On the Thermal Integration of Nuclear Heat in a Solar Thermal Plant for Continuous Thermochemical Processes

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Abstract

High-temperature thermochemical processes enable the generation of non-fossil fuels such as hydrogen, syngas, bio-based crude oil, and coal. These processes take place inside a reactor where different species are mixed and react depending on the product to be obtained. To promote chemical reactions, high temperature and pressure levels are required inside the reactor. Nuclear energy is an interesting source of heat for continuous thermochemical processes. Innovative generation IV reactors have safety and reliability features, which enable them to ensure the sustainable use of nuclear energy. Currently, nuclear heat is used to convert heat into work in power generation systems using Rankine and Brayton cycles, and to produce hydrogen by water splitting. This paper analyzes the challenges facing nuclear energy as a backup heat source for industrial processes, particularly in solar hydrothermal processes.

Keywords: Nuclear heat, GEN-IV reactor, Pink hydrogen, Hybrid thermal plant, Hydrothermal processes, Bio-oil production.

1. Introduction

The generation of strategic fuels such as hydrogen, biogas, and bio-oils is carried out through thermochemical processes [1], [2], [3], [4]. These processes take place within a reactor where different species are mixed and react to obtaining the desired product, according to the specific operating parameters of each process [5]. To promote thermochemical reactions, high levels of temperature and pressure are required within the reactor. For example, hydrothermal processes occur at temperatures and pressures that can reach 600°C and 220 MPa, while thermochemical reduction/oxidation (RedOx) cycles typically occur at temperatures above 1200°C. In most thermochemical processes, the heat required to drive them is generated in boilers that run on fossil fuels, such as natural gas, or on electricity also generated from fossil fuels. Solar energy is a very attractive heat source for driving thermochemical processes [6], [7], [8]. However, due to their natural intermittency, solar plants require thermal storage and backup systems. In this sense, the use of thermal storage increases not only plant costs but also the environmental impact, while backup thermal systems rely on fossil fuels, which brings us back to the root of the environmental and energy problem. One of the technological challenges in the development of solar thermal plants for thermochemical processes is the need to supply continuous, high-temperature heat. In this context, nuclear energy represents a very attractive option, as the integration of thermochemical processes into a consolidated nuclear plant not only increases the plant's energy efficiency but also reduces its environmental impact [9].

Generation IV nuclear reactors (GEN-IV) have safety and reliability features that ensure the sustainable use of nuclear energy [10]. Currently, nuclear heat is commonly used to fuel electrical power generation systems using the Rankine and Brayton cycles. Power plants based on GEN-IV reactors, in addition to generating electricity very efficiently, also provide process heat for thermochemical cycles such as high-temperature hydrolysis [11]. Hydrogen can be generated simply by splitting water. This process occurs through two reactions: the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER), both driven by external energy. Hydrogen generation requires a large amount of energy; the minimum total energy required to produce 1 kg of H_2 is 120 MJ. This energy can be supplied in the form of heat (thermolysis) or power (electrolysis). Hybrid (heat/power) systems are more efficient; thermolysis reactions occur over a wide temperature range, from 100 to 950°C; however, at temperatures below 300°C, thermal processes are less efficient. As temperature increases, processes become more efficient, since higher thermal energy requires lower power. Therefore, the main technical challenge for nuclear hydrogen production is to increase the operating temperature to achieve greater efficiencies [12]. Residues from forestry and agricultural activities (branches, leaves, grasses, etc.) are one of the most abundant resources in Mexico and Latin America. This

10.18086/swc.2025.05.21 Available at http://proceedings.ises.org

residual biomass is composed of cellulose, hemicellulose, and lignin and is highly attractive for generating bioproducts such as chars, oils, gases, etc. [13] [14] [15] [16] and raw material for the production of high added value chemical products whose sales price can be up to 1000 times higher than the sales price of biofuel [17]. These biomass residues, in addition to being abundant, are a very promising energy source to mitigate the current energy and environmental crisis. The processing of this biomass using hydrothermal (HT) methods represents a great opportunity for established nuclear power plants because they can provide the heat needed to carry out the necessary HT processes.

In hydrothermal technology, water is used under subcritical and supercritical conditions as a reaction agent. These thermodynamic states of water occur at high temperatures and pressures. During hydrothermal processes, structural reorganization by degradation, as well as the products obtained from these processes, depend not only on the thermodynamic variables of temperature and pressure, but also on the residence time. However, temperature is crucial in hydrothermal processes, as it allows for the control of degradation reactions (ionic or radical) and is crucial for the reaction rate. The influence of pressure on hydrothermal reactions is practically negligible and is only important for maintaining water in the liquid phase. The design of a nuclear thermochemical plant (NTP) requires a complete understanding of all energy and mass exchanges occurring within the plant, as well as the thermodynamic parameters of the processes. Currently, NTP plants are hybrid, meaning they produce both thermal and electrical energy. Thermal energy is used as the main heat source for various processes, such as hydrogen generation, while the power is sent to the commercial electrical grid. This energy is also used to operate the plant's pumps and electronic instrumentation, allowing it to operate continuously and independently. The proposed NTP concept consists of a gas-cooled fast reactor (GFR), a Brayton cycle plant, a hybrid hydrogen generation plant, and a hydrothermal plant.

2. Methodology

2.1. Plant design

The methodology for plant design includes stages of energy simulation and integration processes, economic analysis and environmental impact analysis. These stages culminate in the analysis of plant feasibility through industrial innovation and investment analysis [18]. During the design process, maximum resource utilization and energy efficiency must be ensured, while minimizing environmental impact (Figure 1). During energy simulation and integration processes (ESIP), mass and energy balances are established within the plant. During this activity, the flowsheet is designed from a general level down to individual unit operations at the process level. ESIP stage combines the following activities:

1. Modeling and simulation of processes and operating conditions
2. Model validation with published results
3. Sensitivity analysis
4. Data extraction
5. Data filtering and classification
6. Data analysis
7. Cogeneration network design
8. Heat exchanger network design
9. Thermal and energy balance

The comprehensive economic analysis includes capital cost estimates, operating cost assessments, and a plant profitability analysis. Plant costs include, among others:

1. Acquisition and installation of instrumentation and control equipment.
2. Electrical installations and systems.
3. Construction of facilities, piping, engineering, and supervision.
4. Legal expenses, contractor fees, and contingencies.

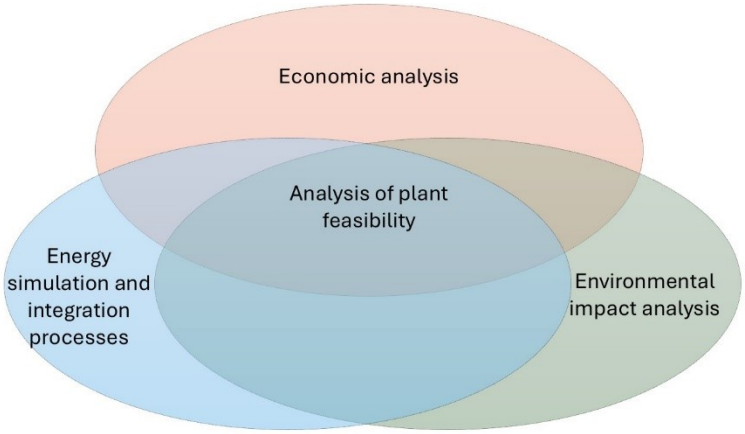

Figure 1. Methodology for plant design.

Environmental impact analysis. The integrated plant must meet four main critical parameters, listed below:

1. Minimize energy consumption and environmental impact by integrating materials and energy across multiple platforms.
2. Accommodate variable seasonal and annual patterns of feedstock procurement and quality by integrating multiple biomass conversion platforms (thermal and biological).
3. Depolymerize target macromolecules (e.g., biomass) into intermediate products that meet the specifications of downstream processing steps.
4. Maximize the yield and quality of the target molecules.

2.2. Nuclear Thermochemical Plant (NTP)

The plant concept contemplates the incorporation of thermochemical processes into an operating nuclear power plant that generates hydrogen and electricity using copper-chlorine, Brayton, and Rankine cycles. The proposed hydrothermal plant will produce bioproducts and coal from biomass waste (Figure 2).

2.3. The Gas-Cooled Fast Reactor (GFR)

The nuclear reactor considered is based on the nuclear power plant reactor concept presented by the U.S. Department of Energy as a fourth-generation reactor (GEN-IV), modeled to have a net thermal capacity of 600 MW [19]. The gas-cooled fast reactor (GFR) is classified as a GEN-IV reactor. This type of reactor does not require a moderator, cools with very high-temperature helium, and has a closed fuel cycle. The GFR has the advantage of being sustainable due to the reduced volume and toxicity of its fuel. It also offers the possibility of using spent fuel from a light water reactor (LWR). In the GFR, the core's structural components are resistant to high temperatures and fast neutron radiation. The GFR operates on a direct Brayton cycle. Furthermore, the energy not harnessed in the thermal cycle can be used in other processes, as the waste heat from the gases passing through the secondary circuit turbine can be used in a steam cycle such as the Rankine cycle.

The GFR uses helium (5210 kJ/kg °C) to cool the reactor core, and it is used as a working fluid in the rest of the plant. The helium exits the reactor core at 850°C (9 MPa, 320 kg/s) and expands to 2.8 MPa in the Brayton cycle. The gas turbine exhaust gases are normally directed to a Rankine cycle boiler. Before re-entering the nuclear reactor, the helium at 490°C is compressed to 9 MPa. The nuclear reactor is the plant's thermal energy source; other subsystems include the gas turbine cycle, the copper-chlorine hybrid cycle with water separation, the hydrogen compression system, and the hydrothermal cycle. Because the helium outlet temperature is much higher than the maximum temperature required by the copper-chlorine cycle and the hydrothermal cycle, its direct use to heat the reactors entails large exergy losses, so the system uses a gas turbine to reduce the temperature and pressure of the helium.

2.4. Hybrid Water Splitting Plant

The splitting of water molecules using electrical methods is as old as the invention of electricity; electrolysis is now

a well-established technology [20], [21].The conversion of thermal energy into electrical energy for hydrogen generation by electrolysis is highly inefficient, as two-thirds of the thermal energy is lost compared to direct hydrogen generation by thermal means. [22].

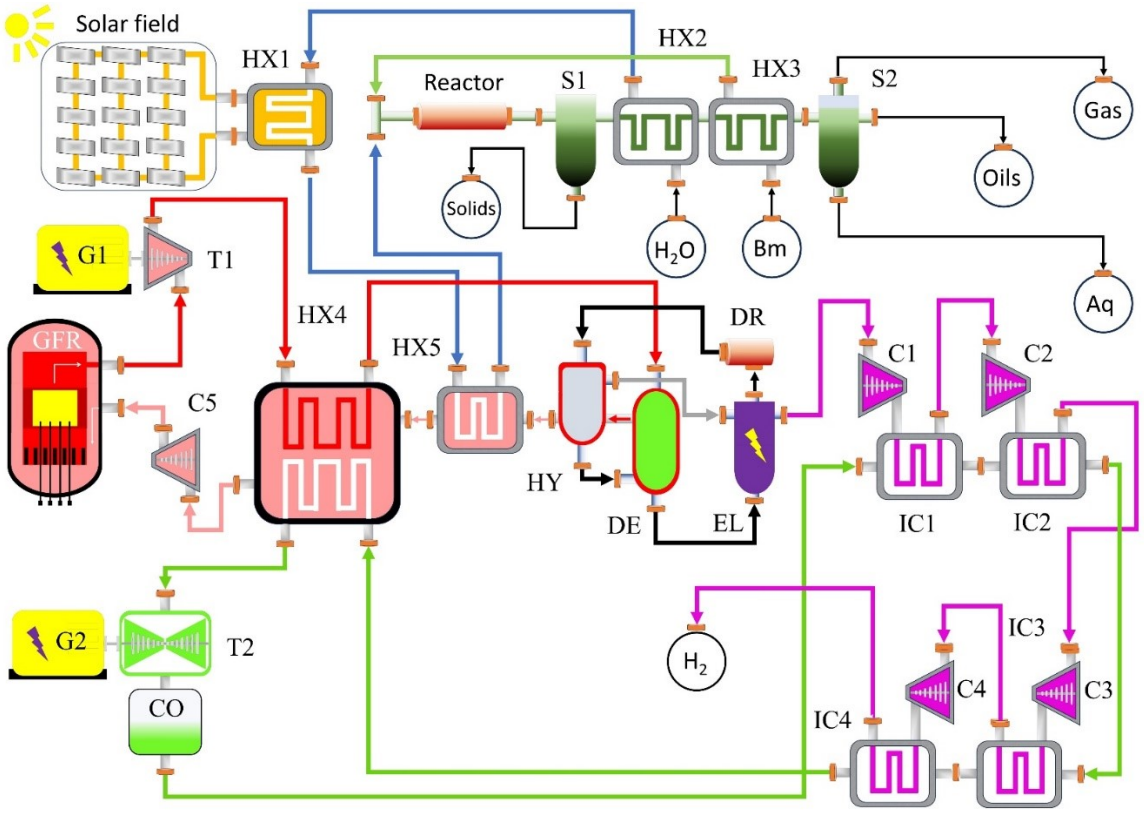

Figure 2. Nuclear thermochemical plant (NTP). The nuclear power plant generates hydrogen and electricity using copper-chlorine, Brayton, and Rankine cycles. The hydrothermal plant produces bioproducts and coal from biomass waste. C: compressor, CO: condenser, DE: decomposition reactor, DR: dryer, EL: electrolyzer reactor, G: electric generator, GFR: gas-cooled fast reactor, HX: heat exchanger, HY: hydrolyzer reactor, IC: intercooler, S: separator, T: turbine.

Therefore, current plants for producing hydrogen by splitting water molecules are based on hybrid systems consisting of thermolysis and electrolysis stages, i.e., high-temperature electrolysis processes. This is because high-temperature thermal processes require the use of materials with suitable thermophysical properties, such as vanadium, zirconium, and tungsten alloys, which have greater thermal resistance, significantly increasing system, operation, and maintenance costs. In contrast, direct medium-temperature hydrogen production cycles can use steel alloys, whose technology is established, and their costs are lower. The thermochemical dissociation of water occurs through a series of chemical-catalytic reactions. There are different dissociation methods: proton exchange membrane (PEM) electrolysis, alkaline water electrolysis, solid oxide electrolysis cells (SOEC), etc. In addition, more than 200 possible thermochemical cycles have been described, including calcium bromide (Ca-Br) thermochemical cycles, hybrid sulfur (HyS) cycles, copper-chlorine (Cu-Cl) cycles, and sulfur-iodine (S-I) cycles. In this work, the Cu-Cl cycle is analyzed due to its high potential for hydrogen production [23] (Fig. 3). The copper-chlorine cycle consists of four stages, the main reactions of which are [24]:

$$CuCl_2(s) + H_2O(g) \rightarrow Cu_2OCl_2(s) + 2HCl(g) \quad \text{(eq. 1)}$$

$$Cu_2OCl_2(s) \rightarrow 2CuCl(l) + 0.5O_2(g) \quad \text{(eq. 2)}$$

$$CuCl(aq) + HCl(g) \rightarrow 0.5H_2(g) + CuCl_2(aq) \quad \text{(eq. 3)}$$

$$CuCl_2(aq) \rightarrow CuCl_2(s) + H_2O(g) \quad \text{(eq. 4)}$$

The hydrolyzer operates at 400°C. In this reactor, $CuCl_2(s)$ and H_2O react to form copper oxychloride ($Cu_2OCl_2(s)$) and hydrogen chloride ($HCl(g)$) (Eq. 1). The copper oxychloride resulting from hydrolysis decomposes at 530°C into $CuCl(l)$ and $O_2(g)$ (Eq. 2). In the electrolyzer, hydrogen chloride gas is dissolved in water to produce hydrogen from hydrochloric acid and copper (I) chloride (aq) by electrical separation. The electrolyzer generates hydrogen gas

and copper (II) chloride (aq). The latter is dried at 100°C to regenerate the main compound from the hydrolysis and restart the cycle. The electrolysis reactor consumes 41.6 kJ for each mole of hydrogen generated.

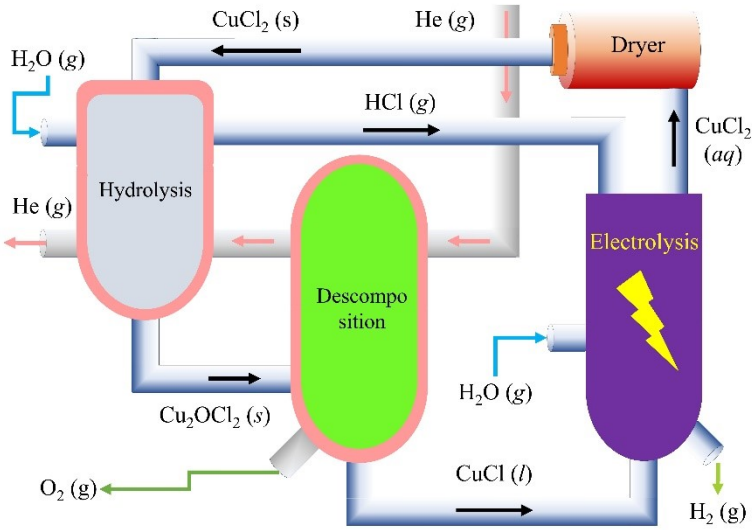

Figure 3. Cu-Cl cycle for hydrogen production

3. Results

3.1. Kinetic Model

The hydrothermal plant is designed to process biomass composed of lipids, carbohydrates, proteins, and lignin. This type of biomass is found in lignocellulosic residues primarily from forestry activities [25]. As an initial hypothesis, it is assumed that reactants composed of lipids, carbohydrates, proteins, and lignin can produce solid products (biochars) and intermediate molecular weight components (liquids). These, depending on their polarity, can dissolve in water (aqueous) or be immiscible at ambient temperature and pressure (biocrude). Furthermore, there is the possibility of the formation of low molecular weight compounds, which at ambient temperature and pressure would be in the gaseous phase. To evaluate the initial assumption, a kinetic model like that proposed by Obeid et al. [26],[27] [28] was simulated, where the reactants interact in a series-parallel reaction scheme through first-order elementary steps [29], [30], [31], considering the nonlinear temperature dependence and according to the Arrhenius law [32], [33]. **Figure 4** shows the kinetic model where a block of reactants (lipids, carbohydrates, proteins, and lignin) irreversibly produces a block of products (solids, aqueous, Bio-oil, and gaseous) [34].

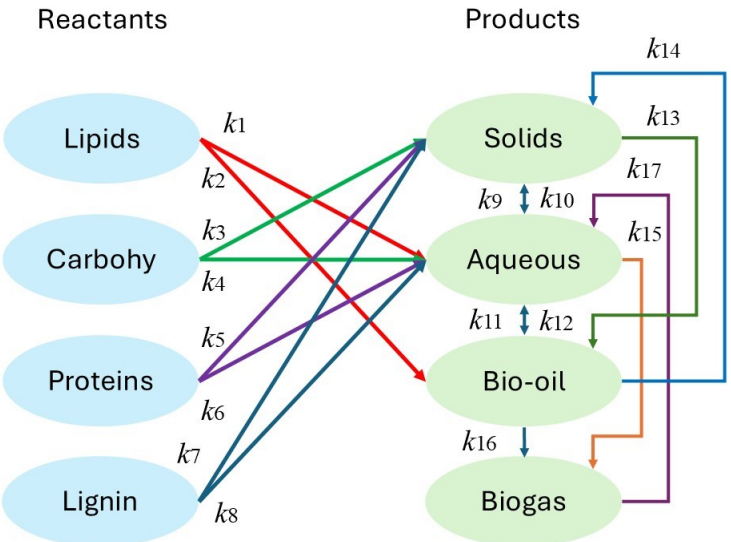

Figure 4. Kinetic model. The reactant block (lipids, carbohydrates, proteins, and lignin) give rise to a product block (solids, aqueous, bio-oil, and gaseous).

The mathematical analysis arising from the reaction scheme is presented in a system of nonlinear ordinary differential equations (ODE) (5) to (12), where $x_i(t=0) = x_{io}$.

$$\frac{dx_1}{dt} = -(k_1 + k_2)x_1 \quad \text{(eq. 5)}$$

$$\frac{dx_2}{dt} = -(k_3 + k_4)x_2 \quad \text{(eq. 6)}$$

$$\frac{dx_3}{dt} = -(k_5 + k_6)x_3 \quad \text{(eq. 7)}$$

$$\frac{dx_4}{dt} = -(k_7 + k_8)x_4 \quad \text{(eq. 8)}$$

$$\frac{dx_5}{dt} = k_3x_2 + k_5x_3 + k_7x_4 - (k_{10} + k_{13})x_5 + k_9x_6 + k_{14}x_7 \quad \text{(eq. 9)}$$

$$\frac{dx_6}{dt} = k_1x_1 + k_4x_2 + k_6x_3 + k_8x_4 + k_{10}x_5 - (k_9 + k_{12} + k_{15})x_6 + k_{11}x_7 + k_{17}x_8 \quad \text{(eq. 10)}$$

$$\frac{dx_7}{dt} = k_2x_1 + k_{13}x_5 + k_{12}x_6 - (k_{11} + k_{14} + k_{16})x_7 \quad \text{(eq. 11)}$$

$$\frac{dx_8}{dt} = k_{15}x_6 + k_{17}x_7 - k_{17}x_8 \quad \text{(eq. 12)}$$

Where a given concentration of lipids (x1) produces biocrude (x7) and aqueous products (x6), while carbohydrates (x2), proteins (x3), and lignin (x4) produce biochars (x5) and aqueous products (x6) in varying proportions. Furthermore, the products interact with each other through reversible reactions, such as those between biochars and biocrude or between the aqueous phase and biogas; only biocrude produces biogas (x8) irreversibly [35]. The ODE system allows you to construct a matrix with operating temperature (T_i) and residence time (t_i) values to calculate the expected yield in each situation. The operating temperature controls the reaction kinetics and is crucial for the reaction rate [36]. Operating temperatures in the range of 180°C to 250°C (20-100 bar) are favorable for the hydrothermal carbonization process, resulting in improved biochar and water-soluble organic species. While hydrothermal liquefaction, which produces improved bio-oils with higher carbon content and high calorific value, occurs in the range of 200-374°C (50-200 bar). At operating temperatures above 400°C, hydrothermal gasification occurs, favoring the formation of methane. As the operating temperature increases, the yield increases, and hydrogen and syngas are formed. In addition to operating temperature, residence time and biomass concentration are factors that influence product properties [37].

Long residence times result in condensed products due to excessive polymerization and can lead to a decrease in oxygen functional groups (OFG). Furthermore, the combination of high biomass concentration and long residence time increases OFG content due to the increased degree of reaction and the formation of secondary carbon [38]. **Figure 5** shows the expected product yields, considering the typical biomass composition: 65-80% w/w carbohydrates, 18-35% w/w lignin, and the remainder lipids and proteins. The temperature ramps were varied by selecting initial and final temperatures between 250°C and 350°C, and residence times between 0 and 60 minutes.

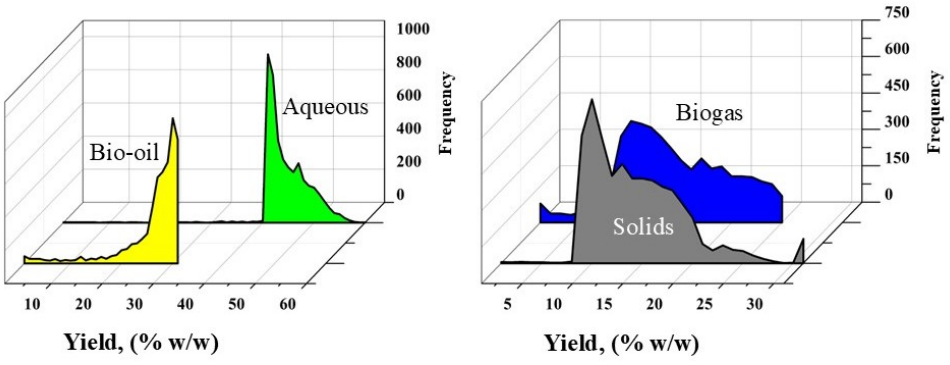

Figure 5. Expected yield of products from plant biomass (65-80% w/w carbohydrates, 18-35% w/w lignin, and the remainder lipids and proteins). Biogas, bio-oil, biochar (solid), and an aqueous phase are expected to be obtained with yields close to 20%, 30%, 10%, and 40% (w/w), respectively [39].

The results show that hydrothermal conversion of lignocellulosic biomass into bioproducts produces biogas, bio-oil, biochar, and an aqueous phase with yields of approximately 20%, 30%, 10%, and 40% (w/w), respectively [39]. Figure 6 shows a detailed view of the hydrothermal plant according to the proposal of Giaconia et al. [35].

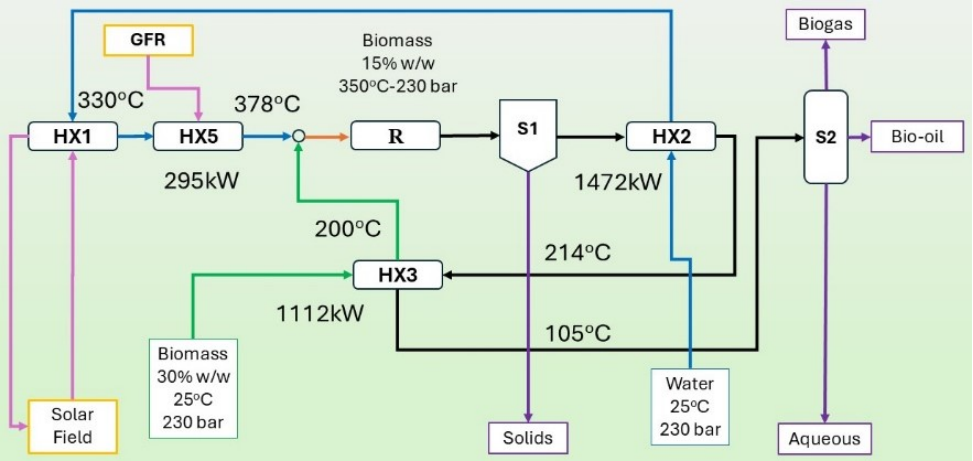

Figure 6. Hydrothermal plant. Water and wet biomass are preheated with heat recovery in HX2 (1472 kW) and HX3 (1112 kW), respectively. In addition, water is heated in HX4 (295 kW) using solar heat and HX1 using nuclear heat as backup. Products are collected in C1 and S1.

Water and wet biomass (30% w/w) are preheated with heat recovery from the products. Preheating takes place in heat exchanger HX2 (ΔT=305°C) for water and HX3 (ΔT=175°C) for biomass. In HX4, the water absorbs 295 kW of working fluid from the solar field to raise its temperature to 378°C. When solar heat is insufficient, heat is obtained from the nuclear power plant. The hydrolyzed biomass (15% w/w) is transferred to the adiabatic reactor (ΔH=0) operating at 350°C and 230 bar.

The HT biomass processes generate solids (biochar, 19.2% w/w) in the cyclone separator C1, while the separator S1 produces bio-oil (37.4% w/w), biogas (0.3% w/w), and an aqueous phase (43.1% w/w) composed of raw biomass and water. The raw biomass and excess water from the processes are separated and reused. The thermal power $Q(T)$ required to raise the temperature of the biomass-water mixture from de T_1 to T_2 is determined by the following equation:

$$Q(T) = k_f[(1 - x_{BM})(h_2 - h_1) + x_{BM}c_{BM}(T_2 - T_1)] \quad \text{(eq. 13)}$$

Where k_f is the mass flow rate (kg/s), x_{BM} y c_{BM} are the concentration and specific heat capacity of the biomass, respectively. While h_i is the specific enthalpy of water at temperature T_i. The total thermal energy required to heat a flow rate of 2.14 kg/s of biomass hydrolyzed at 15% w/w from 25°C to 350°C is estimated at 2879 kW; however, due to the plant configuration, 89% of this power is recovered. The thermodynamic analysis of the proposed plant was performed under the following conditions:

1. The plant operates in steady state, as the duration of the transient phase is negligible compared to the stationary phase. Furthermore, the objective of the analysis is to assess the operational capacity of the nuclear reactor, which supports the steady-state evaluation of the entire integrated system.
2. Kinetic and potential energy variations throughout the system are ignored.
3. The electrical generators convert 95% of the input shaft work into electrical energy.
4. Heat losses in the reactors, turbines, and heat exchangers are considered negligible due to their low values compared to the work of the heat exchangers and the high energy output of the turbines.
5. The unitary efficiency of the heat exchangers was also considered.

According to the Department for Business, Energy and Industrial Strategy's greenhouse gas reports, the amount of CO_2 not emitted into the atmosphere by using a carbon-free source is 0.23314 kg of CO_2 per kWh. This factor includes other greenhouse gases, such as methane and nitrous oxide, which are converted to their carbon dioxide

equivalents. The thermal integration of a hydrothermal process into a nuclear power plant does not affect its operation, as the energy required by the hydrothermal process represents approximately 0.05% of its total capacity. However, the impact on the energy costs of operating the thermochemical process and on its efficiency is extremely significant. Furthermore, the environmental impact of operating the thermochemical process with nuclear heat instead of heat from fossil sources is also highly desirable.

4. Acknowledgments

The authors gratefully acknowledge the financial support received from CONAHCYT within the framework of the Basic and Frontier Science 2023-2024 call, Project No. CBF2023-2024-3410, "Development of advanced methods and new materials for solar thermal energy storage through reversible solid-gas reaction cycles to improve the use of solar technology". Authors thank SECIHTI for granting the scholarships through the programs 'National Scholarships for Postgraduate Studies' (JMBS and LMMR) and 'Postdoctoral Stays in Mexico 2022' (JDM).

5. References

[1] J. V. Briongos, S. Taramona, J. Gómez-Hernández, V. Mulone, and D. Santana, "Solar and biomass hybridization through hydrothermal carbonization," *Renew Energy*, vol. 177, pp. 268–279, 2021, doi: 10.1016/j.renene.2021.05.146.

[2] G. Ischia and L. Fiori, "Hydrothermal Carbonization of Organic Waste and Biomass: A Review on Process, Reactor, and Plant Modeling," *Waste Biomass Valorization*, no. 0123456789, 2020, doi: 10.1007/s12649-020-01255-3.

[3] M. Al Hattab, A. Ghaly, and A. Hammouda, "Microalgae Harvesting Methods for Industrial Production of Biodiesel : Critical Review and Comparative Analysis Fundamentals of Renewable Energy and Applications," *Journal of Fundamentals of Rnewable Energy and Applications*, vol. 5, no. 2, pp. 1–26, 2015, doi: 10.4172/20904541.1000154.

[4] N. S. Shamsul, S. K. Kamarudin, and N. A. Rahman, "Conversion of bio-oil to bio gasoline via pyrolysis and hydrothermal: A review," *Renewable and Sustainable Energy Reviews*, vol. 80, no. April 2016, pp. 538–549, 2017, doi: 10.1016/j.rser.2017.05.245.

[5] Q. Bellouard, S. Abanades, S. Rodat, and N. Dupassieux, "A high temperature drop-tube and packed-bed solar reactor for continuous biomass gasification," *AIP Conf Proc*, vol. 1850, no. June 2017, 2017, doi: 10.1063/1.4984458.

[6] Y. Shuai, B. Guene Lougou, H. Zhang, J. Zhao, C. Ahouannou, and H. Tan, "Heat transfer analysis of solar-driven high-temperature thermochemical reactor using NiFe-Aluminate RPCs," *Int J Hydrogen Energy*, no. xxxx, 2020, doi: 10.1016/j.ijhydene.2020.03.240.

[7] B. Guene Lougou *et al.*, "Thermochemical CO2 reduction over NiFe2O4@alumina filled reactor heated by high-flux solar simulator," *Energy*, vol. 197, pp. 1–15, 2020, doi: 10.1016/j.energy.2020.117267.

[8] J. Ortega, S. Khivsara, J. Christian, C. Ho, J. Yellowhair, and P. Dutta, "Coupled modeling of a directly heated tubular solar receiver for supercritical carbon dioxide Brayton cycle: Optical and thermal-fluid evaluation," *Appl Therm Eng*, vol. 109, pp. 970–978, Oct. 2016, doi: 10.1016/j.applthermaleng.2016.05.178.

[9] A. Belghit and E. D. Gordillo, "Biomass Char Steam Gasification in Fluidized Reactor Using Nuclear Heat," *OAlib*, vol. 07, no. 03, pp. 1–14, 2020, doi: 10.4236/oalib.1106155.

[10] A. S. Ayon, M. A. R. Alif, and A. S. M. Nasim, "A Review and Analysis of Nuclear Hydrogen Production in Generation IV Reactors," *International Journal of Nuclear Security*, vol. 9, no. 2, 2024, doi: 10.7290/ijns09777962.

[11] R. Elder and R. Allen, "Nuclear heat for hydrogen production: Coupling a very high/high temperature reactor to a hydrogen production plant," *Progress in Nuclear Energy*, vol. 51, no. 3, pp. 500–525, Apr. 2009, doi: 10.1016/j.pnucene.2008.11.001.

[12] Q. Gao, X. Qu, W. Peng, P. Zhang, and S. Chen, "Influence of obstacle morphology on safety of nuclear hydrogen production system," *Int J Hydrogen Energy*, vol. 47, no. 86, pp. 36733–36748, 2022, doi: 10.1016/j.ijhydene.2022.08.235.

[13] M. Sevilla and A. B. Fuertes, "The production of carbon materials by hydrothermal carbonization of cellulose," *Carbon N Y*, vol. 47, no. 9, pp. 2281–2289, Aug. 2009, doi: 10.1016/j.carbon.2009.04.026.

[14] Z. Liu, A. Quek, S. Kent Hoekman, and R. Balasubramanian, "Production of solid biochar fuel from waste biomass by hydrothermal carbonization," *Fuel*, vol. 103, pp. 943–949, Jan. 2013, doi: 10.1016/j.fuel.2012.07.069.

[15] J. Fang, L. Zhan, Y. S. Ok, and B. Gao, "Minireview of potential applications of hydrochar derived from hydrothermal carbonization of biomass," *Journal of Industrial and Engineering Chemistry*, vol. 57, pp. 15–21, Jan. 2018, doi: 10.1016/j.jiec.2017.08.026.

[16] J. Akhtar and N. A. S. Amin, "A review on process conditions for optimum bio-oil yield in hydrothermal liquefaction of biomass," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1615–1624, Apr. 2011, doi: 10.1016/j.rser.2010.11.054.

[17] A. Sessa *et al.*, “Levulinic acid biorefinery in a life cycle perspective,” *Curr Opin Green Sustain Chem*, vol. 50, p. 100963, 2024, doi: 10.1016/j.cogsc.2024.100963.
[18] J. Sadhukhan and K. S. Ng, “Economic and European Union environmental sustainability criteria assesment of bio-oil-based biofuel systems: Refinery integration cases,” *Ind Eng Chem Res*, vol. 50, no. 11, pp. 6794–6808, 2011, doi: 10.1021/ie102339r.
[19] A. Dragunov, E. Saltanov, I. Pioro, B. Ikeda, M. Miletic, and A. Zvorykina, “Investigation of thermophysical and nuclear properties of prospective coolants for generation-IV nuclear reactors,” *International Conference on Nuclear Engineering, Proceedings, ICONE*, vol. 4, no. July 2013, 2013, doi: 10.1115/ICONE21-16020.
[20] J. Milewski, J. Kupecki, A. Szczęśniak, and N. Uzunow, “Hydrogen production in solid oxide electrolyzers coupled with nuclear reactors,” *Int J Hydrogen Energy*, vol. 46, no. 72, pp. 35765–35776, 2021, doi: 10.1016/j.ijhydene.2020.11.217.
[21] R. Z. Aminov and A. N. Bairamov, “Performance evaluation of hydrogen production based on off-peak electric energy of the nuclear power plant,” *Int J Hydrogen Energy*, vol. 42, no. 34, pp. 21617–21625, 2017, doi: 10.1016/j.ijhydene.2017.07.132.
[22] S. Şahin and H. M. Şahin, “Generation-IV reactors and nuclear hydrogen production,” *Int J Hydrogen Energy*, vol. 46, no. 57, pp. 28936–28948, 2021, doi: 10.1016/j.ijhydene.2020.12.182.
[23] M. Al-Zareer, I. Dincer, and M. A. Rosen, “Analysis and assessment of the integrated generation IV gas-cooled fast nuclear reactor and copper-chlorine cycle for hydrogen and electricity production,” *Energy Convers Manag*, vol. 205, no. December 2019, p. 112387, 2020, doi: 10.1016/j.enconman.2019.112387.
[24] Q. Wang, C. Liu, R. Luo, X. Li, D. Li, and R. Macián-Juan, “Thermo-economic analysis and optimization of the very high temperature gas-cooled reactor-based nuclear hydrogen production system using copper-chlorine cycle,” *Int J Hydrogen Energy*, vol. 46, no. 62, pp. 31563–31585, 2021, doi: 10.1016/j.ijhydene.2021.07.060.
[25] Z. Anwar, M. Gulfraz, and M. Irshad, “Agro-industrial lignocellulosic biomass a key to unlock the future bio-energy: A brief review,” *J Radiat Res Appl Sci*, vol. 7, no. 2, pp. 163–173, 2014, doi: 10.1016/j.jrras.2014.02.003.
[26] R. Obeid, D. Lewis, N. Smith, and P. van Eyk, “The elucidation of reaction kinetics for hydrothermal liquefaction of model macromolecules,” *Chemical Engineering Journal*, vol. 370, no. December 2018, pp. 637–645, 2019, doi: 10.1016/j.cej.2019.03.240.
[27] R. Obeid, D. M. Lewis, N. Smith, T. Hall, and P. Van Eyk, “Reaction Kinetics and Characterization of Species in Renewable Crude from Hydrothermal Liquefaction of Mixtures of Polymer Compounds to Represent Organic Fractions of Biomass Feedstocks,” *Energy and Fuels*, vol. 34, no. 1, pp. 419–429, 2020, doi: 10.1021/acs.energyfuels.9b02936.
[28] R. Obeid, D. M. Lewis, N. Smith, T. Hall, and P. van Eyk, “Reaction kinetics and characterisation of species in renewable crude from hydrothermal liquefaction of monomers to represent organic fractions of biomass feedstocks,” *Chemical Engineering Journal*, vol. 389, p. 124397, Jun. 2020, doi: 10.1016/j.cej.2020.124397.
[29] P. J. Valdez, V. J. Tocco, and P. E. Savage, “A general kinetic model for the hydrothermal liquefaction of microalgae,” *Bioresour Technol*, vol. 163, pp. 123–127, Jul. 2014, doi: 10.1016/j.biortech.2014.04.013.
[30] F. Yin, H. Chen, G. Xu, G. Wang, and Y. Xu, “A detailed kinetic model for the hydrothermal decomposition process of sewage sludge,” *Bioresour Technol*, vol. 198, pp. 351–357, 2015, doi: 10.1016/j.biortech.2015.09.033.
[31] G. Ischia and L. Fiori, “Hydrothermal Carbonization of Organic Waste and Biomass: A Review on Process, Reactor, and Plant Modeling,” *Waste Biomass Valorization*, no. 0123456789, 2020, doi: 10.1007/s12649-020-01255-3.
[32] M. A. Islam, G. Kabir, M. Asif, and B. H. Hameed, “Combustion kinetics of hydrochar produced from hydrothermal carbonisation of Karanj (Pongamia pinnata) fruit hulls via thermogravimetric analysis,” *Bioresour Technol*, vol. 194, pp. 14–20, 2015, doi: 10.1016/j.biortech.2015.06.094.
[33] F. Yin, H. Chen, G. Xu, G. Wang, and Y. Xu, “A detailed kinetic model for the hydrothermal decomposition process of sewage sludge,” *Bioresour Technol*, vol. 198, pp. 351–357, 2015, doi: 10.1016/j.biortech.2015.09.033.
[34] M. Jatzwauck and A. Schumpe, “Kinetics of hydrothermal carbonization (HTC) of soft rush,” *Biomass Bioenergy*, vol. 75, pp. 94–100, 2015, doi: 10.1016/j.biombioe.2015.02.006.
[35] A. Giaconia *et al.*, “Biorefinery process for hydrothermal liquefaction of microalgae powered by a concentrating solar plant: A conceptual study,” *Appl Energy*, vol. 208, no. June, pp. 1139–1149, 2017, doi: 10.1016/j.apenergy.2017.09.038.
[36] S. Román *et al.*, “Hydrothermal carbonization: Modeling, final properties design and applications: A review,” *Energies (Basel)*, vol. 11, no. 1, pp. 1–28, 2018, doi: 10.3390/en11010216.
[37] M. Lucian and L. Fiori, “Hydrothermal carbonization of waste biomass: Process design, modeling, energy efficiency and cost analysis,” *Energies (Basel)*, vol. 10, no. 2, 2017, doi: 10.3390/en10020211.
[38] A. Jain, R. Balasubramanian, and M. P. Srinivasan, “Hydrothermal conversion of biomass waste to activated carbon with high porosity: A review,” *Chemical Engineering Journal*, vol. 283, pp. 789–805, Jan. 2016, doi: 10.1016/j.cej.2015.08.014.

[39] E. Bautista-Peñuelas *et al.*, "Hydrothermal liquefaction of wood wastes in a concentrating solar plant: A techno-economic analysis," *Energy Convers Manag*, vol. 282, no. December 2022, 2023, doi: 10.1016/j.enconman.2023.116861.