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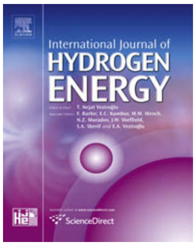

Modeling the energy potential of biomass – H_2RES

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ABSTRACT

Modeling biomass as a renewable energy source poses many challenges with respect to feedstock variability, which are difficult to account for. It is found that at the preliminary stages of energy planning, heating value and moisture content of the feedstock are the most important factors. In addition, the effects of harvesting, transportation and storage are found to be significant even though they are often overlooked. Using the gathered information a biomass module for energy planning is created and integrated to H_2RES, a renewable energy planning program. Using this excel based software, a case study for a wood processing factory is performed, using the waste wood as feedstock. Comparing various scenarios, it is concluded that using a combination of solid oxide fuel cells, solar panels and steam turbines can satisfy the factories energy requirements with excess sold to the grid.

1. Introduction

Biomass is an indispensable and often overlooked resource when assessing potential renewable energy sources. Its main advantage, compared to other renewable sources, is the ability to store feedstock and use it when required, like traditional fossil fuels. Its low density however, goes against the economics of the whole process. Nevertheless, about 3000 EJ/year of energy is stored in land biomass. With world primary energy consumption of 451 EJ/year (2002), this means over six times more energy is stored in biomass than is currently being consumed [2].

In addition to the density, biomass feedstock is faced with many other challenges, which result from external factors. Energy, chemical composition, moisture and production quantities vary yearly, seasonally and even daily (in the case of municipal solid waste (MSW), for example). These variations in the feedstock consequently affect the energy conversion process with issues such as; fouling, corrosion, flame instabilities, etc. These hinder the overall process even further. This makes energy planning from biomass challenging.

To further complicate things, little to no consideration is given to the influence of harvesting, transportation and storage on the biomass feedstock. This is understandable when bearing in mind that a plethora of factors need to be taken into account. However, the conclusion is that every potential site needs to consider this, and may do so with access to more accurate, local information on the topic.

The purpose of this paper is to gauge the biomass energy potential for a typical Croatian wood furniture factory using the H_2RES renewable energy planning software. The methodology of this paper assesses the pertinent criteria when modeling the energy potential of biomass. The information is used to develop and integrate a biomass module for the H_2RES software; consequently there is a focus on biomass to hydrogen conversion. The results are tabulated using the biomass module for the case study. They demonstrate the value of biomass as a renewable energy source and validate the model.

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2. Methodology

2.1. Biomass feedstock

Any type of biomass can be converted into energy. Due to the broad base of potential sources however, the main characteristics which affect the energy potential of the feedstock need to be compiled and highlighted. First, these sources need to be identified. Then important features can be minimized.

2.1.1. Types

Biomass can be categorized into three different groups; agricultural wastes, energy crops and refuse.

2.1.1.1. Agricultural waste. Agricultural waste is of interest because it's exactly that, waste. In some cases it's sown back into the ground or used as animal bedding. In others it's burned or landfilled, and hence a valuable source of energy is being discarded.

Agricultural waste can be divided into wood waste, manure, temperate and tropical crop wastes. Wood waste is an important source of energy since it is often ignored; mill wastes, trimmings and forest residues are commonly left to rot or go to landfill. Manure is produced from farm animals and is a very good energy source due to its high volatility. Collecting it also helps reduce the green house effect since it captures the otherwise released methane.

Temperate and tropical crop residues vary mainly in the quantity of waste they produce. Most temperate crops such as wheat and corn are of the C3 class, which is indicative of the important role that molecules with three carbon atoms play. Plants need both CO_2 and sun for photosynthesis to occur. When sun is plentiful and there's a lack of CO_2 plants can be damaged. In this case C3 plants use a process called photorespiration which is the reverse of photosynthesis. This is a safety mechanism to protect the plant, but no useful energy is produced and hence the plant does not grow. Tropical crops such as sugar cane and rice, on the other hand, are generally of the C4 group, which store CO_2 for times when it is lacking. This results in faster growing, larger plants.

The main problem with agricultural waste is collection. Since it is waste, it's produced in a dispersed fashion. Moreover, the density is low which increases transportation costs and further puts into question the economics of such an energy source. Most beneficial biomass to energy facilities are placed on site where the waste is produced. Such as large farms, saw mills, sugar refineries or olive oil pressing factories, as examples. Energy from manure is also more economical for animals in closed spaces such as dairy cows and pigs where the waste is easily collected.

2.1.1.2. Energy crops. Energy crops are grown for the sole purpose of being converted to energy. The interest is intertwined with mitigating greenhouse gas emissions. Energy crops are considered CO_2-neutral, when they are harvested sustainably, since they consume as much during growth as they release during the energy conversion process. They can be converted to heat, electricity or biofuels. Other benefits are usage of surplus agricultural land and reducing the dependence on oil.

Energy crops can be divided into woody or grassy groups. Woody energy crops such as willow or poplar trees (C3 group) grow faster compared with other trees and has higher densities than grassy ones. However, experience with wood suggests that it's hardly grown in a sustainable fashion, leading to environmental concerns [2]. The concept of short rotation forestry or short rotation coppice implies periodically cutting and allowing re-growth of forests, systematically.

Grassy energy crops are generally of the C4 category due to their higher yields. Favored types are sugar cane and maize, but also miscanthus is gaining interest since it grows well in temperate climates. Energy crops can also be grown for their oils such as rapeseed, soya beans, sunflowers, which can be used as a substitute for diesel.

Energy crops however, do raise certain environmental concerns such as great land use, soil desertification, water table contamination due to fertilizers and loss of biodiversity.

2.1.1.3. Refuse. Refuse is basically waste that is not agricultural which consists of municipal solid waste (MSW), industrial and commercial wastes. Refuse can be a jumble of things; metals, plastics, ceramics, etc. In addition, they can contain hazardous chemicals, biological or even radioactivity mater. Therefore they pose special problems.

The attraction in converting refuse is mainly to reduce landfill quantity and to sterilize hazardous materials. Creating energy from this source is gaining momentum around the world. But due to the inherent composition of refuse, the by-products pose great environmental problems. There exist many solutions to mitigate these, but the key lies in understanding the nature of the refuse and separating it prior to being converted.

2.1.2. Characteristics

The characteristics of biomass are very important since they can vary greatly from location to location, seasonally and yearly. McKendry [3] states that the influential characteristics of biomass that are of greatest interest are:

- moisture content;
- heating value;
- fixed carbon and volatile mater proportions;
- ash content;
- alkali metal content;
- cellulose and lignin ratio.

When energy planning, it is clear that the heating value of the fuel is the most important characteristic. In general biomass has much lower energy content (EC) than traditional fuels since it has a low carbon and high oxygen content. Typically the dry ash free energy content of biomass can be estimated as 20.4 MJ/kg ±15% [28].

The moisture content (MC) is the second greatest factor, affecting the heating value of the fuel; 10% increase in MC means 11% decrease in LHV [2]. The MC can vary widely depending on the type of biomass, the environmental conditions and the degree of drying. In general biomass fuels with a MC higher than 55% are not combusted or gasified. On the other hand, a high MC is suitable for digestion or fermentation.

A benefit of biomass is that, in general, it has a low to negligible sulphur and metal content. However, ash content is high which leads to fouling, and traces of chlorine might be present causing corrosion in the equipment.

Biomass is also highly volatile, being constructed of mostly cellulose, hemi-cellulose and lignin. This promotes a lower flame temperature, but a highly volatile fuel with reactive char. Table 1 gives a general comparison of biomass characteristics with those of coal.

When energy planning, the goal is to identify the potential energy. Therefore, issues with flame stability, corrosion, fouling, etc. can be ignored at this preliminary stage. They help define mitigation measures and maintenance issues for the conversion process. It can then be concluded that the heating value and moisture content are the major characteristics to consider.

Another characteristic not mentioned here is the density. It does not relate to the energy potential but should be considered during the economic feasibility portion of the assessment. It is estimated that transportation accounts for 70% of the total delivered fuel cost [3], and this value is surely to rise with that of fossil fuels. Tables 2 and 3 show the density and transportation costs, respectively for certain biomass.

The easiest way to identify the heating value is to have the ultimate analysis of the feedstock, giving the elemental composition, on a dry basis. This allows calculation of the higher heating value (HHV) of the fuel. Then knowing the MC it's possible to determine the lower heating value (LHV).

2.2. *Harvesting and storage*

Harvesting and storage loses of biomass can be quite considerable depending on the conditions in which these occur. A study in the US concludes that these loses can be quite detrimental on the economics of energy production from biomass [13]. Unfortunately, very little information is available relating to this topic. This section will summarize some of the reports found.

Table 1 – Physical, chemical and fuel properties of biomass and coal fuels [1].

Properties	Biomass	Coal
Fuel density (kg/m^3)	~500	~1300
Particle size	~3 mm	~100 μm
C-content (wt% of dry fuel)	42–54	65–85
O-content (wt% of dry fuel)	35–45	2–15
S-content (wt% of dry fuel)	Max. 0.5	0.5–7.5
SiO_2-content (wt% of dry ash)	23–49	40–60
K_2O-content (wt% of dry ash)	4–48	2–6
Al_2O_3-content (wt% of dry ash)	2.4–9.5	15–25
Fe_2O_3-content (wt% of dry ash)	1.5–8.5	8–18
Ignition-temperature (K)	418–426	490–595
Peak-temperature (K)	560–575	–
Friability	Low	High
Dry-heating value (MJ/kg)	14–21	23–28

2.2.1. *Issues*

The changes that occur during biomass storage range from moisture content variation, loss of dry matter (DM), release of GHGs, changes in chemical composition and most importantly loss in energy content. These vary quite significantly based on type of biomass, storage environment, weather variations, etc. For the purpose of energy modeling the concerns are with MC, DM loss and reductions in EC.

2.2.1.1. *Moisture content*. MC is not easily predicted since it is mainly affected by the storage method, type of biomass and weather conditions. A study from Sweden compares the storage of whole wood and reduced wood chips in piles [14]. It concluded that the average MC in whole wood stayed relatively constant over a year with increases in fall of up to 45% for those stored outside. Reduced wood chips seemed stable for the first 6–9 months but MC increased afterwards. Another study measuring the storage of wood pellets found that moisture content varied between 10 and 19% over 5 months, eventually reaching equilibrium with atmospheric conditions [15].

2.2.1.2. *Dry matter loss*. Dry matter is lost during both harvesting and storage. Stems of crops are usually left after cutting and matter is dropped during collection. A study on switchgrass in the US concluded that over three seasons the average loss due to bailing was between 1.8 and 6% by weight [16].

During storage DM losses vary greatly depending if storage is in or outdoors and also based on the pile size. From the Swedish wood study DM loses of 11, 27 and 47% were noted for wood left 'as is' in the forest from April to August, April to October and for 1.5 years, respectively [14]. The same study notes for piles left on the roadside DM loses of 0.1 and 0.4%/month for piles of 120 m^3 over 9 months and 600 m^3 over 6 months. Reduced wood chip piles of 55 m^3 in size over 4 months reported losses of 5.5%/month. The losses for the reduced wood however, were mainly due to decomposition, as opposed to the whole wood which was due to physical losses. To mitigate this, it was noted that chipped wood dried to less then 20% MC lost only 0.25%/month of DM over 9 months.

Table 2 – Density of biomass for various feedstocks [3].

Biomass	Bulk volume (t/m^3, daf)[a]	Bulk density (t/m^3, daf)
Wood		
Hardwood chips	4.4	0.23
Softwood chips	5.2–5.6	0.18–0.19
Pellets	1.6–1.8	0.56–0.63
Sawdust	6.2	0.12
Planer shavings	10.3	0.1
Straw		
Loose	24.7–49.5	0.02–0.04
Chopped	12.0–49.5	0.02–0.08
Baled	4.9–9.0	0.11–0.20
Moduled	0.8–10.3	0.10–1.25
Hammer milled	9.9–49.5	0.02–0.11
Cubed	1.5–3.1	0.32–0.67
Pelleted	1.4–1.8	0.56–0.71

a Dry, ash-free tonnes.

The same US study on switchgrass compared losses from various storage methods on bails [16]. Bails stored indoors, outside on gravel and sod showed losses of -1.6– 2.2, 4– 4.7 and 5.6– 6.0%, respectively over 12 months. The negative indoor value was attributed to errors in the initial weighing method for one bail. It was concluded that loses indoors are the lowest with outdoor on the sod being the worst. The advantage of gravel storage was noted to be the ability of water to be removed from around the bail. This led to less decomposition of the surface in contact with the ground and hence lower loses.

2.2.1.3. *Energy content*. Generally, variations in EC are due to changes in MC, DM and the result of natural decomposition in biomass. The cellulose and hemi-cellulose are converted to lignin releasing CO_2, methane and water, in the right conditions ethanol can even be produced. This results in an increase of ash and reduction in EC. Wihersaari [17] concludes that these emissions are significant and should not be ignored when storing biomass.

Although few studies conclude on the specific EC changes in biomass storage, the Swedish wood study [14] says this: whole wood in piles of 120 m^3 over 9 months and 600 m^3 over 6 months showed changes of $+4$ and -3%, respectively. The EC content was calculated for LHV and the reported increase was related to the reduction in MC. Wood chips however showed an energy loss of 6.8– 21.4% over 6 and 9 months, respectively. It was concluded that EC variation are due to pile size, particle size, initial MC and quantity of bark and needles.

A study observing the carbon and nitrogen change in pig and cow manure concludes similar findings with reductions in carbon content over time [18]. The carbon in the manure was converted to methane, up to 45% in the center of the 1.1 m deep pile over 3 months.

2.2.2. *Findings*

There are no definitive values in terms of storage and harvesting loses in biomass. It is clear however, that pile size, size of particles, storage location, initial MC, atmospheric conditions and type of biomass need to be considered with respect to this.

Wood in general should be stored whole as opposed to chipped for longer periods. Grassy biomass should be sheltered from the weather and if possible dried prior to this. Manure should not be stored for long periods since methane conversion occurs fairly quickly.

2.2.3. *Other options*

To mitigate adverse storage effects, there exist many other options. Sims and Venturi [19] recommend cutting fast growing eucalyptus over the whole year on a need basis reducing storage and transportation costs. Consequently DM and EC losses will also be mitigated. This method ties into the concept of sustainable farming.

Table 3 – Transportation costs for various feedstocks [3].

Biomass type	Harvested form	Cost (£/dmt)[a]
Forest residues	Timber off-cuts	32–7
Cereal straw	Hesston bales[b]	28
SRC	Chipped timber	47–54

a Dry matter tonnes.
b Large rectangular bales, typically 1 t weight.

Another paper assesses the feasibility of using mobile fast pyrolysis for the same reasons; with the addition of densifying the biomass for ease of transport [20]. This concept would bring the conversion process straight to the source. It has many advantages and its development should be monitored.

2.3. *Transportation and collection*

The transportation of feedstock is what mostly affects the economics of biomass as an energy source, due to its low density. Collection cycles for the biomass are then affected by this last and consequently the availability of feedstock.

Biomass is similar to other renewable energy sources in the sense that yields are related to environmental conditions and hence variable. Considering this variability, harvesting periods, yields, industrial waste production or even MSW collection days it should be noted that biomass might not always be available and with the quantities required. Therefore it's crucial to understand the variations of available feedstock over a year when energy planning with biomass.

2.4. *Conversion process and output*

To produce useful energy, biomass can be converted many different ways using different technologies. They can be categorized into three main groups; thermochemical and biochemical conversion and extraction. The type chosen is based on the desired end-product and the feedstock's characteristics. For example, biomass with low MC is generally good for thermochemical processing and high MC for biological [3].

2.4.1. *Thermochemical conversion*

This type of conversion requires heat to extract the energy trapped in the feedstock. Typical end-products are heat, electricity, producer gas or bio-oil. Sub-categories of this conversion are; direct combustion or upgrading the fuel via gasification or pyrolysis.

2.4.1.1. *Combustion*. Combustion is the most cost effective and wide-spread method to extract useful energy from biomass. The process is common for heating in developing countries or in rural areas. Larger facilities use the heat from combustion to produce steam and run a turbine generator set for electricity. Modern facilities do both, using steam for electricity and the waste heat for heating which greatly improves the overall efficiency of the system.

Biomass with a MC $> 50\%$ is generally not suitable for combustion since the energy required to evaporate the water greatly reduces the efficiency. Feedstock should be dried as much as possible prior to combustion. Combustion gases range in temperature from 800 to 1000 °C.

There exist various types of systems; pile burning, grate fired (stationary, traveling, vibrating), suspension fired and fluidized bed (bubbling (BFB) and circulating (CFB)). Each has its advantages and disadvantages based on efficiency and quality of combustion, leading to reduced un-burnt fuel emissions. In general from pile burning through to fluidized bed combustion implies increase in efficiency, quality of combustion and price.

2.4.1.2. *Gasification*. Gasification involves partially oxidizing the fuel using air or oxygen and steam. The process takes place between 800 and 1000 °C and from 0 up to some 30 atmospheres of pressure [2]. The advantage of such conversion process is to upgrade the quality of the fuel. By gasifying the feedstock, gas cleaning is possible and it can then be used for many other purposes than simply direct heat. The gaseous product of this process is called producer gas and is a mix of combustibles (carbon monoxide and hydrogen with methane and other HC's and condensable tars) along with CO_2 and water [2]. The producer gas is then combusted in a gas turbine, hydrogen and other HC's separated or synthetic gas made. However, some contaminants must be removed from the producer gas prior to further conversion. Table 4 is a summary of these elements, the problems they cause and what method can be used to extract them.

There are two main types of gasifiers; fixed and fluidized bed. Fixed-bed gasifiers are the traditional technology and can be further differentiated by the direction of the air flow; Updraft, downdraft and cross-flow. For more detailed information see ref. [5]. The energy content of the resulting gas is about 75% of the initial feedstock, but initial MC should be less that 15–20% [5].

Fluidized bed (FB) gasifiers have been used for many years with coal. Their main advantage over the fixed bed type is the uniform temperature distribution in the gas chamber. This leads to more complete gasification of the fuel and hence higher efficiencies. There are two main types of gasifiers; circulating (CFB) and bubbling (BFB).

One major factor which contributes to the quality of the produced gas is the gasifying agent (see Table 5). It should be noted however that there is a sharp rise in cost as the quality is increased. For this reason, most gasifiers use air and steam since other agents are not economical with current technologies.

Other research suggests that combining the gasification process with absorption reactions further increases the process efficiency [30]. By adding calcium oxide (a CO_2 sorbent) to pine bark the carbon conversion efficiency increased by 83.5– 56% from the base case. The total gas and hydrogen yield also increased by 62 and 48.6% respectively. It was noted that the additive acted both as a catalyst and a sorbent.

Table 4 – Producer gas contaminants: problems and cleanup processes [24].

Contaminant	Examples	Problems	Cleanup method
Particulate	Ash, char, fluid bed material	Erosion, emission	Filtration, scrubbing
Alkali metals	Sodium and potassium compounds	Hot corrosion	Condensation and filtration
Fuel nitrogen	Mainly NH_3 and HCN	NOx formation	Scrubbing, SCR
Tars	Refractory aromatics	Clog filters, deposit internally	Tar cracking, scrubbing
Sulphur, chlorine	H2S, HCl	Corrosion, emission	Lime scrubbing

Another interesting application of gasification is with respect to hydrogen production. One paper [25] discusses the potential of integrating a solid oxide fuel cell (SOFC) with gasification and a steam turbine. The high temperature output gas of the gasification process is an excellent match to the operational characteristics of the SOFC. The gas not converted in the fuel cell is further combusted and sent to a turbine where more electricity and heat is extracted.

When obtaining hydrogen from biomass using steam in a gasification process, it was found that, amongst other factors, the hydrogen yields are most sensitive to the equivalence ratio [26]. It was possible to obtain 128 g of H_2 per kg of daf biomass, or 78% of the theoretical total, at an equivalence ratio of 0.0, a steam to biomass ratio of 1.7 and a reactor temperature of 850 °C [26].

2.4.1.3. *Pyrolysis*. Pyrolysis is similar to gasification except the fuel is not oxidized. The process takes place around 500 °C in the absence of oxygen. During the process the volatiles are gasified, leaving solid char. Traditionally wood was used to produce charcoal via this process, except the volatiles were not collected. Since biomass is comprised of mostly volatiles this was very wasteful. Present day technology condenses the gas to produce bio-oil, a substitute for petrol products. This oil can then be used for heating or in a gas turbine for electricity or treated and used in vehicles. McKendry [4] reports that if flash pyrolysis is used bio-oil can contain as much as 80% of the initial feedstock energy. When it comes to hydrogen production, up to 47.9% conversion efficiency is possible, based on the HHV [27].

2.4.2. *Biochemical conversion*

Biochemical conversions use natural processes to decompose the biomass into smaller hydrocarbons in a controlled environment. Anaerobic digestion (AD) and fermentation are used to produce gas and liquid biofuels, respectively.

2.4.2.1. *Anaerobic digestion*. Using bacterial action in a warm and wet environment this process produces mainly methane (50–75% of total gas vol.) and CO_2 with traces of hydrogen sulfide. In general the process occurs at mesophilic temperatures (~35 °C), and higher temperatures yield higher biogas rates and shorter residence times in the digester.

Table 5 – Effect of gasifying agent on producer gas quality [5].

Quality of gas	Heating value (MJ/Nm^3)	Gasifying agent
Low	4–6	Air and steam/air
Medium	12–18	Oxygen and steam
High	40	Hydrogen and hydrogenation

Unfortunately higher digester temperatures are not economical since then most of the gas produced must be used to heat the digester tank, depending on the environmental conditions. The moisture content of the slurry should also be between 80 and 95%. This is why manure is a great feedstock for such systems. MSW and sewer sludge (solid by-product from sewage treatment plants) can also be used to help decontaminate the waste and reduce landfill needs; the methane release to atmosphere is also mitigated. Any other biomass can also be used. The solid by-product of the process can be sold as a fertilized, depending on the contaminants of the initial feedstock.

The gas can then be used in an IC engine or in a micro-turbine to produce electricity. The waste heat can be used to heat the digester or for other process heating. The gas can also be stored and redistributed as needed. Except the storage, compression equipment and energy requirements are high which significantly reduce the benefits of such systems. The conversion efficiency from feedstock to gas is 20–50% of the initial energy content. Electrical efficiency is then 10–16% [4].

2.4.2.2. Fermentation. Fermentation is another anaerobic process by which microbes convert sugars to alcohol. The process then produces ethanol that can be used as an additive to gasoline in normal engines or as the primary fuel in converted engines such as in Brazil. The ethanol can also be used in the esterification process used to create bio-diesel from bio-oils. Sugar crops (sugar cane, sugar beet) or starch crops (maize, wheat) are best suited for this. Corn will yield about 450 l of ethanol from 1 dry t [4]. The by-products can be used as cow feed or in the case of bagasse, it can be further converted using a combustor or a gasifier [12].

2.4.3. Extraction

The final method to convert biomass is through mechanical pressing of the feedstock; about 3 t of rapeseed gives 1 t of oil [4]. The useful product is oil that can then replace petrol products. In most cases, this bio-oil can directly be used in a diesel engine except it leaves carbon deposits in the cylinders which can damage the engine. If the oil is further treated using ethanol via the simple esterification process bio-diesel is created. Only minor modifications to the engine are needed in such case. A by-product of esterification is glycerine, which is used to make soap.

The energy content of bio-oils is about 37–39 MJ/kg, this is only slightly less than diesel (~42 MJ/kg). Other than oil, extraction produces a solid cake than can be used as animal fodder.

2.5. Modeling

Based on the information presented in the previous sections it is clear that there are a large number of factors to consider when using biomass as an energy source. However, when at the stage of energy planning many of these things can be approximated or even neglected. Once the energy potential has been identified then other, more in-depth studies can be done.

2.5.1. Feedstock

As seen previously the most influential characteristics of biomass for energy planning are the initial energy and moisture content of the feedstock and their variation over time. The density is also important simply to have a feel for the transportation costs. The collection frequency over a year is also key in knowing how much feedstock is available and when.

2.5.1.1. Energy and moisture content. To calculate the energy content of the feedstock, Sheng and Azevedo [21] conclude that using the ultimate analysis gives a more accurate estimate. They compare many existing formulas to estimate the $\mathrm{HHV_{dry}}$ and propose their own which is the most accurate; greater than 90% in the ±5% range. All heating values are in MJ/kg.

$$HHV_{dry} = -136.75 + 31.37 \times C + 70.09 \times H + 3.18^{*}O^{*} \tag{1}$$

Where,

$$O^{*} = 1 - C - H - ash \tag{2}$$

C, H and ash are given as a mass ratio on a dry basis; MC is given on a wet basis. To further calculate the $\mathrm{LHV_{wet}}$ Phyllis [22] give the following formulas.

Table 6 – Comparison of HHV formula and actual data [22].

Product	Ultimate analysis (%)			Measured (MJ/kg)		Calculated (MJ/kg)		Difference (%)	
	C	H	O	HHV	LHV	HHV	LHV	HHV	LHV
Maize-1	44.6	5.4	39.6	17.7	16.5	17.6	16.5	0.2	0.2
Maize-2	48.2	5.5	42.4	18.9	17.7	19.0	17.8	0.2	0.3
Maize-3	45.6	5.4	43.2	18.0	16.8	18.1	16.9	0.5	0.6
Switchgrass-1	47.8	5.8	35.1	18.0	16.8	18.8	17.5	4.2	4.5
Switchgrass-2	47.7	5.7	40.0	18.1	16.9	18.9	17.6	4.3	4.6
Switchgrass-3	46.9	5.9	41.5	18.6	17.4	18.8	17.5	0.7	0.7
Birch-1	49.8	6.5	43.4	20.1	18.7	20.2	18.8	0.4	0.4
Birch-2	47.6	6.0	45.5	18.2	16.9	19.2	17.9	5.5	6.0
Sugarcane Bagasse-1	48.6	5.9	42.8	19.0	17.7	19.4	18.1	1.9	2.0
Sugarcane Bagasse-2	44.8	5.4	39.5	17.3	16.2	17.7	16.5	2.1	2.2
Cow manure fresh	45.4	5.4	31.0	17.4	16.2	17.6	16.4	1.4	1.5
Cow manure aged	13.0	1.5	10.1	4.2	3.9	4.0	3.7	4.1	4.4

HHV and LHV are on a dry basis.

$$HHV_{wet} = HHV_{dry}(1 - MC) \tag{3}$$

$$LHV_{dry} = HHV_{dry} - 2.442 \times 8.936 \times H \tag{4}$$

$$LHV_{wet} = LHV_{dry}(1 - MC) - 2.442 \times MC \tag{5}$$

Table 6 compares measured data to calculated heating values using formulas (1) and (4). It can be seen that out of 12 samples, only one (Birch-2) is more than ±5%. Based on this, more than 90% of the data is within the stated ±5% range and hence support the validity of the formulas.

2.5.1.2. *Changes in energy and moisture content*. These variation could be the result of storage loses or processing prior to conversion. Processing could involve making pellets, fast pyrolysis, drying or separation, for example. No information was gathered on this topic. The effect would be a net change in EC and MC which could be found in local literature or after experiments.

For changes as a result of storage there is very little to no information available to help treat this aspect for energy modeling. Further research should be done here. However based on the information in Section 2.2 some *very rough estimates* can be made. Table 7 shows these ranges with a brief explanation.

Moisture content during storage is totally dependent on atmospheric conditions and storage method. It could however be assumed that over a long period of time in sheltered conditions MC in biomass would reach equilibrium with the atmospheric conditions.

Regardless of all these details, the important part is to know the ‘as received’ lower heating value of the biomass on a wet basis to obtain best results. All the above details are simply to help account for variation over time in the biomass.

2.5.1.3. *Energy crops*. If excess farmland is available, it’s a good opportunity to plant energy crops. Since this is just the planning phase there is no idea to the yield per year of certain crops. It is therefore important to have a grasp of how much a crop will yield in various climates. Typically this is called potential yield and it is measured in t/ha per year, Table 8 gives an example for certain crops. Details for miscanthus yields in Europe can be found in [23].

2.5.1.4. *Collection*. Since biomass is only available at certain times during the year, this distribution should be accounted for over a whole year. Also, if feedstock is accumulated prior to the 1st h of operation it should be known how much. This allows keeping track of the feedstock available.

2.5.2. *Conversion*

Biomass can be converted into many forms via different processes and technologies. Each has its advantages and disadvantages which need to be weighed carefully based on the input and desired output. Nevertheless, for the purpose of energy planning the conversion process can be seen as a black box, represented by a conversion efficiency. This efficiency should certainly depend on the chosen process and output, but there is no need to go any deeper. Table 9 shows the conversion efficiencies for some technologies. Combustion, gasification and AD to electricity were the focus of this study, hence why there’s nothing else in the table. The efficiency formulas were tabulated from various sources.

Table 7 – Estimates of energy content loss of feedstock during storage.

Type	EC losses – HHV_{dry} [%/month]	Details	Estimation based on
Woody – whole	~0.5%	• Piles left outside	Estimate based on LHV => subject to variation with respect to MC changes
Woody – chips	1.1–2.4%	• Lower value: small piles, little bark and needles • Upper value: large, moist, fine chips	Estimate based on LHV => subject to variation with respect to MC changes
Grassy – bales	0–0.5%	• Lower value: stored indoors, initial MC close to atmosphere • Upper value: stored outdoors on grass	Estimate based on DM loss => material may have been removed and hence would not count as EC loss
Manure	4.3–16.6%	• Lower value: cow manure or manure over time • Upper value: pig manure or manure during 1st month	Estimate based on average C loss

2.6. H_2RES – *energy planning*

H_2RES is a renewable energy planning software that considers hourly sensitive variations in load and weather conditions [29]. It is used to validate different energy mixes for a given location. It has solar, wind, geothermal and hydro modules as the main energy sources with fossil fuels as backup. The

Table 8 – Yield from various energy crops [2].

Crop	Average yield (t/ha per year)
Sugar cane	35
Bagasse	10
Maize, wheat, rice, sorghum, miscanthus	15
Wood (temperate climate)	10
Wood (tropical climate)	20

Note: Yield can vary more than 50–200%.

Table 9 – Conversion efficiency of electricity generation processes [6–11].

Conversion process	Power cycle	Size (MWe)	Efficiency (%)	Efficiency formula (%)
Combustion				
Grate firing	Steam cycle	0.11–150	17–37	$\mathrm{eff} = 2.3365 * \mathrm{Ln(MWe)} + 21.642$
Fluidized bed combustion	Steam cycle	0.5–200	17–33	$\mathrm{eff} = 2.3383 * \mathrm{Ln(MWe)} + 20.204$
Gasification				
Downdraft-gasification	Gas engine	<5	20–30	–
Updraft-gasification	Gas engine	0.5–50	25–30	–
Fluidized bed gasification—atmospheric	Gas engine	0.5–200	20–35	$\mathrm{eff} = 1.7021 * \mathrm{Ln(MWe)} + 24.298$
Fluidized bed gasification—atmospheric	Combined cycle	5–200	30–45	$\mathrm{eff} = 3.8902 * \mathrm{Ln(MWe)} + 23.423$
Fluidized bed gasification—pressurized	Combined cycle	5–300	40–50	$\mathrm{eff} = 1.2537 * \mathrm{Ln(MWe)} + 39.981$
Anaerobic digestion				
Digester	Gas	–	20–50	–
Digester	Gas engine	0.05–30	10–16	–

software can use a hydrogen loop, reversible hydro and/or batteries for energy storage. The load modules consist of; an electrical load, a hydrogen load for transport purposes and a deferrable load, which can be added to help smooth the energy demand. Also a network grid connection is available to buy and sell electricity for peak shaving. H_2RES has proven quite successful in modeling energy potential for remote locations. It has even demonstrated the usefulness of hydrogen as an energy vector [31].

Since a module for biomass did not exist before this paper, the important factors and information previously discussed are used to create one.

2.6.1. Biomass

The previous discussion has enabled some simplifications and highlighted what needs to be considered. Characteristics such as heating value, moisture content, storage methods and energy conversion process are pivotal to create a realistic view of biomass. Although site specific data is preferable for this, it is not always available at the preliminary stages of energy planning; therefore much of this information needs to be generalized. For this reason, the biomass energy model in H_2RES has been developed to group all this information and offer suggested values for the prized characteristics, ensuring adequate consideration to all aspects of the process.

At the outset, heating value, moisture content, storage methods and total yield are identified, giving an overall idea of the potential energy output. Daily collection quantities over a year identify when the biomass is available. This is important for crops, for example, which are collected once or twice annually, compared to MSW which is evenly distributed over the year. Choosing a conversion process, typical efficiencies, number of units and their capacities is possible based on the initial feedstock info. In addition to this, maximum and minimum production capacities are suggested to minimize shutdowns for short periods of time.

Collecting all this information, the biomass module dictates the available energy stock hourly. Before calculating the energy produced however, the maximum and minimum limitations of the units are considered. It foresees how many

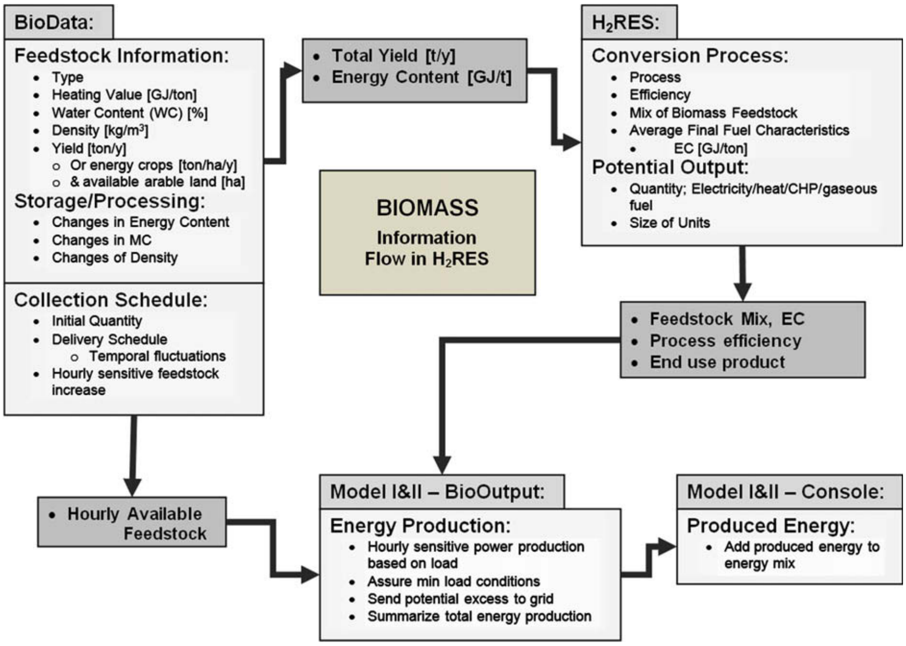

Fig. 1 – Biomass information flow in H_2RES.

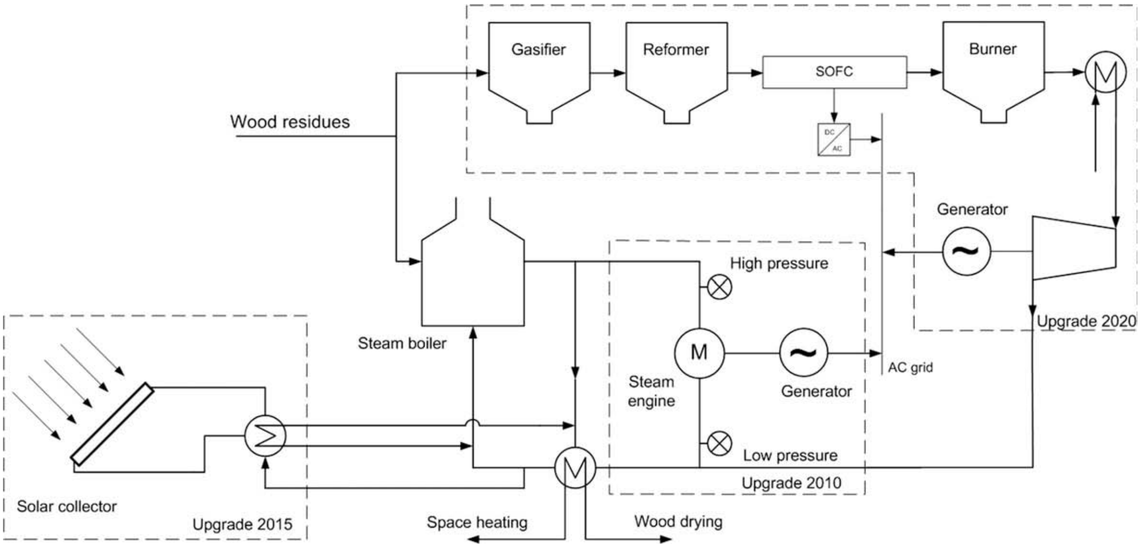

Fig. 2 – Scheme of heat and power production (for 2015 and upgrade in 2020 with SOFC).

production days are possible with the available feedstock and adjusts the output to ensure the units can operate for the minimum number of days dictated by the user, consequently minimizing shutdowns. In reality, the start-up/shutdown of equipment is lengthy and is avoided as much as possible. Not to mention that isolated systems cannot afford to shutdown without significant repercussions. On the other hand, if plenty of feedstock is available, but the load is less than the capacity of the units, energy is sent to the grid. Once again, this brings the model closer to reality.

The schematic view of the biomass information flow within the H_2RES model is presented in Fig. 1. For the purpose of the case study, the model was expanded to include a solar module and a heat load. The heat load can be satisfied from biomass, solar, fossil fuels or biomass and fossil fuel CHP.

3. Results: a typical Croatian furniture factory

The following case study is taken from a project done for the ADEG Project – Advanced Decentralized Energy Generation Systems in Western Balkans, part of the Sixth Framework

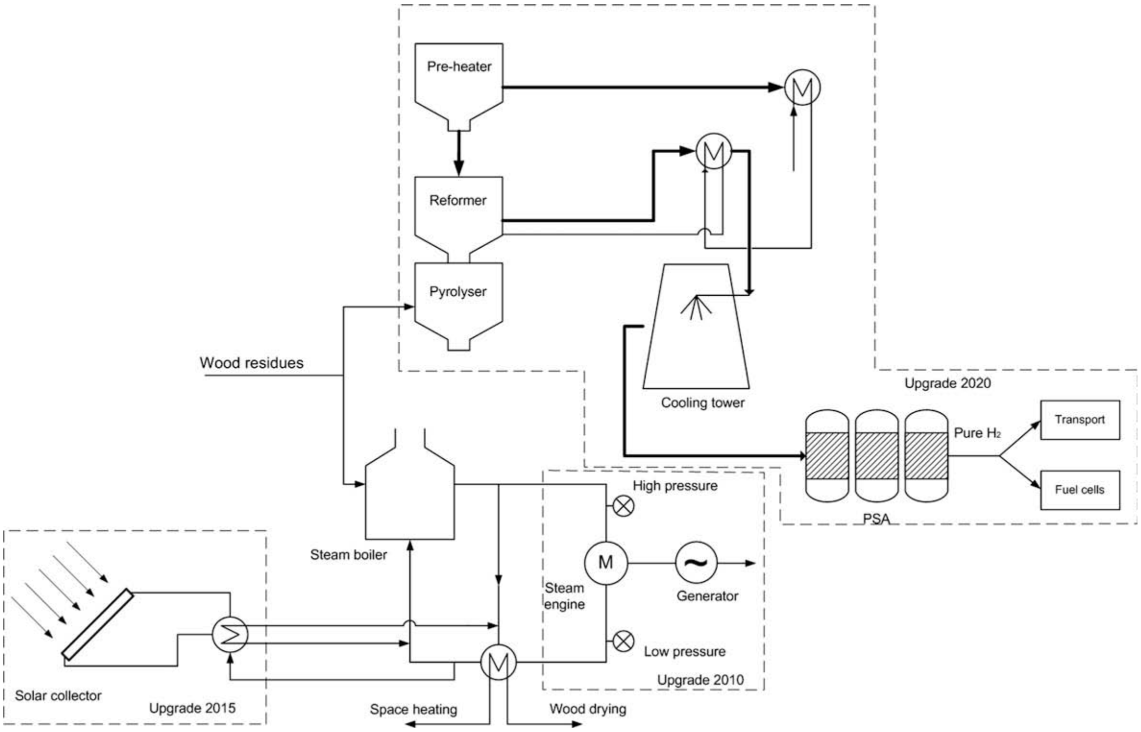

Fig. 3 – Scheme of heat and power production and pure H_2 production in 2020.

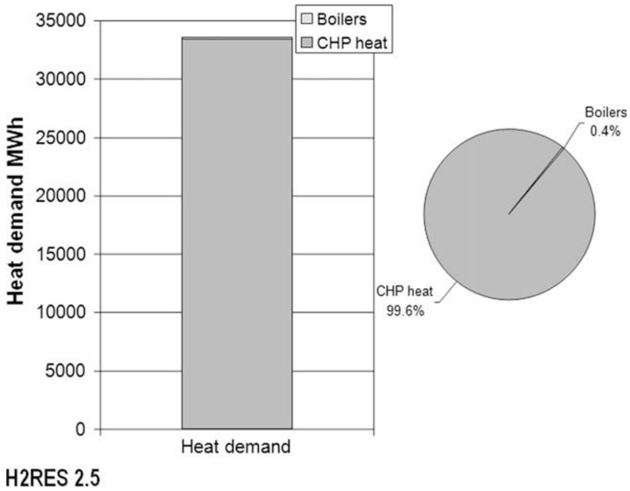

Fig. 4 – Supplying heat demand in 2010.

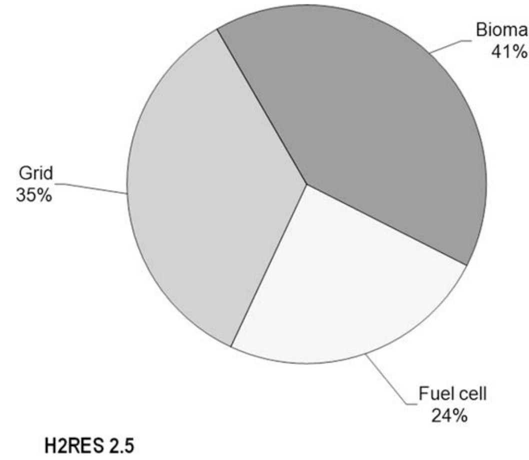

Fig. 6 – Supplying electricity demand in 2020, scenario with pure H_2 production.

program. The study is un-published at time of writing but was conducted by the co-authors of this report.

3.1. *Description*

The typical Croatian furniture factory used in this example produces wood furniture and parquet from various types of wood; primarily Slavonian white oak grown in the area, but also beech and ash. In 2004 the factory employed 760 people and had an annual turnover of €10 million, 3% of which was spent on energy.

Wood residues are used in boilers on site for steam production. The steam is required for wood drying and space heating. Currently there are two boilers which are oversized with respect, to both, steam quality and quantity. The bigger steam boiler (ECO-Celje constructed in ‘89) is producing 12 t/h of steam at 16 bars and 250 °C. The overall boiler efficiency is 84.6%. The smaller boiler (WEISS ’77) can produce 5 t/h of steam at 2.5–3 bars and 135–145 °C and is only used during maintenance of the bigger boiler.

Eight wood drying chambers require steam. Peak winter consumption for the chambers is 4.5 t/h of steam while during the summer it is only 2.5–3 t/h. The rest of the steam is used for heating during the winter times. In 2004 the yearly total heat and electricity consumption were 33,479 and 4,883.33 MWh, respectively with a peak load electricity load of 1499 kW. The boilers are capable of producing steam of greater parameters than required within the factory. Hence, there is a great amount of wasted energy which could be used to produce electricity.

In 2004 the factory used a total of 14,300 m^3 of biomass residues for steam production. If the heating value of the residue is 3 MWh/m^3, then the total energy value of the biomass used was 42,900 MWh which is more than enough to satisfy the heat consumption.

3.2. *Scenarios*

In order to reflect more realistic conditions, the biomass module was altered to make heat the primary product and electricity the by-product. Three progressive scenarios are analyzed here. 2005 is used as the baseline, using data from 2004 since no significant changes occurred in the factory during this time.

In the first scenario, the existing boilers are kept but two piston steam engines, a synchronous generator and associated accessories are added by 2010. The total power output of the new equipment is 275 kW and energy consumption is assumed to be the same as 2005. The high quality steam is first passed through the steam engine to produce electricity and

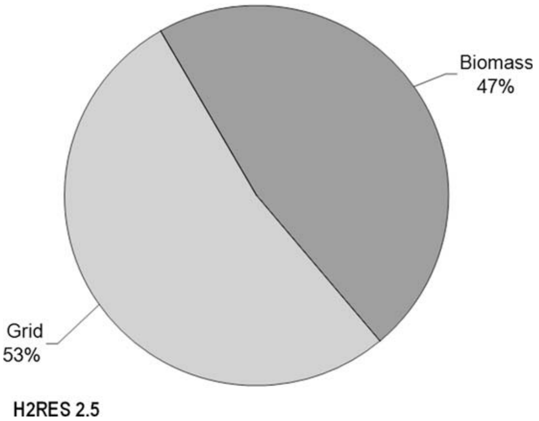

Fig. 5 – Supplying electricity demand in 2010.

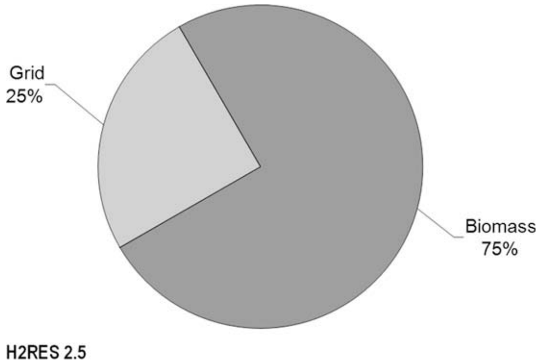

Fig. 7 – Consumed electricity in 2020, scenario with SOFC.

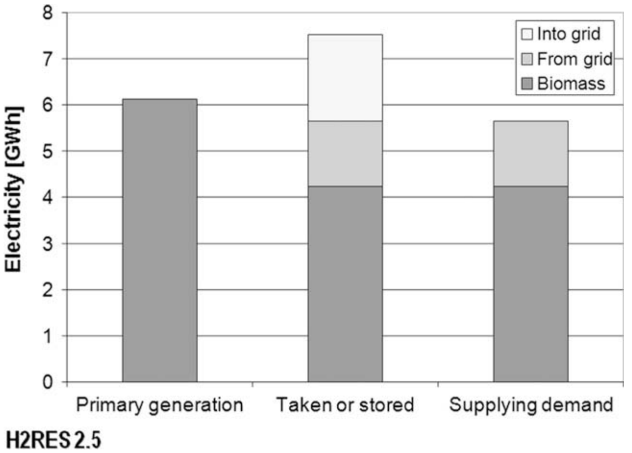

Fig. 8 – Electricity to the grid in 2020, scenario with SOFC.

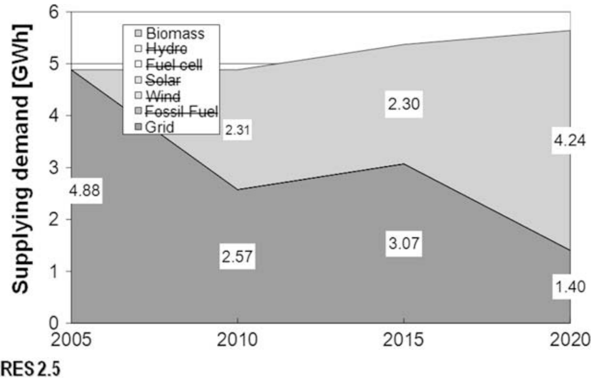

Fig. 10 – Supplying electricity demand with SOFC in 2020.

the low quality steam is then appropriate for use in space heating and wood drying.

In the second scenario, solar collectors are added by 2015, in addition to scenario 1, to match the increasing thermal load. From 2010 to 2015 it is estimated that an increase in heat and electricity demand of 15 and 10% respectively will occur as a result of greater production. Conversely, the biomass residue is estimated to also increase by 10%.

By 2020, a third scenario assesses adding a biomass gasifier to produce hydrogen. Two options are compared; one using a SOFC to provide heat and electricity, and improve the overall efficiency of the system (Fig. 2). The second is using straight hydrogen production to produce electricity in a fuel cell and/or for transportation (Fig. 3). The increase in thermal and electrical load is set to 10 and 5%, respectively for the period from 2015 to 2020. Whereas, collected biomass is augmented by 25%.

3.3. *Findings*

Using the H_2RES model, in 2005 the base year, all the thermal requirements are met by the boilers and electrical needs are fed from the grid. In other words, 33,479 MWh thermal and 4883 MWh electric are consumed.

In 2010 (scenario 1), almost all the heat requirements, 33,479 MWh will be satisfied by the CHP process with the balance coming straight from the boilers. However, in addition to this, 2310 MWh of electricity are generated from the steam engines/generator set satisfying 47% of the plant electrical needs (see Figs. 4 and 5).

By 2015, installing 2635 m^2 (or 2108 MW) of thermal solar collectors in addition to the CHP setup of scenario 1, it is possible to satisfy all heat loads using only biomass. The electricity productions remain the same.

In the third scenario, a gasifier (with associated equipment; pre-heater, reformer, pumps, heat exchangers, etc.) allows for some of the biomass to be converted to hydrogen. The chosen gasification plant is capable of producing 440 kWh of H_2 per hour (13.2 kg/h or 146.67 Nm^3). By 2020 this plant will be able to produce 2,914,769.45 kWh of pure H_2 (or 87,443 kg of H_2). If all the hydrogen is used directly in a 450 kW fuel cell, it can satisfy 24% of factories electrical load. Coupled with the steam generator, 65% of the plants electrical load can be satisfied from biomass (Fig. 6). Produced hydrogen is stored beside the fuel cell in a 500 Nm^3 tank. However, to avoid shortage in thermal production, 65 m^2 of additional thermal solar collectors will need to be installed, for a total of 2700 m^2.

For the second option of this last scenario, combining SOFC and biomass gasification is very attractive since it is well suited for decentralized energy generation in places with abundant biomass. The advantage of this process is due to the high operating temperature of the SOFC in tandem with those required in the gasification process. The waste heat off the

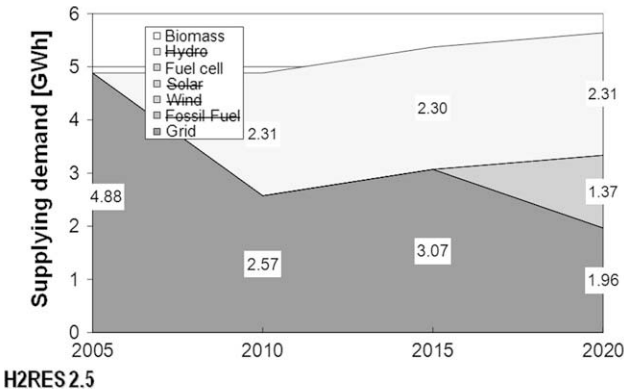

Fig. 9 – Supplying electricity demand with H_2 production in 2020.

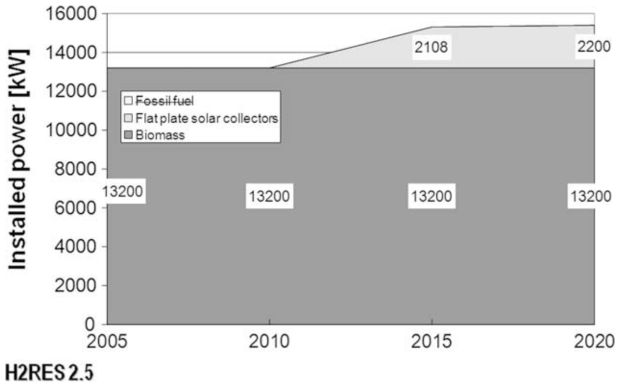

Fig. 11 – Installed useful heat power with pure H_2 production in 2020.

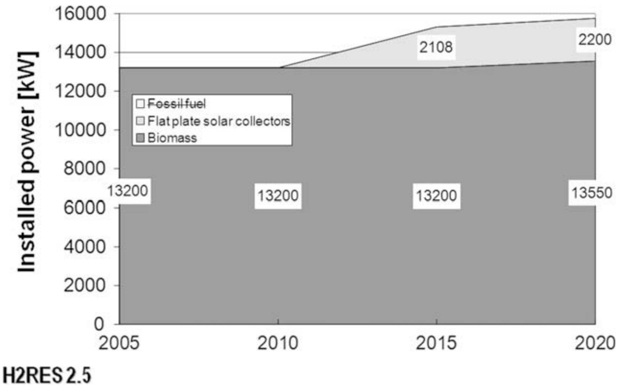

Fig. 12 – Installed useful heat power with SOFC in 2020.

SOFC can be used for the steam reforming of the gasification process, with excess heat used in a traditional steam engine/generator. A 700 kW SOFC is installed with an additional turbine and generator. With this setup it is possible to satisfy 75% of electricity demand (Fig. 7). But the installed power of this system is greater than the load, hence it will also be possible export the excess, 1881 MWh of electricity, to the grid (Fig. 8). This amount represents 33% of factory electricity demand so total produced electricity in 2020 will be equal to 108% of demand.

3.4. *Comparison of results*

It is clear that by installing the appropriate equipment, the wood factory can be self sufficient for its energy productions. And in the case of SOFC, excess electricity can even be fed back into the grid, offsetting the cost of taking from the grid. By simply adding a steam engine and generator 2.31 GWh of electricity can be produced. Whereas, installing a gasification process with a fuel cell or a SOFC can add an additional 1.37 and 4.24 GWh, respectively. (Figs. 9 and 10) show the breakdown of electricity consumed by energy source.

In 2005, the heat consumption of the factory is satisfied by biomass and remains unchanged until 2015 (Fig. 11). At this point solar thermal collectors are required to meet the increasing thermal load. In the SOFC scenario, an additional 350 kW of useful heat can be obtained (Fig. 12).

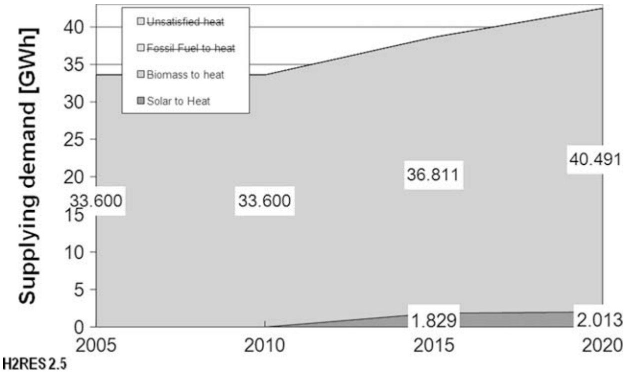

Fig. 13 – Supplying heat demand with pure H_2 production in 2020.

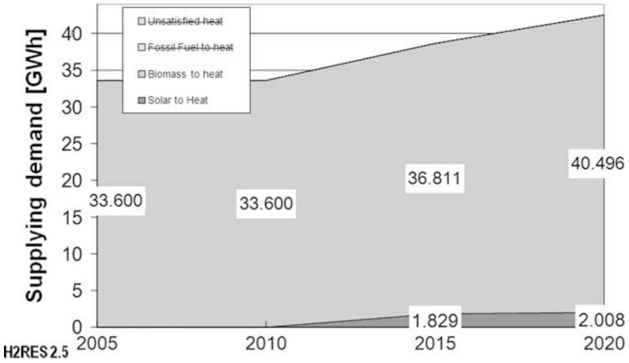

Fig. 14 – Supplying heat demand with SOFC in 2020.

Heat consumption is similar in both SOFC and fuel cell scenarios, with small differences in 2020, as the SOFC process also produces heat which is utilized in the factory's processes or space heating (Figs. 13 and 14).

4. Conclusion

Modeling biomass for energy conversion poses many challenges with respect to feedstock variability which are difficult to account for over any length of time such as; variation in energy and moisture content; fluctuations in biomass yields over a year and from year to year; effects of weather conditions; etc.

The most important factors when considering biomass as an energy source are its energy and moisture content, density, yearly yield and storage environment. The conversion process and desired output is also important since feedstocks are better suited for certain technologies.

However, for the purpose of energy planning some general approximations are adequate. Assuming an average biomass chemical composition for a crop in a certain region to calculate the EC is reasonable when considering that all biomass, on a dry basis, has an energy content of 20.4 MJ/kg ±15%. Loses due to storage are not easily quantifiable and more research is required, but simply acknowledging this issue leads to a more conservative estimate of the energy potential, which is not a bad thing when dealing with renewable energy sources. The moisture content on the other hand, is a more severe factor, which must be taken more seriously, on a site specific basis.

In terms of the energy conversion efficiencies, the ones presented are reasonable assumptions based on proven technologies. The uncertainty lies mainly in the larger facilities which have not seen a full operation lifetime as yet. Another issue facing this is the ability of biomass to corrode and foul the equipment due to condensable tars and chlorine it might contain. Over time this reduces the efficiency of the system, generally at a faster rate than when using fossil fuels. However the 'H_2RES' workbook considers the de-rated technology capacity and can therefore be set to a lower limit to account for long term effects.

The biomass module has proven to be valuable in modeling the energy potential. The various scenarios of the case study show that applying a variety of technologies in tandem, result in more than satisfying the energy requirements of the site in question; ultimately reducing energy costs, contributing to a sustainable development and ensuring a security of supply. Even by adding a simple steam engine and generator by 2010, the steam with higher enthalpy can be utilized and converted to energy. The capital cost of such improvements is relatively low compared to other scenarios and consequently it is considered as the simplest and most economical solution.

Unfortunately the H_2RES version used in this analysis does not support economical optimization. As such, the authors could not evaluate the various scenarios according to the capital and energy production costs. Any further development of these scenarios should include the economic factors. In addition, the scenarios would be more financially viable if heat storage was considered. This would increase the heat and electricity output and the amount of electricity available to exchange with the grid [32,33]. Overall the entire economics would be improved.

For the year 2020 two new installations are considered. One is the gasification of biomass with a SOFC which generates heat and electricity. The other also uses the gasification of biomass but to produce pure hydrogen which can then be used in either a fuel cell or for transportation purposes. The proposed installations for biomass gasification and hydrogen production could not match the overall efficiency which the existing wood factory demonstrates. However, they are interesting solutions when the existing equipment will need to be replaced, especially as hydrogen for transportation purposes becomes more viable. For example, using hydrogen for forklifts used within the factory.

In general, the conclusions presented here are useful for preliminary energy potential assessments and can define if an application of biomass to energy is viable and worth more investigation.

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Appendix A.
Supplemental material

Supplementary information for this manuscript can be downloaded at doi: 10.1016/j.ijhydene.2008.12.055.

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