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BIOMASS GASIFICATION – BASED HYDROGEN PRODUCTION SUPPLY CHAIN ANALYSIS UNDER DEMAND VARIABILITY

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ABSTRACT. In this paper, a discrete event model is developed in order to address biomass gasification based hydrogen production supply chain analysis under demand variability, with Arena software. Hydrogen production supply chain system is evaluated in terms of: hydrogen amount sold and hydrogen amount stored (MW-h), hydrogen lost sales amount (MW-h), partial sales per cent and gasification plant profit (MM Euros). Hydrogen production supply chain assessment under demand variability provide a "what if" analysis and help foresee how hydrogen demand variability, hydrogen delivery distance variation and hydrogen production cost variation would affect the entire biomass gasification based hydrogen production supply chain, especially the gasification plant, during one year time frame (8000 working hours). In order to reduce the wood chips quality degradation and dry matter losses risks over the storage period and to meet the gasification reactor requirements in terms of raw material properties a stock optimization is performed in Arena OptQuest resulting in a decrease of wood chips stock at the gasification plant and at the biomass warehouse. Hydrogen demand variation result is a decrease of gasification plant profit. Also, hydrogen delivery distance influence on gasification plant profit is more pronounced when hydrogen demand variation is higher.

Keywords: *Biomass, Gasification, Supply chain, Hydrogen production.*

INTRODUCTION

Due to outgrowing competitiveness on the market, supply chain analysis and optimization become a matter of great importance in maximizing global system revenue [1]. Supply chain analysis through discrete event simulation techniques can be applied to various types of processes from the pharmaceutical industry, food industry, chemical processes, energy conversion systems, etc. resulting in increased profit, increased service levels, better process understanding [1].

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Given the continued growth in the world's population and demands for higher standards of living and better air quality as well as the progressive industrialization of developing nations, the global demand for energy is expected to continue to escalate in the coming decades [2, 3]. Currently, the world energy production systems are mostly based on fossil fuels exploitation (oil for transportation, coal and natural gas for heating and electricity generation), resulting in large amounts of carbon dioxide emissions, main responsible for climate change and global warming [4]. The current fossil fuel systems must be changed gradually to clean and reliable energy systems, enabling to reach the sustainable vision of future energy systems [5].

Hydrogen is an energy carrier that has the potential to become a significant source of energy generation in the future, both in the transportation sector as well as for power generation [6], but in order to achieve the vision of a sustainable hydrogen based economy the entire hydrogen supply chain system must be considered, from the raw materials production, preparation and storage stages to the hydrogen production and delivery stages [7].

In this paper, a discrete event model is developed in order to address biomass gasification based hydrogen production supply chain analysis under demand variability, with Arena software. Hydrogen production supply chain system is evaluated in terms of: hydrogen amount sold and hydrogen amount stored (MW-h), hydrogen lost sales amount (MW-h), partial sales per cent and gasification plant profit (MM Euros).

This paper focuses on assessing the biomass gasification based hydrogen production supply chain, from the raw material supply, preparation and storage stages to the hydrogen production stage, from which hydrogen is delivered to consumers by pipeline transportation, as depicted in Figure 1.

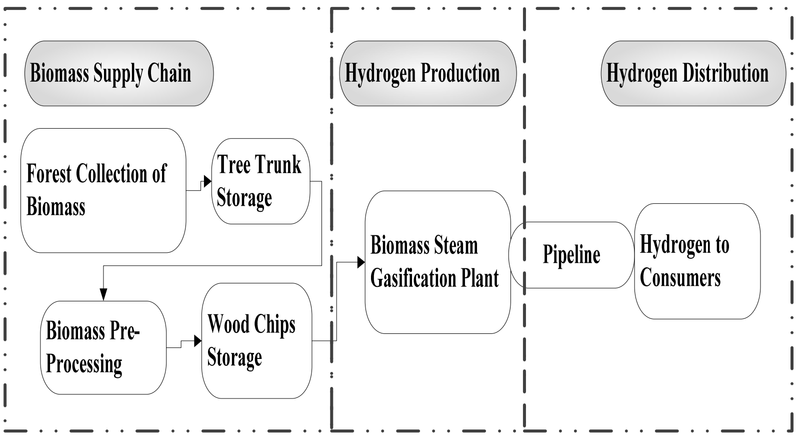


Figure 1. Hydrogen production supply chain (adapted from [7])

PROCESS DESCRIPTION

A. Biomass supply chain

Biomass represents a renewable resource that is CO_2 neutral, making it suitable for hydrogen production as the concern of global warming increases [8]. Biomass characteristics are determined by two type of analysis: ultimate and proximate analysis. The information provided by those analysis and also the calorific determination (high heating values and lower heating values) are used for evaluating the suitability for given application (hydrogen production by gasification in this case) [9]. The characteristics of biomass used as feedstock to the gasifier are given in the Table 1 [10].

Table 1. Biomass characteristics

Parameter	Units	Dry basis
Ash content	[wt.%]	0.29
Volatiles	[wt.%]	86.45
Fixed carbon	[wt.%]	13.26
Carbon	[wt.%]	50.23
Hydrogen	[wt.%]	6.04
Nitrogen	[wt.%]	0.05
Oxygen	[wt.%]	43.382
Sulphur	[wt.%]	0.005
Chlorine	[wt.%]	0.003
LHV	[MJ/kg]	13.61

The following activities are required to supply biomass from its production point to the gasification plant in order to be used as raw material for hydrogen production: collection of biomass in the forest, loading and unloading operations, transportation through the supply chain nodes, storage and pre-processing operations [11]. For the present study it is assumed that the wood is supplied from the surrounding area of hydrogen production plant, from within a radius of 25 kilometers and the wood trunks are dried naturally by open air storage for about 1-2 years [12], then they are pre-processed at the biomass pre-processing plant. Biomass pre-processing in this case involves chipping operations.

Storage throughout the biomass chain is necessary to adequately match biomass supply and hydrogen production plant demand [13]. Storage options depend on the climate, storage period, biomass processing stage and may vary from open air, roof covered and air fan [13]. Wood chips storage type for the present case is assumed to be roof covered.

B. Biomass gasification plant

There are different technologies for biomass conversion to hydrogen based either on bio-chemical or thermo-chemical processes, but main focus is the gasification of woody biomass for which various process concepts and reactor designs have been developed [14]. The hydrogen production process chosen for this study is based on biomass steam gasification in dual fluidized bed reactor system, process developed at the Institute of Chemical Engineering, Vienna University of Technology. Detailed description of the DFB system can be found in [10,15-17].

The results of an Aspen Plus® simulation model [18] for the hydrogen production process based on biomass steam gasification in dual fluidized bed reactor system are used as inputs for developing the Arena discrete event simulation model of the hydrogen production supply chain system. The main overall gasification plant performance parameters resulted from Aspen Plus® simulation and used as inputs for the Arena model are given in Table 2 [18].

Table 2. Main plant performance parameters

Parameter	Units	Value
Biomass input (40% wet, wf)	t/h	18.76
Biomass (LHV)	MJ/kg	9.59
Biomass input	MW	50
Hydrogen output	Nm^3/h	11807
Hydrogen (LHV)	MJ/Nm^3	10.79
Hydrogen output	MW	35.39
$\eta_{hydrogen}$	%	70.78

C. Hydrogen distribution and storage

Hydrogen can be stored as liquid hydrogen, main advantage being its high density at low pressure, making it efficient for truck delivery [19] or as compressed gas in high pressure vessels, method preferred for fuel cell vehicle use, because of the affordable cost and the possibility of indefinite time storage [20,21].

There are several ways of hydrogen delivery: compressed gas truck delivery, cryogenic liquid truck delivery and delivery by pipeline, the latter being the cheapest option with the highest capacity of hydrogen delivery [21]. For the present study it is assumed that hydrogen is delivered to consumers by pipeline transportation. High pressure is needed to ensure the transportation from production sites to end-users with low energy consumption (pressure drop along pipes network).

METHODOLOGY AND MODELING ASSUMTIONS

A discrete event model is developed in order to address hydrogen production supply chain analysis under demand variability, during one year time period (8000 working hours). The model is developed using Arena software and it is based on the methodology described by Tayfur and Melamed [22]. The biomass gasification-based hydrogen production supply chain consist of the following stages: biomass supplier, biomass pre-processing plant, wood chips warehouse, biomass gasification plant where the hydrogen demand arrives, as depicted schematically in Figure 2.

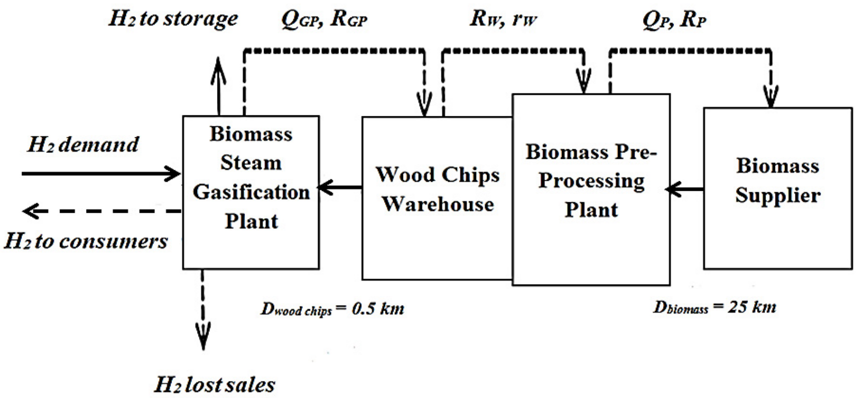


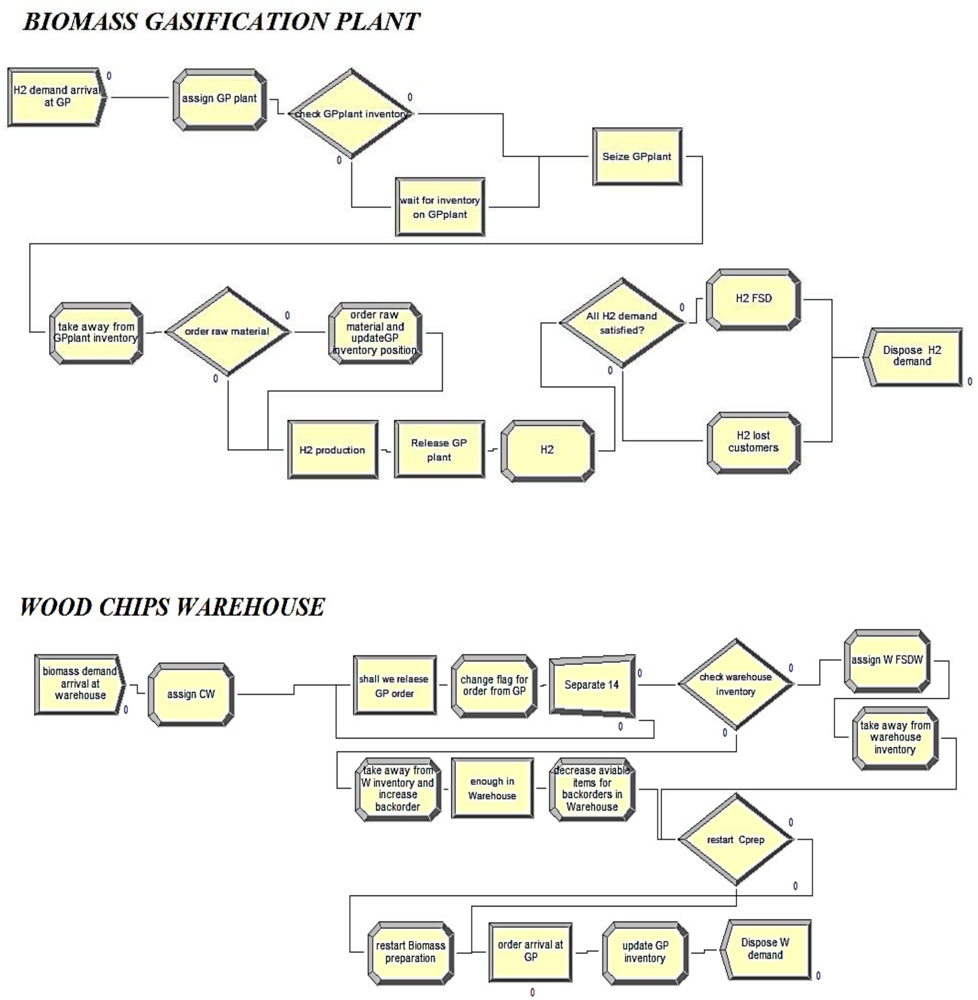
Figure 2. Gasification based hydrogen production supply chain structure (adapted from [7])

Whenever the gasification plant biomass inventory down-crosses level R_{GP}(i), a replenishment of quantity Q_{GP}(i) is ordered from the wood chips warehouse. The unsatisfied demand quantity is backordered from the warehouse [7]. The wood chips warehouse also uses a continuous review (r_W(i), R_W(i)) policy [22]. The biomass at the pre-processing plant is ordered from the supplier. The biomass pre-processing plant orders assumed to be always fully satisfied, and the inventory control policy is a continuous review (Q_P(i), R_P(i)) policy [22]. The inventory control parameters are given in Table 3.

Table 3. Inventory control parameters (tonnes)

Biomass Gasification Plant	Wood Chips Warehouse	Biomass Pre-Processing Plant
R_{GP} = 450.24	R_W = 1350.72	R_P = 706400
Q_{GP} = 112.56	r_W= 900.48	Q_P = 529.68

Each of the biomass gasification-based hydrogen production supply chain stage is modeled in Arena using a series of blocks as depicted in Figure 3. The gasification plant stage is subjected to the following events: hydrogen *demand arrival, wood chips inventory check, order more raw material from the* wood chips warehouse if necessary, hydrogen production, wood chips inventory updating, hydrogen delivery to customers, hydrogen inventory update and gasification plant profit calculation. The other stages are subjected to similar events (biomass order arrival, inventory check and updating, order shipment).



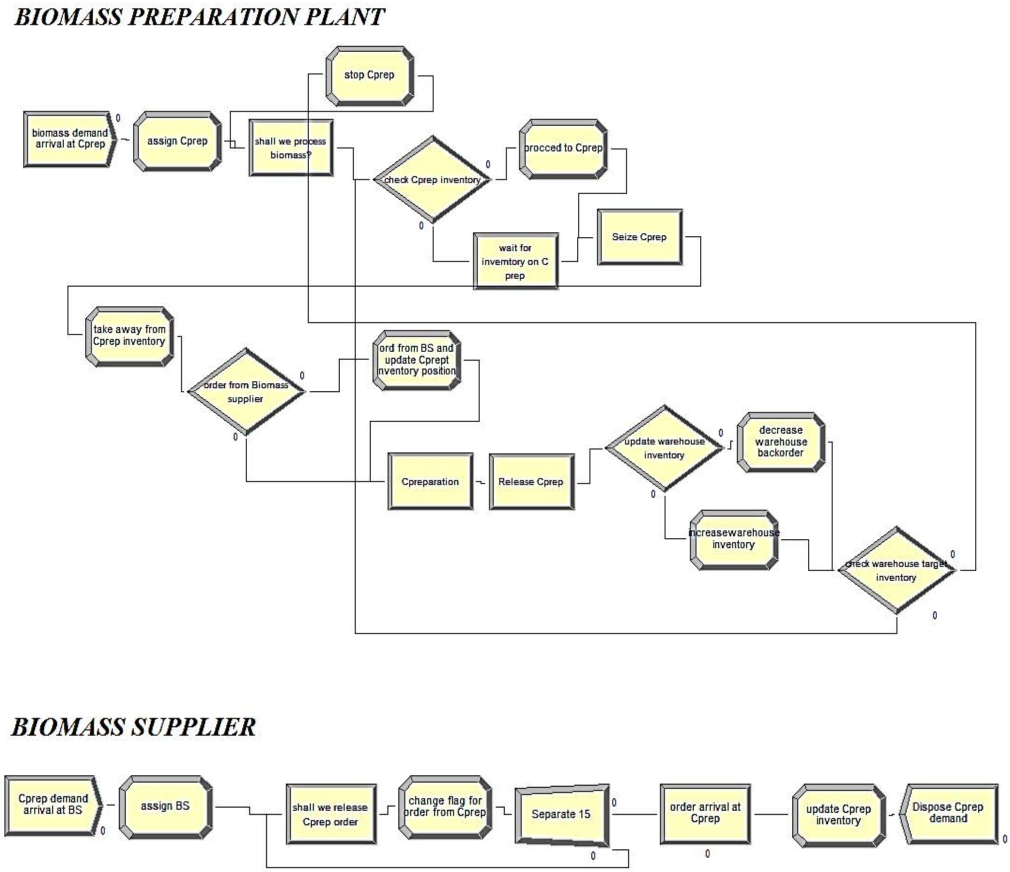


Figure 3. Arena model block diagram

The main Arena model input data are presented in Table 4. Hydrogen production cost is estimated from [23], hydrogen storage and delivery cost derived from [21]. Hydrogen is considered to be stored as compressed gas, for short term and delivered to consumers by pipeline transportation. Gasification plant profit is calculated at each discretization step, with Equation 1 and the value obtained is added to the profit value obtained from the previous step.

$$Profit_{GP} = (H_{2MP} - H_{2DC} \times D_{distance}) \times H_{2ASold} - H_{2PC} \times H_{2AProduced} - H_{2SC} \times H_{2Astored} \quad (1)$$

Table 4. Arena model input data

Tree trunk quantity	22.07 t/h
Chipping efficiency	85%
Wood chips input	18.76 t/h
Wood chips input (LHV)	50 MW
Moisture content	40%
Hydrogen output (LHV)	35.39 MW
Hydrogen production cost [a]	120 €/MW
Hydrogen storage cost [b]	5.3 €/MW
Hydrogen delivery cost [c]	12.21 €/MW/100 km
Hydrogen market price [d]	145 €/MW

[a, b, c] based on LHV, 1 € = 1.35 US $ [24], [d] (∑a, b, c) + 5% mark-up

In order to assess the biomass gasification based hydrogen supply chain the following cases are considered: hydrogen demand at the gasification plant is considered to: i) be equal to hydrogen production rate and hydrogen delivery distance is 50 km (Base case), ii) follow a TRIA (min, mlv, max) distribution of ±5% of hydrogen production rate and hydrogen delivery distance is 50 km (Case 1), iii) follow a TRIA (min, mlv, max) distribution of ±10% of hydrogen production rate and hydrogen delivery distance is 50 km (Case 2). Also for each of the cases considered hydrogen delivery distance is varied according to: i) UNIF (min, max) distribution between 10-50 km, ii) UNIF (min, max) distribution between 50-100 km. For the “Base case” hydrogen production cost is varied: i) between 100 and 120 €/MW (Optimistic Case - OC) and ii) between 120 and 140 €/MW (Pessimistic Case - PC). If the available hydrogen amount is smaller than the hydrogen demand, the current hydrogen demand is partially satisfied, or if it is bigger than the hydrogen demand, the remaining hydrogen amount is stored.

Also the following assumptions are made: the biomass transportation delays (which include transportation time, loading and unloading operations duration) distribution is also UNIF (min, max); no partial orders are delivered (the shipment is delayed until full order becomes available); the wood chips warehouse is located in close vicinity of the pre-processing plant therefore the transportations delays are neglected. Biomass is supplied from the surrounding area of hydrogen production plant, from within a radius of 25 kilometers and the distance between the wood chips warehouse and the biomass steam gasification plant is around 0.5 km.

RESULTS AND DISCUSSIONS

As mentioned above, the following assumptions are made for the Base case (BC): hydrogen demand variation is equal to hydrogen production rate, hydrogen delivery distance is 50 km and hydrogen production cost is 120 €/MW. 100 replications with 8000 hours length and 240 hours warm-up period are simulated. The results for the Base case are illustrated in Table 5.

Table 5. Base case simulation results

Time Persistent	Average value
Biomass pre-processing plant stock (t)	706458.31
Wood chips warehouse stock (t)	914.97
Gasification plant wood chips stock (t)	552.98
Output	**Average value**
Hydrogen amount sold (MW-h×10^4)	28.31
Hydrogen amount stored (MW-h)	0.00
Hydrogen lost sales amount (MW-h)	0.00
Partial sales percent×10^{-2} (%)	0.00
Profit (MM Euros)	5.35

The profit registered by the biomass steam gasification plant is 5.35 MM euros for the Base case. In order to reduce the wood chips quality degradation and dry matter losses risks over the storage period and to meet the gasification reactor requirements in terms of raw material properties a stock optimization is performed in Arena OptQuest for the gasification plant and the warehouse. The gasification plant and warehouse wood chips stocks variations are illustrated in Figure 4 for simulation time between 7900 and 8000 working hours. As can be seen in Table 4 and Figure 4 the gasification plant and warehouse wood chips stocks are quite high (gasification plant: 552.98 tonnes of wood chips – average value, warehouse: 914.97 tonnes of wood chips – average value) and also the wood chips stocks are most of the time above the reordering points. The wood chips stored amount is decreased after the optimization is performed. The control variable for the gasification plant wood chips stock is R_{GP} (reordering point – if the wood chips stock at the gasification plant decreases below the reordering point a new reshipment of material is ordered from the warehouse). The control variable is varied between 20 and 460 tons of wood chips (with a step size of 20) and the objective function is the minimization of gasification plant wood chips stock. Similar optimization is performed for the warehouse wood chips stock. The control variables are r_W and R_W, and they are varied between 80 and 900 tons (step size 20), respectively between 240 and 1360 (step size 20).

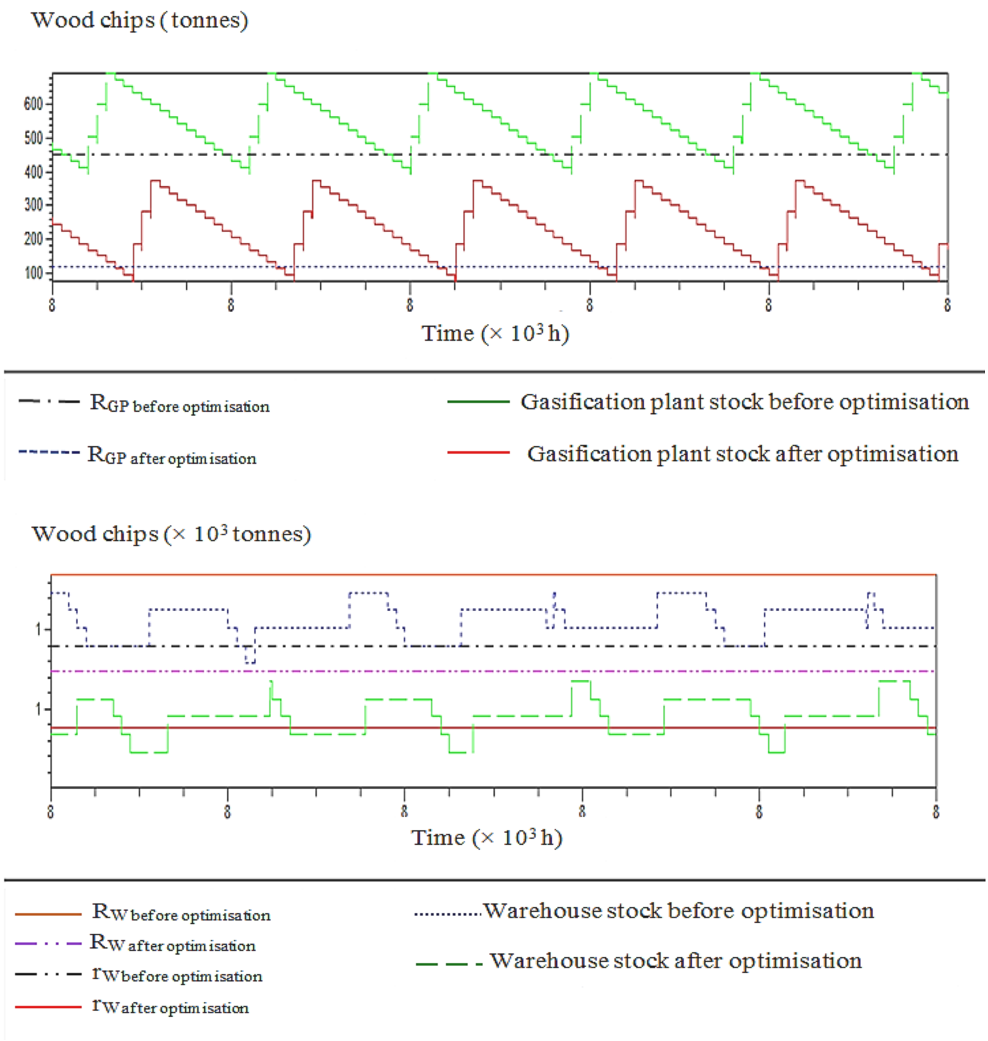


Figure 4. Wood chips stock variation

For each optimization, 100 simulations are made with 100 replications each. The optimum value found for R_{GP} is 120 tonnes which corresponds to the objective function value of 234 tonnes (wood chips – average value for wood chips stock at the gasification plant). The best values found for R_w and r_W are 740 tonnes, respectively 380 tonnes and the objective function is 367.33 tons of wood chips (average value for the warehouse stock). After the optimization step, the gasification plant and warehouse wood chips stocks are decreased by 58%, respectively by 60%.

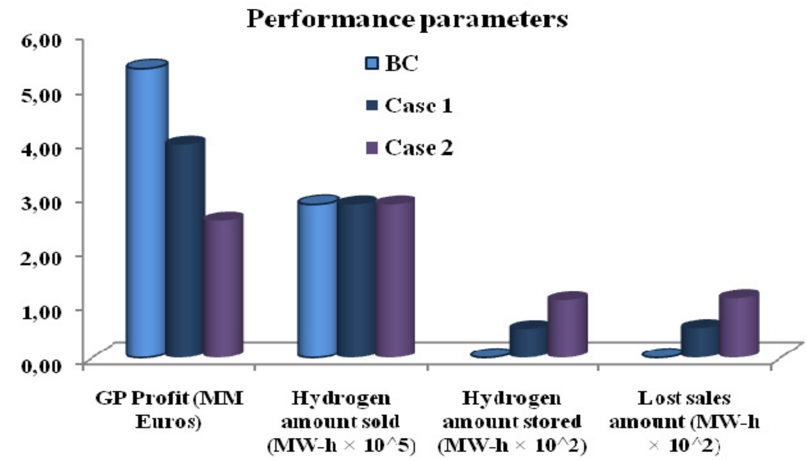


Figure 5. Hydrogen demand variation
($D_{hydrogen\ delivery}$ = 50 km, $H_{2production\ cost}$ = 120 €/MW)

Figure 5 illustrates the performance parameters considered for biomass steam gasification based hydrogen production supply chain analysis under demand variation. The gasification plant profit decreases by 26.3% for Case 1, respectively by 52.6% for Case 2, compared with the Base case. As hydrogen demand increases, hydrogen amount stored and hydrogen lost sales amount increase from zero at Base case to 53 MW-h and 55 MW-h for Case 1 and 106 MW-h and 110 MW-h for Case 2.

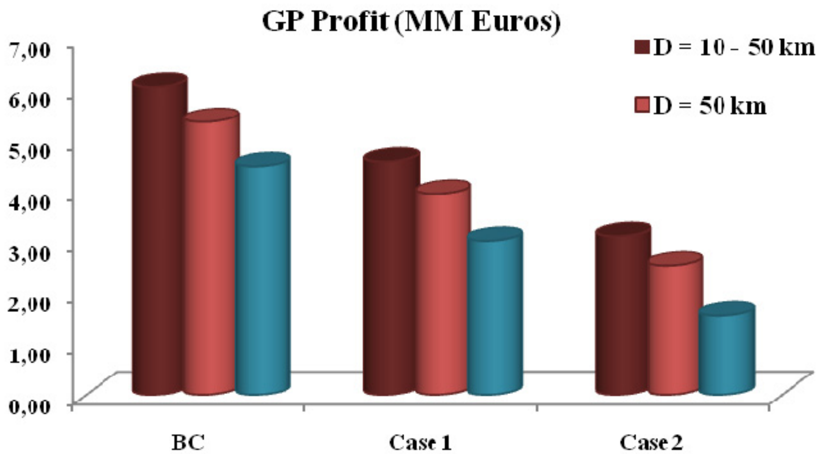


Figure 6. Hydrogen delivery distance variation
($H_{2production\ cost}$ = 120 €/MW)

For each of the three cases considered, hydrogen delivery distance is varied from 50 km to 10- 50 km and 50-100 km. The gasification plant profit variation with hydrogen delivery distance is represented in Figure 6. For the base case hydrogen production plant profit increases by 13% if hydrogen delivery distance is varied from 50 km to an interval of 10-50 km and decreases by 16% if hydrogen delivery distance is varied from 50 km to an interval of 50-100 km.

For Case 1 hydrogen production plant profit increases by 16% if hydrogen delivery distance is varied from 50 km to an interval of 10-50 km and decreases by 23% if hydrogen delivery distance is varied from 50 km to an interval of 50-100 km and for Case 2 the profit increases by 23% if hydrogen delivery distance is varied from 50 km to an interval of 10-50 km and decreases by 39% if hydrogen delivery distance is varied from 50 km to an interval of 50-100 km. Hydrogen delivery distance influence on gasification plant profit is more pronounced when hydrogen demand variation is higher.

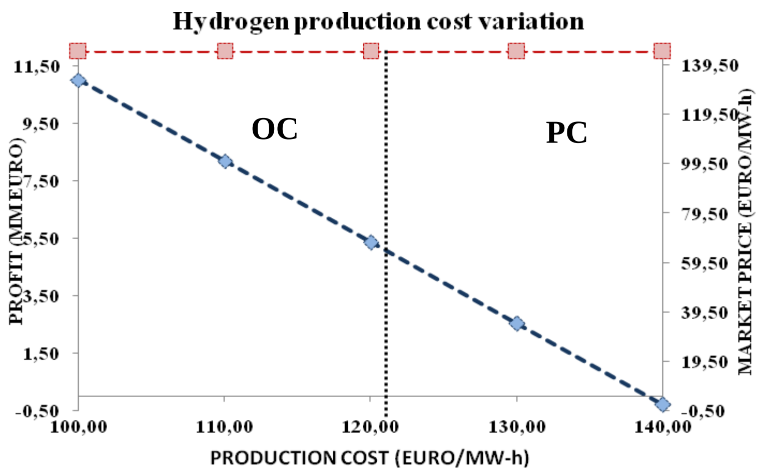


Figure 7. Hydrogen production cost variation
($H_{2\ demand} = H_{2\ production\ rate}$, $D_{hydrogen\ delivery} = 50$ km)

Figure 7 illustrates hydrogen production cost influence on gasification plant profit, for the Base case. In the Optimistic case (OC) it is assumed that hydrogen production cost decreases from 120 €/MW to 110 €/MW and 100 €/MW. In this case, the hydrogen production plant profit increases by 53%, respectively by 103%. In the Pessimistic case (PC) it is assumed that hydrogen production cost increases from 120 €/MW to 130 €/MW and 140 €/MW. Gasification plant profit decreases from 5.35 MM Euros to 2.5 MM Euros and to -0.3 MM Euros. Hydrogen market price it is assumed to be constant (145 €/MW).

CONCLUSIONS

Hydrogen production supply chain assessment under demand variability provide a “what if” analysis and help foresee how hydrogen demand variability, hydrogen delivery distance variation and hydrogen production cost variation would affect the entire biomass gasification based hydrogen production supply chain, especially the gasification plant, during one year time frame (8000 working hours).

In order to reduce the wood chips quality degradation and dry matter losses risks over the storage period and to meet the gasification reactor requirements in terms of raw material properties a stock optimization is performed in Arena OptQuest resulting in a decrease of wood chips stock at the gasification plant and at the warehouse.

Biomass gasification based hydrogen production supply chain system is evaluated in terms of: hydrogen amount sold and hydrogen amount stored (MW-h), hydrogen lost sales amount (MW-h), partial sales per cent and gasification plant profit (MM Euros). Hydrogen demand variation result is a decrease of gasification plant profit. Also, hydrogen delivery distance influence on gasification plant profit is more pronounced when hydrogen demand variation is higher.

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REFERENCES

[1]. M. Muresan, C.C. Cormos, P.S. Agachi, *Proceedings of the 22nd European Symposium on Computer Aided Process Engineering* (ESCAPE 22, London, UK, 17 - 20 June 2012), *Computer Aided Chemical Engineering*, **2012**, *30*, 462-466.
[2]. M. Ball, M. Wietschel, *International Journal of Hydrogen Energy*, **2009**, *34*, 615-627.

[3]. K.K. Pant, R.B. Gupta, Hydrogen fuel: production, transport and storage, Fundamentals and Use of Hydrogen as a Fuel, *CRC Press*, Taylor & Francis Group, 6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742, **2009**.
[4]. K.E. Zanganeh, A. Shafeen, *International Journal of Greenhouse Gas Control*, **2007**, *1*, 47-54.
[5]. H.Dagdougui, *International Journal of Hydrogen Energy*, **2012**, *37*, 5318-5327.
[6]. A. Bhattacharya, A.Bhattacharya, A. Datta, *International Journal of Hydrogen Energy,* **2012**, *37*, 18782-18790.
[7]. M. Muresan, C.C. Cormos, P.S. Agachi, *Chemical Engineering Research and Design*, **2013**, *91, 8*, 1527-1541.
[8]. M.B. Nikoo, N. Mahinpey, *Biomass and Bioenergy*, **2008**, *32*, 1245-1254.
[9]. J. Rezaiyan, N.P. Cheremisinoff, Gasification technologies, *CRC Press,* Taylor & *Francis Group,* 6000 Broken Sound Parkway NW, Suite 300 Boca Raton, FL 33487-2742, **2005**.
[10]. S. Koppatz, C. Pfeifer, H. Hofbauer, *Chemical Engineering Journal*, **2011**, *175*, 468-483.
[11]. A.A. Rentizelas, A.J. Tolis, I.P. Tatsiopoulo, *Renewable and Sustainable Energy Reviews*, **2009**, *13*, 887-894.
[12]. WP 2.1 - 2.2 Case Report: Biomass CHP Plant in Güssing, Austria *http://www.biomob.eu*, April, **2013**.
[13]. S. Gold, S. Seuring, *Journal of Cleaner Production*, **2011**, *19*, 32-42.
[14]. S. Koppatz, C. Pfeifer, R. Rauch, H. Hofbauer, T. Marquard-Moellenstedt, M.Specht, *Fuel Processing Technology,* **2009***, 90*, 914-921.
[15]. H. Hofbauer, G. Veronik, T. Fleck, R.Rauch, The FICFB gasification process, in: D.B.e.A.V. Bridgewater (Ed.), Developments in Thermochemical Biomass conversion, Banff, Canada, vol. 2, Blackie, Glasgow, UK, **1997**.
[16]. H. Hofbauer, R. Rauch, G. Loeffler, S. Kaiser, E.Fercher, H.Tremmel, *12th European Conference on Biomass and Bioenergy*, Eigenverlag, Amsterdam, **2002**.
[17]. S. Muller, J. Kotik, T. Proll, R. Rauch, H. Hofbauer, *Proceedings on Polygeneration Strategies (ICPS 11)*, **2011**, Wien, Austria.
[18]. M. Muresan, R. Rauch, H. Hofbauer, C.C. Cormos, P.S. Agachi, *ICPS 13 - International Conference on Polygeneration Strategies*; Vienna University of Technology, Vienna, Austria**;** September, 3rd - 5th, **2013**.
[19]. S.M. Aceves, G.D. Berry, J. Martinez-Frias, F.Espinosa-Loza, *International Journal of Hydrogen Energy,* **2006**, *31*, 2274-2283.
[20]. V. Ananthachar, J.J.Duffy, *Solar Energy*, **2005**, *78*, 686-694.
[21]. M. Balat, *International Journal of Hydrogen Energy*, **2008**, *33*, 4013-4029.
[22]. A. Tayfur, B. Melamed, Modelling supply chain systems. Simulation modelling and analysis with Arena, *Academic Press, Elsevier*, **2007**.
[23]. R.G. Lemus, J.M. Martınez Duart,*International Journal of Hydrogen Energy*, **2010**, 35, 3929-3936.
[24]. Curs BNR, *http://www.cursbnr.ro*, February, **2013**.