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Assessment of the technological development and economic potential of photobioreactors

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Abstract

In this paper, we investigate the technological development and economic potential of the photobioreactor (PBR) technology for energy purposes, i.e. production of hydrogen or biofuels. The approach adopted is to consider the technology, its expected costs and revenues, and related risks from an investor perspective. To this end we develop an investment model that is used to calculate the economic feasibility of PBRs for different scenarios, including a best-case scenario, with plenty of sunlight and water, inexpensive nutrients, high prices for hydrogen and biomass, and low other costs. The best-case scenario is compared to a scenario with less favorable boundary conditions. We find that PBR efficiencies will likely be less than 10%, with typical values between 1.8-5.6%. We also find that hydrogen production costs would be lower than those for biodiesel or biogas from solid biomass produced in PBRs. Compared to biofuels from traditional agriculture there is a great advantage for the PBR technology if land is scarce, because land is used more efficiently. Since PBRs can be designed as a closed system they can be applied in very dry regions. In the long term this might enable this promising concept to penetrate the energy supply market.

Key words: photosynthesis; economics; technology; analysis; algae; bioenergy; hydrogen; market forecast; land use

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1. INTRODUCTION

The idea behind photobioreactors (PBRs) is to hold easy-to-handle phototrophic microorganisms, such as algae or cyanobacteria, in a translucent reactor. Phototrophic organisms can supply themselves with energy from sunlight by converting it into chemical energy. In recent years, PBRs have been widely discussed and praised as an innovative energy technology that in the future could also be utilized for commercial energy supply purposes.

In contrast to conventional biomass production in the field, a PBR is essentially a closed system with well-defined interfaces towards the environment. This bears potentials to reduce the ecological impact on the environment and to increase the efficiency of energy conversion. Also, under the influence of solar irradiation, some algae are even able to produce hydrogen from water. Moreover, phototrophic organisms, during photosynthetic activity, consume CO_2, thus enabling the establishment of a local carbon cycle by interconnecting coal-fired power plants with nearby PBR systems. The ability to absorb CO_2 and to produce biomass and hydrogen at the same time is unique and makes PBR an interesting new technology to be investigated further as a future option for power generation systems with reduced CO_2 emissions, despite its currently low conversion efficiency of at best around 6%.

So far, photobiological hydrogen could only be produced in small-scale systems. Because of the hydrogenases' (i.e. enzymes which are responsible for biological hydrogen production) sensitivity to the presence of oxygen, the desirable direct water split into hydrogen and oxygen has not been achieved yet, or only achieved for a short period of time. In our analysis, this approach shall be considered as 1-stage hydrogen production. The current way to face this challenge is to switch the organisms to anaerobic conditions and to induce a 2-stage hydrogen synthesis, in order to avoid large concentrations of oxygen. Unfortunately, this implies that organic cell material is catabolized, which has to be synthesized by photosynthesis in an earlier step and thus results in a loss of efficiency. A recent thermodynamic analysis came to the conclusion that hydrogen-producing PBRs with 2-stage photosynthesis will feature low efficiencies of between 1.8 and 4.1% and those with 1-stage photosynthesis between 2 and 5.6%, whereas biomass-producing PBRs feature 2 to 5.25% (excl. additional processes needed) [42,43].

In this paper, the approach adopted is to consider the technology, its expected costs and revenues, and related risks from an investor perspective. To this end we develop an investment model that is used to calculate the economic feasibility of PBR for different scenarios, including a best-case scenario, with plenty of sunlight and water, inexpensive nutrients, high prices for hydrogen and biomass, and low other costs, that is compared to a scenario with less favorable boundary conditions.

The results from our analysis indicate that the sufficient availability and opportunity cost of land for PBR, the vicinity of large water resources, and the structure of the power generation market are decisive factors for the economic feasibility of PBR systems. We conclude from the analysis that further economic investigations are worthwhile pursuing, especially with regard to the economic consequences of future technological developments.

The remainder of this paper is organized as follows. Section 2 comprises the discussion of inputs and outputs, the analysis of costs and revenues involved and a net present value calculation. Section 3 reports on the profitability analysis of the PBR systems investigated, and Section 4 contains a summary and offers some conclusions.

2. COST AND REVENUE ESTIMATION

In this section the markets for the mentioned input and output factors are analyzed and the expected cash flows of the project are estimated. Especially the development of markets for hydrogen and biomass is of interest here, as these will strongly depend on the development of related technologies such as cost-efficient fuel cells, hydrogen infrastructure and available processes for biomass conversion. On the other hand, the economic availability of water and light is essential and might be a limit for an extensive and profitable use of the PBR technology.

For a comprehensive analysis both the necessary investments for the PBR systems itself and related devices have to be estimated. Energy supply projects are often characterized by high initial capital investments and long lifetimes, depending on the technology, of several decades. Even if a project is expected to be cost-effective, depending on the internal rate of return this often implies patience on the side of investors, or special financing instruments such as contracting. Furthermore, uncertainty plays a significant role in long-term investments. Especially the development of energy markets and prices over the next decades is difficult to predict. It is quite obvious that there will be some dramatic changes, e.g. due to climate policy and peak-oil, but how the large number of alternative technologies will contribute to the solution is quite uncertain.

In this context especially the development of competing renewable energy technologies plays a significant role. The use of solar photovoltaics (PV), concentrating solar thermal and conventional biomass are only a few examples of technologies which convert the power of the sun into commercial energy forms. PV can already achieve energy conversion efficiencies greater than 30% under laboratory conditions [23] and greater than 18% under real conditions [32], while that of photosynthesis, the central process of energy conversion in plants, does not exceed 6% in crops under best conditions [42]. But why to use PBRs if more efficient technologies are already available on the market? This question will be answered by identifying the "economic niche" for PBR systems, i.e. to identify fields of application where PBR systems, in the longer term, could actually crowd out some of the competing technologies for economic reasons.

It might be the case that future PBR systems will simply be less expensive than other systems, but there might be other unique advantages as well. For example, one can already realize that PBR systems can absorb carbon dioxide and produce biomass and hydrogen at the same time. This is a unique property and might be an advantage in comparison with competing technologies.

Nevertheless, the economic calculations conducted here are based on the analysis of expected cash-flows [11]. In the different scenarios considered, profitability is evaluated by regarding the net present values (NPV) for several commercial products *j* (e.g. hydrogen, biomass and possibly absorption of carbon dioxide),

$$NPV = -Inv_0 + \sum_{t=1}^{T} \frac{1}{(1+i)^t} \left\{ \sum_j \left[(p_{j,t} - c_{j,t}) Y_{j,t} \right] - C_t \right\}, \tag{1}$$

where Inv_0 denotes the necessary investment at the project start-up, *i* the interest rate, *p* the price for product *j*, *c* the variable costs of product *j*, and *C* the fixed costs. Quantities are symbolized by *Y*. Appropriate parameter values will be based on the analysis of the technology itself and on the related markets. Thus the NPV method will be picked up in detail again further below.

Achievable output quantities of hydrogen and biomass depend on three factors: reactor size (area *A* in m^2), environmental conditions depending on the location (the local amount of solar irradiation q''_{solar} in MWh per $m^2 \cdot yr$), and technological characteristics of the system (e.g. total reactor efficiency η in %). As a necessary condition for its functionality the availability of water, carbon dioxide and nutrients is of special relevance.

All these factors have to be put into an economic framework. Eq. (1) shall now be adapted for this purpose. The NPV method allows a first statement whether PBR projects might be advantageous for investors. On a perfect capital market an investment would be realized if a positive NPV was achievable at the relevant interest rate [6]. In reality there might be numerous obstacles, e.g. due to capital shortage, risks, different interest rates etc., so that even projects with a positive NPV would not be realized. Nevertheless, we will consider the NPV as a first indicator of profitability.

With $AF_{i,T}$ as annuity factor and the assumption of constant revenues and costs in all periods eq. (1) can be simplified as

$$\begin{aligned} NPV &= -Inv_0 + AF_{i,T} \cdot [(p_H - c_H) \cdot Y_H + (p_B - c_B) \cdot Y_B - C] \\ &= -Inv_0 + AF_{i,T} \cdot [(\overline{\eta}_H \cdot (p_H - c_H) + \overline{\eta}_B \cdot (p_B - c_B)) \cdot q''_{solar} \cdot A - C] \end{aligned} \quad (2)$$

with p_B and p_H as the prices for biomass and hydrogen, respectively, and c_B and c_H as related variable costs, e.g. water and nutrients costs. Fixed costs C comprise those costs that do not causally depend on output quantities, such as operation and maintenance (O&M) costs. The investments Inv_0 will be of special importance, because they occur at the project start-up, which makes their influence on the NPV independent from any temporal preferences.

To estimate the mentioned parameters the related markets have to be analyzed. In this context the influence of experience effects on new markets will be of special interest for evaluating the future development. Especially in undeveloped markets one might expect potentials for significant cost reductions. Particularly these are markets for hydrogen, biomass products, and PBR reactor systems.

A very common approach is to describe the unit cost development as a function of cumulative production. In a double-logarithmic scale the result is often a straight line following the mathematical description

$$log(C_{\mathrm{cum}}) = log(C_0) + m \cdot log(Y_{\mathrm{cum}}) \quad (3)$$

$$PR = 2^m \quad (4)$$

$$LR = 1 - PR \quad (5)$$

with C_{cum} as cost per unit, C_0 as cost of the very first unit produced, Y_{cum} as cumulative production and m as experience parameter. The progress ratio PR measures the rate of cost decline if the cumulative production doubles. Thus the learning rate LR can be defined according to eq. (5). If cost data are not available, price information may serve as a proxy provided that possible estimation errors due to this approach are kept in mind. On a market with perfect competition prices will be equal to marginal production costs. However, especially during the product launch phase, the relationship between prices and costs may be distorted [20].

2.1 Input factors

In this section the above-mentioned input factors light, water, carbon dioxide and nutrients are considered and discussed in turn.

2.1.1 Light

Sunlight as a primary energy carrier and driver of photosynthesis is an essential input factor that deeply influences the capacity *Cap* and output *Y* of a PBR system. Investors can be expected to be interested primarily in areas with high solar irradiation to yield a high return. Furthermore, a temporal correlation between irradiation and demand is advantageous, because this might reduce the necessity of storage. In this context basically the same arguments are valid as for PV. This allows applying the same procedures for the analysis of possible locations.

The average amount of solar radiation that reaches our planet every second, E_{solar}, is about 1,367 W/m^2, defined as the solar constant [32]. The actual amount of irradiation in contrast is very volatile and depends on geographic factors, seasonal factors and weather phenomena. Sunlight itself is a public good and there exists no market. But the illuminated surface on earth is an economic production input factor. Thus it can be justified to treat light as a relevant input factor.

The aim of this section is to identify relevant attributes of different regions and to give ideas how to evaluate them concerning economic aspects. Table 1 depicts significant annual solar irradiation data for different locations. Due to the immense differences in irradiation intensities and their distribution over the year, location decisions are a crucial aspect. Measures that are often applied in this context are the maximum irradiation intensity, $q''_{solar,max}$, the annual amount of irradiation, q''_{solar}, and the intensity of irradiation, ν, which describes the regularity of solar irradiation, with values between zero (completely irregular) and unity (completely regular). It is quite clear that regions close to the equator are characterized by a greater and more continuous supply of sunlight. Furthermore, one realizes that solar irradiation is steadier in regions closer to the equator, expressed by increasing intensities of irradiation, ν.

Table 1: Solar irradiation data for different locations

Location	$q''_{solar,max}$ [W/m^2]	q''_{solar} [kWh/m^2·a]	ν
Bergen (Norway)	-	785	-
Helsinki (Finland)	828	970	0.1338
Stuttgart (Germany)	906	1126	0.1419
Madrid (Spain)	974	1657	0.1943
Lisbon (Portugal)	-	1726	-
Rabat (Morocco)	1010	1837	0.2076
Sahara Desert	-	2350	-

Source: Data generated with the software tool WetSyn developed by Solarenergieförderverein Bayern e.V. and adopted from Quaschning, 2006, p.56

2.1.2 Water

As already mentioned photosynthesis needs water as substantial input factor to produce hydrogen or biomass. It can be considered as a non-substitutable production factor. For an output of one molecule of glucose six molecules of water are needed, and for one molecule of hydrogen one molecule of water. Important performance figures are the necessary amounts of water per energetic unit of output.

The heating value of glucose is H_s = 2,870 kJ/mol. The molar mass of water M_{H_2O} is about 18 g/mol. Thus six mols of water weigh about 0.108 kg. If biomass is considered as glucose, the specific input of water per unit of biomass output, $x_{H_2O,B}$, results in

$$\begin{aligned} x_{H_2O,B} &= \frac{0.108}{2,870} = 37.63 \cdot 10^{-6}\ kg/kJ = 135.47\ kg/MWh \\ &\approx 0.135\ m^3/MWh \end{aligned} . \qquad (6)$$

This formula can be specified for hydrogen analogously, which has a heating value of 285.8 kJ/mol, resulting in $x_{H_2O,H} \approx 0.227$ m^3/MWh. Thus the question of having access to sufficient amounts of water is quite essential and might even be a trade-off concerning the requirement of sufficient solar irradiation. For example, the Sahara region seems to be a very attractive location for its high irradiation intensities, but the lack of water might be a problem.

There are several parameters that determine the importance of this trade-off. Due to the fact that only a low percentage of water on earth is fresh water, the use of marine algae would attenuate this conflict. One can expect that salt water is available even in dry regions. Furthermore, the use of salt water could avoid ecological and ethical problems.

Salt water itself can be considered as a good that is available free of charge. Although the ongoing experiments with *C. reinhardtii* deal with non-marine algae, we can assume that similar results might be achievable with marine algae in the future. In the case of marine algae only costs of transportation and sterilization will be of interest. Sterilization is important to prevent PBR systems from infections and from undesired microorganisms that might reduce the system's efficiency. It is quite clear that locations close to (salt) water reservoirs will be of economic advantage, because the development of water supply infrastructure will be less expensive there.

For the case of fresh water algae water itself causes additional costs. Table 2 represents typical prices for drinking water in different regions of the world to get a first impression. As can be seen, prices for drinking water range widely. Furthermore, price increases are particularly high, and those countries with high amounts of solar irradiation (South Africa, Australia, USA, Italy and Spain) are characterized by high annual increases.

If p_{H_2O} represents the local water price, $c_{H_2O,tp}$ the transportation costs, and $c_{H_2O,treat}$ the costs of sterilization, the variable water costs for product j, c_{j,H_2O}, are given as

$$c_{j,H_2O} = x_{j,H_20} \cdot \left(p_{H_2O} + c_{H_2O,tp} + c_{H2O,treat} \right) . \tag{7}$$

Transportation costs will only be significant if there is no existing water infrastructure. Otherwise one may assume that local prices already include these costs. Based on available estimates from the literature transportation costs for water $c_{H_2O,tp}$ per m^3 are assumed to be around 4.5 €-cents per 100 km of horizontal and 3.8 €-cents per 100 m of vertical transport in the case of a capacity $X^0_{H_2O}$ of 100 million m^3/a[1].

Table 2: Prices for drinking water in different regions of the world

Country	Av.net price [€-ct/m^3]	2006/7 increase [%]	5-yrTrend (03-08) [%]
Germany	231.54	+1.6	+4.4
France	153.54	+0.2	+13.8
Australia	139.62	+18.5	+86.4
Italy	121.38	+4.7	+35.4
Spain	100.62	+9.8	+11.0
S. Africa	78.46	+69.2	+70.0
USA	57.00	+7.2	+29.8

Source: Based on NUS Consulting Group, 2007-2008 International Water Report and Cost Survey, p.4; €1 = US$1.30

[1] Cf. Kaltschmitt, 2001, p.641

To account for different production capacities economies of scale have to be considered. We assume that, in analogy to pipeline transportation, costs just increase by two thirds if the capacity was doubled[2]. This allows the introduction of the following relationship

$$\frac{c_{H_2O,tp}}{c^0_{H_2O,tp}} = \left(\frac{X_{H_2O}}{X^0_{H_2O}}\right)^{\log_2\left(\frac{5}{6}\right)} = \left(\frac{x_{j,H_2O} \cdot \overline{\eta}_j \cdot q''_{solar} \cdot A}{X^0_{H_2O}}\right)^{\log_2\left(\frac{5}{6}\right)}. \tag{8}$$

with x_{j,H_2O} from eq. (6) and the reactor's annual capacity $\overline{\eta}_j \cdot q''_{solar} \cdot A$. In Figure 1 this equation for the transportation costs is plotted over the system's capacity.

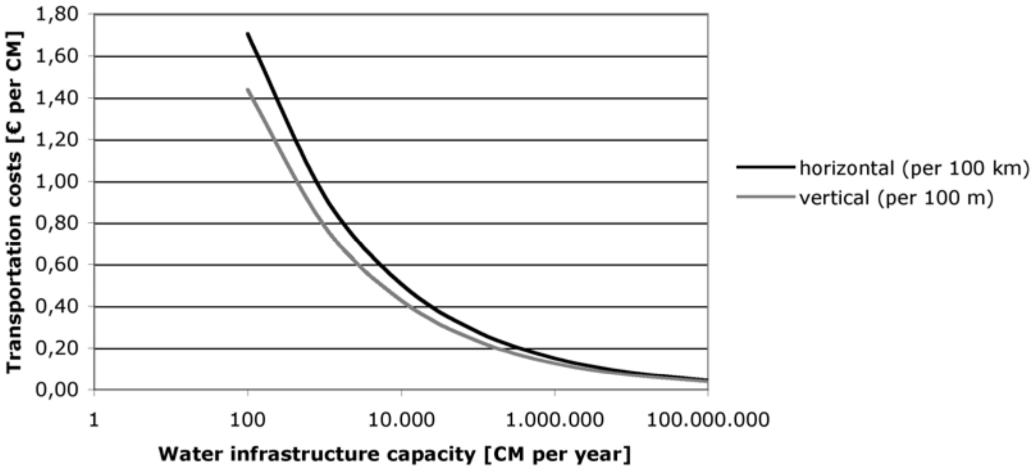


Figure 1: Transportation cost as a function of water infrastructure capacity
Source: Own illustration

To get a first impression of the water capacity needed one realizes easily from eq. (8) that for systems of one km^2, an efficiency of about 5%, and solar irradiation between 1000 and 2000 kWh per m^2 will be in the range of 10,000 to 20,000 m^3 per year, much less than 100 million m^3. Thus costs for horizontal and vertical transportation would probably be between 0.30 and 0.60 € per m^3. Regarding x_{H_2O}, one might expect values between 0.04 and 0.08 € per MWh in the case of biomass, and values between 0.07 and 0.14 € per MWh in the case of hydrogen, each per 100 km of horizontal transport or 100 m of vertical transport.

For water treatment costs, $c_{H_2O,treat}$, there were no precise data available. But in the mentioned literature costs for cleaning and desalinating water are indicated as low as 1 $ per m^3, in the case of

[2] Cf. Erdmann and Zweifel, 2008, p.227

brackish water even as low as 0.6 $ per m^3. Thus it will be assumed in this context that $c_{H_2O,treat}$ will be around 0.5 € per m^3 and in the case of marine algae even lower.

2.1.3 Carbon dioxide

Carbon as the central chemical element in organic matter usually comes from atmospheric CO_2 as it was pointed out in the discussion on photosynthesis above. Furthermore, one could identify a determined relation between biomass output and CO_2 consumption. Because hydrogen does not contain any carbon, the specific input of carbon dioxide is zero, but both alternatives, biomass and hydrogen, are CO_2 neutral if utilized as combustible in energy conversion processes. There might be chances to participate in greenhouse gas emissions trading, because biomass and hydrogen can substitute for fossil fuels and thus reduce CO_2 emissions in a sustainable way.

The amount of emission reductions will depend on the emission factor x_{subst} of the substituted fuel, and not the emission factor of the replacing CO_2-neutral fuel. For some typical fossil fuels this value is indicated in Table 3.

Table 3: Emission factors and values for different combustibles

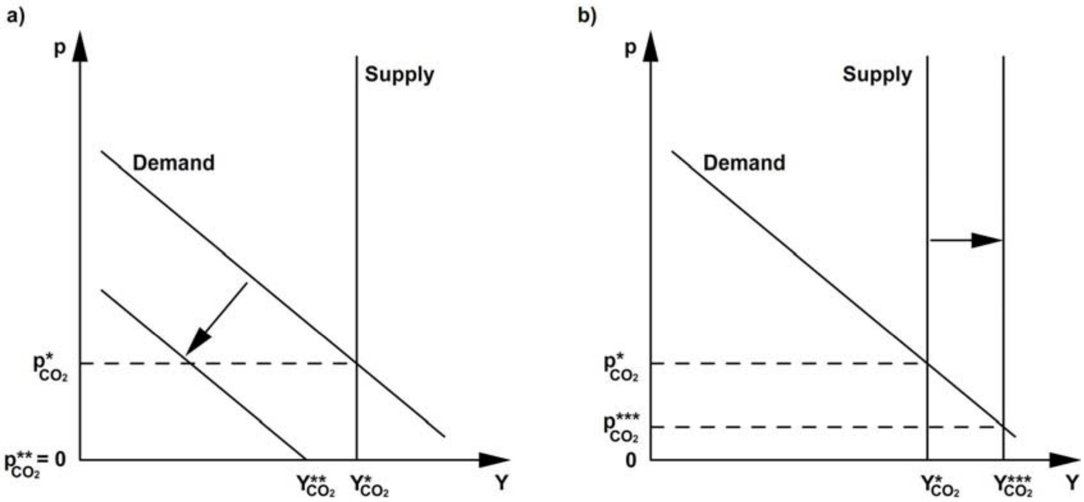
Fuel	Emission factor x_{subst} [kgCO_2/MWh]	x_{subst}·15 €/tCO_2 [€/MWh]
Nat. gas	201.6	3.03
Lignite	399.6	5.99
Gasoline	≈250.0	≈3.75

Source: Adapted from Lucas, 2006, p.137f

Each unit of biomass produced would create further revenues of about $x_{subst} \cdot p_{CO_2}$. The last column of Table 3 indicates unit revenues per MWh if p_{CO_2} is assumed to be 15 € per ton. Furthermore, it becomes quite clear that the revenues strongly depend on the emission factor of the substituted fuel. These thoughts may be applied to both, hydrogen and biomass, although hydrogen does not contain any carbon.

A central question is whether this might be a sustainable source of income or whether this might only be a temporal phenomenon. Development of prices for CO_2 emission allowances in 2005-2007 were highly fluctuating, and in 2006 it became more and more obvious that there would be less CO_2 emissions in the EU than tradable allowances. This effect caused allowance prices to deteriorate and finally made allowances temporarily worthless [36].

Figure 2 describes the pricing mechanisms for emission permits. The supply curve for a specified trading period is fixed and results from governmental decisions. This way, governments define an upper limit for greenhouse gas emissions. The equilibrium price, $p_{CO_2}^*$, would be at the intersection of the supply and the demand curve while the demand curve is determined by the marginal utility of producing CO_2. Declines in demand or increases in supply will lead to lower prices and vice versa.



(a) Decrease in demand (b) Increase in supply

Figure 2: Market for emission permits

Source: Own illustration

Even prices close to zero are possible as described above. One realizes that prices strongly depend on the political goals, which eventually define the supply curve. On the other hand, developments on the demand side have a great influence as well. Presumably the demand curve is highly correlated with the demand curve for fossil fuels. This is quite an important aspect, because if technologies like PBR reactors or others were capable of producing cost-efficient substitutes for fossil fuels their existence might reduce the demand for fossil fuels. Thus also the demand curve for emission allowances would be lower as shown in Case (a). This means that the availability of competitive green energy technologies could suppress this potential source of income. Of course one might argue that governments would then decrease the quantity of emission allowances for the next trading period, but this underlines the dependency on political goals. Also, these political goals will be influenced by future scientific research on global warming due to greenhouse gases.

Directly feeding CO_2 from smoke stacks into PBR reactors would be advantageous, because industrial exhaust gases, compared to air, contain large amounts of this gas. Greater concentrations can support photosynthesis activity and thus optimize the systems' efficiency [18]. Furthermore, the warm gases can serve to control the system’s temperature. Moreover, it is obvious that there are no good economic reasons for using CO_2 from smoke stacks, but only technological ones.

2.1.4 Nutrients

Nutrients are inorganic matter that is essential for plant growth. Besides of carbon, hydrogen and oxygen these are basically nitrogen, potassium, calcium, phosphor, magnesium and sulphur. They are essential, because biological molecules do not only consist of carbon and water. By assimilation processes, as they have already been described above, inorganic nutrients are converted into organic compounds and become part of the organisms' biomass. The energy necessary for this assimilation generally comes from respiration activities, an issue that has already been discussed above, too. The essential remaining question is what quantities of nutrients will be necessary to run the reactor, because they might incur significant costs.

In a closed system nutrients only have to be substituted if nutrient containing substances leave the system. Thus it becomes quite clear that escaping hydrogen gas will not make nutrient input necessary. In the case of biomass this is different. Dry biomass consists of about 96% of carbon, oxygen and hydrogen[3]. This means that only about 4% of biomass output are composed of said further elements.

A possibility of nutrient supply is the utilization of fertilizers. Internet research allowed us to estimate fertilizer prices p_{nut} at around 250 \$ per ton [29]. If €1 is assumed to equal \$1.30 and if the heating value of biomass is assumed to be equal to that of glucose (H_s = 2,870 kJ/mol, M_{glucose} = 180 g/mol), then nutrient costs c_{nut} can be estimated as:

$$c_{nut} = x_{nut} \cdot p_{nut} \approx \frac{0.04 \cdot 0.180\text{kg/mol}}{2{,}870\text{kJ/mol}} \cdot 250\$ \cdot 1.30^{-1} Ū/\$$$

$$= 0.482 \text{ €/MJ} = 1.74 \text{ €/MWh} . \qquad (9)$$

Smoke stacks could be a further source of nitrogen. The toxic oxidized forms NO_x in exhaust gas can be assimilated by algae species. This way also the investment into denox devices for cleaning smoke gases from power plants could be saved. The remaining amount of necessary elements would have to be added in other forms. Since fuels usually consist of carbon, hydrogen, and partially oxygen, and not of the further elements mentioned above, it might be possible to establish a nutrient cycle that leads to comparatively low nutrient costs.

[3] Cf. Kaltschmitt et al., 2001, p.37

2.2 Output factors

In this section we discuss the relevance of the output factors biomass and hydrogen.

2.2.1 Biomass

Biomass has been identified as one of the central output factors of PBR systems. It is known that biomass is not a homogeneous substance like most common fossil fuels. Furthermore, it has to be separated from great amounts of water which would make its use as a fuel difficult or even impossible. Thus it is necessary to convert it into utilizable and standardized energy carriers, such as ethanol, biodiesel or biogas, which are capable of substituting significant amounts of conventional energy carriers. This implies that products from biomass have to compete with these fuels on economic grounds.

Studies on the development of the energy markets forecast that fossil fuels will still play a significant role in the future, even after the year 2030 [7]. This justifies assuming exogenous prices for products from PBR systems in the mid-term. The role of fossil fuels in the long-term crucially depends on the development of energy from biomass.

If biofuels can be produced at large scale and at low prices they might dampen fossil fuel prices. But even if biofuels could not be produced at competitive prices the existence of innovative technologies, such as PBR systems, might establish a new backstop price for fossil fuels what might be an effective threat against oil cartels and their pricing policy.

For the following estimations we assume that similar energy carriers can be compared by their energetic value (e.g. ethanol and biodiesel with gasoline or biogas with natural gas). Sometimes, however, there are special reasons not to do so, e.g. in the case of emission trading or further known differences which might lead to different prices for energetically equivalent fuels. Because biomass has to be converted into standardized energy carriers, costs and energy losses due to these processes are of special interest. To include these effects in the calculation model an energetic process efficiency $\eta_{\text{post},j}$, and additional variable costs for processing and distribution, $c_{\text{post},j}$, shall be introduced. That means for a certain biomass output Y_B the resulting commercial amount Y_j of product j is be given by

$$Y_j = \eta_{post,j} \cdot Y_B = \eta_{post,j} \cdot \overline{\eta}_B \cdot q''_{solar} \cdot A$$
$$=: \overline{\eta}_j \cdot q''_{solar} \cdot A \qquad (10)$$

This allows, in analogy to the derivation of the technological models, the introduction of a new measure $\overline{\eta}_j$ that characterizes the overall process efficiency. So far, estimations of variable costs have been related to biomass production, but not to final products. Thus the variable costs for final product *j* have to be adopted as:

$$c_j = c_{post,j} - \frac{c_B}{\eta_{post,j}}. \qquad (11)$$

In the literature there are different approaches to convert biomass into commercial energy carriers. One option has already been identified by regarding the 2-stage photosynthesis which converts biomass into gaseous hydrogen. In the following, different approaches are listed:

In the case of gasification, biomass can be converted into biogas (a mixture of methane and CO_2) that still contains about 90% of the original energetic value[4]. Data on the Danish biogas production from biomass show that marginal processing costs are quite stable on a level since 1991 of around 0.30 € per dry cubic meter under standard conditions (approximately 22 MJ of energy) (4). This corresponds to 49.1 € per MWh of biogas. Due to the high percentage of CO_2 (25-50%) the heating value of biogas is lower than that of natural gas.

Nevertheless, it can serve as a substitute for the above-mentioned fossil energy carrier[5]. Algae oil for biodiesel can be extracted if algae are switched to anaerobiosis. Then up to 70% of algae mass can be converted into oil [33]. A study on Fischer-Tropsch fuels indicates processing costs from biomass to biodiesel of about 39.6 € per MWh of biodiesel in 2010 and of about 25.2 € per MWh in 2030[6].

Algae strains for ethanol production are also in the focus of discussion. In that case sugar and starch are converted via fermentation [8]. Experiences with ethanol from US corn and Brazilian sugar cane show that ethanol yields per unit of biomass input vary significantly. Thus it does not seem to be meaningful to utilize these data for further estimations.

If the considered fuels are not consumed close to the PBR system distribution costs will be a further factor of interest. Existing infrastructure could be used. In analogy to investments in water infrastructure, investments in product infrastructure will be necessary in the case of systems that are not in the range of existing infrastructure access points.

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[4] Cf. Junginger et al., 2006, p.4036
[5] Cf. Erdmann and Zweifel, 2008, p.223
[6] Cf. Junginger et al., 2008, p.86

In the case of gaseous energy carriers, comparable with natural gas via pipelines, one may assume costs of about 30 $ per ton of oil equivalent (toe) and 1000 km in the case of liquid fuels, comparable with oil, one may expect costs around 2 $ per t.o.e. and 1,000 km[7]. Knowing that one toe equals 11.6 MWh and assuming again an exchange rate of €1 to be equal to $1.30, unit costs of €1.99 for gas and €0.13 for liquids result, each per MWh and a transportation distance of 1000 km.

Depending on the applied technology (pipeline, LNG, ships) and due to different characteristics of the considered energy carriers (e.g. lower volumetric heating value in the case of biogas) there might be differences, but the great advantage of liquid energy carriers becomes quite clear in this context. Thus the production of liquid fuels will be the more advantageous the larger the distance between production and consumption is.

2.2.2 Hydrogen

Under the mentioned circumstances PBR systems are able to produce hydrogen which is often in the focus of discussion as a promising energy carrier of the future. For this reason there is a necessity to regard the possible development of future hydrogen markets separately. The development of hydrogen-producing PBR systems will strongly depend on the development of hydrogen infrastructure and available technologies on the consumer side (e.g fuel cells), and vice versa. Today, hydrogen is usually produced by steam reforming from fossil fuels and basically used in chemical industry branches (e.g. ammonium synthesis) close to the location of production. Current annual production worldwide is only about 120 million tons per year[8].

A large-scale infrastructure for hydrogen does not exist yet and is still laden with problems. A study of process chains in a future hydrogen economy identified unresolved problems in hydrogen production and distribution even in the long term. According to the analysis, a distribution network similar to natural gas via pipelines would be the favorable solution for hydrogen transport in comparison to other hydrogen infrastructure options [38].

Another study came to a similar conclusion, favoring pipeline distribution in large-scale scenarios and compressed gas trucks in the low-scale. Liquified hydrogen seems to be much more expensive [30]. A central problem is the low volumetric heating value, a value that, beside others, characterizes the transportation capacity of pipelines. Under standardized conditions (T = 273.15 K, p = 1013 mbar) the heating value of natural gas is $H_{s,NG} \approx 41$ MJ/m^3 and that of hydrogen $H_{s,H2}$ = 12.75 MJ/m^3, i.e. only 31% of that of natural gas. If both gases are assumed to be ideal gases this

[7] Cf. Erdmann and Zweifel, 2008, p.233

[8] Cf. ibid, 2008, p.225

relation will be the same at greater pressures as they occur in pipelines. Thus if existing pipelines were applied for this purpose one would expect higher transportation costs in the case of hydrogen if similar kinetics in pipelines are assumed. Furthermore, because of the widespread flammability and explosive limits of hydrogen, safety devices will be necessary[9].

Such a hydrogen infrastructure with decentralized electricity production by fuel cells is often propagated as energy supply concept of the future, a view which is not shared by the authors of this paper, because such an infrastructure does not exist yet and it is extremely uncertain whether it will really develop in such a dominant way. Beside the hydrogen option there are further possible strategies in the focus of research. An example is the Cluster of Excellence on "Tailor-Made Fuels from Biomass" at RWTH Aachen University, whose goal is to identify liquid fuels from biomass as a future energy carrier especially for the transportation sector[10]. Further studies propagate an energy economy dominated by electricity [4]. This is just to point out that a hydrogen-dominated energy economy is not predestined, but just one of many possible future options.

At this point some general thoughts about the possible development of hydrogen markets are provided, by regarding conditions for such a development. Due to the laws of thermodynamics, energy forms can be converted into each other if a certain amount of losses due to dissipation is accepted and is also applicable to carriers of final energy. From an economic point of view this means that carriers of final energy can be considered as substitutes within technological and physical constraints. In today's energy economy electricity and derivatives of fossil fuels can be identified as the most common carriers of final energy. Both forms have their specific fields of application due to available and cost-effective technologies. It is quite clear that a hydrogen infrastructure will only develop if economic advantages can be identified in comparison with other available infrastructures.

This includes the process of hydrogen production from primary energy, the processes of storing and transportation and the number of available consumer technologies compatible with hydrogen. The process chains from primary energy to final energy are characterized by typical costs and efficiencies. The overall efficiency is given by multiplying all partial efficiencies. This implies that efficient partial processes cannot outweigh inefficient ones. Low cost fuel cells with efficiencies close to 100% would not penetrate into the market if there was not an efficient technology of hydrogen supply, and vice versa. Thus an efficient hydrogen production technology, such as PBR systems might be, makes a hydrogen infrastructure more attractive, but is not the only determinant

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[9] Cf. Erdmann and Zweifel, 2008, p.225
[10] Cf. Institute for Combustion Engines (VKA) of RWTH Aachen University, accessed: 12 November 2008, http://www.vka.rwth-aachen.de/tmf/Englisch/Index e.htm

of future development.

Nevertheless, an approach for the determination of revenues from produced hydrogen must be found. For this purpose the notion of factor mobility is utilized. In the short- and medium-term, hydrogen can be considered as a substitute for natural gas and thus we can use the same arguments as they were pointed out in the context of biomass.

In the long term one may assume that hydrogen prices will always be lower than those of electricity. This assumption can be justified, because even if there were efficient and cheap fuel cells on the market one would always receive a lower energetic amount of electricity.

Under some circumstances this assumption might be wrong, if heat from fuel cells was used for indoor climate applications at the same time. With today's technology hydrogen could power combined-cycle gas turbine (CCGT) power plants, which are characterized by high efficiencies of about 60%, possibly even reaching 65% within the next years, and specific capital costs c_{CCGT} between 9.8 and 12.6 € per MWh_{el}[11].

CCGT power plants do already exist and are usually powered by natural gas. Technological and economic performance figures are known quite well. A hydrogen-producing PBR system could be linked with such a power plant and produce electricity. Thus it is quite easy to estimate revenues for hydrogen produced in PBR. The CCGT technology was chosen, because there is no other thermal process that provides electricity in such an efficient way. Furthermore, costs of capital are comparatively low [3].

We assume an efficient hydrogen fuel cell technology; hydrogen would have to be transported to consumers. As pointed out above, transportation costs will be greater than in the case of other gaseous energy carriers, because under similar conditions hydrogen has a comparatively low volumetric heating value and thus decreases the energetic transportation capacity of pipelines. If it is assumed that, under the same conditions, hydrogen pipelines only transport 31% compared to the case of natural gas, and that all costs remain constant transportation costs of about 6.42 € per MWh and 1000 km of distance may be assumed, based on the value €1.99 for natural gas identified above.

2.3 Investment cost

Investments that have to be made at the project start-up are of great importance for the profitability of PBR. Since they have to be made in the very first period, every increase of

[11] Costs between 4.9 and 6.3 Rp/kWh, assuming an exchange rate of 1:50 CHF/€ and that 70% are due to fuel costs that must be subtracted in this case. Cf. Axpo, accessed: 22 October 2008, http://www.axpo.ch/internet/axpo/de/medien/perspektiven/stromerzeugung/gaskombikraftwerk.html

investments will decrease the net present value by the same amount.

In the context of the technological analysis it could be shown that outputs are proportional to the systems' size A and that it is the amount of solar irradiation shining on that surface which is responsible for photosynthetic activity. The consequence is that doubling of the capacity implies doubling the required surface area and thus also doubling the reactor material. Economies of scale concerning investments may only be expected in devices that can be centralized such as control units and linking infrastructure.

A first approach shall be the consideration of already available PBR systems. The Dutch company AlgaeLink N.V. offers modular algae cultivation systems of 300 and 1200 m^2. On their website prices of €144,000 and €194,000 are listed for complete systems, including the reactor tubes, control units and necessary storages[12]. Although these prices do not necessarily represent marginal costs and do not contain any information about future cost declines they can still serve for a first estimation. If investments are assumed to consist of a fixed value Inv_{fix} and a area-related value, $Inv_{\text{A}} \cdot A$, the following system of linear equations allows an estimation of these parameters:

$$144,000 = Inv_{\text{fix}} + Inv_{\text{A}} \cdot 300 \quad (12)$$

$$194,000 = Inv_{\text{fix}} + Inv_{\text{A}} \cdot 1200 \quad (13)$$

$$\Rightarrow Inv_A = 55.6 \text{ €/m}^2 \text{ and } Inv_{fix} = \text{€}127,333 \quad (14)$$

In the following, PBR investments shall be considered in detail. For this reason, investments shall be distinguished by their expected correlation with the system's size. Assumptions concerning this categorization are indicated in Table 4. The assumptions made might seem quite bold, but will be justified later.

Table 4: Investment categories and assumed correlations with system size

Investment	Correlation with system size
Reactor material	Linear (positively)
Infrastructure	Economies of scale (degressive)
Land	Linear (positively)

Source: Own data

[12] Cf. AlgaeLink N.V., accessed: 2 Dec 2008, http://www.algaelink.com/commercial-cultivation-plants.htm

2.3.1 Reactor material

PBR systems basically consist of translucent containments. There are different translucent materials available on the market. Possible solutions might be glass or different types of plastic. It is quite clear that the necessary amount of these materials depends on the system size. A reactor that is double in size will probably need the double amount of material if the same technology is applied. Furthermore, geometric attributes, such as thickness and shape, will play a significant role. Nevertheless, it makes sense to introduce material costs as a function of the reactor size (approximated by its area A), $C_{mat}(A)$, and area-specific costs, $c''_{mat} = C_{mat}/A$.

Thus the central issue is to identify realistic values for specific material costs. Prices for low-temperature solar thermal collectors might serve for a first estimation, because many constructional aspects are quite similar. Water is pumped through pipes wherein it is warmed up by solar irradiation. Processes in PBR systems are very different, but the construction itself is probably comparable. Thus without having better knowledge this assumption will be made in our analysis. Figure 3 shows how the prices for these collectors developed over the aggregated shipments in the US from 1998-2007 and allows a first estimation of c''_{mat}.

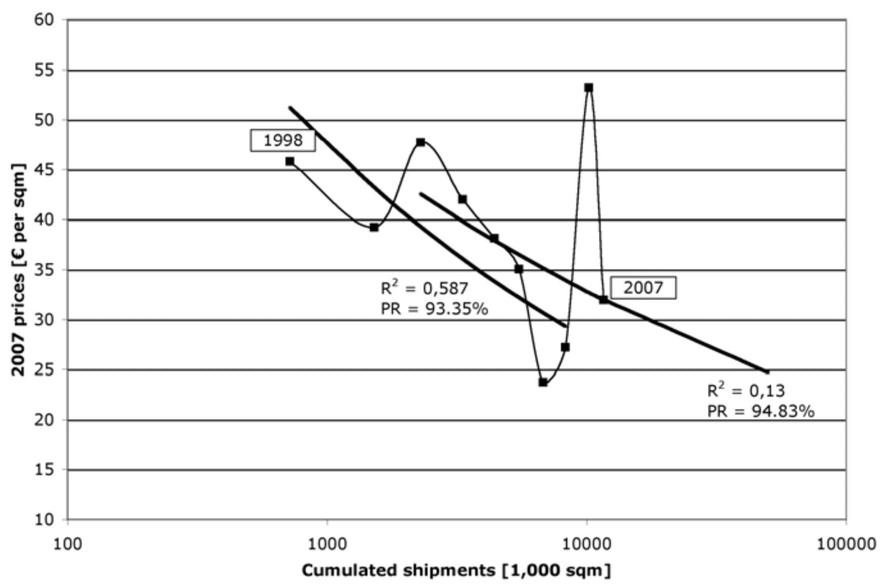


Figure 3: Learning curves for solar thermal collectors in the US

Source: Adapted from EIA, accessed: 22 Nov 2008, http://www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/solar.html

To allow easier calculations prices have been converted from dollars per square foot into € per m^2. Although the trend lines only approximate the real price development very roughly one can identify a price decline. Progress ratios of about 93 to 95% are in the upper range compared to other modular technologies[13]. That means that price declines due to experience effects are assumed conservatively in the considered time interval.

2.3.2 Infrastructure

The term infrastructure shall contain all further devices necessary to run a PBR system, including devices for the yield collection, control units and infrastructure to link the systems with the surrounding infrastructure. For this reason internal devices (to run the processes in PBR systems) and external devices (that are to connect PBR systems with the environment) will be distinguished. Internal infrastructure will basically consist of devices to control growth and to collect yields.

Investments in control systems are necessary, because inside PBR systems many parameters have to be controlled to ensure optimal physiological conditions [2]. Examples are the pH-value and temperature. Furthermore, the mentioned processes of switching algae to anaerobiosis and of gathering products could be executed and controlled automatically. A question of great importance in this context is whether it might be advantageous to develop modularized or centralized systems. Modularized systems would consist of numerous, basically identical systems. Each module would have to be connected with the external infrastructure separately and would require an independent control unit. Due to the modularization concept these control units could be standardized and thus R&D costs could be shared. Centralized systems would only require one control unit and one connection with external infrastructure, but one might expect this control unit not to be a standardized solution. An advantage in lower infrastructure costs would have to be paid by higher R&D costs.

The AlgaeLink system mentioned above contains a control unit beside the reactor material. If we assume that the fixed investment cost Inv_{fix} of €127,333 can be considered as investment in the automation control unit this value would represent a first approximation. In the following, external infrastructure will be considered which will basically consist of (1) Water supply infrastructure (e.g. pipelines); (2) Linkage with carbon dioxide and nitrogen sources; and (3) Product infrastructure (e.g. pipelines for gases or liquids, storages).

Depending on the location these infrastructure costs may vary significantly, but it is possible to identify determinants. Since PBR reactors need great amounts of water, investments into water infrastructure will not be avoidable. Accordingly, costs including variable and capital costs have already been introduced as costs of water transportation and treatment in the section on water. It is

[13] Cf. Junginger et al., 2008, p.33

quite clear that these investments will increase the greater the distance from available water sources is. Especially the influence of height differences could be shown there. Summing up, these investments will be comparatively low in coastal regions.

Similar arguments are valid for carbon dioxide. If it cannot be taken from smoke stacks other technologies have to be applied in order to enrich water with this gas, or suboptimal conditions for algae growth have to be accepted. Product infrastructure has also been discussed in the subsections on biomass and hydrogen by introducing specific transportation costs for liquid and gaseous fuels (cf. section 2.2).

2.3.3 Land

Evaluating the development of land prices seems to be quite a difficult task. Of course, the area needed for a PBR system depends on its size and thus this question is of great importance. In regions that are characterized by agriculture, industry, settlements or further human activities prices of land can usually be considered as a value driven by scarcity. This can be very different in other regions where this is not the case. One example might be the Sahara region which is widely non-utilized by humans today because of unfriendly environmental conditions. Thus costs for land could be assumed to be very low. But especially these regions seem to be interesting for solar energy systems due to the high levels of solar irradiation. If investors of such solar systems expect greater net present values in said regions, they would be willing to pay a premium (relative to PBR investments) for occupying land there, which might lead to increasing prices for land.

But how can these prices be estimated? For these reasons some assumptions have to be made. Land that will be considered in this context is not cultivated by humans yet in any way, because of missing economic attractiveness. As mentioned above such landscapes do exist and are particularly interesting for PBR systems, but probably for PV or similar technologies as well. This implies that the existence of those technologies originally creates and determines the economic value for investors of land utilization which will depend on its productivity. Productivity will strongly depend on solar irradiation and on the technology itself. Furthermore, one can assume that investors would only pay for land utilization if they expected a project to be profitable.

Based on these thoughts characteristics of the demand curve for land shall be considered. If exogenous prices and variable costs are assumed the change in the net present value, $dNPV_k$, will result in:

$$dNPV_k = -dInv_{0,k} + AF_{i,T} \cdot [(p_k - c_k) \cdot dY_k - dC_k]. \qquad (15)$$

Basically this increase of NPV_k will depend on three factors:

(1) further investments for land acquisition, material costs and infrastructure:

$$dInv_{0,k} = (p_{A,k} + c''_{mat,k})dA + dC_{is,k}; \qquad (16)$$

(2) further net revenue from additional outputs

$$(p_k - c_k) \cdot dY_k = (p_k - c_k) \cdot \overline{\eta}_k \cdot q''_{solar} \cdot dA\text{; and} \qquad (17)$$

(3) further fixed costs (e.g. O&M).

Additional land dA for technology k would be acquired up to the point where the increase in the project's net present value, $dNPV_k$, reaches zero. Thus the maximum price $p_{A,k}$ that would be paid by investors in technology k can be derived as:

$$p_{A,k} = AF_{i,T}[(p_k - c_k) \cdot \overline{\eta}_k \cdot q''_{solar} \cdot dA - \frac{dC_k}{dA}] - c''_{mat,k} - \frac{dC_{is,k}}{dA}. \qquad (18)$$

On the demand side, we can identify the following important determinants for the price of land:

- *Environmental characteristics*: greater amounts of irradiation q''_{solar} lead to higher prices.
- *Geographic characteristics*: increasing costs for infrastructure $C_{\mathrm{is},k}$ will result in decreasing land prices. There might be significant differences between technologies. PBR systems need a water source what will make infrastructure investments increase the further away from water the location is situated, a characteristic that is not shared for example with PV.
- *Technological characteristics*: greater efficiencies $\overline{\eta}_k$, greater net revenues ($p_k - c_k$) and lower land-specific investments $c''_{\mathrm{mat},k}$ lead to increasing prices. Of course, also in this context one may expect differences between technologies. Furthermore, technological characteristics do determine the importance of geographic influences as it was shown by the PBR system dependency on water sources.

In the following, these thoughts shall be applied to the specific characteristics of PBR systems and PV as examples of two competing solar energy technologies. To this end, based on our assumptions, the main differences between both technologies are pointed out in Table 5.

Table 5: Assumed characteristics of PBR and PV systems

Variable	PBR vs. PV	Comment
System investment	$c''_{mat,PBR} < c''_{mat,PV}$	
Infrastructure investment	$dC_{is,PBR} > dC_{is,PV}$	PBR: distance from sources ↑ $\Rightarrow dC_{is,PBR}$ ↑
Product prices	$p_{PBR} < p_{PV}$	
Variable costs	$c_{PBR} > c_{PV}$	
Efficiency	$\overline{\eta}_{PBR} \approx \overline{\eta}_{PV}$	
Fixed costs	$dC_{PBR} > dC_{PV}$	

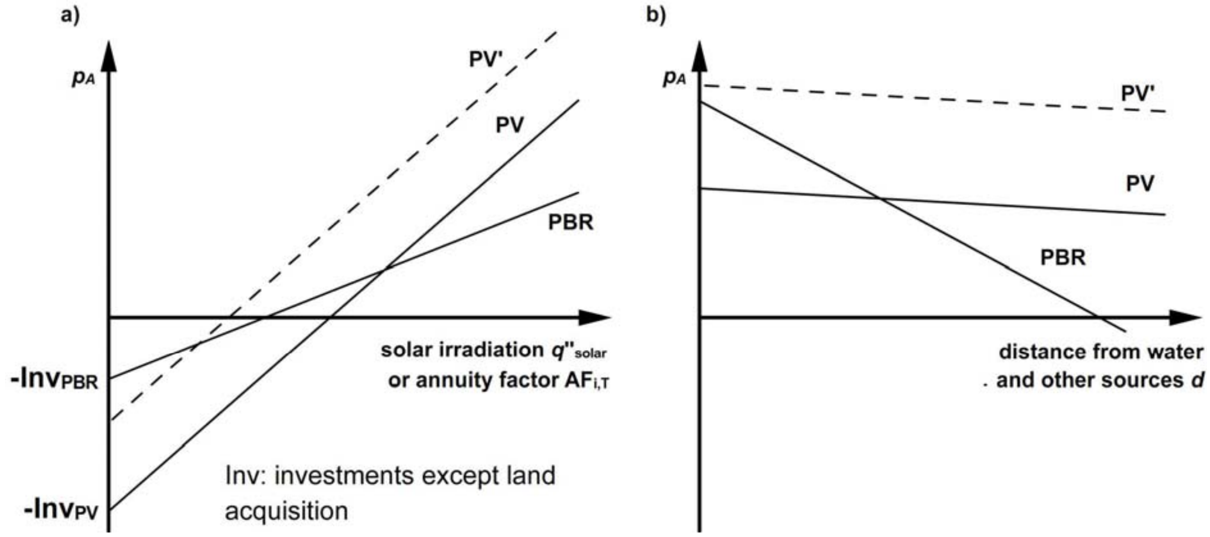
Source: Own data

Figure 4 shows the consequences of the assumptions made on reservation prices. Since net revenues (p - c) of PV systems have been assumed to be greater than those of PBR systems, it is quite clear that the slope of the PV reservation price subject to solar irradiation will be greater as well. Furthermore, we assume that specific investments for PV systems are comparatively large. From Figure 4(a) it becomes quite clear that, due to these assumptions, one can identify an intersection point where PV outpaces PBR technology. This intersection point can either be on the positive (straight line) or the negative (dashed line) side of the land price axis. The former would lead to an interval where PBR reservation prices are greater than those of PV which would lead to a preferred realization of PBR systems.

It might be possible that said intersection point was characterized by irradiation amounts greater than they occur on earth. Under these circumstances PBR systems would always be more profitable. In the second case (dashed line) PV would outpace PBR technology in every potentially profitable scenario ($pA > 0$).

Eq. (18) makes clear that an increase of the annuity factor $AF_{i,T}$, i.e. a stronger weighting of future cash flows, leads to qualitatively similar consequences as those identified for solar irradiation.

Figure 4(b) shows the influence of a system's distance from necessary production inputs, such as water for PBR systems. It was assumed that PBR systems are more sensitive in this respect than PV systems. The consequence is that PBR systems are more advantageous if they are located close to water and further sources. If infrastructure investments exceeded the advantage of lower area-related investments, PBR systems would lose in terms of its relative advantage.



(a) Influence of annual solar irradiation and of discounting (b) Influence of infrastructure investments

Figure 4: Consequences for reservation prices of land

Source: Own illustration

In the following, land supply shall be considered. The rights to utilize these landscapes shall be owned by economic subjects, e.g. the states in the region who would try to achieve possibly high profits from transferring property rights to investors. This might either be in the form of selling land to investors or in the form of taxes or rents. Let us now assume the first case. The only relevant cost of transferred rights from the owners' point of view is the loss of the option of trading them at a later point in time. This might be of relevance if technological change allowed greater earnings in the future.

Another influencing factor is the behavior of suppliers, whether they act in a monopolistic or a more competitive market environment. It might be possible that countries in warmer regions form a cartel by limiting the quantity of offered rights for land utilization.

2.4 O&M costs

Unfortunately, there were no data on O&M costs available to us, but it is quite clear that they might play a significant role. For this reason expert opinions have to be considered. Based on data from the literature and on expert opinions, Junginger et al. estimated annual O&M costs $C_{o\&m}$ to consist of 2% of investment cost and further variable costs $c_{o\&m}$ of 2 € per MWh output in the case of biofuel technologies[14]. This 2% assumption is adopted here for simplicity and due to the lack of better data.

[14] Cf. Junginger et al., 2006, p.4031

3. PROFITABILITY ANALYSIS

Based on our thoughts on market developments and technological aspects we now analyze the expected profitability of PBR systems. By using scenario analysis, we also investigate whether hydrogen or other biomass products may have greater economic merits, and how competitive PBRs can be expected to be relative to other renewable and non-renewable energy technologies.

3.1 Hydrogen and biomass production costs

In this section prices at which products from PBR systems could be sold profitably shall be estimated. The NPV of a single product PBR system will be set to zero for this reason. Then the price p_j, which will be considered as benchmark for comparisons, can be calculated as follows

$$NPV = -Inv_0 + AF_{i,T} \cdot [\overline{\eta}_j \cdot (p_j - c_j) \cdot q''_{solar} \cdot A - C] = 0 \tag{19}$$

$$\Rightarrow p_j = \frac{AF_{i,T}^{-1} \cdot Inv_0 + C}{\overline{\eta}_j \cdot q''_{solar} \cdot A} + c_j \tag{20}$$

For the following calculations PBR system lifetime T will be assumed to be 30 years and the interest rate i to be 10%. Then the annuity factor $AF_{i,T}$ results in

$$AF_{10\%,30a} = 9.42691 \Leftrightarrow AF_{10\%,30a}^{-1} = 0.10608. \tag{21}$$

Investments consist of expenditures for the reactor material, infrastructure and control systems. Costs for land use shall be excluded at this point. If further annual fixed costs C are assumed to be 2% of the investment sum Inv_0, eq. (20) can be simplified as follows:

$$\begin{aligned} p_j &= \frac{0.10608 \cdot Inv_0 + 0.02 \cdot Inv_0}{\overline{\eta}_j \cdot q''_{solar} \cdot A} + c_j \\ &= \frac{0.12608}{\overline{\eta}_j \cdot q''_{solar}} \cdot \frac{Inv_0}{A} + c_j . \end{aligned} \tag{22}$$

As a first step PBR systems in optimal environments are analyzed. Optimal means that all resources that have been identified in the preceding sections shall be available at best conditions. Water does not have to be transported, CO_2 and nitrogen come from smoke stacks, and products do not have to be transported neither.

Table 6 shows the values for this scenario which are based on the preceding thoughts. For this first consideration the more conservative estimates concerning costs and investments have been chosen. The first two subtables contain the very basic parameters as they have been identified in the preceding sections. Furthermore, the other two subtables contain the derived variables which are compatible with eq. (22). In Figure 5 prices resulting from these assumptions are plotted as high investment scenario over the annual supply with solar irradiation.

Table 6: First scenario assumptions

Variable	Formula	Value
c_{H,H_20}		0.11 € /MWh
c_{B,H_20}		0.07 € /MWh
c_{nut}		1.74 € /MWh
$c_{o\&m}$		2.00 € /MWh
c_H	$c_{H,H_2O} + c_{nut} + c_{o\&m}$	3.85 € /MWh
c_B	$c_{B,H_2O} + c_{nut} + c_{o\&m}$	3.81 € /MWh
Inv_0/A		45 €
$\overline{\eta}_{H,1stage}$		5.0%
$\overline{\eta}_{H,2stage}$		3.5%
$\overline{\eta}_B$		5.0%
$\eta_{post,biogas}$		90%
$c_{post,biogas}$		49.10 €/MWh
$\eta_{post,biodiesel}$		70%
$c_{post,biodiesel}$		39.60 €/MWh
$c_{hydrogen}$	c_H	3.85 €/MWh
c_{biogas}	$c_{post,biogas} + c_B/\eta_{post,biogas}$	53.33 €/MWh
$c_{biodiesel}$	$c_{post,biodiesel} + c_B/\eta_{post,biodiesel}$	45.04 €/MWh
$\overline{\eta}_{hydrogen,1stage}$	$\overline{\eta}_{H,1stage}$	5.00%
$\overline{\eta}_{hydrogen,1stage}$	$\overline{\eta}_{H,2stage}$	3.50%
$\overline{\eta}_{biogas}$	$\eta_{post,biogas} \cdot \overline{\eta}_B$	4.50%
$\overline{\eta}_{biodiesel}$	$\eta_{post,biodiesel} \cdot \overline{\eta}_B$	3.50%

Source: Own data

The advantageous characteristics of 1-stage hydrogen and even 2-stage hydrogen compared to the other options become quite clear. Of course, 1-stage hydrogen would win a competition, but one has to keep in mind that a technological solution for this process could not be identified so far. In the range between 1700 and 2300 kWh one realizes that prices for biogas and biodiesel are quite close to each other. The importance of large amounts of solar irradiation becomes obvious: in a range of between 800 and 2300 kWh prices almost decline by two thirds.

Furthermore, one realizes that variable costs of PBR operation of less than 5 € per MWh only have a weak influence on final prices, which are significantly higher. This is due to the great impact of area-related investments on the one hand and, where applicable, due to post-processing costs. The great impact of investments is also shown in Figure 6. It shows the increase in production costs if area-related investments are increased by 1 € per. As one can see easily from eq. (22) these curves are independent of the original value of area-related investments.

This underlines the influence of the above-mentioned factor. By decreasing investments by 1 € per m^2 one will achieve a cost reduction greater than 1 € per MWh of final products.

Because the great impact of investments on final prices has been identified, in the following a low-investment scenario shall be considered as it might be realistic in the future. Investments are assumed to be as low as 25 € per m^2. Furthermore, lower costs for biodiesel from biomass of 25.20 € per MWh are chosen in this scenario as they could be identified in the section on biomass. Above we discussed that for the conversion from biomass to biogas no cost declines could be identified during the last years. For this reason the value in question is not changed here. Consequences from these assumptions are also shown in Figure 5 as low investment scenario. Under these circumstances 1-stage and 2-stage hydrogen could break the barrier of 50 € per MWh which was hit by the oil price during the oil price peak in summer 2008.

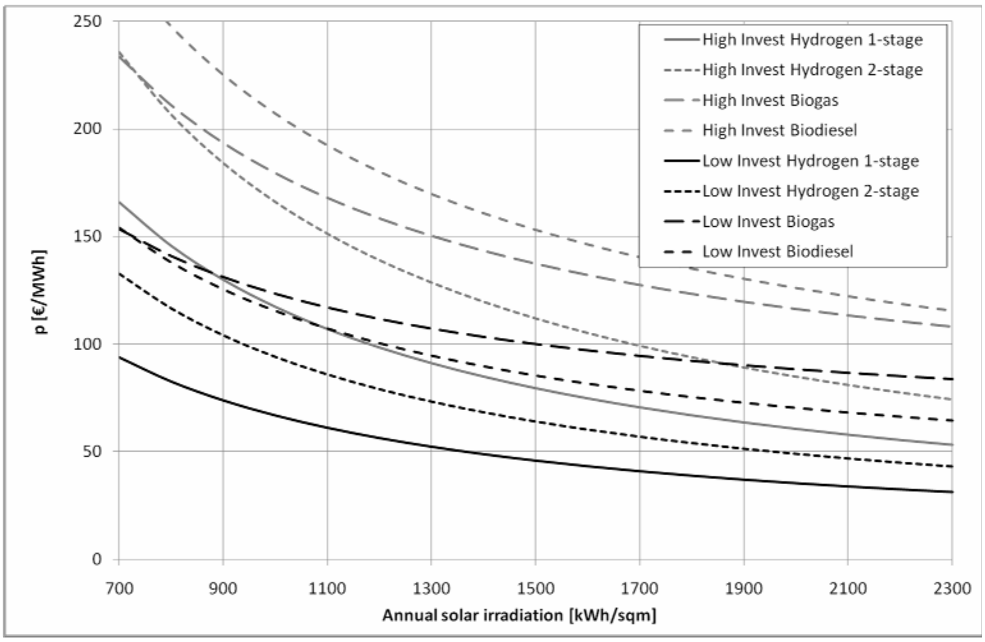


Figure 5: Investment scenarios as a function of annual solar irradiation

Source: Own illustration

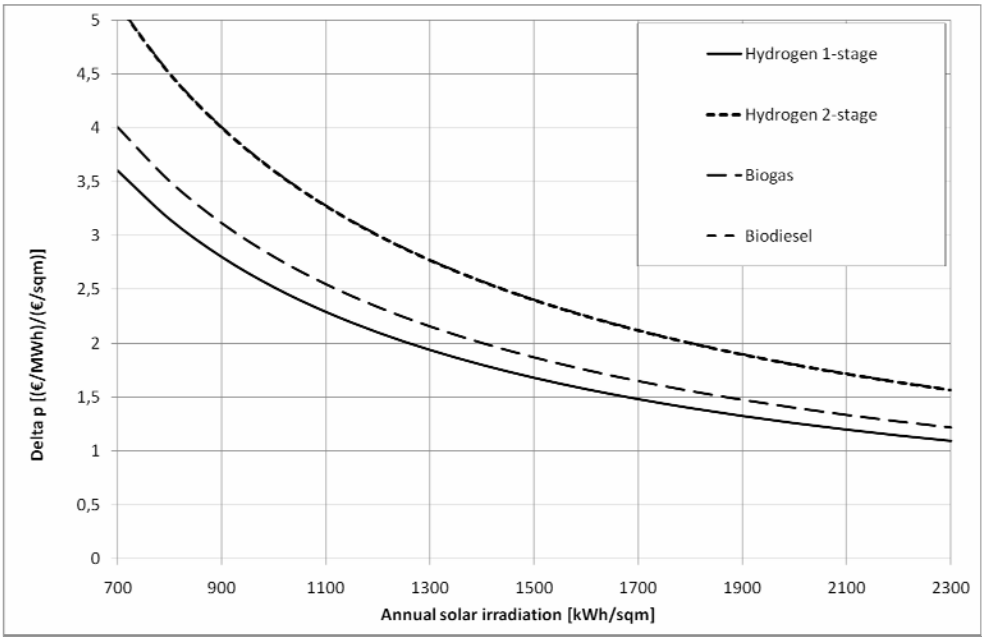


Figure 6: Sensitivity of specific investment costs to changes in final product prices

Source: Own illustration

For the case of participating in emission trading one might expect further cost reductions. Indeed, in the related section we find values between 3-6 € per MWh, depending on the substituted fuel.

So far we have excluded transportation costs of input and output factors, although they have been considered in the preceding sections. For this reason Table 7 summarizes the estimation results obtained in this context. It becomes quite clear that transportation of gases is much more expensive than that of liquids. Even over longer distances of several hundred kilometers transportation of water and liquid products does not seem to be a significant cost driver, especially if production costs of the preceding scenarios and the influence of area-related investments are considered. In the case of gaseous products and especially hydrogen one may expect significant additional costs if they have to be transported over longer distances.

Table 7: Transportation costs

Input/Output factor	Distance	Costs (approx.)
Water	100 km horizontal or 100 m vertical	0.04 €/MWh
	⇒ 1000 km horizontal	0.40 €/MWh
Liquids (similar to oil)	1000 km	0.13 €/MWh
Gases (similar to natural gas)	1000 km	1.99 €/MWh
Hydrogen via pipeline	1000 km	6.42 €/MWh

Source: Own data

But even transportation over 2000-3000 kilometers, e.g. from Southern Spain or Northern Africa to Germany, seems to be advantageous, due to the greater expectable yields from production there.

3.2 Other renewable energy sources

A very interesting question is whether PBR systems will actually be able to compete with other renewable energy technologies that might substitute fossil fuels. The competition with PV has already been discussed in the context of land prices.

In addition, a comparison with traditional biomass would be of interest. For this reason US ethanol shall be considered. It has already been pointed out that yields per unit of area are much lower in the case of traditional biomass. But, on the other hand, investments in reactor systems are unnecessary, a factor of great importance on PBR product prices as it could be shown. Thus the question arises whether this advantage of crops might outweigh low yields per unit of area. In the case of ethanol production in the US costs declined from 712 $\$_{2005}/m^3$ in the early 1980s to approximately 300 $\$_{2005}/m^3$ in 2005 (16). If one US$ is assumed again to be €1.30 and with a heating value of ethanol of $H_{s,\text{ethanol}}$ = 6.52 MWh/m^3, ethanol costs are given by $p_{ethanol,1980} = 84.00$ €/MWh and $p_{ethanol,2005} = 35.39$ €/MWh.

Only low-investment 1-stage hydrogen, and possibly 2-stage hydrogen, seems to be capable of achieving low production costs at the level of, say, 2005 ethanol production costs. Although yields in traditional biomass production are much lower per unit of area ethanol can be produced at relatively low cost. This might be different if land was a more restricted resource, because it is known from eq. (20) that a greater productivity of land utilization, measured by $\bar{\eta}_k \cdot q''_{\text{solar}}$, raises the willingness to pay of investors, $p_{A,k}$..

If a typical area-related ethanol output of $Y_{\text{ethanol}}/A = y''_{\text{ethanol}}$ = 4.3 kWh per year and square meter in the Brazilian case is assumed it is easy to estimate how prices will react on rising land prices by substituting $\bar{\eta}_k \cdot q''_{\text{solar}}$ by y'' ethanol in eq. (20).

The annuity factor $AF_{i,T}$ is assumed to be the same as in the scenarios above. Then the sensitivity on land prices can be evaluated:

$$\frac{dp_{\text{ethanol}}}{dp_A} = \frac{dp_{\text{ethanol}}}{d(Inv_0/A)} = AF_{i,T}^{-1} \cdot \frac{1}{y_{\text{ethanol}}''} = 24.67 \text{ (€/MWh)/(€/m}^2\text{)} \qquad (23)$$

Compared with the sensitivity of PBR systems this value is much greater and thus underlines the described advantage in the case of restricted land resources.

To allow a comparison with renewable electricity producing technologies, such as PV and solar heat, electricity production costs from PBR outputs via CCGT power plants shall be estimated. Assumed values, as they could be identified above, are η_{CCGT} = 65% and c_{CCGT} = 10 €/MWh. With p_{PBR} as the price for PBR products the electricity price p_{el} can be calculated as

$$p_{el} = c_{CCGT} + \frac{p_{PBR}}{\eta_{CCGT}}. \tag{24}$$

Basing on these assumptions Table 8 contains electricity generation costs depending on the PBR product costs. Since in CCGT power plants only gaseous energy carriers can be utilized, only hydrogen and biogas are considered in this context. The comment column on the right indicates the scenarios in which the related values are achievable if solar irradiation is greater than 1700 kWh per m^2 and annum, values that can be achieved in Southern Spain or Northern Africa for example.

Table 8: Electricity production costs from PBR products by CCGT power plants

p_{PBR} [€/MWh]	p_{el} [€/MWh]	Comment
35.00	63.85	1-stage hydrogen, low-investment
60.00	102.31	2-stage hydrogen, low-investment
		1-stage hydrogen, high-investment
100.00	163.85	Biogas, low-investment
		2-stage hydrogen, high-investment
125.00	202.31	Biogas, high-investment

Source: Own data

To compare these results, values for PV, solar heat and conventional power plants are considered as they were estimated by Quaschning in 2005 [31]. Although PV and solar heat with costs greater than 100 € per MWh are not competitive today (2005). Quaschning concludes that PV from Northern Africa will be available at 30-40 € per MWh and PV from Southern Spain at 40-50 € per MWh in 2025. For the 2005 scenario PV investments of 4500 € per kW_p were assumed. For the 2025 scenario a 30% annual growth of the PV market was assumed and, furthermore, ongoing research and development with progress ratios between 0.80 and 0.82 as they could be observed in the past. Under these circumstances the installed PV capacity would rise from 2.6 GW_p in 2003 to about 1000 GW_p in 2025, approximately 385 times as much as in 2003. One realizes easily that if the assumptions made on PV development are correct, then electricity from PBRs will probably not be competitive in 2025, because PV in Southern Spain and Northern Africa might be capable of providing electricity at lower costs (between 30-50 € per MWh). Only the 1-stage hydrogen solution might be competitive under similar environmental conditions. This comparison can be justified by assuming a similar growth of the PBR technology in the considered period and assuming a progress ratio of 0.94 concerning PBR investments. If one started with the high-investment scenario at 45 € per m^2 one might expect investments to decline as in eq. (25) and would thus be close to the assumptions of the low-investment scenario.

$$\left(\frac{Inv_0}{A}\right)_{2025} = 45 \text{ €/m}^2 \cdot 0.94^{\frac{log(385)}{log(2)}} = 26.45 \text{ €/m}^2 \tag{25}$$

Summing up, competitiveness with other renewable energy technologies seems to be limited. This might be different if either prices for land occupation increased or if there was an economy preferring hydrogen as an energy carrier, as it might be the case when cost-efficient fuel cells, only compatible with hydrogen, were available. In the first case, PBRs could unfurl their more efficient use of land compared to traditional biomass. In the second case, the specific capability of direct hydrogen production would be of advantage if hydrogen could not be considered as a direct substitute for other gaseous energy carriers.

3.3 Optimal reactor size

A further question of interest is the optimal size of PBR modules. Increasing module sizes, on the one hand, will lead to economies of scale because fixed expenses (e.g. control units) could be identified above. On the other hand, there might be increasing local transportation costs that could attenuate said economies of scale. Also, technological constraints might limit the maximum reactor size. Examples are the system's observability and controllability, because it is an urgent need that the control unit ensures a stable service by measuring and adjusting system variables.

To develop some first ideas on the optimal module size from an economic point of view, we ignore possible technological constraints. Let us assume a circular module shape, with the control unit in its center, also serving as an interface to the reactor's environment (Figure 7).

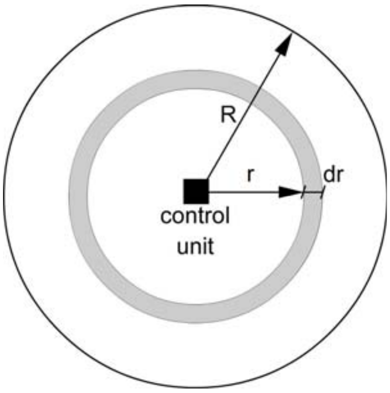


Figure 7: Circular PBR module
Source: Own illustration

We assume further that the control unit makes water circulate within the module to provide all parts with needed input factors and to collect outputs from returning water. Then the marginal required amount of water dX in a very small ring, characterized by its thickness dr and its radius r, results in $dX = K\cdot 2r\cdot dr$, with K as required amount of water per unit of area. If the module radius is given by R, the total amount of water $X(r)$ that passes the circle of radius $r < R$ can be calculated easily by solving the integral

$$X(r) = K \cdot 2\pi \int_r^R r \cdot dr = K \cdot \pi (R^2 - r^2)\,. \qquad (26)$$

Transportation costs per unit of length and per unit of water c_{tp} are assumed to be a function of the local water transportation amount, similar to the identified economies of scale in external water transportation (cf. section 2.1.2)

$$c_{tp} = c_{tp}(X(r)) = c_0 \cdot \left(\frac{X(r)}{X_0}\right)^m \text{ with } m = log_2\left(\frac{5}{6}\right). \qquad (27)$$

Marginal water transportation costs dC at radius r thus result in

$$\begin{aligned} dC_{tp} &= X(r) \cdot c(X(r))dr \\ &= K \cdot \pi \cdot (R^2 - r^2) \cdot c_0 \cdot \left(\frac{K \cdot \pi \cdot (R^2 - r^2)}{X_0}\right)^m dr \\ &= \frac{c_0 \cdot (K \cdot \pi)^{m+1}}{X_0^m} \cdot (R^2 - r^2)^{m+1} \cdot dr \end{aligned} \qquad (28)$$

Total water transportation costs C_{tp} are then be given by

$$\begin{aligned} C_{tp} &= \frac{c_0 \cdot (K \cdot \pi)^{m+1}}{X_0^m} \cdot \int_0^R (R^2 - r^2)^{m+1} \cdot dr \\ &= \frac{c_0 \cdot (K \cdot \pi)^{m+1}}{X_0^m} \cdot \left[R^{2(m+1)} \cdot r - \frac{1}{2m+3} \cdot r^{2m+3} \right]_{r=0}^{r=R} \\ &= \frac{c_0 \cdot (K \cdot \pi)^{m+1}}{X_0^m} \cdot \frac{2m+2}{2m+3} \cdot R^{2m+3} \\ &=: K^* \cdot R^{2m+3} \end{aligned} \tag{29}$$

If these costs are related to the reactor size, one can calculate the average water transportation costs c''_{tp} per unit of area as

$$c_{tp}'' = K^* \cdot \frac{R^{2m+3}}{\pi \cdot R^2} = \frac{K^*}{\pi} \cdot R^{2m+1} \tag{30}$$

Table 9 shows estimated values for the considered variables. Without having better knowledge reference costs c_0 and capacity X_0 are approximated by the known approach from the section on water as input factor. Costs are doubled, because it shall be assumed that cycling water flows in both directions, away from the control unit, and vice versa. The value of 3000 m^3 per m^2 and year must be considered as a vague estimation. Each square meter would then be rinsed by approximately 350 liters per hour if the system was running 8760 hours a year.

Table 9: Assumed values for the estimation of local water transportation costs

Variable	Value	Comment
c_0	$900 \cdot 10^{-9}$ €/m^4	Twice 4.5 ct/m^3 and 100 km
X_0	$100 \cdot 10^6$	
m	-0.263	$\log_2 (5/6)$
K	3,000 $m^3/(m^2\ a)$	
K^*	0.0579	
K^*/π	0.0184	

Source: Own data

The goal of investors would be the minimization of average costs per reactor size (in m^2), by deciding on the optimal reactor radius R. For this reason fixed investments $Inv_{\text{fix}} = A$ have to be annualized and to be added to the local transportation costs. Then the crucial average annual costs c'' result in

$$c'' = AF_{i,T}^{-1} \cdot \frac{Inv_{fix}}{\pi \cdot R^2} + \frac{K^*}{\pi} \cdot R^{2m+1}. \quad (31)$$

The necessary condition to minimize average costs can then be calculated easily by

$$\frac{dc''}{dR} = -2 \cdot AF_{i,T}^{-1} \cdot \frac{Inv_{fix}}{\pi \cdot R^3} + (2m+1) \cdot \frac{K^*}{\pi} \cdot R^{2m} \overset{!}{=} 0 \quad (32)$$

$$\Rightarrow (2m+1) \cdot \frac{K^*}{\pi} \cdot R^{2m} = 2 \cdot AF_{i,T}^{-1} \cdot \frac{Inv_{fix}}{\pi \cdot R^3}$$
$$\Rightarrow R_{opt} = \left[2 \cdot AF_{i,T}^{-1} \cdot \frac{Inv_{fix}}{(2m+1) \cdot K^*} \right]^{\frac{1}{2m+3}} \quad (33)$$

Testing the sufficient condition shall not be done here, but can be done easily by showing that the second derivative of c'' is positive in R_{opt}. Figure 8 shows the optimal module size over fixed investments under the assumptions made. A first estimation of fixed investments was around €130,000, but did not contain any further infrastructure investments. In that case the optimal module size would be around 22 hectares. The optimal module size increases when fixed investments are greater, e.g. due to further infrastructure. Because of very inexact assumptions concerning the data of Table 9 results presented here may also only be interpreted as a rough estimate and have to be interpreted with some caution.

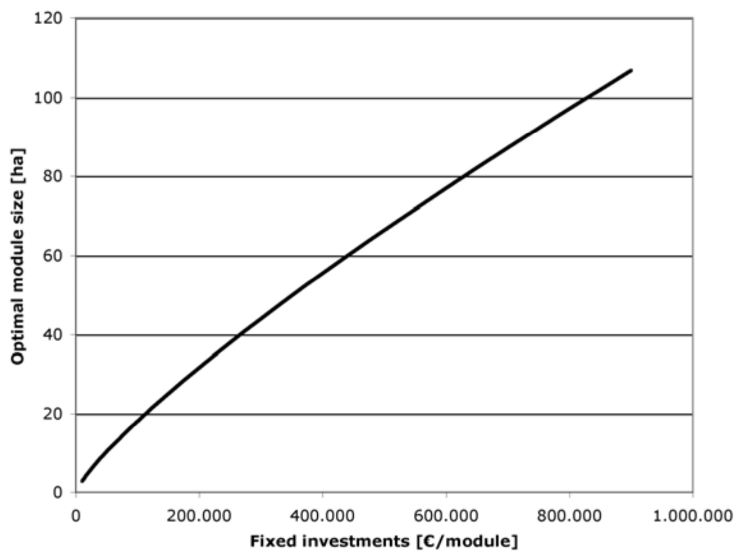


Figure 8: Optimal module size as a function of investment costs per module

Source: Own illustration

4 SUMMARY AND CONCLUSIONS

In this paper we have analyzed the technological and economic chances and risks of PBR systems. For the technological evaluation a generalized approach – the thermodynamic description of the fundamental biological processes – was adopted, allowing us to abstract from the possible technological realization of those systems.

The economic analysis was based on the dynamic calculation of the profitability, taking into account the results of the technological evaluation and further boundary conditions resulting from the analysis of related markets. Based on the thermodynamic analysis it could be shown that, depending on the reactor type, PBR efficiencies will probably be less than 10%, with typical values between 1.8 and 5.6%. Hydrogen-producing PBRs will be characterized by low efficiencies of between 1.8 and 4.1%, if a 2-stage photosynthesis has to be applied, because of oxygen sensitivity of hydrogenases, a problem that remains to be solved. This means that greater efficiencies of up to 5.6% for hydrogen-producing systems have to be considered as hypothetical, and may only be considered as valid if the required scientific quantum leap succeeded. For the case of biomass-producing PBR systems efficiencies have been estimated in the range of between 2 and 5.25%, i.e. they are found to be higher than those of 2-stage hydrogen production. But due to additional processes, which convert biomass into commercial products, overall efficiencies decline and additional costs incur.

In the context of the scenarios we have shown that production costs of hydrogen will be lower than those of biodiesel or biogas from biomass. Hypothetical 1-stage hydrogen could be produced at significantly lower prices, but the spread between 1-stage and 2-stage hydrogen declines with decreasing area-related investments. In the longer term, hydrogen production costs of less than 50 € per MWh seem to be possible in sunny regions, such as Southern Spain or Northern Africa.

If traditional biomass and technologies like solar PV and solar heat are considered, the "economic niche" for PBR systems seems to be quite small. Ethanol prices from US corn have been compared with PBR equivalents. Although PBR systems allow for much greater yields per unit of area, economic advantages could not be identified as long as land is not sufficiently scarce. Concerning electricity generation we find that PBR systems will probably be outpaced by PV in the future if market growth and learning rates of that technology remain on a high level.

Several specific advantages could be identified, including the more efficient use of land compared to traditional agriculture. Apart from that even regions unsuitable for agricultural use may be covered by PBRs because of the closed system design. This way, the PBR technology may ease bottlenecks in the availability of low-cost agricultural land. Another advantage might be expected if there were future technologies enforcing the application of hydrogen. For example, this might be the case in cases where cost-efficient fuel cells in the transportation sector were available that can only be powered by hydrogen. Then other gaseous energy carriers could not be considered as a direct substitute.

The rare feature of PBR systems of being capable of producing hydrogen directly would promote the development of the considered technology. R&D should focus on the reduction of area-related investments and possibly the identification of ways to realize 1-stage hydrogen systems.

The strong sensitivity of final energy prices with regard to investment has also been pointed out. In the 2-stage hydrogen case a reduction of 1 € per m^2 results in a cost reduction greater than 1.50 € per MWh. Use of materials has to be optimized and control systems should be standardized. The advantages of 1-stage hydrogen solutions are obvious, because at comparable capital and operating costs yields will always be larger. But in spite of the research over the last decades, a solution to this challenge still seems to be far away.

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