Proceedings of the HTR 2014
Weihai, China, October 27-31, 2014
Paper HTR2014-21431

Conceptual evaluation of hybrid energy system comprising wind-biomass-nuclear plants for load balancing and for production of renewable synthetic transport fuels

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Abstract – *Future energy systems will increasingly need to integrate variable renewable energy in order to reduce greenhouse gas emissions from power production. Addressing this trend the present paper studies how a hybrid energy systems comprising aggregated wind farms, a biomass processing plant, and a nuclear cogeneration plant could support high renewable energy penetration. The hybrid energy system operates so that its electrical output tends to meet demand. This is achieved mainly through altering the heat-to-power ratio of the nuclear reactor and by using excess electricity for hydrogen production through electrolysis. Hybrid energy systems with biomass treatment processes, i.e. drying, torrefaction, pyrolysis and synthetic fuel production were evaluated. It was shown that the studied hybrid energy system comprising a 1 GW_e wind farm and a 347 MW_e nuclear reactor could closely follow the power demand profile with a standard deviation of 34 MW_e. In addition, on average 600 m^3 of bio-gasoline and 750 m^3 bio-diesel are produced daily. The reduction of greenhouse gas emissions of up to 4.4 $MtCO_2eq$ annually compared to power generation and transport using conventional fossil fuel sources.*

I. INTRODUCTION

Renewable energy is a fundamental component of the strategy of the European Union to achieve 80 % reduction of greenhouse gas emissions by 2050 compared to levels of 1990 [1]. In the Energy Roadmap 2050 seven different scenarios or routes to decarbonisation were studied. In these the share of renewables is projected to range from 40-60 % of the electricity production by 2050 [1].

The large share of variable renewables in the energy mix will require measures to stabilize the electrical grid. Several studies indicate that a reliable and affordable match between demand and supply based on renewable energy sources can be achieved [2], [3], [4]. However, substantial cost and performance improvements of renewable technologies are required to make such a transformation affordable, as well as significant investments in grid infrastructure and storage systems. Additional ancillary services including power reserves would be required in the future too [5], [6].

Higher shares of variable and decentralized renewable energy systems (RES) challenge the current practice of power plant dispatch, since a large share of renewables imply reduced load factors of conventional power generation and increased ramping of these. Currently load balancing for predictable changes is performed by operating coal plants and combined cycle gas turbine (CCGT) plants at part load. Unexpected and extreme changes are balanced by, for instance, hydro-electric plants, natural gas and oil-fired turbines.

Nuclear reactors are typically dispatched as base load units providing power to the grid at their rated output for 90 % of the time. The reason for this is economical due to the high capital and low operation costs of nuclear power plants. Nevertheless, most nuclear reactors have the technical ability to perform load following [7]. A mid-load regime is currently practiced in some countries, e.g. France. A higher share of renewables in the energy mix together with a substantial share of installed nuclear capacity would challenge the base load operation model of nuclear power thereby requiring more flexible operation.

Hybrid energy system (HES), which is a combination of energy producing technologies that provides a more constant energy flow, is an alternative to achieve load balancing of the future electricity grid under high RES deployment. The individual components of the HES can vary. In this study, the HES is composed of three wind farms, one biomass processing plant and a nuclear cogeneration plant. The load balancing is performed in two ways: (i) by altering the ratio between heat and power production to compensate for power production variations from the wind farms and (ii) by using excess power peaks of the HES for hydrogen production, which later is used for synthetic fuel production. In addition, the implementation of HES would mitigate the need for investments in grid infrastructures, storage, and ancillary services.

Due to that a nuclear cogeneration can alter the heat to power ratio, it can perform load following and still operate at a high capacity factor. Revenue is earned both through selling electricity and high temperature heat. It is worth noting that the heat market in Europe is about as large as the electricity market, so the demand is potentially great.

This use of hydrogen, comparing with fuel cells, reduces the need for investments in new refueling infrastructures and it requires fewer modifications of vehicle engines.

Earlier studies made by Bogart et al [8] has described synthetic fuel production using nuclear power for military, as well as commercial applications. Forsberg studied nuclear cogeneration used for synthetic liquid fuel or hydrogen production based on nuclear-fossil light-oil and nuclear-biomass liquid-fuels production systems [9],[10],[11]. Cherry et al. [12] studied balancing of wind power production by using nuclear cogeneration while producing methanol from natural gas.

The unique approach in the presented study is that it focuses on reducing the power variability at a local electrical node by employing an HES, and compares it to wind farm only system. Although, the results cannot be directly extrapolated to the total EU energy system, since for the complete grid, local variations will to some degree balance each other out [13], it establishes an upper boundary in terms flexibility needed for the nuclear reactor to balance intermittent wind power production. A second unique property of this study is the use of biomass as a carbon source to produce synthetic bio-diesel and bio-gasoline.

II. METHOD

A spreadsheet model was developed to optimize the operation of the HES over a period of one year. Hourly time steps were used to represent changes in wind power production, see Section on 'Wind' for more information. Demand load curves were adjusted to seasonal variations, see Section on 'Variable power demand in EU-27 for more information'.

The following steps were performed for each calculation:

- Determine the size of the HES (wind and nuclear cogeneration reactor) to meet the annual electricity demand over a year and to meet the electricity demand from hydrogen production through electrolysis.
- Determine the size of the nuclear reactor to meet heat demands of biomass processing.
- Minimize standard deviation of power supplied by the HES relative the hourly power demand curve during one year. The standard deviation is calculated as follows:

$$\sigma = \sqrt{\frac{\Sigma_{i=1}^{n}(a_i - b_i)^2}{n}} \qquad \text{(Eq. 1)}$$

Where a_i is the HES power production, bi is the power demand at hour i, and n is the number of hours.

- The first level of load balancing is performed by changing the ratio between heat and power production based on one hour wind forecasts. The ratio is changed once per hour.
- The second level of load balancing is performed though using the excess electricity production compared to demand for power. The excess electricity is used for hydrogen production through electrolysis.

III. DESCRIPTION OF THE HYBRID ENERGY SYSTEM

The HES consists of wind farms, a nuclear cogeneration reactor, and a biomass processing plant.

The starting point when designing the HES is the economical biomass production area, i.e. the radius around the biomass processing plant at which it is economical to grow, cultivate and harvest biomass.

An 80 km radius around the biomass processing plant is considered to have potential for economical biomass collection [14]. This estimate was made for American conditions. In Europe, where both fuel prices and the value of biomass are higher, the viable collection radius may be different, but we do not attempt to determine it here. Within the collection area of 20 000 km^2 or 2 million hectares, biomass crops are assumed to cover 2.5 % of the surface area (in accordance with typical national averages) or 50 000 ha.

A second generation bio energy crop like for instance switchgrass and miscanthus yields about 20 t DM/ha/yr, which means that, in total, 1 Mt DM is produced annually. Because high temperature heat cannot be pipelined efficiently over long distances, the nuclear reactor must be located near the collection center. The biomass processing acts like a buffer, where energy produced by the nuclear reactor can be utilized when electricity demand is low.

Normal turbine operation would be down to about 60 % of design power, but to back up wind generation, a wide range of rates is useful. To achieve this, two turbines, each with 50 % of the full plant capacity, are assumed. When the required total generation rate is low, one of the turbines is put into hot standby mode so that it does not generate power, but remains ready to resume operating smoothly and rapidly. Shifting the entire generation load to one turbine allows it to operate more efficiently and closer to its design power output. Shifting back heat supply to the turbine generators is assumed to be equally smooth.

Another way to balance power production is to use excess electricity to generate hydrogen through electrolysis. The hydrogen is then used to produce synthetic transport fuels, i.e. bio-diesel and bio-gasoline. Hydrogen production provides an additional efficient layer of flexibility that acts like a buffer. The generation of hydrogen through electrolysis can respond more quickly to changes in demand for electricity.

Maintenance and shutdowns are assumed to take a similar fraction of operation time (nuclear, wind, and biomass) of all three plants and therefore do not affect production ratios, only total annual production and revenues.

Figure 1 shows a schematic view of the HES used for the analysis of this paper. Here, 1 Mt/year of biomass is dried, torrefied, pyrolysed, and then transformed into synthetic fuel.

The nuclear reactor and the wind farms are sized to ensure that heat and electricity production matches the biomass process heat requirements and local demand for electricity. At the same time, variability of power exported to the grid by the HES relative to the hourly demand should be minimized.

Therefore, the wind park and the nuclear reactor operate to deliver a combined output as close as possible to demand for electricity. When wind power production is lower, the nuclear reactor compensates by supplying steam to the turbine to produce more electrical power. As wind generation increases, the nuclear reactor reduces electricity production and supplies heat to the biomass processing plant. It is assumed that this diversion of steam flow from the turbine generators can occur smoothly over a range of 30-100 % of rated turbine power, and that the thermal efficiency of the power plant does not drop significantly in these conditions.

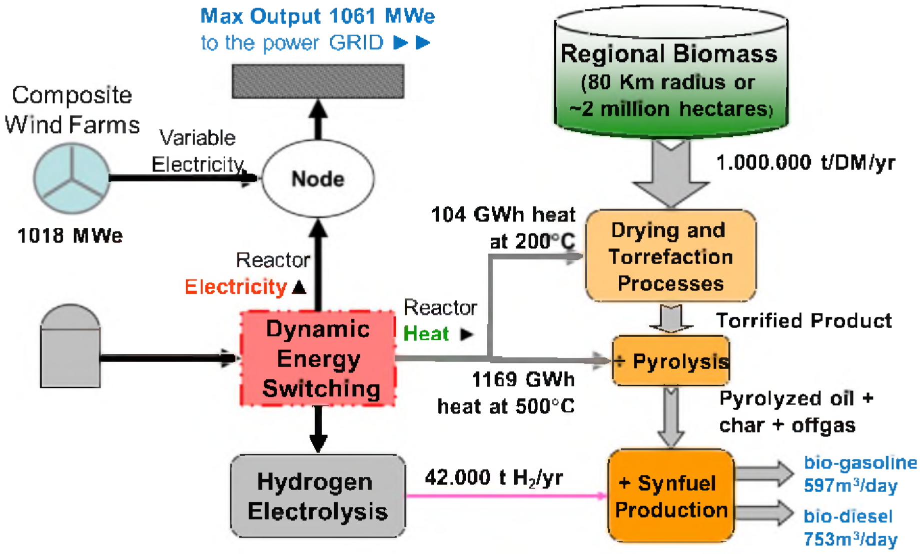

Figure 1. Schematic view of Hybrid Energy System studied in this paper (drying, torrefaction + pyrolysis + synthetic fuel production).

Table 1 shows performance data of HES investigated.

Table 1. Performance specifications of a Hybrid Energy System for biomass processing.

	Units	Amount
High Temperature Nuclear reactor		
Capacity factor		0.90
Required heat delivery temperature (steam)	°C	550
Thermal to electricity conversion efficiency	MW_e / MW_{th}	0.46
Wind farm		
Capacity factor (annual)		0.28
Power rating	MW_e	1018
Annual generation	GWh	2309
Biomass farm		
Biomass specific yield	tonnes DM/ha/yr	20
Collection radius	km	80
Land usable for energy crops	fraction	0.025
Area for biomass growth	km^2	20106
Biomass production	tonnes DM/yr	1005312
Yield to dry and torrefy biomass	GJ/tonne water evap'd	2326
Fresh moisture content	wt frac	0.40
Dried water content	wt frac	0.07
Energy used for drying	GJ(th)/tonne moist feed	0.83
Heat demand (at 200°C)	GWh_{th}/year	105104
Yield to torr/pyrol from biomass @ 7 % moisture	GJ/tonne input	3.440 [36]
Heat demand (at 500°C)	GWh_{th}/year	1169
Yield of pyrolysis char	kg/kg dried biomass	0.12
Yield of bio-oil	kg/kg dried biomass	0.77 [37]
Yield of light off gas	kg/kg dried biomass	0.11
Production of pyrolysis char	tonnes/year	130000
Production of bio-oil	tonnes/year	832000
Production of light offgas	tonnes/year	119000
Synthetic fuel production		
Consumption of hydrogen	tonnes/year	41800
Electricity consumption hydrogen production	GWh_e/year	910
Production of motor gasoline	m^3/year	220000
Production of diesel fuel	m^3/year	280000

A key issue for the HES is how well the fluctuations in wind generation can be counterbalanced. There is extensive ongoing work at Idaho National Laboratory on this and related dynamics issues. A Fast Fourier Transform analysis shows that most of the fluctuations in wind energy occur at frequencies corresponding to periods of one day to one week. This is not to dismiss the load-following difficulties caused by small high frequency variations. [15]

III.A. Biomass availability for HES in the EU-27

The amount of renewable energy expected to be derived from biomass in 2020 in the EU-27 is shown in Figure 2. In 2020, biomass is expected to contribute 19 % of the renewable electricity, 78 % of the renewable heating and cooling, and all of the renewable energy for transport. Overall, at 1583 TWh, biomass is expected to provide 55 % of renewable energy in 2020 [16]. It is important to understand this context and the demand on agricultural capacity to determine the viability of the proposed HES in this study.

The National Renewable Energy Action Plans (NREAPs) of EU Member States include all renewable energy sources, including biomass, which is categorized as solid biomass, biogas, and bioliquids. The national projections for biomass production in 2020 and the associated land requirements are shown in Figure 2. The countries with the highest biomass projections (more than 5 Mt dry matter annually) include Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Italy, Netherlands, Poland, Portugal, Spain, Sweden, and the UK.

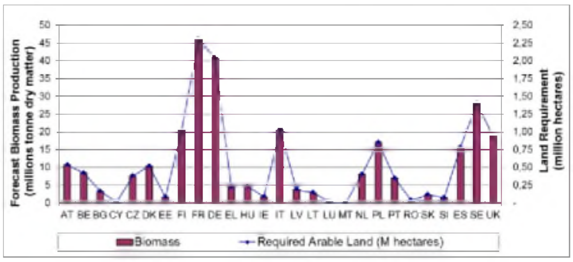

Figure 2. EU-27 Biomass Production and Land Requirements (@20t DM/ha/yr) for 2020 [16]

The land area required to grow biomass is directly proportional to crop productivity. The second generation of herbaceous ligno-cellulosic crops has yields applicable to the EU in the range from 5-24 and 4-45 t dry matter per hectare annually (t DM/ha/yr) for switchgrass and miscanthus clones, respectively [17],[18]. Assuming a medium yield of 20 t DM/ha/yr for 2020 results in land requirements of up to 2.3 million hectares to meet the goals of NREAPs in the case of France.

The impacts of biomass production on other agricultural products will vary. Assuming each country produces enough biomass for its own needs, in Belgium, Finland, Netherlands, and Sweden, the share of arable land required for energy production is probably too large, exceeding 40 %, as shown in Figure 3. However, also to be considered is the actual land surface area required for biomass energy production. For small countries with a high population density such as Belgium, Denmark, and the Netherlands, the land needed for biomass production exceeds 10 % of the total country surface area. Thus, for some countries, using biomass might encroach too much on traditional agriculture and might be unsustainable if competition between cultivation of energy and traditional crops is to be avoided [19].

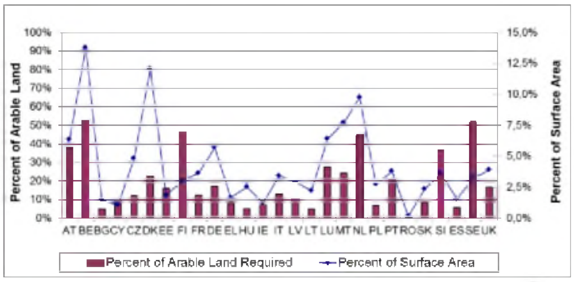

Figure 3. EU-27 Biomass Land Use Requirements (@20t DM/ha/yr for 2020) [16]

Although adequate wind conditions need to be established for the HES, this is seen as less of a limiting factor than biomass availability due to the fact that the wind potential is greater than the biomass potential in the NREAP of EU Member States.

Combining information about available land use and biomass potential in EU-27 suggests that the countries that are better suited to wind-biomass-nuclear cogeneration HES are the Czech Republic, France, Germany, Italy, Poland, Spain, and the UK. This would have to be confirmed by thorough analyses on a case-by-case basis. Other factors public attitudes towards nuclear power will be important for the ability to construct HES.

III.B. Biomass Treatment Needs

There are some challenges to overcome to expand the biomass sector for power production and the use of biofuels in transport. Its rather low energy density makes it a bulky fuel with poor handling and transportation characteristics and the high moisture content results in low fuel value and storage complications such as degradation and self-heating. Therefore drying and processing are needed to reduce the biomass into small homogeneous particles (i.e., wood pellets) that are suitable for burning.

Various biomass conversion processes can be used, depending on the desired product (e.g., wood pellets, torrefied product, synfuel, biofuel). The heat required for conversion varies considerably. The first step of the process is torrefaction. Torrefaction is a thermo-chemical process conducted in the absence of oxygen, at a temperature of 200-300 °C, at typically 1-hour residence time, during which biomass partially decomposes, giving off volatiles and producing a solid final product [20]. Torrefaction produces a modified fuel pellet with superior properties to standard wood pellets. The process reduces moisture content from 40 % to 7 %, and drives off organic volatile components that tend to foul power plant emission control systems. The volatiles released are reused for heating, which reduces external heat demand. The resulting torrefied product has increased energy density (18-20 GJ/m^3), which makes it suitable for co-firing with coal or thermal processing into biofuels [21].

The second step is pyrolysis, which offers a way of converting solid biomass into an easily stored and transported liquid, which can be used for the production of heat, power and chemicals. Pyrolysis is performed in the absence of oxygen at temperatures of up to 500 °C. It decomposes the organic material and produces char, gases and vapors. The vapors condense at ambient temperature to a dark viscous liquid, i.e. bio-oil. A slow pyrolysis at 400 °C produces approximately 30 % liquid, 35 % char, and 35 % gas. A faster pyrolysis at a higher temperature alters the distribution to a liquid bio-oil product of about 75 %. The fast pyrolysis requires a very high heat flux to the biomass and must occur in a very short time with immediate quenching, otherwise the oil will crack further to permanent gases or polymerise to char.

In the last step hydrogen is used to upgrade the bio-oil to synthetic bio-diesel and bio-gasoline. The hydrogen reacts with the oxygen in the bio-oil and forms water, allowing the remaining biomass (methylene — CH_2) to form a synthetic fuel. Another example of a process that can be envisaged is the bio-syntrolysis process, which is based on biomass gasification rather than pyrolysis. This would allow conversion of biomass to biofuels at higher efficiencies, i.e. about 90 % of the carbon is used instead of 35 % in traditional processes, but with more energy required. [22]

III.C. Wind power

One-hour time series for onshore wind speeds at an altitude of 10 m measured in De Bilt, Hupsel and Valkenburg in the Netherlands were used [23] to establish the wind power generation profiles as a function of time. The distances between the sites are between 100 and 200 km. The combined output from the three wind farms is shown in Figure 4. Their annual load factor is 28 % and standard deviation around the average power production is 87 %. The combined power profile of the three existing wind farms in the Netherlands was multiplied with a factor to reach a desired total size of wind power production suitable for this study.

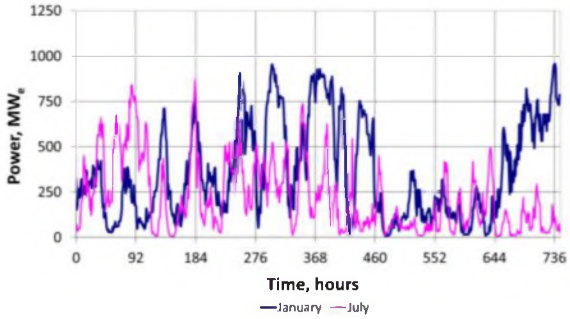

Figure 4. Combined power production from three wind farms in the Netherlands during January and July.

A logarithmic extrapolation to estimate wind speeds at 100 m height was done according to Equation 1[24].

$$V = \frac{V_0 \cdot \ln(H/k)}{\ln(H_0/k)} \qquad \text{(Eq .2)}$$

where: V is wind speed at the height H (100 m); V_0 is wind speed at the height H_0 (10 m); k is a roughness length constant. Maximum power does not reach rated power in reality due to, for example, the array efficiency (due to wakes of upstream wind turbines), high wind speed cut out, spatial averaging, availability, and electrical losses. Rather, the maximum is 94 % of rated power [25]. The error in the one hour ahead wind forecast is assumed to be a normal distribution with a standard deviation of 5 % [26].

III.D. Flexible nuclear power

Modern nuclear power reactors like the EPR are capable of load following in the range of 60-100 % of nominal power [27] at a rate of up to 5 % per minute. Small and medium sized nuclear power reactors can be used efficiently for balancing the electrical grid too [28]. However, load following of power reactors reduces the capacity factor, which increases the levelized cost of electricity.

Nuclear cogeneration reactors would allow continuous operation at rated power and trading between electric and heat load according to demand for electricity. Although it is more profitable to produce electricity, the heat production for e.g. biomass processing will generate income too. Based on price projections for natural gas [29] the alternative cost for producing heat using a natural gas boiler is expected to be about EUR 30-60/MWh in 2030 [30]. For heat produced by coal, the alternative cost is about EUR 10-20/MWh in 2030. The alternative heat cost of producing heat with a boiler is strongly linked to the price of fuel.

Nuclear cogeneration can in principle be performed with all types of reactors, but in this case study a reactor operating at elevated temperatures is needed to sustain pyrolysis of biomass at 500 °C, e.g. the High Temperature Reactor (HTR). These types of nuclear reactors are developed, for example, in the Next Generation Nuclear Plant (NGNP) programme. The proposed concepts are modular reactor designs operating with core outlet temperatures of 700 to 850 °C at ratings between 200 and 625 MW_{th} [31] per module. Such plants can operate in cogenerating mode, electricity production only, or heat production only. Both low and high pressure steam can be extracted. The schemes can be adapted to the processes served. Such reactors can typically ramp up power by 5 % per minute during rapid events, but the normal ramping time is 0.5 % per minute. Transfer from electric to heat mode can be performed at 5 % per minute. [32]

An indirect Rankine cycle with steam bleeds is assumed for this study, see Figure 5. The reactor core heats the helium coolant of the primary circuit, which heats water/steam in the steam generator. From there, the steam goes to the High Pressure (HP) turbine, then the steam is reheated before entering the Low Pressure (LP) turbine. And feedwater is heated to bring it up to saturation temperature before reentering the steam generator. Steam is bled off at the HP and/or LP turbines, depending on the temperatures at which heat is needed. Low temperature heat demand is preferably taken from the LP turbine, as this reduces the total thermal efficiency less. For this study, steam is bled at the LP turbine to provide heat for drying and torrefaction of biomass in temperatures up to 200 °C, whereas the steam bled from the HP turbine at 500 °C is used for pyrolysis.

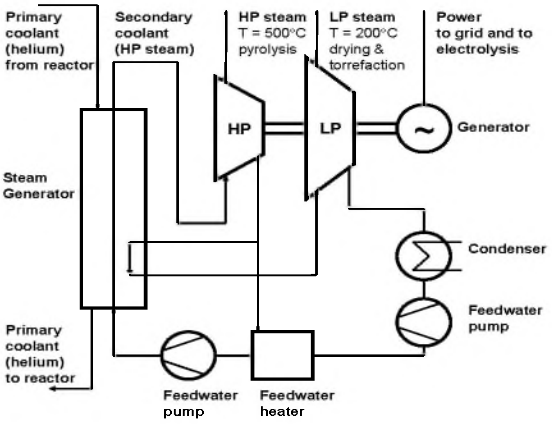

Figure 5. Illustrative flow chart for indirect Rankine cycle.

III.E. Variable power demand in the EU-27

Both variable demand and generation can be exploited for heat production applications by Hybrid Energy Systems (HES). Power demand per month in Germany, France, and Netherlands is illustrated in Figure 6 [33], [34]. Seasonal variation is greatest in France, due to its large share of housing heated by electricity. Demand for electricity in Germany and Netherlands is more stable. The low demand periods can be used for larger heat production. The power demand curve of France was used in this study since it shows a greater difference in electricity demand over the seasons and thereby better portray the potential of HES.

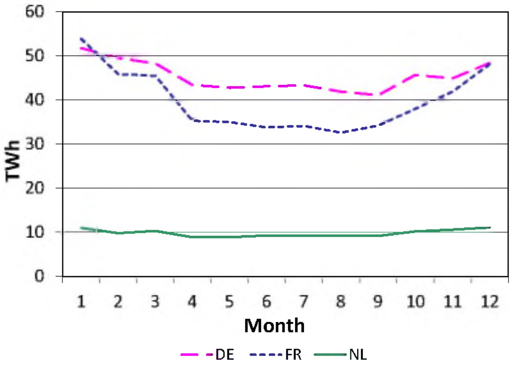

Figure 6. Illustrative EU monthly electricity demand cycles in Germany, France and Netherlands during 2011 [33].

Daily fluctuations in electricity demand also provide an opportunity to switch the ratio between power and heat production for all three countries [34], see Figure 7. The daily 'low-hour' period lasts for about eight hours. Diurnal electricity demand variations have similar profiles for all three countries. Typically, demand drops about 20-30 % at night compared to daily peak demand.

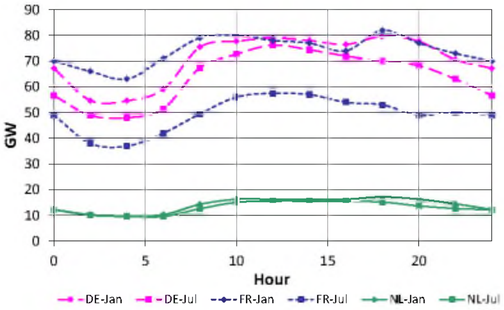

Figure 7. Illustrative diurnally electrical demand cycles for Germany, France, and Netherlands during a typical day in January and July of 2011 [34].

In the electricity system of today, for both seasonally and diurnally varying generation, part-time operation generally means selecting systems with lower capital costs at the expense of higher fuel costs. Grid level system costs like back-up costs, balancing costs, grid connection, and grid reinforcement and extension were evaluated in several studies. A recent study by IEA [35] estimates the costs range to up to USD 40/MWh for onshore wind with 30 % penetration. If balancing costs were not included, costs would be USD 10-20/MWh lower. Balancing costs depend largely on how flexible other power generation resources are, so the cost range will be wide. In relation to the cost of power production, this cost is greater in less flexible energy systems.

IV. Analysis

The objective was to design an HES system producing low carbon electrical output and low carbon synthetic fuel for the transport sector. Also, the HES should be able to closely follow the electrical demand, which in practice means that the variable wind production is balanced.

The design considerations were presented in Section 3. 1 Mt DM of biomass is harvested annually, which requires heat treatments in a three-step process:

(1) The first step is to dry and torrefy the biomass. The water content is reduced from 40 % to 7 % weight fraction. The torrefaction process requires 345 GWh of heat annually. However, due to that combustible gases are released during the torrefaction process, which can be reused, the external heat demand is only 104 GWh of steam at 200 °C.
(2) The second step is pyrolysis, which requires 1169 GWth of high temperature steam at 500 °C.
(3) For the synthetic fuel production 42000 tonnes of hydrogen is needed annually. The hydrogen is assumed to be produced via a low temperature electrolysis process operating at 75 % efficiency (approximated from data at NEL 2012), requiring in total 910 $\mathrm{GWh_e}$. The hydrogen is used for the production of bio-diesel and bio-gasoline.

The size of the nuclear reactor will mainly be determined to meet the annual heat demands of the three bioprocessing plant incorporating the three steps described above. To level the combined electricity generation from the HES, the nuclear reactor will trade between electricity and heat production in order to balance the output from the wind farms. Compared to the wind farms alone, this roughly halves the standard deviation of the electricity production around the hourly electricity demand over a year. To match the electricity production with demand even further, electricity production of the HES exceeding demand is used for hydrogen production through electrolysis.

Here, the wind farm produces 2497 GWh$_e$ in a year, whereas the nuclear reactor produces 15901628 GWh$_e$. The share of electricity and heat produced by the nuclear reactor is 52 % and 48 %, respectively. 23 % of the electricity produced by the HES is used for hydrogen production.

Figure 9 shows the wind power production, the power and heat production from the nuclear power plant, the electricity demand, as well as the power diverted for hydrogen production. The electricity production of the HES can nearly be matched with the demand profile for a 10001018 MW$_e$ rated power of wind farm and 347 MW$_e$ power of the nuclear reactor. The wind farms alone with a capacity of 1018 MW$_e$, produce on average 287 MW$_e$ with a standard deviation of 237 MW$_e$. Within the framework of the HES, the standard deviation around the demand is reduced to 34 MW$_e$.

The from the bioprocessing plant is about 0.83 Mt of pyrolysis oils, 0.13 Mt of char, and 0.12 Mt of light off-gas annually. The oils are hydrotreated using 42 kt of hydrogen and yield 218 000 m^3 of bio-gasoline and 275 000 m^3 of bio-diesel annually.

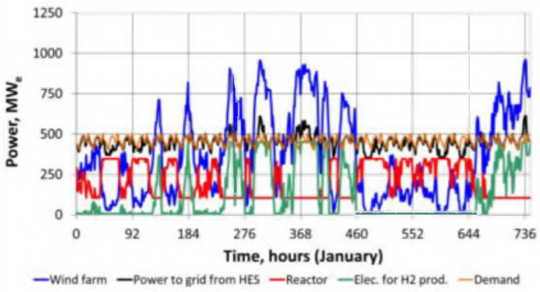

Figure 9. Power production from a 347 MW$_e$ (755 MW$_{th}$) nuclear reactor and a wind farm of 1018 MW$_e$ rated power for the month of January. Hydrogen is produced through electrolysis. The average electricity demand in January is about 350 MW$_e$.

The analysis revealed that the needed shifting between heat and power of the nuclear reactor are mostly mild or gradual. Usually it is less than 10 % power change per hour during 82 % of the year, see Figure 8. Trading between heat and power of more than 30 % per hour was required at 140 occasions (1.5 %) in a year. It should be kept in mind that even 50 % per hour can be a rather mild transient. More detailed wind data is required to identify steep transients. In this study the wind data is based on three aggregated wind farms located 200-300 km from each other. Due to their geographical distance, it is assumed the trading rates and the total number of occasions at would be limited.

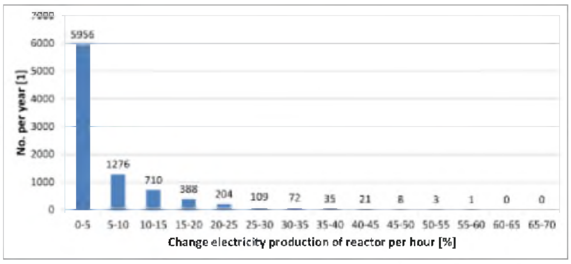

Figure 8. Number of occurrences as a percentage of size of power production ramping of nuclear reactor.

IV. Brief discussion on the environmental impact for biomass-wind-nuclear Hybrid Energy System

When evaluating the greenhouse gas reduction potential, the comparison for the power and heat production is made with the technologies presented in Table 2 [29].

Replacing technologies	**Life cycle emissions, kg CO_2eq./MWh**
Combined Cycle Gas Turbine (CCGT)	420
Pulverised Coal Combustion (PCC)	820
Natural gas boiler	280
Coal boiler	520

For the transport sector the comparison is made with combustion of gasoline and diesel fuels with emissions of 0.65 kg CO_2/liter and 0.7 kg CO_2/liter, respectively.

Table 3. CO_2eq emission savings per HES.

	Nuclear power vs fossil power, Mt CO_2eq.	**HES vs CCGT + fossil fuels, Mt CO_2eq.**	**HES vs PCC + fossil fuels, Mt CO_2eq.**
Wind farm, 1 GWe	-	1.05	2.05
Nuclear energy, 347 MWe/755 MWth	1.17 (CCGT) or 2.29 (PCC)	0.68 (el.) 0.36 (heat)	1.33 (el.) 0.67 (heat)
Replacing fossil transport fuels	-	0.3	0.3
Total	*1.17 (CCGT) or 2.29 (PCC)*	*2.39*	*4.35*

Table 3 shows that an HES replacing power and heat production from a CCGT, a natural gas boiler and replacing fossil transport fuels will achieve GHG emission reductions of 2.4 Mt CO_2eq annually. If instead the HES would replace heat and power production from a PCC and a coal boiler, the emission reductions would be 4.4 Mt CO_2eq annually.

At last a comparison is made to a single nuclear reactor of the same size operating at 90 % capacity factor. Compared to power production from either CCGT or PCC such a reactor can achieve greenhouse gas emission reductions by 1.2 and 2.3 Mt CO_2eq annually, respectively.

VI. Conclusions

The technical viability of employing a low carbon Hybrid Energy System (HES) comprising a wind farm, a biomass processing plant and a nuclear cogeneration plant was studied. In the HES, the nuclear reactor balances the power output of variable wind farm and supplies heat for biomass processes, i.e. drying, torrefaction, pyrolysis, and synthetic fuel production. On average, 600 m^3 of bio-gasoline and 750 m^3 of bio-diesel are produced daily.

In this paper, an HES with a biomass processing plant with annual heat demands of 1273 GWh, a wind farm of 1018 MW_e rated power, a nuclear cogenerating reactor of 347 MW_e is studied. It is shown that the variable wind power generation is efficiently balanced by the HES from shifting between heat and power production from the nuclear cogeneration reactor, and by using peak electricity production for hydrogen production through electrolysis.

For the HES studied, the load balancing can reduce the power production variability relative to the energy demand over a year from 237 MW_e for wind only to 34 MW_e, i.e. reduction of 85 %). Hereby, it can be assumed that the HES can mitigate required investments in electricity grids, energy storage and back capacity in the future energy system with a large share of intermittent renewables.

Assuming that the electricity production of a HES replaces electricity and heat production using natural gas and the bio-diesel and bio-gasoline replace regular diesel or fuel, the total greenhouse gas emission savings are about 2.4 Mt CO_2eq annually. If instead the HES replaces heat and power production using coal then the total emission reductions would be 4.4 Mt CO_2eq.

Energy security benefits can also be realized, since less natural gas, oil and coal has to be imported.

Since nuclear power requires large upfront investments, high load factors are needed to recoup the investment. A nuclear cogeneration reactor can continuously operate at full or close full capacity since it can adapt its operation to meet the electricity and useful heat demand at a certain point in time. Thus, there appears to be an opportunity for nuclear cogeneration to provide load balancing power services for which the revenue per MWh_e tend to be higher than for traditional base load production, and also to sell heat for alternative uses. However, a detailed economic study is required to confirm this.

VII. Acknowledgements

This work has been carried out within the multi-annual work programme of the ‘Assessment of Energy Technologies and Systems’ (ASSETS) Action of the European Commissions’ Joint Research Centre. Any interpretations or opinions in this paper are those of the authors and do not necessarily represent the views of the European Commission.

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