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# Sustainability assessment of an integrated High Temperature Steam Electrolysis - enhanced Biomass to Liquid Fuel process

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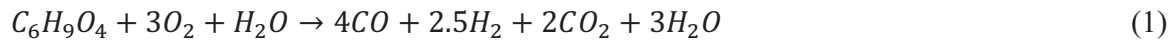
This work addresses the integrated design of the High Temperature Steam Electrolysis (HTSE) and Biomass to Liquid (BtL) hybrid process. The comprehensive gate-to-gate analysis includes BtL and hydrogen production on-site operations. Simulations are carried out using commercial process simulation software – ProSimPlus<sup>®</sup> – to allow physical modeling as well as mass and energy balances; modeling is based on standard elementary and user modules and supported by various CEA (French Atomic Energy and Alternative Energies Commission) previous works. The framework for assessment is proposed. Considering productivity, efficiency, cost and environmental issues, five sustainability criteria are chosen: carbon matter yield; energy

efficiency; greenhouse gas emissions; electrolysis water use; levelized biofuels production cost. Simulations results verify that hydrogen input is almost doubling the biogenic carbon conversion into liquid biofuels. They bring out significant secondary energy saving for HTSE compared to standard process; and clear advantages over alkaline electrolysis considering technical and environmental criteria. HTSE coupling allows a sharp increase in productivity (biofuels/biomass) with a limited increase in cost and environmental impacts at almost constant primary efficiency.

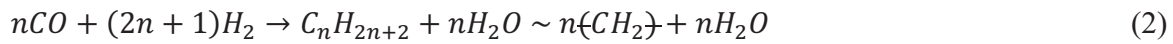
## 1. Introduction

Transport undergoes an increase in energy consumption, consisting almost exclusively in petroleum products.<sup>1</sup> This has a negative impact on major challenges of the energy system, such as GreenHouse Gas Emissions (GHGE), energy insecurity and depletion of resources. Biomass could address these issues and is the raw energy most considered regarding the substitution of oil.<sup>2,3</sup> However the first-generation biofuels (using agricultural biomass) are criticized for their environmental impacts (mainly change of land use). They also compete with the agriculture food chain (land use, pressure on prices) and generate significant non-recoverable by-product. The second generation liquid biofuels (using lignocellulosic biomass from forest resources, and agriculture and forestry residues) are promising regarding substitution of petroleum: they offer both interesting energy efficiency and potential for GHGE cut.<sup>3,4</sup> Additionally, the Biomass to Liquid (BtL) thermochemical route can produce fuels similar to conventional fuels with higher quality<sup>5</sup>; this allows to keep the current distribution network and internal combustion engines and thus to benefit from their maturity. This route is based on the gasification of the biomass followed by Fischer-Tropsch Synthesis (FTS), producing naphtha, gasoline, kerosene and diesel; so BtL fuels are also called FT biofuels.

However, lignocellulosic resources are significant but not plentiful: in Europe, the primary energy feedstock from forestry<sup>6</sup> is about the third of the final energy consumption for transportation<sup>1</sup>. As a consequence it is necessary to use the biogenic carbon to the utmost. This increase in productivity is possible using optimized energy efficiency of the BtL processes, but also by providing extra hydrogen input. Hydrogen production coupled with BtL process is therefore studied.<sup>7,8</sup> This interest is obvious referring to chemical equations: biomass gasification is roughly described by eq. (1)

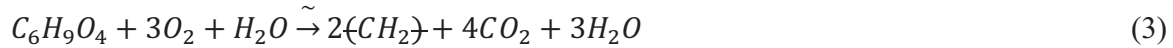


while desired FTS (producing mainly saturates<sup>5</sup>) is described by eq. (2) for alkanes,

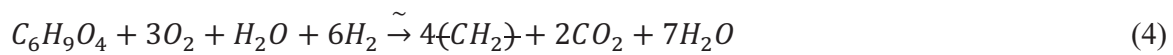


with n belonging to [5, 20],

which leads to eq. (3) for the BtL process.



Only one-third of the biogenic carbon is valorized in biofuels. With extra hydrogen input, the process equation can be described by eq. (4) instead.



Then, by adding extra hydrogen, two-third of the biogenic carbon can theoretically be valorized in biofuels.

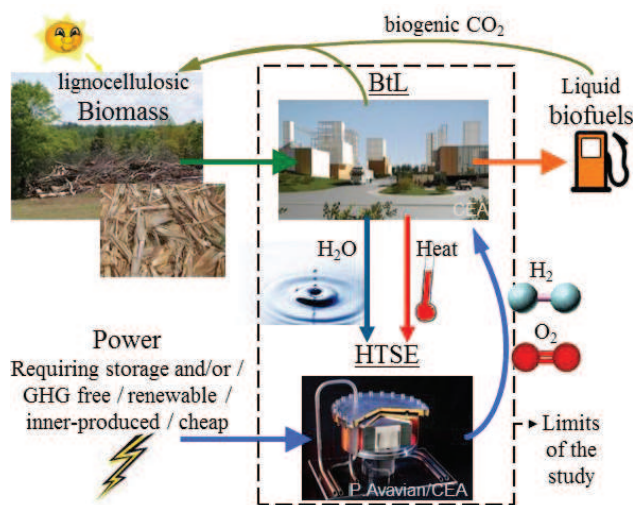
For consistency, primary energy to produce hydrogen has to be in line with energy issues such as GHGE, this is possible considering electrical power due to numerous alternatives in raw energy. Water electrolysis produces both hydrogen for extra input and oxygen for gasification, in the required one half ratio shown above (eq. (5)).



Furthermore, water reuse from BtL could theoretically lead to full matter integration for the hybrid process (eq. (6)). Note that, in this case, there is still no net extra matter input to the process, only extra energy as electrical power is required.



Contrary to standard alkaline electrolysis, High Temperature Steam Electrolysis (HTSE) can use heat at different temperature levels, both for water vaporization and for the high temperature electrochemical reaction, so it allows the recovery of free heat from BtL<sup>7</sup>. HTSE also allows to reuse easily the FTS coproduced water (and so to get close to eq. (6)) due to inherent handling of hydrocarbons and additionally it offers very high secondary efficiency<sup>9</sup>. **Figure 1** sums-up these relevant synergies of HTSE coupling to BtL process.



**Figure 1.** Principle and interest of BtL and HTSE hybrid process to produce biofuels.

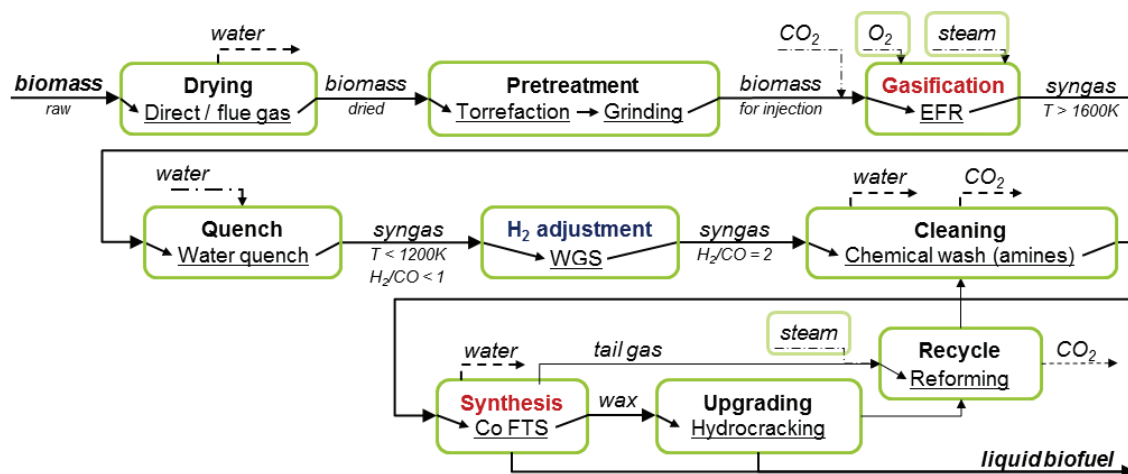
This paper aims at defining the framework for assessment, validation and quantification of the relevance of the HTSE and BtL hybrid process regarding sustainability, suitable for instance for multicriteria optimization. Both integrated design and further optimization require a detailed modeling: selected technologies and method used are first presented through a brief description

of the modeling, in the next section. Sustainability criteria and matching performance data of the base case integrated design are then discussed. Finally the proposed framework and a comparison with the standard BtL process are summed-up.

## 2. Process description

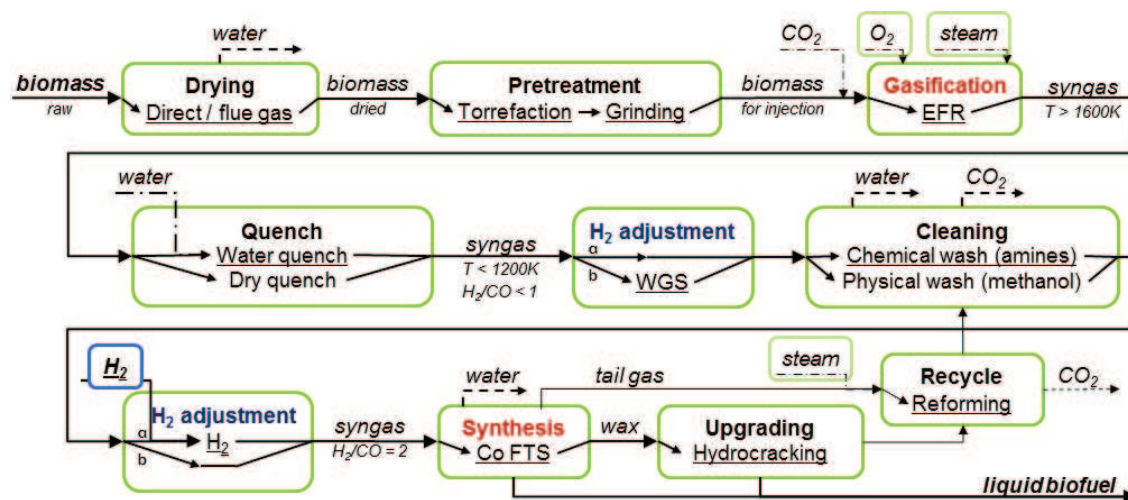
### 2.1 Integrated process

The BtL process is based on two main steps: gasification of the biomass into syngas then FTS of desired fuels: naphtha, gasoline, kerosene and diesel. Cobalt catalyst is chosen for FTS in order to favor the diesel range, most used in Europe<sup>1</sup>. In addition, the complete process includes preparation or recovery operations that impact process performance data. Operations involving heat or matter are simulated, from raw biomass to liquid fuels. Selected technologies are shown in the block diagram **Figure 2** (EFR: Entrained Flow Reactor, WGS: Water Gas Shift). Regarding extra-hydrogen input and alternate technologies shown in **Figure 3**, base case is used for the results presented here with three options for hydrogen ratio adaptation: HTSE, Alkaline Electrolysis (AE) and WGS.



**Figure 2.** Block diagram of the standard BtL process. Material streams in italics, operations in bold, technologies underlined.





**Figure 3.** Block diagram of the integrated HTSE-enhanced BtL process. Material streams in italics, operations in bold, base case technologies underlined.

Simulations are carried out using a commercial process simulation software (ProSimPlus<sup>®</sup>) to allow physical modeling, including mass and energy balances as well as thermodynamic computing. Concerning reactions modeling, equilibrium is considered when possible (i.e. temperature (EFR and combustions) or catalyst (reforming, WGS) provides near-equilibrium output), accounting for potential changes in the reaction conditions; in case of non-standard kinetics (torrefaction, FTS, hydrocracking), phenomenological modeling at fixed conditions and conversions is used; HTSE is managed by user-built module. The process model is built from standard elementary and user modules, supported by various CEA (French Atomic Energy and Alternative Energies Commission) previous works, including modeling work and selection of relevant elementary processes and technologies<sup>8,10,11</sup>. Modeling is briefly presented in the next section.

## 2.2 BtL process

Fixed characteristics of the raw material is a major simplification, commonly assumed for process analysis. Wood is considered as biomass; it is 51% C, 6% H, 41% O, 2% N and 35% water (mass, dry basis) with a Lower Heating Value (LHV) of 18 MJ/kg.

First, raw biomass is dried by direct contact with flue gas or heated air. This type of drying is the most widely used industrially, due to its maturity and low cost.<sup>12</sup> Drying is modeled by the mixing of process exhaust gases and wet biomass followed by separation of steam and flue gas from the biomass. For this first order modeling, output residual moisture of the biomass, output steam and flue gas temperature (over temperature from dew point), and input hot gas temperature (through the use additional fresh air) are set to match standard values. Secondly, torrefaction<sup>13</sup> is used to lower the energy consumption of biomass grinding. Mechanical grinding is necessary to achieve the required particle size for fluidization of biomass for feeding into the EFR. A fraction of the biomass is converted into a poor gas mixture, usually burned to provide energy to the reaction, resulting in a slight loss of biogenic carbon. Modeling includes fixed reaction at 550 K, torrefied wood moisture uptake and gas combustion.

Adiabatic pressurized oxygen-blown EFR is used for gasification. The thermodynamic equilibrium and the operating temperature (1600-1900 K) avoid the formation of methane and thus maximize the conversion of biomass into useful compounds for the FTS. It also avoids the formation of particulates, all this in a single step. In addition, working under pressure is particularly useful for large installations.<sup>11,14</sup> These benefits can be found on the production cost, and this reactor benefits from development for the coal-based integrated gasification combined cycle. Oxygen is recovered from electrolysis if available, or supposed to be otherwise produced by an Air Separation Unit (ASU). Modeling includes oxygen compression (if produced from

ASU), oxygen demand computing (to meet the temperature), CO<sub>2</sub> compression, steam generation and equilibrium reaction at 1673 K, 3 MPa.

Between gasification and synthesis, it is necessary to process the gas in order to comply with the requirements of the FTS.<sup>15</sup> First gas quenching aims at fixing syngas composition. Modeling includes water consumption computing (water quench) to reach 1170 K and fixed sudden WGS reaction. Radiant heat exchanger or recirculating cold raw syngas can also be considered as dry quench in order to minimize sudden shift reaction. Considering the gas cleaning step, only CO<sub>2</sub> (diluent) removal is modeled. Both chemical (amines) and physical (methanol) washings are considered. Chemical washing generates a high heat demand (set at 420 K<sup>16</sup>) for solvent regeneration while physical washing consumes more electrical power. Modeling includes separation of CO<sub>2</sub> and water from the syngas as well as heat and electrical power consumption.

Cobalt catalyzed FTS requires near stoichiometric H<sub>2</sub>/CO feed and works at around 500 K, temperature range for efficient liquid production is narrow. Modeling of the reaction is performed with a fixed  $\alpha$  parameter (the probability of propagation instead of termination in the polymerization process, typically alkanes' growth), and includes short-loop tail gas recycling as well as products separation. Some works<sup>15</sup> offer correlations for  $\alpha$ , but the validity range is narrow and values obtained are not in agreement with state-of-art FTS regarding liquid production. Therefore  $\alpha$  is set in this work at 0.92, value which is both currently achievable<sup>17</sup> and ensuring a good conversion into liquids<sup>14</sup>. Products are modeled as alkanes up to C<sub>20</sub>H<sub>42</sub>, while a single component is used for wax (C<sub>20+</sub>).

Finally too light (tail gas) or too heavy (wax) products from the FTS are valued given that they can contain up to a quarter of the introduced carbon each. Wax upgrading is performed by hydrocracking long-chains molecules into liquids and gas. Modeling includes a fixed reaction

(alkanes' distribution) and hydrogen consumption. The tail gas recycling improves performance on the system by reinjecting the biogenic carbon upstream.<sup>18</sup> The tail gas is reformed using conventional steam reforming. This reaction requires high temperature heat (1100 K); modeling includes steam generation and equilibrium reaction. As with any recycling, a part must be purged to prevent the accumulation of inerts (mainly nitrogen from biomass itself) and it is burned to provide high temperature heat.

### 2.3 Hydrogen adjustment

An adjustment of hydrogen is required to bring the H<sub>2</sub>/CO ratio of the synthesis gas (lower than 1 out of gasification) to stoichiometric conditions (higher than 2) for the cobalt catalyzed FTS. This adjustment can be either a conversion of a part of the syngas into H<sub>2</sub> and CO<sub>2</sub> using WGS reaction or an extra hydrogen input to the process in order to increase the carbon yield. Using steam reforming of natural gas to produce hydrogen creates GHGE. With low-carbon electricity (e.g. renewable or nuclear power), the Alkaline Electrolysis (AE) (consuming only electricity) can reduce these GHGE, the downside is an increase in production cost and a poor energy yield with generation of waste (80°C) heat<sup>9</sup>. Finally, HTSE (using heat both to vaporize the water and to the electrochemical reaction at 1000 K) brings the advantage of better energy efficiency of the process, but with an increased cost. Modeling of HTSE includes steam generation, water consumption and excess oxygen production computing, and HTSE reaction with a user-built module, at 3 MPa and with hydrogen production matching the consumption for syngas adjustment. WGS, NG reforming (not presented here) and AE can be considered as touchstones for HTSE performance and suitability.

### 2.4 Energy calculations

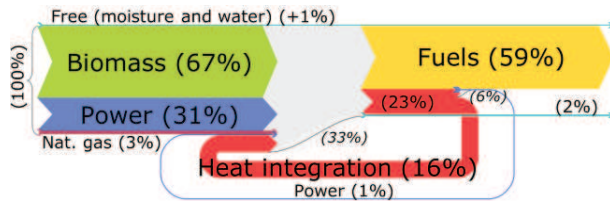
Electrical power consumption is obtained from consumption of pumps and compressors as well as electrolysis and ASU if used. Concerning heat, heat integration<sup>19</sup> is performed as part of the simulation from the results obtained simulating the complete flowsheet, which are input-output temperatures and enthalpy changes along the operations (steam generations, reactions, ...) involving heat in the process. Thus, contrary to matter computing, heat integration is computed for the hybrid process, as shown in **Table 1**.

**Table 1.** Heat and matter integration of BtL and HTSE hybrid process: computing issues.

	HTSE		BtL	Note
H <sub>2</sub> , O <sub>2</sub>	Produces required H <sub>2</sub> and additional O <sub>2</sub>	→ →	Requires H <sub>2</sub> and also O <sub>2</sub>	Excess O <sub>2</sub>
H <sub>2</sub> O	↻ internal reuse and reuse from FTS	←	Requires and produces H <sub>2</sub> O  ↻ internal recycling (treatment required, not simulated)	HTSE additional water use computed
Heat	↔ Complete heat integration performed			Net heat exchange is from BtL to HTSE

**Figure 4** shows the importance of heat integration for the whole process while major sources and HTSE thermal coupling is studied later (**Figure 5**). Hot utility is considered to be produced using natural gas; cold utility is valued by producing electrical power (with 40% exergetic efficiency) if it is higher than 373 K, modeling a steam turbine (slight power loop in **Figure 4**). As the standard pinch analysis, this integration is a techno-economic sub-optimization based on the parameter  $\Delta T_{min}$  (minimum temperature difference in exchangers), supposed to offer a trade-off between investment cost and energy savings: temperatures of sinks and sources are corrected

using half matching typical fixed  $\Delta T_{min}$  values<sup>19</sup>. This method allows targeting both utilities and capital cost without explicit heat exchange network.



**Figure 4.** Heat integration for the BtL and HTSE hybrid process: Grassmann (exergy flow) diagram. Basis (100%) costing inputs only (Biomass, Power and Natural Gas); exergy destruction in italics.

### 3. Criteria and preliminary analysis

In order to study the relevance of the HTSE and BtL hybrid process, issues of second-generation biofuels bring us to select several criteria as performance indices or compliance constraints. Matching key points of the process are discussed using the base case results, in order to provide a relevant framework and analysis for further multicriteria optimization, not considered in this study.

#### 3.1. Energy

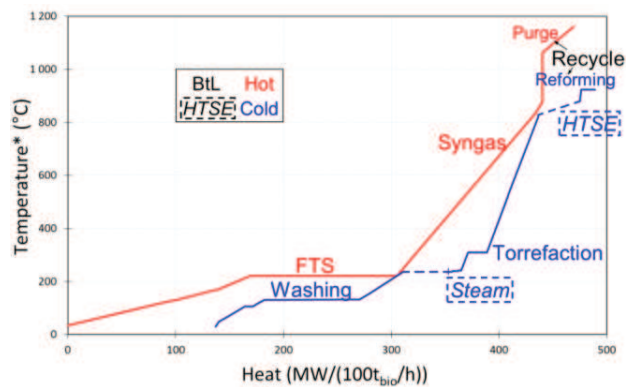
The first criterion needed for an energy transformation process is the energy efficiency of such a process. This technical criterion is used in all publications on the BtL process, expressed in energy (lower or higher heating value for fuels) or, in some papers, exergy (work equivalent)<sup>18</sup>. Exergy is particularly useful to point out irreversibilities, so it is relevant for a given process analysis. It also allows to value heat, that is why it is used in **Figure 4**. Given that no steam credit is considered<sup>21</sup> for the processes under study, only high-exergy inputs/outputs are involved, so energy does not distort the efficiencies. Additionally, exergy of fuels is higher than LHV (biomass: 113%, liquid fuels: 107%<sup>22</sup>) but exergy equals power for electricity. Thus,

exergy inputs/outputs data favor the use of electrical power over biomass; we choose not to use exergy in studying this electrical power hybrid process relevance. Finally, we must account for upstream electrical power production and inferred technical energy efficiency of this prior conversion <sup>21</sup>. The energy criterion is then expressed as the yield of equivalent primary energy: the primary energy of a fuel (biomass, produced liquid biofuel) is taken as its LHV; electrical power is affected by a conversion efficiency<sup>7,16</sup>, fixed here at 1/2.6 or 39%. Considering terminology, primary energy is found in nature (e.g. wind, biomass or natural gas); on the contrary secondary energy has been converted (e.g. electricity) and thus it has been affected at least once by a conversion efficiency; primary energy is sometimes referred as thermal value<sup>7</sup>. Primary efficiencies are then computed according to eq. (7) using net costing inputs and outputs (**Figure 4**): biofuels are outputs; and biomass, electrical power and natural gas are inputs.

$$\frac{\sum flowrates_{out} \cdot LHV_{out}}{power \cdot 2.6 + \sum flowrates_{in} \cdot LHV_{in}} \quad (7)$$

Regarding heat integration, the composites curves (**Figure 5**) plot cumulative heat demand and heat excess versus availability temperature for process operations. They show two pinch points: heat integration is limited in two different points; further integration would require acting on several operations. Contrary to expectations, the heat of FTS is not required to HTSE steam generation: in the studied case, the steam can be generated by the heat of syngas cooling from gasification. Otherwise, i.e. to achieve heat integration between these two operations, adjusting FTS temperature or HTSE pressure is needed. For example, a synthesis at 500 K allows producing hydrogen by HTSE at 1.8 MPa maximum (taking into account pressure losses and difference temperature in exchangers); to avoid further compression of hydrogen, EFR should operate at 2.3 MPa. This analysis addresses the first (500 K) pinch point. Regarding the second pinch point, high temperature heat consumption due to HTSE reaction can be supplied either by

heat or by electrical power (Joule effect), given that from a thermodynamic point of view only free Gibbs energy is required as electrical power for electrolysis. The results presented here use high temperature heat for the HTSE reaction, that is why heat consumption appears in the cold composite curve. On the contrary, by fully supplying reaction enthalpy by electrical power, the surface is reduced (and so capital cost) but it would not be possible to value high temperature heat from a process source (purge combustion). Thus the flexibility of HTSE regarding pressure and heat behavior allows more advanced heat integration.



**Figure 5.** Heat integration for the BtL and HTSE hybrid process: composite curves with main sources labeled.

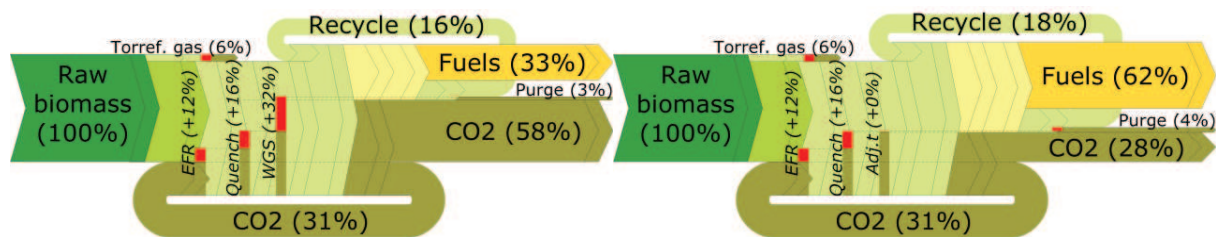
Regarding HTSE efficiency, standard process secondary (i.e. gate-to-gate) efficiency is 46% while hybrid process efficiency is 59%. The specific or marginal<sup>23</sup> efficiency of HTSE, calculated as additional energy in produced biofuels against additional input energy compared to the standard process, is 89% (using exergy, it would reach 95%). This point illustrates how efficient the HTSE is. However, accounting for upstream electrical power production efficiency (39%), primary specific efficiency of HTSE is cut down to 36%. Recalculated breakeven electrical power production efficiency is 47%: for more efficient production (e.g. renewable is conventionally 100%) the hybrid process is more efficient than the standard one, but for less



efficient electrical power generation (as in this study) the HTSE and BtL integrated process is considered less efficient than the standard process.

### 3.2. Biogenic carbon

The main function of the coupling is to enhance the conversion of biogenic carbon into liquid biofuels, so a yield is required as a technical performance criterion, biomass as input and fuels as output. The process basically removes oxygen from the input, leading to limited mass yield: eq. (6) mass yield is 40%. Biogenic carbon yield (also called carbon utilization <sup>7</sup>) is therefore selected as criterion, maximum biogenic carbon yield being 100% (in this case the process indeed requires net additional matter input as hydrogen element). Flow diagrams are presented for the standard and HTSE coupling case in **Figure 6**.



**Figure 6.** Biogenic carbon flows for the standard and HTSE coupled BtL process, CO<sub>2</sub> formations emphasized.

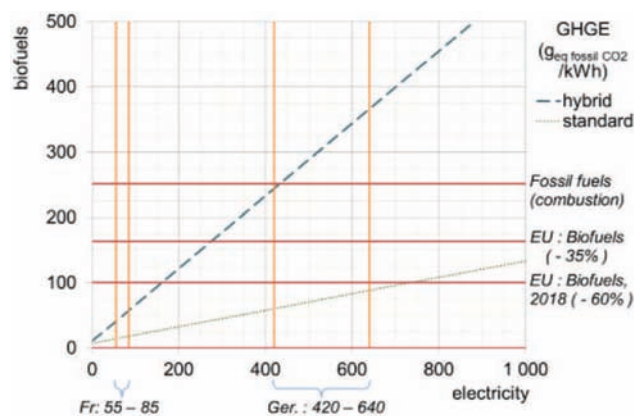
CO<sub>2</sub> formations translate in loss of energetic biogenic carbon; roughly one-third of input biogenic carbon remains as material for the produced biofuel in the standard process. The loss avoidable using extra hydrogen input instead of WGS adjustment is roughly an additional third of the input biomass. Water quench also induces an important shift, that is why dry quench is proposed as alternative in **Figure 3** in order to save a sixth of biogenic carbon as support for fuel (not studied here). Biogenic carbon losses at pretreatment (torrefaction) and gasification are due to the chosen EFR technology; on the other hand this technology offers to perform CO<sub>2</sub> reuse for

the injection of biomass, and to recycle <sup>18</sup> tail gas thanks to minimum inert (nitrogen) input in the process. Due to remaining CO<sub>2</sub> in the washed syngas in the standard case there is almost no net CO<sub>2</sub> formation for tail gas purge and reforming.

### 3.3 GHGE

The impact of biofuel in GHGE is the subject of much research, the change of land use is particularly discussed and impacting. Additionally it is questionable whether the biomass is a renewable energy or not. These variables are outside the scope of this work: it is assumed that the biomass available at the entrance of the process and biogenic CO<sub>2</sub> emitted during combustions (in the process or as biofuel) are not responsible for any GHGE. Additionally, avoided emissions are directly related to productivity (or in this study, the conversion of biogenic carbon), therefore raw emissions are preferred. GHGE are calculated for the process from natural gas consumption for hot utility and for electrical power production from indirect emissions.

GHGE due to electrical power highly impact the relevance of the hybrid process: if they are low (nuclear or renewable), the HTSE-coupled BtL process offer biofuels suitable with European Union requirements <sup>3</sup>; for moderate GHGE due to electrical power (> 150 g<sub>eq fossil CO<sub>2</sub></sub> / kWh) the produced biofuels can't meet European Union 2018 requirements; and finally for high GHGE (> 400 g<sub>eq fossil CO<sub>2</sub></sub> / kWh) the hybrid process leads to higher GHGE than fossil fuels (**Figure 7**). This is another example of how the relevance of the HTSE and BtL hybrid process depends on electrical power characteristics.



**Figure 7.** Raw GHGE for the standard and HTSE coupled BtL process, versus GHGE of electrical power. French and German electricity mix<sup>1,24,25</sup>, and European threshold values are shown.

### 3.4 Water use

Water consumption of energy processes is under recent and growing concern. Fresh water consumption is used in life cycle analyses and water consumption due to cooling (cold utility of heat integration) is presented in recent studies<sup>20</sup> using a process engineering approach. As electrolysis uses water as raw material, additional fresh water consumption due to electrolysis is accounted here in order to compare the hybrid process from the standard BtL process. Focusing on matter, water consumption due to upstream electrical power production or to process cooling is not accounted here. The process is always globally a net producer of water due to moisture of raw biomass; the additional water consumption is calculated then without waste water recycling facilities.

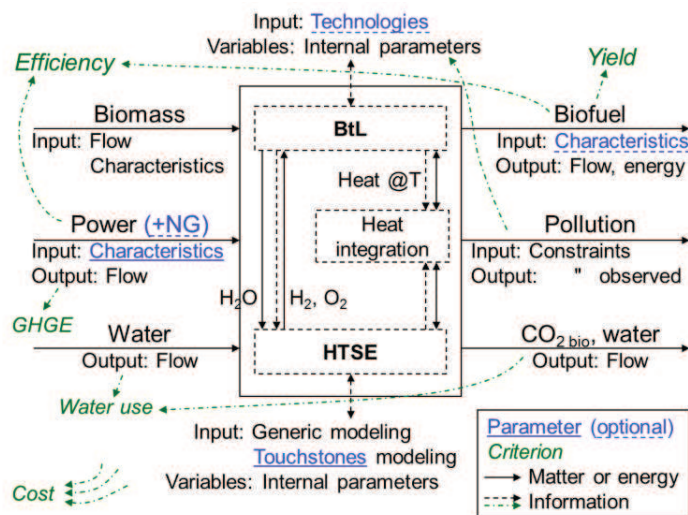
Consumption of fresh water by HTSE can be notably reduced with simple reuse of the water byproduced by the FTS. This water meets specifications for HTSE catalysts due to harsh specifications for FTS<sup>15</sup> and organics are harmless for HTSE.

### 3.5 Cost

The cost criterion is included in almost all studies of the process. Indeed the production cost of the fuel must be given special attention, as an indicator of economic suitability of the process; even though the confidence on the calculated production cost is narrow due to sensitivity to cost assessment parameters. As standard economic evaluation, the levelized cost is calculated from annualized investment and operating costs.<sup>11,26</sup> Capacity based correlations are applied for a  $100 \text{ t}_{\text{anhydrous biomass}} / \text{h}$  or  $500 \text{ MW}_{\text{biomass heat power}}$  plant; as a consequence capital expenditure (capex) cost of the integrated plant is almost twice as high as for the standard plant, matching the increase in productivity. Biomass price is 70 €/t, power 70 €/MWh and natural gas 35 €/MWh.

#### 4. Results

Simulations have been carried out for the proposed base case (**Figure 3**) for standard BtL process and electrolysis. Two technical criteria (yield or efficiency; to maximize) are used for the two main functions of the process and three other criteria (expressed per produced liquid biofuels) are presented (the standard economic criterion and two environmental criteria). Computing issues are summarized in **Figure 8**. Base case results (**Table 2**) are consistent with expectations: the use of electrolysis can nearly double the conversion of biogenic carbon, but this leads to lower performance in terms of environmental and economic criterion; the HTSE use can limit the drop in performance compared to the AE. Concerning energy, the secondary energy efficiency increases with HTSE but the equivalent primary energy efficiency is lower (39%) than the standard BtL process (42%). This is due to poor efficiency of electrical power production: the criterion in equivalent primary energy is indeed necessary. Concerning GHGE emitted by the process, they are strongly linked to power consumption in case of electrolysis, given that little natural gas is used compared to electrical power.



**Figure 8.** Framework for BtL and HTSE hybrid process evaluation.

**Table 2.** Comparison of standard and HTSE hybrid BtL process.

	Standard BtL	BtL + HTSE
Biogenic carbon yield	33%	62%
Primary energy efficiency	42%	39%
GHGE ( $\text{g}_{\text{eq fossil CO}_2} / \text{kWh}_{\text{liquid biofuels}}$ )	14	41 (59 for AE)
Additional water use ( $\text{kg} / \text{GJ}_{\text{liquid biofuels}}$ )	reference basis	+12 (+51 without water reuse)
Levelized cost ( $\text{€}_{2011, \text{France}} / \text{L}_{\text{liquid biofuels}}$ )	1.4 (capex: 0.9 B€)	1.5 (capex: 1.7 B€)

The biogenic carbon yield and additional water use are the most accurate results, directly based on flowsheet simulation. However they still suffer from major assumptions, such as fixed moisture (35%) and chosen LHV (18 MJ/kg) of the input biomass. Primary efficiency, GHGE and levelized cost strongly depend on the parameters used for their calculation. Regarding GHGE and primary efficiency these parameters are electrical power characteristics, chosen here to account for French industrial electricity mix.

## Conclusion

This paper presents the comprehensive framework for the assessment of HTSE-enhanced BtL process regarding sustainability. The challenges of the energy system and particularly second-generation biofuels lead to select five criteria: carbon matter yield; energy efficiency; greenhouse gas emissions; water use; levelized biofuels production cost. Results are presented for base case flowsheets; they allow discussing key points of the process.

The first concluding elements in studying integrated HTSE-BtL process verify that hydrogen input is almost doubling the biogenic carbon conversion compared to the standard BtL process. They bring out significant secondary energy saving for HTSE; and clear advantages over AE considering technical and environmental criteria.

HTSE is therefore suitable and promising, although its performance data is strongly linked to electrical power characterization. With a clean ( $< 150 \text{ g}_{\text{eq fossil CO}_2} / \text{kWh}$ ) and efficient ( $> 50\%$ ) production, HTSE coupling offer a more efficient biofuel production with limited environmental impact ( $< 100 \text{ g}_{\text{eq fossil CO}_2} / \text{kWh}$ ,  $+12 \text{ kg} / \text{GJ}_{\text{liquid biofuels}}$ ) and over cost ( $0.1 \text{ €}_{2011, \text{ France}} / \text{L}_{\text{liquid biofuels}}$ ) while almost doubling the productivity (biofuels/biomass). On the contrary GHGE intensive ( $> 400 \text{ g}_{\text{eq fossil CO}_2} / \text{kWh}$ ) electrical power production would lead to more GHGE than fossil fuels.

Finally the results presented suffer from major assumptions for estimated or average parameters, such as input biomass or electricity characteristics. For a specific case study, these parameters have to be chosen matching situations and sensitivity analysis have to be carried out matching inputs data accuracy; statistical evaluation would also be appropriate. Regarding the process modeling, multicriteria optimization would make the proposed comparison more accurate by providing adapted operating points for the integrated design under study; this is

currently under study. Further work would take into account multi-period issues (both characterization and modeling) in order to study the suitability of the integrated process with inconstant electrical power.

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### Abbreviations

AE, Alkaline Electrolysis;

BtL, Biomass to Liquid;

capex, capital expenditure;

EFR, Entrained Flow Reactor;

FTS, Fischer-Tropsch Synthesis;

GHGE, GreenHouse Gas Emissions;

HTSE, High Temperature Steam Electrolysis;

LHV, Lower Heating Value;

WGS, Water Gas Shift

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