seawater irrigation. Its widespread seeds carried by wind and waves and 60 cm root in depth enhance its productivity.

Tamarix chinensis Lour: This is a highly salt-resistant species and spreads alone in China coastal land. It also shows strong adaptability and can easily survive because of its tolerance towards extreme drought, flood and cold.

Achnatherum splendens: This perennial herb has powerful roots of 80–150 cm and tolerates drought, alkalinity, salt and direct seawater irrigation. Fiber content in barks is more than 40%. In China it is regarded as weed or grazing grass and can grow in both coastal zone and hinterland.

Clerodendrum inerme: Belonging to Verbenaceae family and Clerodendrum genus, this kind of frutex is 1–2 m tall with poisonous branch and leaf and originally used for coastal forestation.

Miscanthus plants: Large growth rate is its characteristics, and the output is about 30–40 t/ha, which is almost equivalent of 36 barrels of petroleum. When harvested, it contains only 20–30% water and can be used as fuel directly or converted into bioethanol. Large-scale plantation of this species is going on in Europe and UK has developed the fourth-generation of this species. Also German has built a 120-thousand-KW power plant using *Miscanthus* plants as fuel.

2.1.3. Grease-rich species

Diesel is composed of alkane with about 15 carbon atoms while plant oil and grease are usually combined by molecules of 14–18 carbon atoms. Technically, plant oil can be converted into diesel through a chemical or biochemical process—esterification (see Fig. 1).

Kosteletzkya virginica (L.) Pres1: As a perennial oil plant belonging to Malvaceae family, malvoideae subfamily and Tribehibisceae genus, this plant tolerates seawater irrigation and growth matrix with salt content of 0.5–1.5% [4–6]. Protein content of seed is 25–35% and fatty acid is 20–30%. Seed production of natural species is 0.5–0.8 t/ha.

Suaeda salsa: As an annual herb, it grows in tideland or alkaline land where direct seawater irrigation is inevitable. Fat content of the seed accounts for 36.5% of the total dry matter, resulting in an oil yield ratio of 26.1%.

Salicornia bigelovii Torr: This is another species that tolerate direct seawater irrigation without diminishing its yield. Oil content of the seed reaches 27.2–32.0%, ranking between soybean and rape.

Helianthus annuus: This species has a strong adaptability towards adverse conditions such as seawater, cold, drought, alkalinity and lack of nutrition. Now it has become an important and stable oil plant in semiarid area and slight saline-alkaline coastal zone. Oil content of the seed is about 50–70%.

2.2. Marine plants

Every year over 146 billion tons of organic matters are produced on earth, 40% of which is from algae. Because of its large amount, specific surface area and amazing growth rate, alga has greater advantage over other terrestrial plants in producing energy-related materials and is becoming one of the most important raw materials of biofuel in the coastal zone.

2.2.1. Hydrocarbon-producing algae

Macrocystis pyrifera: Belonging to Lessoniaceae family and Maerocystis genus, algae of this kind are so huge that 70–80 m is a common length of their bodies and the biggest can reach 150 m in length. Growth rate reaches amazingly 30–60 cm per day and it can be easily harvested every 3 months since its leaves float on the water. Its biomass can be used to produce CH_4 from its methane-rich leaves [7]. Now this alga has been bred in many places of China such as ChangDao in YanTai city and DaLian in LiaoNing province (Fig. 2).

Botryococcus braunii: Scientist studies much of this kind due to its oil content and possibility to industrialize. Hydrocarbon content usually varies between 25% and 40% of the dry weight and even reaches 85% at the highest level [8].

Other species of this type include: *Dunaliena salina*, *Chlorella vugaris*, *Anacystis montana*, *Dictyopteris aerostichoides* and *Nostoc muscorum* [16].

2.2.2. Fat/oil-producing algae

Some algae produce oil or fat that is very similar with diesel in chemical composition. Fig. 1 shows us how biodiesel (fatty acid methyl ester) is made chemically [9]. Typical species of this kind include Diatom, *Dunalienasalina*, and *Chlorella*, in most of which oil content is about 30–50% and the highest is 85%.

2.2.3. Hydrogen-producing algae

Algae of this type can split water into oxygen and hydrogen. Representative species is listed as follow: *Chlamydomonas reinhardtii* [10], *Anabaena cylindrica1* [11,12], *Anabaena azollae* [13], *Anabaena siamesis* [14] and *Spirulina platensis* [15].

3. Distribution of coastal zone plants in China

Table 1 and Fig. 3 clearly shows the unbalanced distribution of energy plants in coastal zone of China. No doubt, more coastal energy plants are distributed in southern provinces (such as Hainan, Yunnan, GuangDong, TaiWan and GuangXi) than in northern provinces (such as ShanDong and LiaoNing).

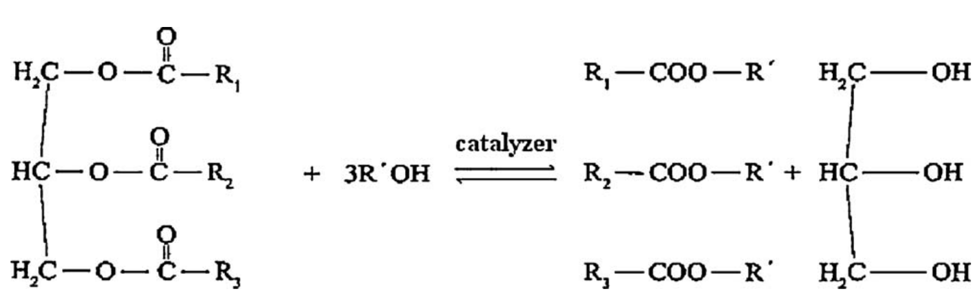

Fig. 1. Chemical equation to produce biodiesel (fatty acid methyl ester).

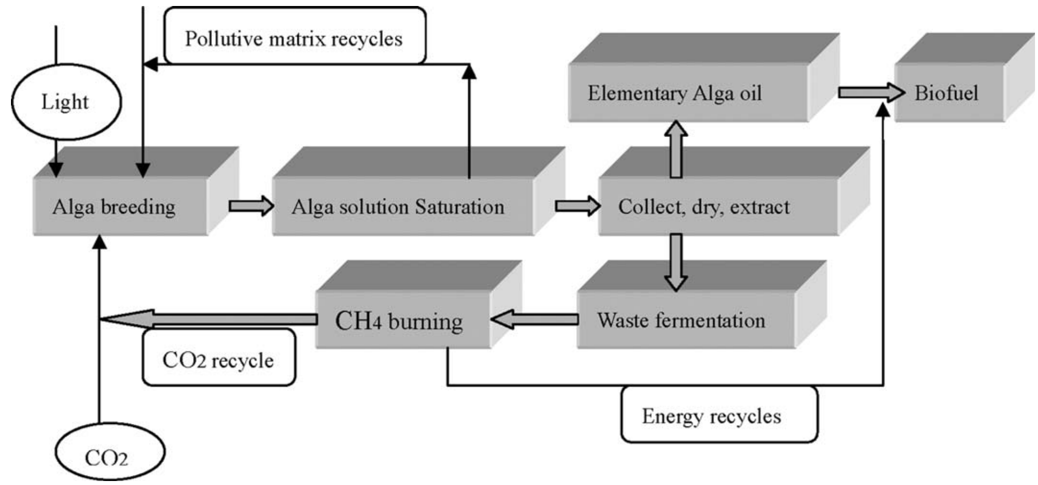

Fig. 2. Simplified process for producing biofuel and CH_4 using algae.

This is probably because southern China receives more heat and light from the sun and is thus more suitable for energy plants, the majority of which are C4 plants derived from tropic plants. For example, in Hainan and Taiwan, both of which are islands, so many energy plants are identified and developed on large scale due to the high temperature and marine climate.

4. Development and utilization of coastal energy plants

In the world, industrialized biofuel-producing species include sugarcanes (Brazil), soybeans (US), corns (US and China), rapeseeds (EU), palms (Malaysia), cottonseeds (Greek) and olives (Spain). China is a country with abundant biodiversity because of its large span in spatial layout. According to the strategical plan issued by Chinese government, in the future 11 years bioenergy would replace 25% of total imported oil and CO_2 emission would reduce for 0.2 billion tons. And that means by 2020 production of both bioethanol and biodiesel will reach 15,000,000 t.

4.1. Studies and exploitation of several representative and promising species

K. virginica: Six new species have been selected in China with an average seed production of 957 kg/ha, which is 49.76% higher than that of natural species (639 kg/ha) [21,22]. Currently, technology of producing biodiesel from *K. virginica* is available and quality of this biodiesel is very satisfying: cetane value is 56 and mass fraction of sulfur is 0.0038%. Since mature technology of chemical engineering was introduced in the production, the price of this biodiesel is relatively low [21,23].

Helianthus annuus: In 1998 JiangSu province introduced three new species (G101B, DK1 and DK3792) from US and the former two showed strong slat-tolerance with a seasonal yield of 2331–3035 kg/ha. Even growing in soil of 0.62–0.77% salt content, seasonal yields of these two species also reached 1285.2–2364.5 kg/ha. Following studies showed that G101B, under seawater irrigation, also demonstrate good tolerance and satisfying yield. And this made *Helianthus annuus* nearly the most tolerant and high-yield species among oil plants [20].

Sweet potato: Five salt-resistant species are selected which tolerate soil with about 0.5% salt content. Yield varies between 31.71 and 38.59 t/ha which is equivalent to 7.93–9.65 tons of sweet potato stark [19].

4.2. Five ways to utilize energy plants in the coastal zone

4.2.1. Bioethanol

Bioethanol is probably the most ideal approach to solve energy crisis in the future for the following reason: first, technology of producing bioethanol is very mature and already applied into

Table 1
The distribution of main coastal zone energy plants in China[a].

	Species		Distribution (province)
Hydrocarbon-rich species	*Euphorbia tirucalli Linn*		South HN, YN, GD, and TW
	Calotropis gigantean		GD, GX and south and west of HN
	Sindora glabra		HN and YN.
Grease-rich species	*Kosteletzkya virginica* (L.) Pres1		South China, JS, etc.
	Suaeda salsa		SD, JS.
	Salicornia bigelovii Torr		SD, JS, ZHJ, GX, YN.
	Helianthus annuus		Widely distributed
Carbohydrate-rich species	Sugar-rich plants	*Helianthus tuberous L*	Wide. GD, GX, JS, etc.
		Sorghum dochna var. dochna	Wide. Especially south of the Yellow River
		Sugar beet	Widely distributed
		Sugarcanes	GD, TW, GX, FJ, etc.
	Stark-rich plants	Corn (special breed)	Widely distributed
		Potato (special breed)	Widely distributed
	Cellulose-rich plants	*Spartina alterniflora*	JS, JZ, GD, LN, etc.
		Tamarix chinensis Lour	South China, SD, etc.
		Achnatherum splendens	Widely distributed
		Clerodendrum inerme	South China
		Miscanthus plant	Wide. Especially south

[a] Abbreviations of each province: HaiNan(HN), YunNan(YN), GuangDong(GD), TaiWan(TW), GuangXi(GX), ShanDong(SD), JiangSu(JS).

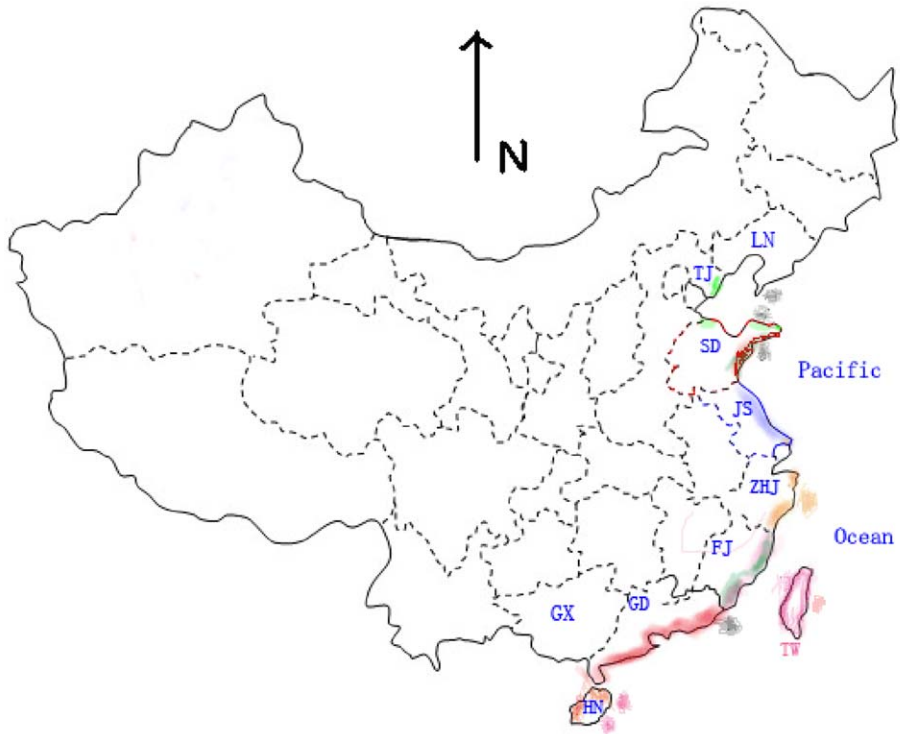

Fig. 3. The distribution of terrestrial energy plants and marine algae in China. [Abbreviation of each province: HaiNan(HN), GuangDong(GD), TaiWan(TW), GuangXi(GX), ShanDong(SD), JiangSu(JS), ZheJiang(ZHJ), FuJian(FJ), LiaoNing(LN), TianJin(TJ).]

industrialization; second, ethanol has a big caloric value and full combustion; third, bioethanol shows good compatibility with normal engine, and no change in engine is needed if the proportion of ethanol is less than 25% of the blended fuel. Moreover, adding bioethanol lowers octane number and makes blended fuel safer [24].

Traditionally bioethanol is made from sugar, stark and cellulose. Sugar fermentation is regarded as the easiest and most low-cost method while the cellulose is the most difficult. The reason is obvious: degrading cellulose is hard due to its complex structure and low activity of cellulase. However, cellulose does have to be utilized since it is almost the most abundant material in the earth and cannot be digested or absorbed by humans. So far, AFEX (ammonia fiber explosion) technology is most promising for cellulose pretreatment.

China, next to US and Brazil, is the third biggest bioethanol-producing country with a 0.44-billion-gallon yield in 2007. The main raw material in China is the corn but the government strictly controls the amount that is converted into biofuel since there is a big population and crops are quite necessary to avoid famine. Using non-crop plants is highly encouraged by government and in 2006 more than 190 dollars is provided to companies for every ton of biofuel they produced. Total production potential of China is estimated as more than 74 million tons [25].

4.2.2. Biodiesel

Fig. 2 shows one process that biodiesel is produced. Technically three ways are feasible: chemical, biological and supercritical method. The first method is widely used all over the world. Catalyzed by vanadyl phosphate, an ester cross-exchange reaction converts grease into biodiesel (fatty acid methyl ester) as shown in Fig. 1. However, this method needs a high temperature, large consumption of energy and will discharge alkali waste water. Also alcohol should be 8-fold-excess which means alcohol recovery equipment should be built and this increases the cost. The second approach employs enzyme to produce biodiesel in mild conditions. For example, soybean oil can be converted below 40 °C with a transformation rate of 92% and very little waste liquid is produced [26]. However, the high cost of enzyme and variation of composition and carbon chain length of grease inhibit this method's wide utility because enzyme is not good at catalyzing short-chain fat. As to the supercritical method, scientists have found that under SCM (supercritical methanol) system the conversion of rapeseeds oil needs no catalyst and ends up with a 95% transformation rate [27]. However, this process needs high pressure and temperature, which raises the production cost and energy consumption.

Currently biodiesel is more expensive than normal diesel because the raw materials account for the majority of its cost. Moreover, corresponding technology is not mature enough to lower biodiesel's price dramatically. Even so, the future perspective of diesel is optimistic due to the following advantage: first, biodiesel releases less SO_2 compared with traditional diesel and is thus more environmentally friendly; second, engines using biodiesel can start more easily in cold weather; third, biodiesel has better lubricating property than traditional diesel and can prolong life span of engines; fourth, biodiesel has a higher flash point and therefore better safety performance.

4.2.3. Methane

China has long history of making methane by fermenting straws. Related theory and technology is relatively mature and the cost is very low. Traditionally people dig a methane tank to produce gas and this is one of the most elementary ways. Another way is to extract or gather methane from marine plants or algae such as *M. pyrifera* and this seems more efficient since algae grow much faster than corns or other terrestrial plants and have a bigger biomass within certain period of time [28–30].

4.2.4. Fuel cell

The study of fuel cell using energy plants is a very new field and so far only a few applications are reported. Peter has conducted an

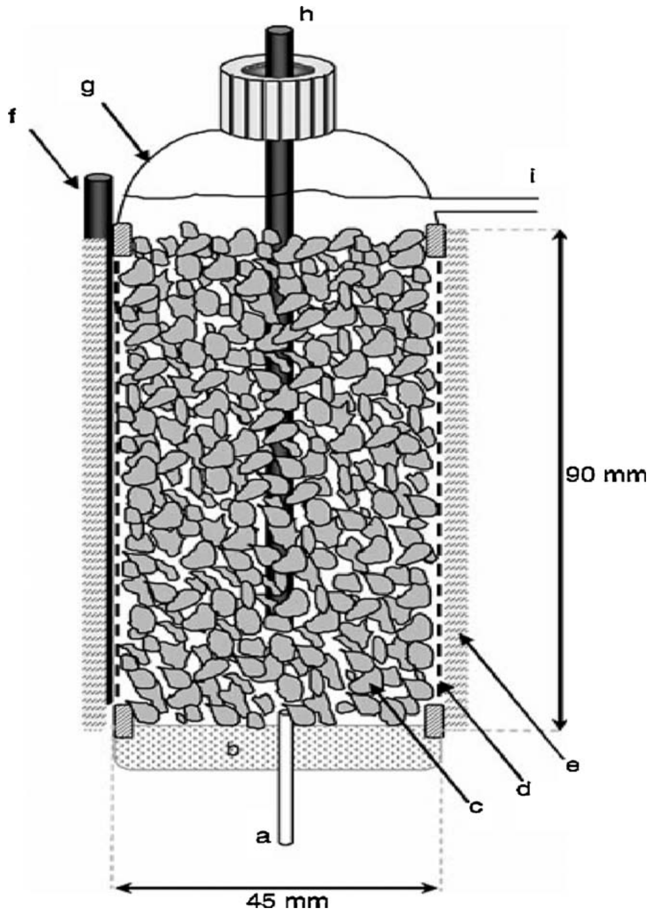

Fig. 4. MFC (microbial fuel cell) overview.

experiment where such equipment—MFC (microbial fuel cell) is built [28] (see Fig. 4).

In the future the development of fuel cell is very exciting since chemical energy can be directly converted into electricity and no intermediaries such as gas/fuel is needed. Thus the efficiency of energy conversion and usage would be very high.

4.2.5. Direct combustion

This is a method known by even the ancient humans. Recently fast-growing algae are collected and dried and then they are burned directly in a power plant to generate electricity. CO_2 would be recycled by pumping back to alga culture tank and this recycling method is feasible since very few waste materials are produced and the only driving force is solar energy fixed by algae [28–30].

5. Advices for the future exploitation of coastal energy plants

First, large industrial base should be established. Small companies are not well organized and cannot afford expensive equipment and technology of biofuel production. Moreover, large-scale plantation lowers the price and makes fuel products more competitive.

Second, plantation of energy plants should refer to local conditions. For example, some places are slight-alkali or saline and sugar beet and *Sorghum dochna var. dochna* should be planted; for moderately saline lands *H. tuberous L* is ideal; for severely alkali or saline land we have to choose *Salicornia bigelovii Torr*, *Tamarix chinensis Lour* or *Achnatherum splendens*. Other environmental factors such as rainfall, temperature, and light should also be considered.

Third, transgenic technology should be properly employed to create more tolerant species that are suitable for all coastal zones in China. And more studies on fuel cell are needed since this field is new and promising.

Fourth, considering the unbalanced distribution, more energy plants should be cultivated in northern China, where cheap labor force and temperate climate are available.

Fifth, government should take some financial measures to encourage people to grow energy plants and subsidize companies to produce more biofuel by policy priority.

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