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Non-thermal production of pure hydrogen from biomass: HYVOLUTION

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HYVOLUTION is the acronym of the Integrated Project "Non-thermal production of pure hydrogen from biomass" which has been granted in the 6[th] EU Framework Programme on Research, Technological Development and Demonstration, Priority 6.1 Sustainable Energy Systems. This IP has started on Jan 1, 2006 and will end on Dec 31, 2010. Its aim: "Development of a blue-print for an industrial bioprocess for decentral hydrogen production from locally produced biomass" adds to the number and diversity of H_2 production routes giving greater security of supply at the local and regional level. Moreover, this IP contributes a complementary strategy to fulfill the increased demand for renewable hydrogen expected in the transition to the Hydrogen Economy. The novel approach adopted in the project is based on a combined bioprocess employing thermophilic and phototrophic bacteria, to provide the highest hydrogen production efficiency in small-scale, cost effective industries. In HYVOLUTION, 10 EU countries, Turkey, Russia and South Africa are represented to assemble the critical mass needed to make a breakthrough in cost-effectiveness.

1. Introduction

Hydrogen will be an important energy carrier in the future according to reports like 'Future Needs and Challenges for Non-Nuclear Energy Research in the European Union' (2002), 'Hydrogen Energy and Fuel cells' (2003), and prominent journals as e.g. RTD info (The Hydrogen Fairy, 2004), Science (Toward a hydrogen economy, 2004) and Scientific American (Wald, 2004). However, to make the future Hydrogen Economy fully sustainable, renewable resources instead of fossil fuels have to be employed for hydrogen production. The concept of HYVOLUTION is based on the exploitation of bacteria, which freely and efficiently produce pure hydrogen as a by-product during growth on biomass. This approach, which started in the FP 5 project BIOHYDROGEN, allows a great reduction in CO_2 emission and provides independence of fossil imports. Both topics are dominant in all global agreements on climate protection and urgent in mitigating the greenhouse effect. The technologies developed as a result of the research in this Integrated Project will be commercialised post-2015. This will be in time to facilitate the transition to mass hydrogen markets, even more so since the European Commission has set an objective of 20% substitution by bio-fuels in

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the road transport sector in 2020. Hydrogen as an alternative motor fuel is seen in FP 6 as a market coming to maturity in 2015-2020.

The main scientific objective of this project is the development of a 2-stage bioprocess for the cost-effective production of pure hydrogen from multiple biomass feedstocks. The bioprocess starts with a thermophilic fermentation of feedstock to hydrogen, CO_2 and intermediates. In a consecutive photo-heterotrophic fermentation, all intermediates will be converted to more hydrogen and CO_2, to achieve an efficiency of 75% (nearly 9 moles of hydrogen per mole of hexose).

Several sub-objectives contributing to the main scientific objective are:

1. Pretreatment technologies for optimal biodegradation of energy crops and bio-residues
2. Maximum efficiency in conversion of fermentable biomass to hydrogen and CO_2
3. Assessment of dedicated installations for optimal gas cleaning and gas quality protocols
4. Minimal energy demand and maximal product output through innovative system integration
5. Identification of market opportunities for a broad feedstock range spread over Europe

The main technological objective is the construction of prototype modules of the plant which, when assembled, form the basis of a blue print for the whole chain for converting biomass to pure hydrogen.

The sub-objectives to be achieved are prototypes of:

1. Equipment for mobilisation of fermentable feedstock
2. Reactors for thermophilic hydrogen production
3. Reactors for photo-heterotrophic hydrogen production
4. Devices for monitoring and control of the hydrogen production processes
5. Equipment for optimal gas cleaning procedures

Besides scientific and technological objectives, also socio-economic activities are included to increase public awareness and societal acceptance, and for identification of future opportunities, stakeholders and legal consequences of this specific bioprocess for decentral hydrogen production.

2. State of the Art

Distinct advanced strategies for the production of H_2 from biomass are currently being studied:

- thermal processes like gasification or supercritical water gasification
- non-thermal (biological or fermentative) processes, which are the issue in HYVOLUTION

Non-thermal processes have a specific advantage for the efficient conversion of biomass with high moisture content to pure hydrogen. Secondly, fermentative processes do not require large installations for economy of scale. In this way, small-scale installations can be constructed for cost-effective conversion of the locally produced biomass on-site and loss of energy through transport is prevented.

Most research in biologically produced H_2 has been performed with hydrogen producing bacteria, which have optimum growth and hydrogen production at ambient temperatures. The main drawback of these bacteria is that, besides hydrogen, they produce other reduced intermediates which compete with hydrogen production. As a result, the efficiency of biomass conversion to hydrogen is low.

In a Dutch project, a conceptual design has been made for the biological production of hydrogen from potato steam peels (Claassen and de Vrije, 2004). The conceptual design was based on hydrogen production rates, regarded feasible after further R&D. The outcome was a cost price of circa 4 Euro/kg H_2 (comparable to 30 Euro/GJ) which is about 3 to 4 times higher than the present price for hydrogen, derived from fossil fuels produced in large-scale installations. The new approach focuses on a combination of a thermophilic fermentation with a photofermentation to enable the complete conversion of biomass to hydrogen with the highest efficiency theoretically possible.
The consortium for 'HYVOLUTION' was formed to exploit the acquired knowledge and make a breakthrough with a new taskforce aiming at the development of a hydrogen industry producing H_2 at a cost competitive with other biofuels. The price target will be achieved by reducing costs in the biomass pretreatment, by optimizing the efficiency and rate of the fermentations enabling low cost thermo- and photo-bioreactors, by developing dedicated, low cost gas upgrading procedures and optimum system integration for making economic balances with respect to energy and heat utilization.

3. Methodology

The aim of HYVOLUTION is to deliver prototypes of process modules which are needed to produce hydrogen of high quality in a bioprocess which is fed by multiple biomass feedstock. To achieve this aim, a coherent set of scientific and technological activities is required (described in detail below) which are interdependent and flanked by system and societal integration for optimal economics and societal implementation.
In HYVOLUTION the approach is based on the combination of a thermophilic fermentation (also called dark fermentation) with a photoheterotrophic fermentation. This approach has been initiated in a previous FP 5 project BIOHYDROGEN and shown to be very challenging and promising. The novel issue is the application of thermophilic bacteria to start the bioprocess. This offers two important benefits in non-thermal hydrogen production. First of all, thermophilic fermentation at ≥70 °C is superior in terms of hydrogen yield as compared to fermentations at moderate temperatures (de Vrije and Claassen, 2003). In thermophilic fermentations, glucose is converted to, on the average, ≥3 moles of hydrogen and ≤2 moles of acetic acid as the main by-product. In other, mesophilic fermentations at ambient temperatures, the average yield is only 1 to 2 moles of hydrogen, at the most, per mole of glucose. This is due to the production of more reduced by-products like butyrate, propionate, ethanol or butanol under mesophilic growth conditions. The second advantage lies in the production of acetic acid as the by-product of the first fermentation. Acetic acid is a prime substrate for photoheterotrophic bacteria. Energy from light enables photoheterotrophic bacteria to overcome the thermodynamic barrier in the conversion of acetic acid to hydrogen (Akkerman et al., 2003). Through the combination of thermophilic fermentation with photoheterotrophic bacteria, complete conversion of the substrate to hydrogen and CO_2 can be established, resulting in 75% conversion efficiency or 9 moles of hydrogen per mole of glucose, which is the main scientific objective of this IP. The various components (WP) are integrated to a coherent project as shown in Fig. 1, with both fermentations forming the core of the project.

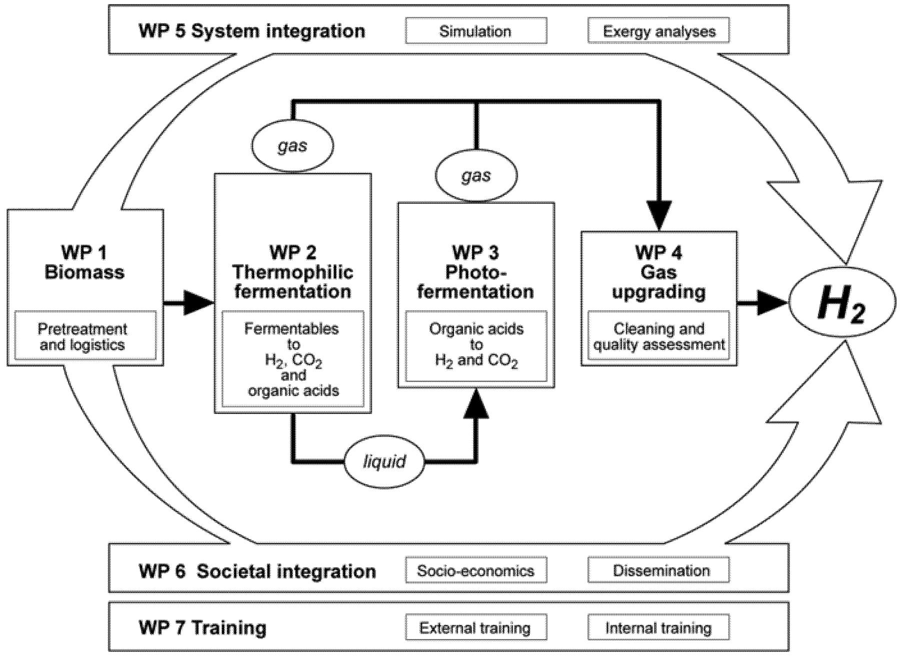

Fig. 1. HYVOLUTION: An integrated approach for non-thermal hydrogen production, which covers the whole chain from biomass to hydrogen, including societal integration for implementation in society.

WP 1 Biomass

Closely associated to the development of this bioprocess is the acquisition of suitable feedstock. In contrast to the industrial yeasts employed for ethanol production, hydrogen producing bacteria offer the great advantage of having a wide range of potential substrates (Claassen et al., 2002). In FP 5 project BIOHYDROGEN, the simultaneous utilization by thermophilic bacteria of hexose sugars and pentose sugars as well as oligomeric carbohydrates has been confirmed (de Vrije et al. 2002, Kádár et al. 2003, Kádár et al. 2004). These observations confer as yet unknown opportunities for new agro-industrial chains in terms of biomass for biofuel production. However, the large contribution of biomass cost price to the final production cost requires the development of tailor-made pretreatment procedures enabling the utilization of low cost biomass. Furthermore, HYVOLUTION is specifically aimed at small-scale hydrogen production units. As such, this opens new logistic opportunities which have not been studied before. Concurrent with developments at the level of new logistics due to the scale of the envisaged production plants, new opportunities for European rural areas arise. These issues will be addressed in the WP 1 Biomass, through the participation of industrial participants, but also in WP 6 Societal Integration.

WP 2 Thermophilic Fermentation and WP 3 Photofermentation

To make this bioprocess technically and economically feasible, several issues are addressed in HYVOLUTION. Through extended research of the physiology, biochemistry and genomics of pure cultures of thermophilic as well as phototrophic bacteria, insight in metabolic pathways is obtained (de Vrije et al. 2007, Kovács et al. 2006). This is needed to model fermentations for optimal productivity and adjustment of the two consecutive fermentations. This insight will be the basis for identifying and/or developing improved strains and creating mixed cultures which are generally known for robustness, an important asset for industrial performance. With the elucidation of the fundamental microbiological properties, the development of dedicated bioreactors also resides in WP 2 and WP 3 with the construction of prototype bioreactors being part of the technological objectives. The thermophilic bacteria are, as observed until now, inhibited by a partial concentration of 20 % hydrogen (van Niel et al., 2003). This confers specific challenges for hydrogen removal (van Groenestijn et al., 2002) in the thermo-bioreactor to be developed in WP 2. With photoheterotrophic bacteria, the technological challenge is the optimal penetration of light to establish high photochemical efficiency (Modigell et al., 2007) in the photo-bioreactor to be developed in WP 3. Both issues are extensively addressed in HYVOLUTION, because they are of paramount importance for overall efficiency. As the main objective is the integration of the fermentations into one bioprocess, accurate monitoring and control devices are considered as essential and will also be developed in HYVOLUTION to support optimal performance of the thermophilic and phototrophic fermentation.

WP 4 Gas Upgrading

Besides the upstream processing as described in WP 1, HYVOLUTION also addresses downstream processing. The raw gas produced in the bioreactors requires specific gas treatment. This is primarily because of the fairly high concentration of CO_2 in the raw gas and the relatively small and perhaps fluctuating quantity of hydrogen, and to a lesser extent because of the presence of contaminants, which are considered to contribute little to the final composition. It is known that fuel cells can be economic on small-scale. It is the area in between production and application that will be addressed to deliver technically and economically feasible gas cleaning devices as described by Modigell et al. (2008), handling and safety procedures suitable to a small-scale hydrogen production plant.

WP 5 System Integration and WP 6 Societal Integration

System integration and societal integration form a basis to secure the scientific and technical objectives. These issues are fundamental to develop this new process for small-scale hydrogen production and to make it viable in terms of process-economics and socio-economics, including environmental impact. Both disciplines are integrated in HYVOLUTION to enable identified adjustments right from the start. This is necessary to avoid routes which will have no economic future or do not adhere to sustainability, and to make optimal use of the integrated approach.

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