energies

Article

Optimal Incorporation of Intermittent Renewable Energy Storage Units and Green Hydrogen Production in the Electrical Sector

Tania Itzel Serrano-Arévalo [1], Javier Tovar-Facio [2] and José María Ponce-Ortega [1,*]

[1] Department of Chemical Engineering, Universidad Michoacana de San Nicolás de Hidalgo, Morelia 58060, Mexico
[2] Faculty of Chemical Sciences, Universidad Autónoma de Chihuahua, Chihuahua 31125, Mexico
* Correspondence: jose.ponce@umich.mx; Tel.: +52-443-3223500 (ext. 1277)

Abstract: This paper presents a mathematical programming approach for the strategic planning of hydrogen production from renewable energies and its use in electric power generation in conventional technologies. The proposed approach aims to determine the optimal selection of the different types of technologies, electrolyzers and storage units (energy and hydrogen). The approach considers the implementation of an optimization methodology to select a representative data set that characterizes the total annual demand. The economic objective aims to determine the minimum cost, which is composed of the capital costs in the acquisition of units, operating costs of such units, costs of production and transmission of energy, as well as the cost associated with the emissions generated, which is related to an environmental tax. A specific case study is presented in the Mexican peninsula and the results show that it is possible to produce hydrogen at a minimum sale price of 4200 $/tonH_2$, with a total cost of \$5.1687 $\times 10^6$ and 2.5243 $\times 10^5$ $tonCO_{2eq}$. In addition, the financial break-even point corresponds to a sale price of 6600 $/tonH_2$. The proposed model determines the trade-offs between the cost and the emissions generated.

Keywords: optimization; green hydrogen; energy demand; planning; energy storage

Citation: Serrano-Arévalo, T.I.; Tovar-Facio, J.; Ponce-Ortega, J.M. Optimal Incorporation of Intermittent Renewable Energy Storage Units and Green Hydrogen Production in the Electrical Sector. *Energies* **2023**, *16*, 2609. https://doi.org/10.3390/en16062609

Academic Editors: Ho Wai Shin and Peng Yen Liew

Received: 9 February 2023
Revised: 26 February 2023
Accepted: 7 March 2023
Published: 9 March 2023

1. Introduction

One of the main problems of electricity generation is satisfying the variable energy demand that increases according to population and economic growth [1]. Generally, energy production results from the operation of thermal or conventional power plants [2] and renewable technologies [3]. The production of energy from conventional technologies requires fossil fuels (natural gas, coal, oil, among others); however, in certain regions, the availability of these resources is limited due to the infrastructure required to obtain them [4] and the problem that some fossil fuels require a huge amount of energy to extract them and, therefore, have an ever-increasing energy cost [5,6]. Due to factors such as the aforementioned, it is not possible to fully operate conventional plants because of the large fossil fuel requirements, resulting in energy security concerns [7]. Many countries still rely heavily on fossil fuels [8], leading to concerns that the energy sector plays an important role in increasing wealth and, therefore, in the growth of the country [9]. Hydrogen is mainly used in the chemical industry; however, it can also be used as a fuel and is produced mainly from fossil and renewable biomass resources, including steam reforming, pyrolysis [10] and biomass gasification [11]. In addition, hydrogen can be generated from water in the electrolysis process; being a promising substitute for fossil fuels, hydrogen has become a clean and renewable energy [12].

Electrolysis is an electrochemical process of splitting water (H_2O) that produces molecular oxygen (O_2) and hydrogen (H_2) [13]; however, producing hydrogen by this method in so-called electrolyzers [14] entails different processes after obtaining it, such as storage [15]. Although hydrogen is zero-carbon-emission energy at the point of end use, it depends on the production route and the energy used to produce it [16]. In this sense, the production of hydrogen from renewable energy sources is called “Green Hydrogen” [17], so electrolysis is a good option to make the most of surplus renewable energy [18] and has a significant economic impact [19]; however, a problem in the production of hydrogen with renewable technologies is the climatic conditions [20]. Studies have recently been carried out specifying that it is possible to operate these conventional energy production technologies with a mixture of natural gas and hydrogen as fuel [21] and biofuels with hydrogen [22], highlighting their competitiveness as part of the transition from the current electrical system to the electrical systems of the future [23].

On the other hand, energy storage is important for electric systems, allowing load leveling and the reduction of peaks, energy oscillations and the improvement of the quality and reliability of energy [24], this is achieved by storing excess or unused energy and supplying it to the grid when necessary [25]. Among various battery technologies, so-called lithium-ion and vanadium for renewable energy storage (solar and wind) exhibit a high energy efficiency, long life cycle and relatively high energy density [26,27]. Likewise, it is well known that conventional technologies generate large amounts of emissions as a consequence of the burning of fossil fuels [28], unlike renewable technologies that offer a friendly option for the environment, benefiting the mitigation of emissions of CO_2 [29], a good example is photovoltaic panels reducing climate change [30,31]. An environmental tax (carbon tax) has recently been considered on the carbon emissions emitted in the different processes to mitigate climate change [32], this type of tax is dependent on the government policies of each country [33].

It is important to consider the above aspects to design adequate energy production networks, searching for cost-benefit compensation solutions, which has resulted in considering factors such as equipment selection and capacity (generation technologies [34], energy storage [35], electrolyzers [36], among others), as well as associated economic and environmental aspects. Decision tools have been used within energy systems as multi-objective problem techniques with operational constraints [37], optimization methods [38], the formulation of stochastic and deterministic programming models [39], design and optimization algorithms based on mixed integer linear programming (MILP) [40], uniform progressive optimization methods with successive approximation strategies [41] and mathematical modeling [42]. This project proposes to determine the minimum cost (*TC*) of the energy production network, considering conventional and renewable technologies; in addition, it is intended to quantify the emissions generated, simultaneously limiting the fossil fuel required by conventional technologies, mitigating the demand for said fuel and supplying it with a natural gas-hydrogen mixture, which will be produced by renewable technologies. A disjunctive optimization model is presented to select the set of different energy generation technologies, as well as the different hydrogen production and storage units; in addition, the necessary capacities of said units will be selected to satisfy a variable demand with a long planning horizon. Finally, it is sought that the production of green hydrogen within an energy network achieves an interesting, viable, renewable and sustainable economy. It should be noted that the novelty addressed in this work consists in producing energy with different types of technologies (conventional and renewable), as well as the necessary units in the storage of renewable energy and the production of green hydrogen. In other words, previous methodologies (related to the electrical sector) have not considered the configuration of the energy and hydrogen production network and its storage in a single planning. In addition, another relevant aspect is the appropriate sale price of hydrogen that represents economic income to the project.

2. Problem Statement

The addressed problem involves a set of conventional and renewable technologies in the production of electrical energy in a macroscopic region. These sources must be able to produce enough energy to satisfy a given energy demand at a specific time and, at the same time, optimally segregate the energy flows to directly satisfy the electrical energy demand of a specific region or store it for later use. Firstly, renewable sources must be able to select the energy flows produced to be stored and meet energy demand or be used in electrolyzers and produce hydrogen that will be stored for use in conventional technologies, replacing a percentage of natural gas with hydrogen and contributing to reducing greenhouse gas emissions generated by technologies that consume fossil fuels and the demand for these. Green hydrogen production must be suitable for blending with natural gas and used as a fuel source in conventional technologies that use natural gas. Conventional technologies will be classified into those that use natural gas and those that use another type of fuel, which will not be mixed with hydrogen; on the other hand, renewable technologies will be classified into variable and non-variable according to the availability of the natural resource in each one of them. The proposed disjunctive optimization problem consists of determining the appropriate selection of electric power generation technologies that must operate simultaneously, the energy storage units that must be used for the correct operation of the process, as well as the electrolyzers that must be installed to produce the energy, and the amount of hydrogen required by conventional technologies. The capacities of the units and the costs associated with them are also considered. An important aspect is to determine the sale price of hydrogen within the system so that the process is optimal, and the production of hydrogen is carried out in different regions (see Figure 1).

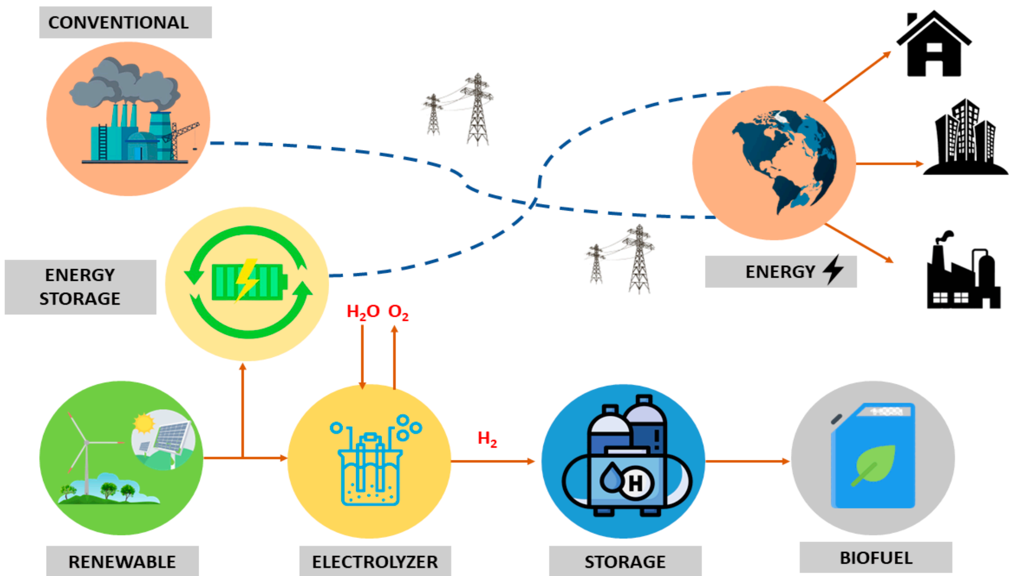

Figure 1. Addressed problem involving the production of electricity and green hydrogen to satisfy the electrical energy demand in each region.

3. Model Formulation

This section presents the mathematical model proposed for the optimal production of electrical energy and the production of green hydrogen efficiently in a macroscopic system. The schematic representation of the proposed superstructure is shown in Figure 2, where a set of technologies ($j = 1, 2, \ldots, J$) operate to meet energy demands in a given geographical region ($r = 1, 2, \ldots, R$), in a specific period ($t = 1, 2, \ldots, T$), energy from renewable technology, ($jrt = 1, 2, \ldots, J$) variable ($jr = 1, 2, \ldots, J$) and non-variable ($jrh = 1, 2, \ldots, J$), is used to produce hydrogen in electrolyzers ($h = 1, 2, \ldots, H$) or is stored in energy storage batteries ($i = 1, 2, \ldots, I$) to be used to meet the required energy demand. On the other hand, conventional technologies ($jt = 1, 2, \ldots, J$) are classified into those that use natural gas as fuel ($jg = 1, 2, \ldots, J$) and those that use fuel oil as fossil fuel ($jc = 1, 2, \ldots, J$). When hydrogen is produced, it can be stored ($g = 1, 2, \ldots, G$) to later be mixed with natural gas in conventional technologies that require such fuel according to the requirements established by the technologies. It is important to highlight the relevance and applicability of the proposed superstructure since the production of green hydrogen within an energy system carries with it a plus because it can be used as fuel in conventional technologies, helping to reduce the demand for fossil fuels and reduce the emissions generated by burning these. The mathematical formulation includes equations to model the generation for each type of technology, incorporating sizing, and associated costs in the production and equipment used. Then, the optimization model for energy planning and green hydrogen production is presented as follows.

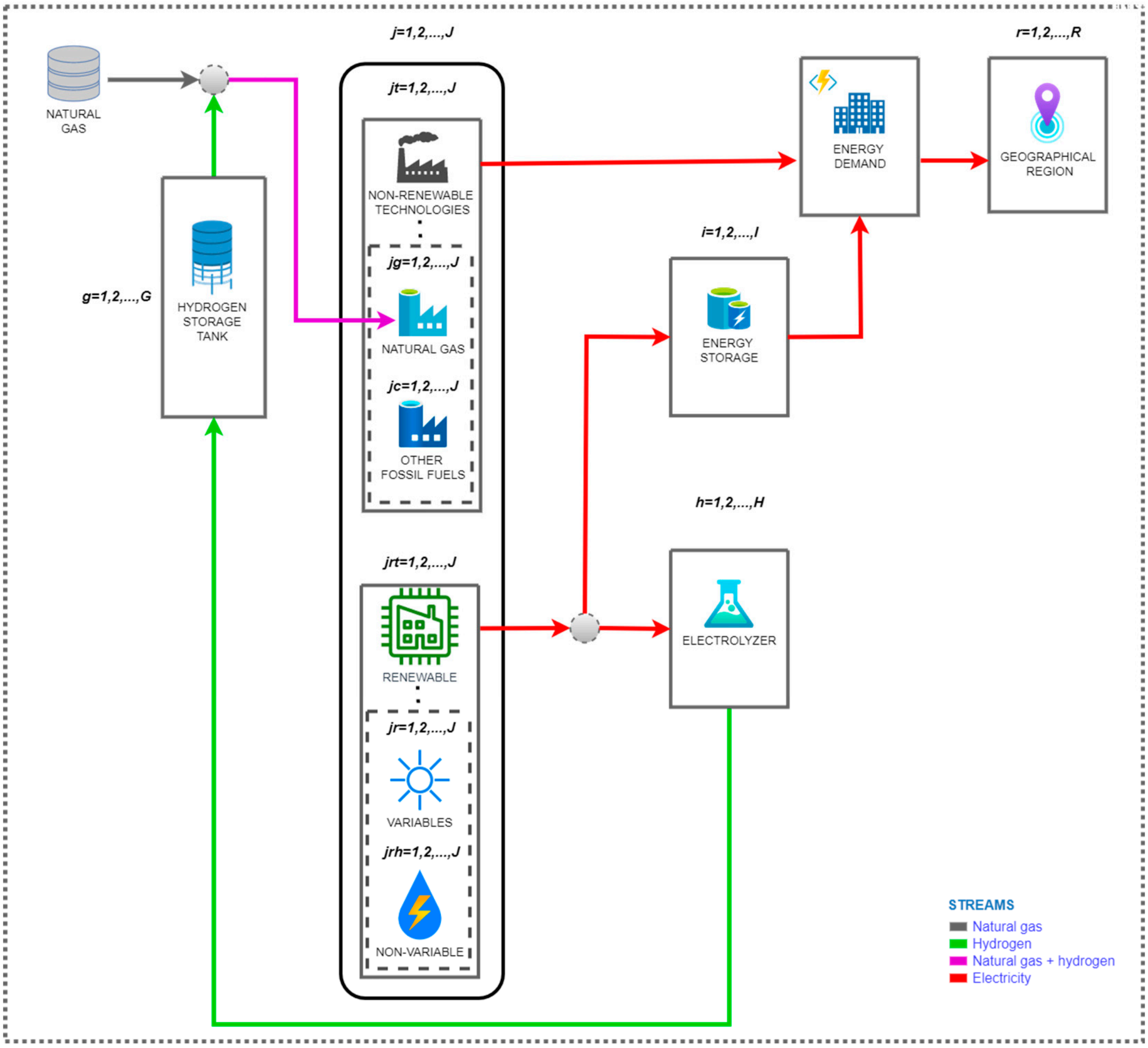

Figure 2. Schematic representation of the proposed superstructure for the generation of electrical energy.

3.1. Electricity Demand in Each Transmission Region

Electricity demand ($EDEM$) in each region (r) and time interval (t) can be satisfied with the local generation ($eprodem$) of available technologies (j), energy produced and transmitted from a different region (r'), and the energy that is discharged from energy storage systems. When using energy external to the r region, it is necessary to consider the transmission efficiency (η^{trans}) to consider losses due to electricity transport. In addition, a term of the unsupplied demand is included ($umdem$) to complete the balance and avoid unfeasible scenarios. However, it is expected that the demand will always be satisfied so that the unsupplied demand is penalized in the target function.

$$EDEM_{r,t} = umdem_{r,t} + \sum_{j} eprodem_{r,j,t} + \sum_{r' \neq r} \sum_{j} etrans_{r',r,j,t} \left(\eta^{trans}\right) + \sum_{i} edes_{r,i,t} \qquad \forall r \in R, \forall t \in T \qquad (1)$$

3.2. Production of Conventional Electricity

The electricity generated ($ep_{r,jt,t}$) in every conventional technology (jt) of the region (r) is obtained by adding the energy that is used to meet local demand plus the energy transmitted from region r to region r' corresponding to a different region with available streaming infrastructure.

$$ep_{r,jt,t} = eprodem_{r,jt,t} + \sum_{r \neq r'} etrans_{r,r',jt,t} \ \forall r \in R, \forall jt \in J, \forall t \in T \quad (2)$$

3.3. Amount of Fuel Consumed by Conventional Technologies

The amount of fuel needed in thermal technologies that use natural gas (jg) is quantified by adding the mass of natural gas ($mgas$) and the mass of hydrogen used in power plants ($m^{H_2,burn}$) multiplied, respectively, by the calorific value of each of them, ($LHVG$) and ($LHVH$), and the ratio of thermal efficiency of fuels to electricity ($\eta_{jg}^{convgas}$) and ($\eta_{jg}^{convH_2}$).

$$ep_{r,jg,t} = \frac{mgas_{r,jg,t}(LHVG)}{\left(\eta_{jg}^{convgas}\right)} + \frac{\sum_h m_{r,h,jg,t}^{H_2,burn}(LHVH)}{\left(\eta_{jg}^{convH_2}\right)} \ \forall r \in R, \forall jg \in J, \forall t \in T \quad (3)$$

Some of the thermal technologies (jt) work with other types of fuels, for this type of technology (jc) the amount of fuel is quantified as follows:

$$ep_{r,jc,t} = \frac{mcom_{r,jc,t}(LHVC)}{\left(\eta_{jc}^{convotr}\right)} \ \forall r \in R, \forall jc \in J, \forall t \in T \quad (4)$$

where $mcom$ is the mass of other fuels.

3.4. Renewable Electricity Production

Electricity generated by renewable technologies in each region (ep) is obtained by adding the energy used to charge the energy storage systems ($ecar$), renewable energy transmitted to other regions ($etrans$), untapped energy (cu), called "*curtailment*", and renewable energy used by electrolyzers in hydrogen generation ($eelec$). On the other hand, renewable technologies (jrt) are classified into variable technologies (jr) that are limited by the availability of the resource and variability by climatic conditions (solar or wind) and non-variable technologies (jrh) that are not limited by resources (hydroelectric), which is modeled as follows:

$$ep_{r,jr,t} = eprodem_{r,jr,t} + \sum_i ecar_{r,jr,i,t} + \sum_h eelec_{r,jr,t,h} + \sum_{r \neq r'} etrans_{r,r',jr,t} + cu_{r,jr,t} \quad \forall r \in R, \forall jr \in J, \forall t \in T \quad (5)$$

$$ep_{r,jrh,t} = eprodem_{r,jrh,t} + \sum_i ecar_{r,jrh,i,t} + \sum_h eelec_{r,jrh,t,h} + \sum_{r \neq r'} etrans_{r,r',jrh,t} + cu_{r,jrh,t} \quad \forall r \in R, \forall jrh \in J, \forall t \in T \quad (6)$$

3.5. Total Unused Renewable Energy

Renewable energy that cannot be used by the system due to technical limitations in the infrastructure is penalized in the objective function:

$$cuT = \sum_r \sum_{jrt} \sum_t cu_{r,jrt,t} \quad (7)$$

3.6. Operating Constraints for Conventional Technologies

It is important to restrict the operation of the different conventional technologies to comply with specific energy production, as shown in Equations (8)–(11).

3.6.1. Increase in Electricity Generation

The increase in electricity generation considers the production capacity ($CAPROD$) of the different (jt) thermal technologies, as well as the fraction of installed capacity that can be increased per hour ($RUMAX$).

$$ep_{r,jt,t} - ep_{r,jt,t-1} \leq RUMAX_{jt}\left(CAPROD_{r,jt,t}\right),\ \forall r \in R, \forall jt \in J, \forall t > 1 \in T \quad (8)$$

3.6.2. Decrease in Electricity Generation

The decrease in electricity generation considers the production capacity ($CAPROD$) of the different thermal technologies (jt), as well as the fraction of installed capacity that can be reduced per hour ($RDMAX$).

$$ep_{r,jt,t-1} - ep_{r,jt,t} \leq RDMAX_{jt}\left(CAPROD_{r,jt,t}\right),\ \forall r \in R, \forall jt \in J, \forall t > 1 \in T \quad (9)$$

3.6.3. Maximum and Minimum Generation of Conventional Technologies

The following relationships limit the plants to avoid shutdowns, and these are associated with the production capacity ($CAPROD$), where the maximum and minimum generation limits are specified as follows:

$$ep_{r,jt,t} \leq MAXPROD_{r,jt,t}\ \forall r \in R, \forall jt \in J, \forall t \in T \quad (10)$$

$$ep_{r,jt,t} \geq MINPROD_{r,jt,t}\ \forall r \in R, \forall jt \in J, \forall t \in T \quad (11)$$

3.7. Operating Constraints of Renewable Technologies

The energy generated by variable renewable technologies (jr) is limited by the availability of the resource (solar or wind). It is not possible to use 100% of the installed capacity so the capacity factor is used (CF) to estimate the fraction of the installed capacity that different technologies can take advantage of in each region and each period. The new capacity to be installed for each technology is also considered (ic^{renew}).

$$ep_{r,jr,t} = CAPROD_{r,jr,t} \cdot CF_{r,jr,t} + ic^{renew}_{r,jr} \cdot CF_{r,jr,t},\ \forall r \in R, \forall jr \in J, \forall t \in T \quad (12)$$

3.8. Installation of Renewable Technologies

If it is convenient to install any renewable technology (jr) in a certain region (r), the binary variable y^{RENEW} takes the value of 1. If it is not convenient, the binary variable takes a value of zero. In addition, binary variables allow limiting the selected capacity of renewable technologies ic^{renew} in the range of minimum and maximum capacities available on the market ($CMINRENEW$ and $CMAXRENEW$).

$$y^{RENEW}_{r,jr}\left(CMINRENEW_{r,jr}\right) \leq ic^{renew}_{r,jr},\ \forall r \in R, \forall jr \in J \quad (13)$$

$$y^{RENEW}_{r,jr}\left(CMAXRENEW_{r,jr}\right) \geq ic^{renew}_{r,jr},\ \forall r \in R, \forall i \in I \quad (14)$$

3.9. Installation of Energy Storage Systems

The decision to install ESS is modeled using binary variables. Whether it is convenient to install a storage system in a particular region (r), the binary variable y^{ESS} takes the value of 1. If it is not convenient that there is a storage unit, the binary variable (y^{ESS}) takes a value of zero. In addition, binary variables allow the selected capacity of the storage system $icess$ to be in the range of minimum and maximum capacities available on the market ($CMINESS$ and $CMAXESS$).

$$y^{ESS}_{r,i}(CMINESS_{r,i}) \leq icess_{r,i},\ \forall r \in R, \forall i \in I \quad (15)$$

$$y^{ESS}_{r,i}(CMAXESS_{r,i}) \geq icess_{r,i},\ \forall r \in R, \forall i \in I \quad (16)$$

3.10. Energy Balance in Storage Systems

To be able to know the amount of energy contained in energy storage systems ($ealm$) of each region (r) in a certain time (t), an energy balance must be made that considers the energy that is charged and discharged in each period, as well as their respective charging and discharging efficiencies (η_i^{car} and η_i^{des}).

$$ealm_{r,i,t} = ealm_{r,i,t-1} + \left(\sum_{jrt} ecar_{r,jrt,i,t}\right)(\eta_i^{car}) - \frac{edes_{r,i,t}}{\eta_i^{des}},\ \forall r \in R, \forall i \in I, \forall t > 1 \in T \quad (17)$$

$$ealm_{r,i,t} = EALM^0_{r,i} + \left(\sum_{jrt} ecar_{r,jrt,i,t}\right)(\eta_i^{car}) - \frac{edes_{r,i,t}}{\eta_i^{des}},\ \forall r \in R, \forall i \in I, \forall t = 1 \in T \quad (18)$$

3.11. Operating Constraints of Energy Storage Systems

Equation (19) limits the amount of energy that can be stored so that this amount does not exceed the installed capacity of the ESS. Additionally, it is specified that the amount of energy that is injected into the storage system ($ecar$) does not exceed the capacity that each technology can receive in a period and that it comes from the available conventional technologies (jrt).

$$ealm_{r,i,t} \leq icess_{r,i}\ \forall r \in R, \forall i \in I, \forall t \in T \quad (19)$$

$$\sum_{jrt} ecar_{r,jrt,i,t}(\eta_i^{car}) \leq icess_{r,i},\ \forall r \in R, \forall i \in I, \forall t \in T \quad (20)$$

In the same way, the discharged energy is limited ($edes$) by the storage system i in a period t so that ESSs do not discharge more electricity than they can.

$$\frac{edes_{r,i,t}}{\eta_i^{des}} \leq icess_{r,i},\ \forall r \in R, \forall i \in I, \forall t \in T \quad (21)$$

On the other hand, the following equations are specified to consider the existence of energy storage units, they also limit the charge and discharge of the storage in the same period, forcing the model to load and unload storage in a different period determined using the binary variable ω^{ESS}, which is related to the percentage of capacity that the battery can discharge $CAPDESC$ and the maximum storage capacity ($CMAXESS$) [43].

$$\sum_{jrt} ecar_{r,jrt,i,t} \leq \omega^{ESS}_{r,i,t}(CAPDESC_{r,i})(CMAXESS_{r,i}),\ \forall r \in R, \forall i \in I, \forall t \in T \quad (22)$$

$$edes_{r,i,t} \leq \left(1 - \omega^{ESS}_{r,i,t}\right)(CAPDESC_{r,i})(CMAXESS_{r,i}),\ \forall r \in R, \forall i \in I, \forall t \in T \quad (23)$$

3.12. Hydrogen Generation

The generation of hydrogen depends on the amount of electricity that is consumed, but the optimization model must make the decision to install it or not to install it, so it is necessary to use binary variables (y). In this case, the installation of an electrolyzer that can generate hydrogen will be considered depending on the amount of electricity supplied. In addition, if the electrolyzer is installed, a storage unit will also be installed to serve as temporary storage of the fuel. The electrolyzer and hydrogen storage will have a minimum and a maximum capacity that can be installed and the model will have to select a capacity within the established range.

3.13. Installation of the Electrolyzers

Binary variables allow the optimal capacity of the electrolyzer ic^{elect} in the desired interval (between $CMIN$ and $CMAX$). If it is convenient to install an electrolyzer h in a certain region (r), the binary variable (y^{elect}) takes the value of 1. If it is not convenient that there is an electrolyzer, the binary variable (y^{elect}) takes a value of zero.

$$y_{r,h}^{elect}\left(CMIN_{r,h}^{elect}\right) \le ic_{r,h}^{elect},\ \forall r \in R, \forall h \in H \tag{24}$$

$$y_{r,h}^{elect}\left(CMAX_{r,h}^{elect}\right) \ge ic_{r,h}^{elect},\ \forall r \in R, \forall h \in H \tag{25}$$

3.14. Hydrogen Storage System

If the electrolyzer is installed, then the storage g is installed. In this way, the binary variable of the electrolyzer in the region r will be 1, and therefore hydrogen storage will be needed (EHS). Otherwise, the binary variable associated with the electrolyzer will be zero. Using the following relationship, it indicates that y^{EHS} will only be 1 if y^{elect} is also 1, and it will be zero when y^{elect} is zero.

$$y_{r,h}^{elect} - y_{r,g}^{EHS} = 0,\ \forall r \in R,\ \forall h \in H,\ \forall g \in G \tag{26}$$

Binary variables allow determining the optimal capacity of the storage ic^{EHS} and limit this capacity into the desired interval (between $CMIN$ and $CMAX$).

$$y_{r,g}^{EHS}\left(CMIN^{EHS}\right) \le ic_{r,g}^{EHS},\ \forall r \in R, \forall g \in G \tag{27}$$

$$y_{r,g}^{EHS}\left(CMAX^{EHS}\right) \ge ic_{r,g}^{EHS},\ \forall r \in R, \forall g \in G \tag{28}$$

3.15. Electrolyzer Operation

The electrolyzer will produce hydrogen ($m^{H_2,gen}$) depending on the energy supplied ($eelec$); however, not all the energy supplied is used 100%, so efficiency is related (η^{elect}) in the electrolyzers h. The model is restricted to the production of hydrogen from renewable energy jrt.

$$\sum_{jrt} eelec_{r,jrt,h,t}\left(\eta_h^{elect}\right) = m_{r,h,t}^{H_2,gen},\ \forall r \in R, \forall h \in H, \forall t \in T \tag{29}$$

The operation of the electrolyzers is related to the capacity of the electrolyzer (ic^{elect}), which must be greater than the energy supplied.

$$\sum_{jrt} eelec_{r,jrt,h,t} \le ic_{r,h}^{elect},\ \forall r \in R, \forall h \in H, \forall t \in T \tag{30}$$

3.16. Balance in the Hydrogen Storage System

The following equations are needed to represent the balance in EHSs:

$$m_{r,g,t}^{EHS} - m_{r,g,t-1}^{EHS} = m_{r,h,t}^{H_2,gen} - \sum_{jg} m_{r,h,jg,t}^{H_2,burn},\ \forall r \in R, \forall g \in G, \forall h \in H, \forall t > 1 \in T \tag{31}$$

$$m_{r,g,t}^{EHS} - M_{r,0,g}^{EHS} = m_{r,h,t}^{H_2,gen} - \sum_{jg} m_{r,h,jg,t}^{H_2,burn},\ \forall r \in R, \forall g \in G, \forall h \in H, \forall t = 1 \in T \tag{32}$$

where $m^{H_2,burn}$ corresponds to the mass of hydrogen used in natural gas thermal power plants and $m^{H_2,gen}$ to the mass of hydrogen generated by the electrolyzer h. The second equation must include the amount of hydrogen contained in the storage at time zero M^{EHS} as a parameter. The first equation applies to the rest of the periods.

3.17. Hydrogen Generated and Used

The following relationships ensure that the burned hydrogen ($m^{H_2,burn}$) must be lower than that generated in electrolyzers ($m^{H_2,gen}$):

$$m^{H_2,gen}_{r,h,t} \geq \sum_{jg} m^{H_2,burn}_{r,h,jg,t},\ \forall r \in R, \forall h \in H, \forall t \in T \tag{33}$$

3.18. Operating Constraints on Power Transmission

For the energy transmitted ($etrans$) between two regions, all flows passing through a transmission line must be considered. This value must not exceed the transmission link capacity CT of the line. The energy is transmitted from the r region to a different r' region.

$$CT \geq \sum_{r' \neq r} \sum_{j} etrans_{r',r,j,t},\ \forall t \in T \tag{34}$$

3.19. Emissions

Total emissions are associated with the amount of fuel used in each region r, for each of the different conventional power plants jrt. It is considered an emission factor $EMIS$ that specifies the amount of emissions of CO_{2eq} generated by the amount of fuel used.

$$\begin{aligned} Emisiones = &\sum_t \left[\sum_{jc} \sum_r mcom_{r,jc,t} (EMIS_{jc}) \right] + \sum_t \left[\sum_{jg} \sum_r mgas_{r,jg,t} (EMIS_{jg}) \right] + \\ &\sum_t \left[\sum_{jg} \sum_h \sum_r m^{H_2,burn}_{r,h,jg,t} (EMIS_{jg}) \right] \end{aligned} \tag{35}$$

3.20. Total Unsupplied Demand

Unsupplied demand $umdem$ was considered, which allows for avoiding unfeasible solutions in the optimization process.

$$umdemT = \sum_r \sum_t umdem_{r,t} \tag{36}$$

3.21. Costs of Conventional Energy Production

The costs in the production of electrical energy in conventional generators are given by the relationship between the amount of energy that is produced ep in a time t and a variable cost of production in each of the conventional technologies jt.

$$opex^{conv}_t = \sum_r \sum_{jt} ep_{r,jt,t} (CPROD_{jt}),\ \forall t \in T \tag{37}$$

3.22. Renewable Energy Production Costs

The costs in the production of renewable electrical energy are given by the relationship between the amount of energy that is produced ep in a time t and a variable cost of production $CPROD$ in each of the renewable technologies jrt.

$$opex^{renw}_t = \sum_r \sum_{jrt} ep_{r,jrt,t} (CPROD_{jrt}),\ \forall t \in T \tag{38}$$

3.23. Transmission Costs

Transmission costs are associated with the cost of transporting energy ($etrans$) from one region to another, considering a unit cost of transmission $CTRANS$ from the region r to the region r'.

$$cost^{trans}_t = \sum_{r' \neq r} \sum_j etrans_{r,r',j,t} (CTRANS_{r,r'}),\ \forall t \in T \tag{39}$$

3.24. Cost of Installing the Energy Storage System (ESS, Energy Storage System)

Storage facility costs consider capital costs based on the installed capacity of the storage system (*icess*). Cost of capital considers a cost (FC^{ESS}), which is only considered when deciding to install these systems, as shown below:

$$Capex^{ess} = \sum_r \sum_i \left[FC_i^{ESS} icess_{r,i} \right] \tag{40}$$

3.25. Cost of Electrolyzer Installation

Electrolyzers consider a unitary charge (FC^{elect}) that to be activated depends only on the existence of the unit and multiplies the capacity of the unit ic^{elect}, as follows:

$$Capex^{elect} = \sum_r \sum_h \left[FC_h^{elect} ic_{r,h}^{elect} \right] \tag{41}$$

3.26. Cost of Installing the Hydrogen Storage System

The unit cost of capital FC^{EHS}, which to be activated depends only on the existence of unit g, multiplies the capacity of the unit ic^{EHS} by its unit cost, as follows:

$$Capex^{EHS} = \sum_r \sum_g \left[FC_g^{EHS} ic_{r,g}^{EHS} \right] \tag{42}$$

3.27. Cost of Installing Variable Renewable Technologies

The installation of renewable technologies (jr) considers a unitary charge (FC^{renew}) related to the capacity of the unit ic^{renew}.

$$Capex^{renew} = \sum_r \sum_{jr} \left[FC_{jr}^{renew} ic_{r,jr}^{renew} \right] \tag{43}$$

3.28. Total Capital Cost

The total capital cost considers the costs for the acquisition of the energy storage units, electrolyzers and hydrogen storage units:

$$CostcapT = Capex^{ess} + Capex^{elect} + Capex^{EHS} + Capex^{renow} \tag{44}$$

3.29. Operating Cost of Energy Storage

The operating cost ESSs depends on the amount of energy in the storage systems ($ealm$) of each r region and a variable unit operating cost ($UC^{ess-CV-O\&M}$) of the storage unit i. A fixed operating cost is also considered for each of the storage units ($UC^{ess-CF-O\&M}$).

$$Opex_t^{ess} = \sum_r \sum_i ealm_{r,i,t} \left(UC_i^{ess-CV-O\&M} \right) + UC_i^{ess-CF-O\&M} y_{r,i}^{ESS},\ \forall t \in T \tag{45}$$

3.30. Operating Cost of Electrolyzers

The operating cost of electrolyzers is calculated considering the mass of hydrogen produced ($m^{H_2,gen}$). A unit operating cost of the electrolyzer is required (UC^{elect}).

$$Opex_t^{elect} = \sum_r \sum_h m_{r,h,t}^{H_2,gen} \left(UC_h^{elect} \right),\ \forall t \in T \tag{46}$$

3.31. Operating Cost of Hydrogen Storage

The operating cost of any hydrogen storage unit is calculated based on the mass of hydrogen contained in the storage g, which is associated with a unit operating cost of the hydrogen storage (UC^{EHS}).

$$Opex_t^{EHS} = \sum_r \sum_g m_{r,g,t}^{EHS} \left(UC_g^{EHS} \right), \ \forall t \in T \tag{47}$$

3.32. Total Operating Cost

The total operating cost considers the costs for the operation of the units of energy storage plants, electrolyzers and hydrogen storage units:

$$CostopT = \sum_t Opex_t^{ess} + \sum_t Opex_t^{elect} + \sum_t Opex_t^{EHS} \tag{48}$$

3.33. Profit

The purpose of green hydrogen production is to be used as a fuel in conventional technologies replacing natural gas, having a natural gas-hydrogen mixture, representing economic and environmental benefits. However, producing green hydrogen within the system can generate some added value ($Profit^{H_2,gen}$), which is associated with a unit sale price (PV^{elect}) that depends on the mass of hydrogen generated in the electrolyzers h. The following equation shows the economic income from the sale of green hydrogen:

$$Profit^{H_2,gen} = \sum_r \sum_h \sum_t m_{r,h,t}^{H_2,gen} \left(PV_h^{elect} \right) \tag{49}$$

3.34. Total Cost

The production costs of conventional and renewable energy and the costs of transmission of energy to the different regions are considered. The capital cost in the acquisition of energy storage units, electrolyzers and hydrogen storage units is also considered, as well as the operating costs of said units and the difference for the sale of hydrogen. On the other hand, the cost associated with the emissions generated is considered, which is associated with an environmental tax ($UC^{CARNBONTAX}$) on the emissions of CO_{2eq}. The energy not supplied and used is also considered using a unit cost (U^{UMDEMT} and U^{CUT}). In addition, it is considered a factor to annualize the investment (K^{inv}).

$$\begin{gathered} TC = \sum_t opex_t^{conv} + \sum_t opex_t^{renw} + \sum_t cost_t^{trans} + CostcapT\left(K^{inv}\right) + CostopT \\ cuT\left(U^{CUT}\right) + umdemT\left(U^{UMDEMT}\right) + Emisiones\left(U^{CARBONTAX}\right) - Profit^{H_2,gen} \end{gathered} \tag{50}$$

3.35. Objective Function

The objective function considers minimizing the total cost, which is given as follows:

$$fo = min\ (TC) \tag{51}$$

where the objective function is subject to all the above constraints.

Therefore, the presented approach corresponds to a mixed integer linear programming problem (MILP), where the total cost is to be minimized (TC) in the production of electrical energy. In addition, it is important to mention that the previously developed mathematical model can be applied in any region of the world if the specific restrictions and configurations of the network, as well as the options for the production of renewable energy, are considered.

4. Case Study

A case study in Mexico is selected to show the applicability of the proposed approach, in particular, the peninsular electrical system is studied. The production of electrical energy in the peninsular region is considered, which includes the following transmission regions: Grijalva (RA), Tabasco (RB), Campeche (RC), Mérida (RD), Chetumal (RE), Cancún (RF), and Cozumel (RG), where each region has a transmission line whose function is to carry electrical energy to different distances (see Figure 3). Currently, the electricity supply in the peninsular region is generated with different types of energy technologies, of which the eight most important have been selected because they are the ones that provide the greatest amount of electrical energy in total production [44]. In addition, these technologies are classified as conventional (those that use fossil fuels for their operation) and renewable (they use natural resources that can be restored by natural processes). Conventional technologies include turbogas, combined cycle, efficient cogeneration, internal combustion and conventional thermoelectric, while renewable technologies that require variable energy resources in power systems include wind and solar (they are limited by the availability of the resource) and finally within the non-variable renewable technologies, hydroelectricity is considered. On the other hand, the type of technology necessary to meet the energy demand in each period will be selected, as well as the installation of electrolyzers and hydrogen and energy storage devices necessary to produce green hydrogen (from renewable technologies). The necessary energy production capacities of the technologies and the production of hydrogen in the electrolyzers are also shown to later use within the system as a mixture of natural gas-hydrogen in conventional technologies to study the demand for natural gas and the impact on the environment given by the emissions produced by fossil fuels. The necessary parameters have been taken from technical reports with updated data [44] to be used in the optimization model, which are shown in Table 1; other parameters such as equipment capacities, operating and maintenance costs, charge and discharge efficiencies, emission factors are also considered [45]. The energy transport efficiency is considered to be 95% from one region to another, which means that up to 5% of the total energy transmitted is lost in this distribution period. While the factors to annualize the investment of storage units, electrolyzers and renewable technologies (K^{inv}) have a value of 0.1. The capacities of the electrolyzers are a minimum of 1 MWh and a maximum of 10 MWh, the hydrogen storage capacity of a minimum of 0.001 ton and a maximum of 0.00354 ton (50 L) [46] and the cost of hydrogen production in the electrolyzers is 3900 \$/tonH_2 [47]. It is considered that conventional technologies manage to work using natural gas, hydrogen or fuel oil; in this sense, the low calorific values of natural gas, hydrogen and fuel oil ($LHVG$, $LHVH$, $LHVC$) are 50.03 GJ/ton, 119.90 GJ/ton and 40.10 GJ/ton, respectively [48,49].

Table 1. Parameter of capacities of technologies and costs of storage [44,45].

Generation Technology	**Production Capacity (MW)**						
	Grijalva (RA)	**Tabasco (RB)**	**Campeche (RC)**	**Mérida (RD)**	**Chetumal (RE)**	**Cancún (RF)**	**Cozumel (RG)**
Conventional							
Turbogas	121.00	217.00	47.00	60.00	71.20	190.00	53.00
Combined cycle	0.00	0.00	252.40	1229.00	0.00	0.00	0.00
Efficient cogeneration	0.00	367.00	112.50	243.00	0.00	0.00	0.00
Internal combustion	1.00	47.00	0.00	13.13	0.00	0.00	0.00
Conventional thermoelectric	0.00	0.00	0.00	1.06	0.00	3.20	0.00
Variable renewable							
Wind	17.37	0.00	40.36	145.31	8.07	18.19	5.05
Solar	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-variable renewable							
Hydroelectric	4828.00	0.00	0.00	0.00	0.00	0.00	0.00
				Energy storage			
Classification	Charging efficiency	Discharge efficiency	Fixed costs (\$)	Variable costs (\$/MWh)	Maximum capacity (MW)	Minimum capacity (MW)	Energy at time zero (MWh)
Li-ion	0.98	0.98	540.00	2220.00	100.00	6.00	0.00
VRB (vanadium redox battery)	0.85	0.85	944.00	1000.00	100.00	6.65	0.00

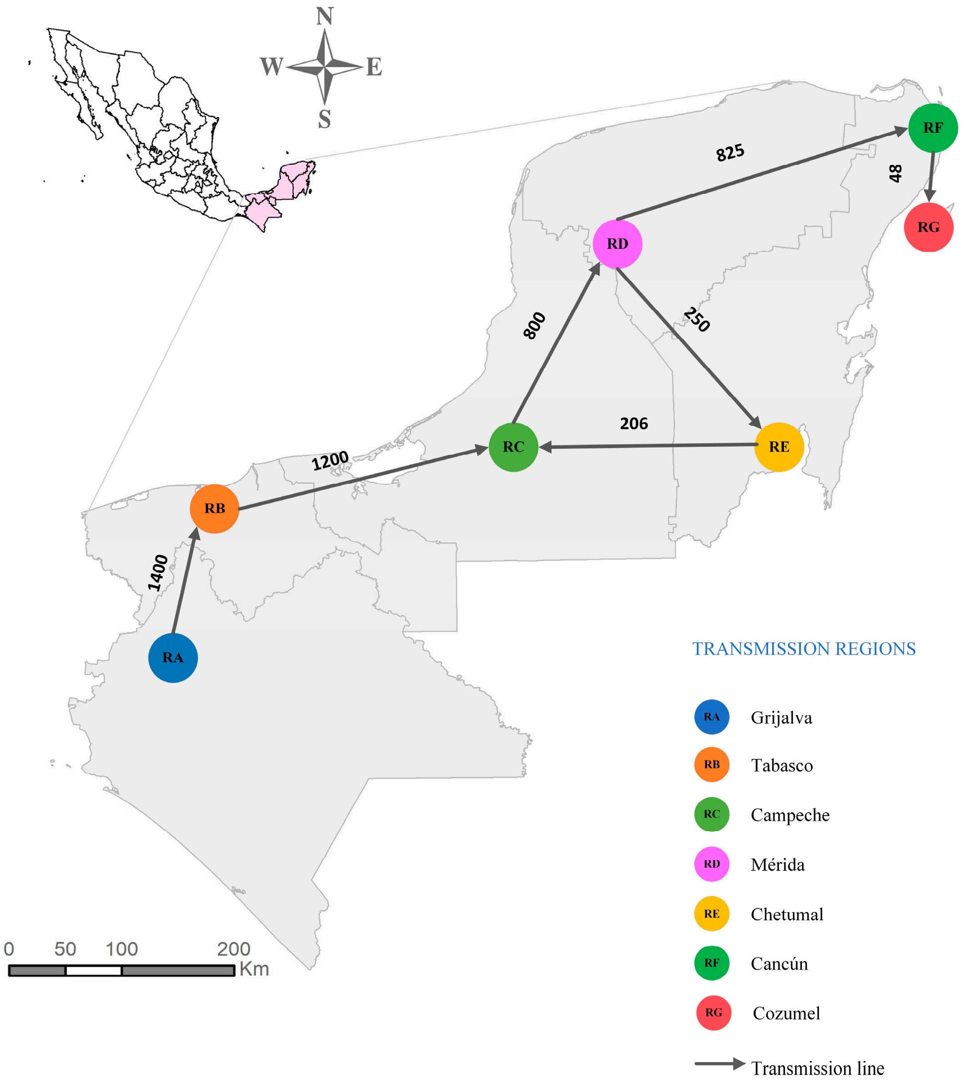

Figure 3. Peninsular transmission region in Mexico.

For this specific case, the considered energy storage devices are lithium-ion batteries (Li-ion) and vanadium redox batteries (VRB) [45]. The production of emissions represents an environmental tax ($CARBONTAX$), which was considered 3 $/ton$CO_{2eq}$ according to the conditions of the country under study [50] and the unit cost of energy not supplied of 2600 $/MWh [44]. To characterize the system over a time horizon, without the need for massive amounts of computing resources, a small number of representative weeks are optimally selected to jointly characterize energy demand and production of variable energy resources using a methodology [51] that results in a valid approximation in planning a long-term time horizon. In this work, the analysis of 4 representative weeks corresponding to 672 h is considered, which were selected from 52 total weeks (8760 h) corresponding to one year through the methodology described above. It is important to highlight that in this work, the proposed methodology was used in Mexico because there are data available to carry out the planning in the Mexican peninsula (Grijalva, Tabasco, Campeche, Mérida, Chetumal, Cancún and Cozumel). In addition, this region has natural gas supply problems and great possibilities for the use of renewable energy, making this region a good candidate to apply the mathematical model.

To show the use of the proposed methodology and the importance of hydrogen production in the electric power generation process, the following scenario is proposed (Scenario A). In this case, the solution of the mathematical model described above is considered, where the possibility of obtaining economic benefits in the production of green hydrogen ($Profit^{H_2,gen} > 0$) is presented, looking for the appropriate unit selling price of hydrogen (PV^{elect}), where the system can produce hydrogen, satisfying the objective function. A maximum generation of 40% is considered in conventional technologies [44].

5. Results and Discussion

The proposed mathematical formulation was coded in the software GAMS® (General Algebraic Modeling System) release 42.3.0 as a mixed integer linear programming (MILP) model. The model includes 334,088 continuous variables, 9450 binary variables and 262,793 constraints. The program was solved in a computer with a processor AMD Radeon R3 of 2.30 GHz and 8 GB of RAM in 31.32 s of CPU time using the solver CPLEX [52].

Once the mathematical model has been implemented and considering the previous information, the results obtained are shown below. First, Table 2 shows the economic, environmental and energy results obtained by the type of technology. Scenario A shows the minimum sale price with which this system can start the production of hydrogen, having economic and environmental benefits, with the above, minimum profits of \$6.3572 $\times$ 10^5 and a unit sale price of 4200 \$/tonH_2, which correspond to similar values in technical reports [53]. The total cost (TC) is \$5.1687 $\times$ 10^6 and in the environmental aspect, the emissions are 2.5243 $\times$ 10^5 tonCO_{2eq}. It is important to mention that different types of technologies are used in energy production. Scenario A produces a total of 1.8869 $\times$ 10^6 MWh, where 72.01% corresponds to total renewable energy (hydroelectric, wind and solar) and 27.99% is energy from conventional sources. An important aspect is to calculate the emission factor of the electrical system studied to validate results with other types of studies already carried out, in this sense, values like those reported in the literature were obtained (0.494 tonCO_{2eq}/MWh for 2020) [54], which correspond to 0.4780 tonCO_{2eq}/MWh for scenario A. The emission factor was calculated according to the quotient of the total energy produced from conventional technologies and the emissions emitted by them.

Table 2. Resulting configuration for scenario A with a minimum TC in the total network.

Concept	Scenario A
Emissions (tonCO_{2eq})	2.5243 $\times$ 10^5
Total cost (\$)	5.1687 $\times$ 10^6
Produced energy (MWh)	1.8869 $\times$ 10^6
Conventional technologies	5.2810 $\times$ 10^5
Variable renewable technologies	8.2449 $\times$ 10^4
Non-variable renewable technologies	1.2764 $\times$ 10^6
Power not supplied (MWh)	0.0000
Curtailment (MWh)	0.0000
Economic profit (\$)	6.3572 $\times$ 10^5
Emission factor (tonCO_{2eq}/MWh)	0.4780
Produced hydrogen (ton)	1.5136 $\times$ 10^2
Fuel oil used (ton)	1.7349 $\times$ 10^3
Used natural gas (ton)	9.1691 $\times$ 10^4

Because conventional technologies in the proposed scenarios require fossil fuels for their operation, the results show that scenario A requires 93,577.16 tons of total fuel. In addition, they show the use of fuel oil, natural gas and hydrogen, the latter being used as a natural gas-hydrogen mixture to be supplied in conventional technologies, showing 0.16% hydrogen, 1.85% fuel oil and 97.98% natural gas.

Additionally, if in a hypothetical case the production of hydrogen in scenario A were from conventional techniques, such as methane steam reforming (MSR), and not in a renewable way (green hydrogen) as stated in the proposed superstructure, the MSR emission factor is 6.038 tonCO_{2eq}/tonH_2 [55]. In this sense, the 1.5136 $\times$ 10^2 tonH_2 produced in scenario A represent 913.92 tonCO_{2eq} additions to the system to produce hydrogen in a conventional way, thus generating a total of emissions of 2.5334 × 10^5 tonCO_{2eq} (considering emissions from MSR and energy-producing technologies).

Minimizing the objective function includes the costs associated with the electricity production process, so Figure 4 shows the costs, which are made up of energy transmission costs from one region to another, costs of capital for the acquisition of units (energy storage units, electrolyzers, hydrogen storage units and energy production technologies), operating costs (energy storage units, electrolyzers and hydrogen storage units), costs associated with the production of energy in each technology, cost associated with the emissions generated as an environmental tax and the cost for the existence of energy not supplied (*umdem*). Scenario A has a total cost of \$5.1687 × 10^6, from which \$5.1003 × 10^5 corresponds to transmission costs, representing 8.79% of the total cost. The capital costs are \$2.1492 × 10^6 which represent 37.03% of the total cost, given by the acquisition of energy storage (\$3.7776 × 10^5), electrolyzers (\$2.5000 × 10^4) and renewable technologies (\$1.7464 × 10^6). Operating costs are \$7.5776 × 10^5, while conventional production costs are \$1.6302 × 10^6, representing 28.09%, and the operating costs in the electrolyzer units are \$5.9031 × 10^5. The curtailment and the energy not supplied do not exist and for this reason, do not represent a cost. Finally, the emissions represent an important environmental tax of 13.05% (\$ 7.5729 × 10^5) of the total cost.

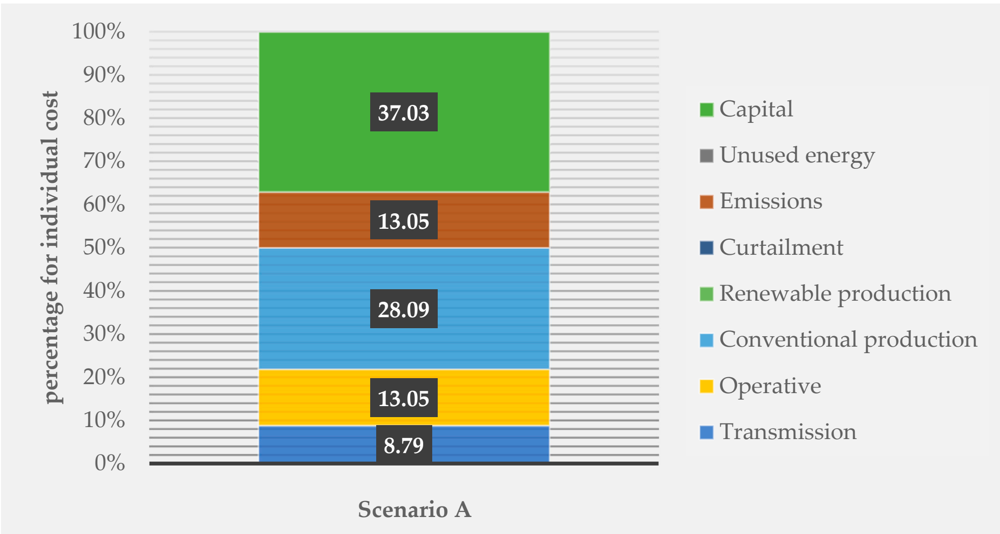

Figure 4. Individual costs in the proposed scenario.

It is important to mention that the analysis carried out on the previous scenario in the Mexican peninsula also considers the energy production by transmission region; therefore, Table 3 shows the energy demand, the installed equipment and its capacity in each of the regions. Scenario A (Table 3) shows that the transmission region RA produces 99.33% (8572.90 MWh) of electrical energy, mainly with renewable technologies (hydroelectric and wind) and the rest with turbogas and internal combustion, contrary to RB, which satisfies the production of electrical energy by conventional technologies in its entirety (turbogas, efficient cogeneration and internal combustion). RC generates 85.37% of conventional technologies, mainly turbogas, combined cycle and efficient cogeneration (3.93%, 62.77% and 18.67%, respectively) and 14.63% with wind. RD produces 88.56% of electricity with conventional technologies (326,282.39 MWh) and the rest with renewables (42,146.47 MWh). RE produces electricity with turbo gas, wind and solar with 37.41%, 4.19% and 58.40%, respectively. RF makes use of 64.36% (turbogas and conventional thermoelectric) with conventional technologies and 35.64% with wind and solar. Something similar occurs with RG, which generates 5525.72 MWh with turbogas technologies and 3652.71 MWh with wind and solar.

Table 3. Total energy produced and capacity of equipment installed in each transmission region at a minimum *TC*.

Scenario A							
Generation Technology	**Energy Produced in Each Transmission Region (MWh)**						
	Grijalva (RA)	**Tabasco (RB)**	**Campeche (RC)**	**Mérida (RD)**	**Chetumal (RE)**	**Cancún (RF)**	**Cozumel (RG)**
Turbogas	8488.00	16,684.24	4017.90	5006.24	6289.14	18,773.33	5525.73
Combined cycle	0.00	0.00	64,200.15	288,016.46	0.00	0.00	0.00
Efficient cogeneration	0.00	53,173.01	19,097.97	31,707.10	0.00	0.00	0.00
Internal combustion	84.90	5182.52	0.00	1466.62	0.00	0.00	0.00
Conventional thermoelectric	0.00	0.00	0.00	85.97	0.00	299.84	0.00
Wind	600.35	0.00	14,964.14	38,802.29	704.42	2931.86	760.59
Solar	0.00	0.00	0.00	3344.19	9817.86	7631.52	2892.13
Hydroelectric	1,276,394.85	0.00	0.00	0.00	0.00	0.00	0.00
Total energy (MWh)	1,285,568.10	75,039.78	102,280.16	368,428.87	16,811.41	29,636.54	9178.44
Capacity	Acquisition of Equipment						
	Grijalva (RA)	Tabasco (RB)	Campeche (RC)	Mérida (RD)	Chetumal (RE)	Cancún (RF)	Cozumel (RG)
Wind technology (MW)	0	0	57.647	0	0	0	0
Solar technology (MW)	0	0	0	0	69.18	58.415	21.279
Storage Li-ion (MW)	10.204	0	10.204	20.83	13.999	30.612	24.714
Storage VRB (MW)	0	0	0	0	0	0	0
Electrolyzer (MW)	10	0	0	0	0	0	0
Hydrogen storage (tonH_2)	0.001	0	0	0	0	0	0

The acquisition of equipment is an option in the proposed superstructure; for this reason, the transmission regions are specified in which the installation of renewable technologies, energy storage, electrolyzers and hydrogen storage is required. As can be seen, scenario A (Table 3) shows that the RA region can produce hydrogen, for this reason, the installation of 10 MW of capacity in electrolyzer equipment, in addition to a capacity of 0.001 ton in hydrogen storage and 10.204 MW in energy storage (Li-ion). The RC region uses 57.647 MW capacity in wind technology and the same energy storage capacity as RA. RD only considers the energy storage installation (Li-ion). The region that needs the greatest energy storage capacity is the RF (30.612 MW), while RE is the one that requires greater capacity in the production of solar energy (69.180 MW).

Figures 5 and 6 show the electricity demand (*EDEM*) in each transmission region at different time intervals, considering the analysis of 4 representative weeks corresponding to 672 h, which were selected from 52 total weeks (8760 h). The energy balance can be satisfied with local generation (*eprodem*) produced by the technologies available in each of the regions, the energy exported and imported from one region to another, the energy not supplied (*umdem*) and the energy that is discharged from energy storage systems. In addition, the losses due to the transport of energy electricity with the transmission efficiency are also considered (η^{trans}).

Scenario A (Figure 5) shows that in none of the transmission regions, the locally generated energy is the only one used to meet energy demand because it is more convenient to interact with other regions; it is because of this that each of its transmission regions is associated with imports and exports among themselves, in addition to making use of locally generated energy to meet the required energy demand. The total energy demand (1,773,632.71 MWh) of the peninsula that is made up of the seven regions RA, RB, RC, RD, RE, RF and RG (Figure 5) corresponds to 349,529.30 MWh, 543,133.28 MWh, 134,778.93 MWh, 278,124.31 MWh, 39,612.0 MWh, 406,738.56 MWh and 21,716.31 MWh, respectively. This analysis represents the entire four weeks considered as a time horizon. The transmission region RA satisfies its energy demand with local production, storage discharge and energy export to other regions (see Figure 5a); local production is 349,160.00 MWh, import from other regions to RA is null and export to others is given as follows: RA-RB (468,093.50 MWh), RA-RC (32,571.48 MWh), RA-RD (370.60 MWh), RA-RE1 (22,753.24 MWh), RA-RE2 (55.17 MWh), RA-RF (301,017.99 MWh) and RA-RG (3043.99 MWh), and discharge of energy storages corresponds to 369.30 MWh. Similarly, another of the regions that exports energy is the RD (see Figure 5d), where the energy produced locally is 276,874.01 MWh, the imported energy comes from RA with a value of 370.60 MWh and that coming from RB and RC is zero. On the other hand, of the total energy exported (85,607.64 MWh), 88.92% is for the RF region and 11.08% for the RG region. The regions RB, RC, RE, RF and RG do not export energy (see Figure 5b,c,e–g); however, to meet energy demands, they receive energy from other regions; in this sense RB imports 468,093.50 MWh, RC 32,571.48 MWh, RE 22,820.20 MWh, RF 377,145.22 and RG 12,566.74 MWh. In addition, the energy produced locally in the regions RB, RC, RE, RF and RG is 75,039.78 MWh, 101,933.66 MWh, 16,316.63 MWh, 28,545.43 MWh and 8449.46 MWh, respectively. The non-supplied energy is zero in all regions. The energy discharge of the storage systems (Li-Ion) in each of the regions is 369.30 MWh, 273.79 MWh, 879.69 MWh, 475.19 MWh, 1047.91 MWh and 700.11 MWh for the regions RA, RC, RD, RE, RF and RG, respectively, and the energy coming from storages in the RB region is null. Figure 6 shows in detail the behavior of the Li-ion storage for scenario A and its transmission regions, where the charge and discharge are displayed in each of the hours that make up the selected time interval, it also shows that the RB region does not consider the installation of energy storage within its planning.

According to scenario A, it was found that the minimum unit sale price at which the system begins to produce hydrogen is 4200 $\$/tonH_2$, with a total cost (*TC*) of $\$5.1687 \times 10^6$ and a minimum profit of $\$6.3572 \times 10^5$ (Table 2). That is why Figure 7 shows an analysis of the sale price of hydrogen concerning the total cost of the proposed planning, where it is presented that a sale price of 4500 $\$/tonH_2$ carries a *TC* of $\$5.0753 \times 10^6$ and profits of $\$1.9604 \times 10^6$; this shows that the increase in 300 $\$/tonH_2$ in the sale price decreases the *TC* $\$9.3400 \times 10^4$; in addition, profits triple ($\$1.9604 \times 10^6$), hydrogen production increases considerably to 4.3565×10^2 ton and require 1.7899×10^3 ton and 9.2980×10^4 ton of fuel oil and natural gas, respectively. On the other hand, the storage equipment (energy and hydrogen) and electrolyzers are activated in the regions RA, RC, RD, RE, RF and RG, unlike scenario A where the electrolyzers only activate in the RA region. The analysis of the sale price is carried out in a range of 4200–6900 $\$/tonH_2$, which shows that as the sale price increases, *TC* decreases and profits gradually increase; however, this behavior shows the sale price at which the system reaches the so-called "break-even point" where positive cash flows (in this case the profits) are balanced by the negative flows (fixed and variable costs) expected during the useful life of the project [56], in such a way that the sale price that represents said event is approximately 6600 $\$/tonH_2$ which involves profits and *TC* of $\$3.8643 \times 10^6$ with emissions of 2.5943×10^5 $tonCO_{2eq}$. In addition, system emissions increase as the selling price increases; with an increase of 4200 $\$/tonH_2$ to 4500 $\$/tonH_2$ in the sale price, emissions increase by 1.77% (2.5243×10^5 $tonCO_{2eq}$ to 2.5684×10^5 $tonCO_{2eq}$) and with an increase of 4200 $\$/tonH_2$ to 6600 $\$/tonH_2$ in the sale price, emissions increase 7.0000×10^5 $tonCO_{2eq}$ which represents 2.70%. With the above, it is possible to visualize the behavior of the system choosing between the sale prices that are the most convenient according to the expected goal (economic and environmental).

In previous works, the problems of energy production, energy storage and green hydrogen production have been addressed individually. In this work, we are approaching the problem in such a way that it is studied as a configuration of the network together, evaluating environmental and economic aspects. On the other hand, the objectives are focused on the production of energy with different technologies (conventional and renewable), production of green hydrogen and energy storage from intermittent renewable technologies. Results reported in previous works are consistent with those obtained in this work. For example, green hydrogen sales prices of 6000–10.00 $\$/tonH_2$ [53,57] have been reported while in this work sale prices of 4200–6900 $\$/tonH_2$ were obtained; the hydrogen break-even price is found to be 4–7 €$/kgH_2$ (4000–7000 $\$/tonH_2$) [58] and the results in this work are 6600 $/ton, in addition to results of previous investigations involving the use of energy storage [59]. It should also be taken into account that the model developed in this work can be applied in any region of the world if the specific configurations of the network and the options for the production of renewable energy are considered. However, the availability of data used as parameters in the model could be a limitation for its use.

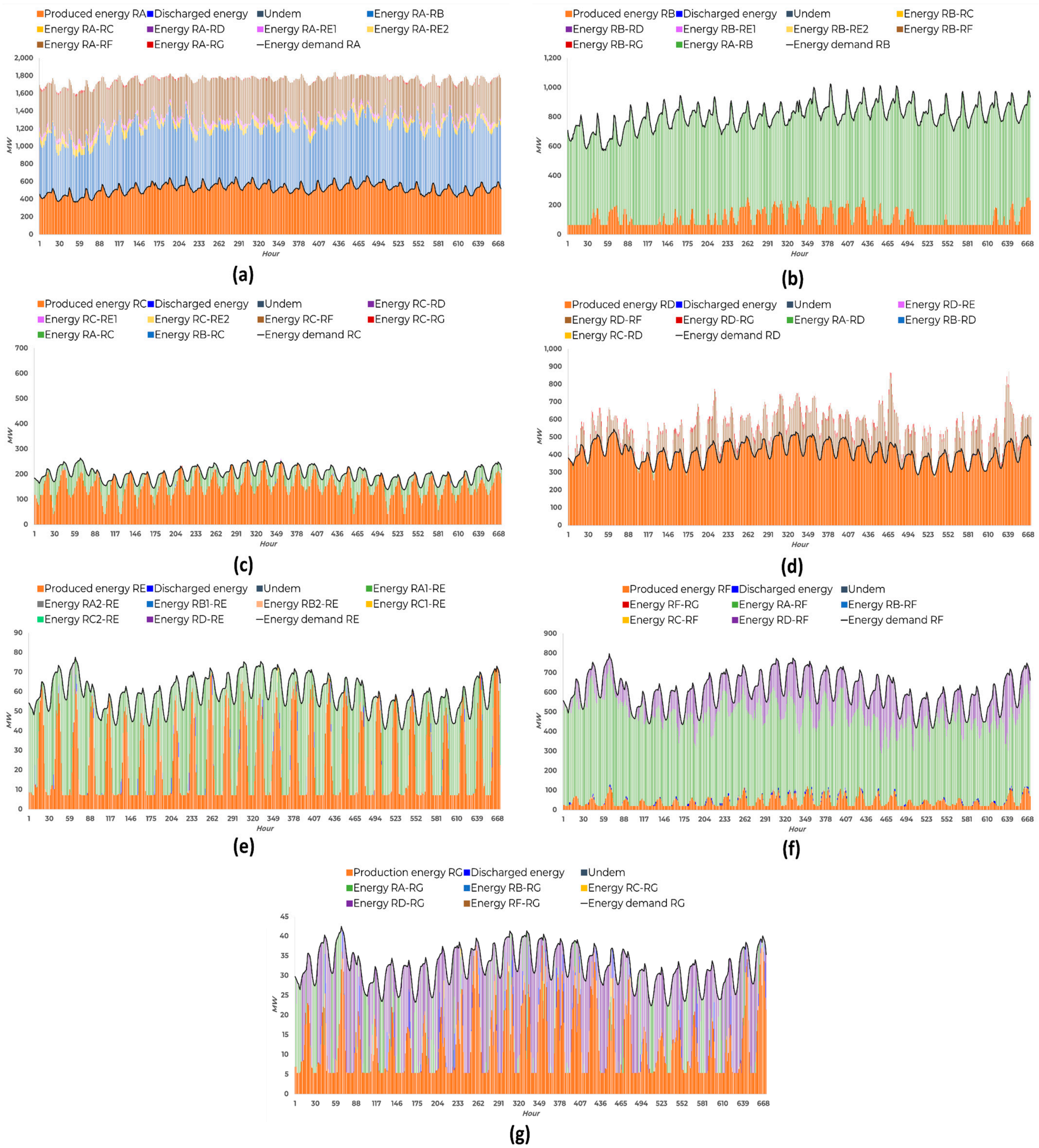

Figure 5. Energy demand in transmission regions for scenario A. (**a**) RA region; (**b**) RB region; (**c**) RC region; (**d**) RD region; (**e**) RE region; (**f**) RF region; (**g**) region RG.

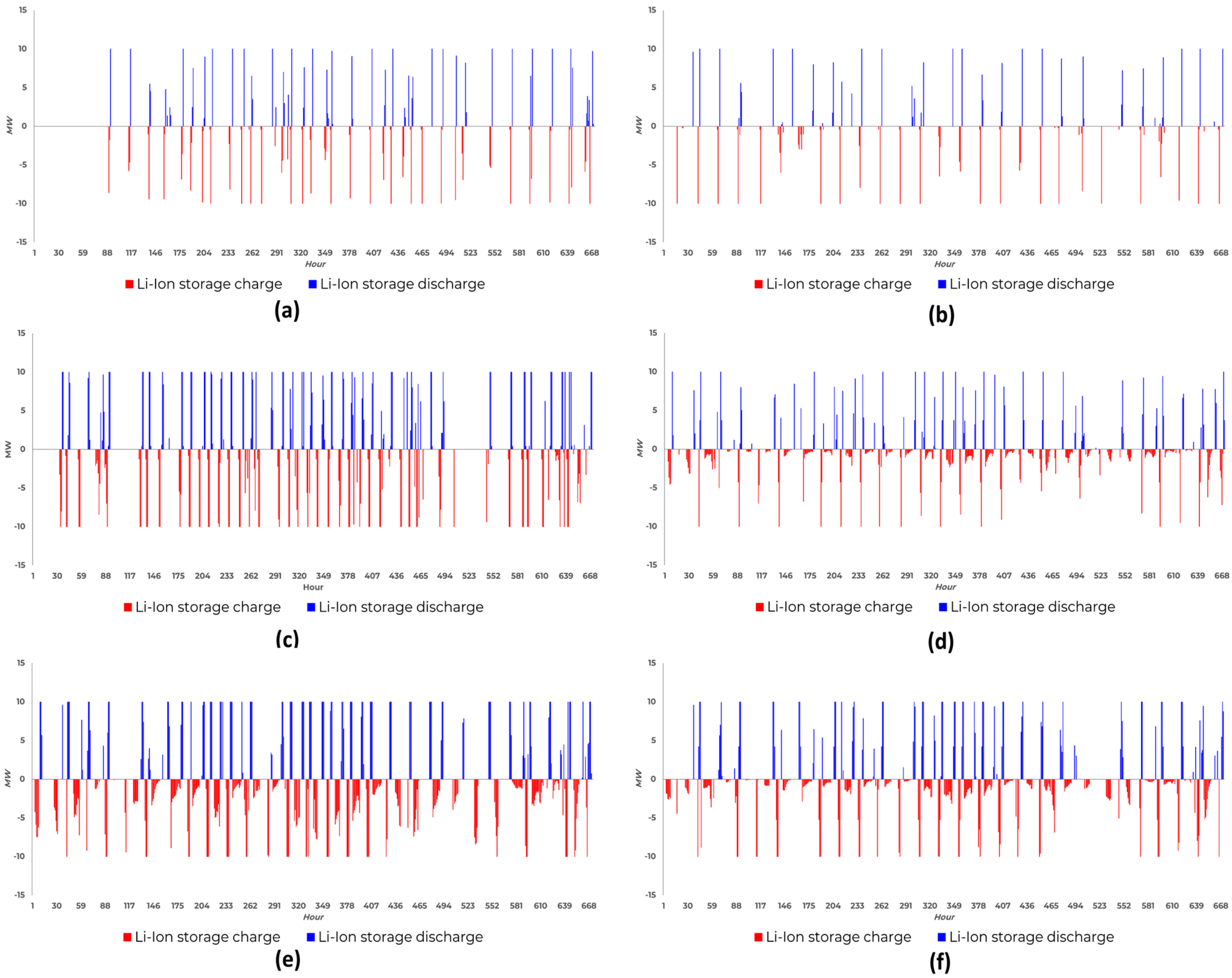

Figure 6. Charge and discharge of energy storages in scenario A. (**a**) RA region; (**b**) RC region; (**c**) RD region; (**d**) RE region; (**e**) RF region; (**f**) RG region.

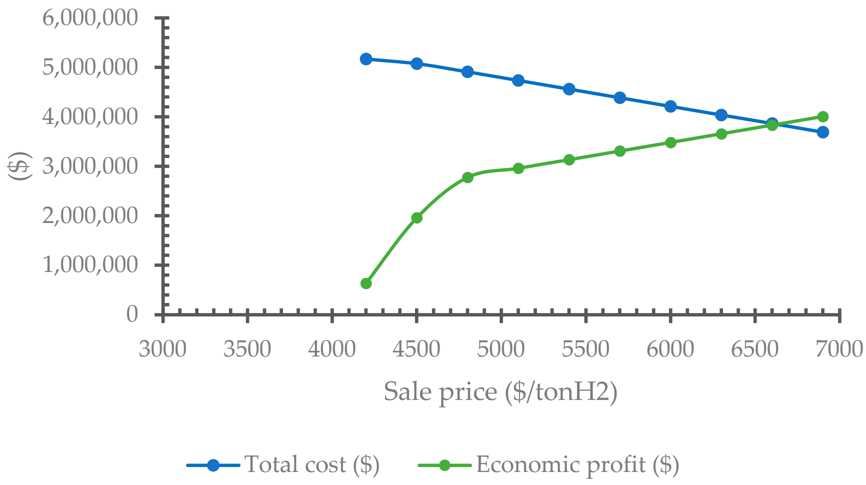

Figure 7. Hydrogen sales price analysis.

6. Conclusions

This work has presented a mathematical programming formulation for the optimal planning of green hydrogen production within an energy production system considering economic and environmental concerns. The objective function allows minimizing the total cost associated with planning that considers costs of operation, capital and electricity transmission; in addition, it allows the function to be restricted by employing a cost associated with emissions of CO_{2eq} generated with an environmental tax. The proposed model allows for determining the installation and capacities of the different equipment required in energy production and green hydrogen in a specific time horizon, such as technologies, energy storage, electrolyzers and hydrogen storage to meet the energy demand. The model attends the macroscopic region in specific transmission subregions, allowing the exchange of energy between them. This structure allows for the efficient management of energy production, satisfying the energy demand and the fossil fuel used in conventional technologies, supplying a percentage of natural gas with green hydrogen as raw material. Emissions of CO_{2eq} are related to the production of energy in mainly conventional technologies, so the model quantifies these. A method of selecting a representative sample of a time horizon was implemented to characterize the energy demand and the production of renewable resources. In this project unlike other works, the production of green hydrogen as well as the storage of energy given by intermittent renewable technologies and the production of conventional energy in a single network, shows the novelty in the economic and environmental strategic planning that currently is one of the greatest world challenges to replace fossil fuels with renewable energy. It is important to mention that it is very useful to perform this type of study in order to know the system's behavior before they are applied. It should also be taken into account that the model developed in this project can be applied in any region of the world if the specific configurations of the network and the options for the production of renewable energy are considered. The proposed approach was applied to a specific case study of Mexico in the peninsula (covering the regions of Grijalva, Tabasco, Campeche, Mérida, Chetumal, Cancún and Cozumel) to satisfy the energy demand and reduce the use of natural gas with the production of green hydrogen, where the results show that in scenario A, the minimum sale price with which the system has the option of producing this corresponds to 4200 $\$/tonH_2$; in addition, the production of hydrogen generates minimal profits of \$6.3572 $\times 10^5$ with a total cost (*TC*) of \$5.1687 $\times 10^6$ and 2.5243 $\times 10^5$ $tonCO_{2eq}$ in the environmental aspect. Additionally, an increase of 300 $\$/tonH_2$ (4500 $\$/tonH_2$) in the sale price decreases the *TC* (1.80%), and profits triple and hydrogen production increases considerably. A selling price analysis is applied where the financial break-even point is found with a value of 6600 $\$/tonH_2$ which involves profits and *TC* of \$3.8643 $\times 10^6$, and the system emissions increase by 2.70% concerning scenario A. The results highlight that in none of the transmission regions is the energy generated locally the only one used to meet the energy demand, because it is more convenient to carry out interactions with other regions. It is also notable that additionally in scenario A, there is a saving of 913.92 $tonCO_{2eq}$, to the general hydrogen in a renewable way and not in a conventional way such as methane steam reforming (MSR). The results support the production of green hydrogen within the energy system with economic and environmental savings, highlighting the benefits of considering the proposed methodology. Studying this type of analysis is important to have a greater number of feasible options for decision-makers seeking reasonable trade-offs between the economy and the environment. In addition, the mathematical model can be applied to obtain approximations in the behavior of different energy-producing systems, which are necessary worldwide.

Author Contributions: Conceptualization, methodology, software and writing (review and editing), T.I.S.-A., J.T.-F. and J.M.P.-O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are available upon reasonable request to the corresponding author.

Acknowledgments: The authors acknowledge the financial support from the Mexican Council of Science and Technology (CONACyT) and CIC-UMSNH.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Indexes	
g	Hydrogen storage
h	Electrolyzer
I	Electric energy storage
j	Power generation technology
jt	Conventional power generation technology
jg	Conventional natural gas power generation technology as fuel
jc	Conventional fuel oil-fuel power generation technology
jrt	Renewable energy generation technology
jr	Variable renewable energy generation technology
jrh	Non-variable renewable energy generation technology
r	Geographical area
t	Time period
Binary variables	
$y_{r,i}^{ESS}$	Binary variable to model the existence of electrical energy storage
$\omega_{r,i,t}^{ESS}$	Binary variable to model the charge/discharge of electrical energy storage in a specific period
$y_{r,h}^{elect}$	Binary variable to model the existence of electrolyzers
$y_{r,g}^{EHS}$	Binary variable to model the existence of hydrogen storage
$y_{r,jr}^{RENEW}$	Binary variable to model the existence of variable renewable technologies
Variables	
$Capex^{ess}$	Cost of capital of electric power storage, $
$Capex^{elect}$	Cost of capital of electrolyzers, $
$Capex^{EHS}$	Cost of capital of hydrogen storage, $
$Capex^{renew}$	Capital cost of variable renewable technologies, $
$CostcapT$	Total cost of capital, $
$cost_t^{trans}$	Cost of power transmission, $
$CostopT$	Total operating cost, $
$cu_{r,jr,t}$	Energy not used in variable renewable technologies, MWh
$cu_{r,jrh,t}$	Energy not used in non-variable renewable technologies, MWh
$cu_{r,jrt,t}$	Energy not used in available renewable technologies, MWh
cuT	Total untapped energy from available renewable technologies, MWh
$eprodem_{r,j,t}$	Local generation of available technologies, MWh
$etrans_{r',r,j,t}$	Energy produced in available technologies and transmitted from one region to a different one, MWh
$edes_{r,i,t}$	Energy discharged from the electricity storage system, MWh
$ep_{r,jt,t}$	Electricity generated by each of the conventional technologies, MWh
$ep_{r,jr,t}$	Electricity generated by each of the variable renewable technologies, MWh
$eprodem_{r,jt,t}$	Local generation of conventional technologies, MWh
$ep_{r,jc,t}$	Amount of fuel needed in conventional technologies using fuel oil, GJ
$ep_{r,jr,t}$	Electricity generated by each of the variable renewable technologies, MWh
$eprodem_{r,jr,t}$	Local generation of variable renewable technologies, MWh
$ecar_{r,jr,i,t}$	Energy charged to the electricity storage system by variable renewable technologies, MWh
$eelec_{r,jr,t,h}$	Variable renewable energy used by electrolyzers, MWh
$etrans_{r,r',jr,t}$	Energy produced in variable renewable technologies and transmitted from one region to a different region, MWh
$etrans_{r,r',jt,t}$	Energy produced in conventional technologies and transmitted from one region to a different one, MWh
$ep_{r,jg,t}$	Amount of fuel needed in conventional technologies using natural gas, GJ

$ep_{r,jrh,t}$	Electricity generated by each of the non-variable renewable technologies, MWh
$eprodem_{r,jrh,t}$	Local generation of non-variable renewable technologies, MWh
$ecar_{r,jrh,i,t}$	Energy charged to the electricity storage system by non-variable renewable technologies, MWh
$eelec_{r,jrh,t,h}$	Non-variable renewable energy used by electrolyzers, MWh
$etrans_{r,r',jrh,t}$	Energy produced in non-variable renewable technologies and transmitted from one region to a different one, MWh
$ealm_{r,i,t}$	Amount of energy contained in storage systems, MWh
$ecar_{r,jrt,i,t}$	Energy charged to the electricity storage system by available renewable technologies, MWh
$edes_{r,i,t}$	Energy discharged from the electricity storage system, MWh
$eelec_{r,jrt,h,t}$	Renewable energy from available technologies used by electrolyzers, MWh
$Emisiones$	Total emissions generated by conventional technologies, $tonCO_{2eq}$
$ep_{r,jrt,t}$	Electricity generated by each of the renewable technologies, MWh
$ic_{r,h}^{elect}$	Electrolyzer capacity, MW
$ic_{r,g}^{EHS}$	Hydrogen storage capacity, $tonH_2$
$icess_{r,i}$	Storage system capacity, MW
$ic_{r,jr}^{renew}$	Capacity of variable renewable technologies, MW
$mgas_{r,jg,t}$	Mass of natural gas used by conventional technologies, ton of natural gas
$m_{r,h,jg,t}^{H_2,burn}$	Mass of hydrogen using conventional natural gas technologies, $tonH_2$
$mcom_{r,jc,t}$	Fuel oil mass used by conventional technologies, ton of fuel oil
$m_{r,h,t}^{H_2,gen}$	Mass of hydrogen generated in electrolyzers, $tonH_2$
$m_{r,g,t}^{EHS}$	Mass of stored hydrogen, $tonH_2$
$opex_t^{conv}$	Cost of energy production in conventional technologies, \$
$opex_t^{renw}$	Cost of energy production in renewable technologies, \$
$Opex_t^{ess}$	Operational cost of energy storage, \$
$Opex_t^{elect}$	Operational cost of electrolyzers, \$
$Opex_t^{EHS}$	Operational cost of hydrogen storage, \$
$Profit^{H_2,gen}$	Profits obtained from the sale of hydrogen, \$
TC	Total cost, \$
$umdem_{r,t}$	Energy not supplied to each of the regions, MWh
$umdemT$	Total energy not supplied, MWh
Parameters	
$CAPROD_{r,jt,t}$	Production capacity of conventional technologies, MW
$CAPROD_{r,jr,t}$	Production capacity of variable renewable technologies, MW
$CF_{r,jr,t}$	Capacity factor of available renewable technologies, MWh/MW
$CMINRENOW_{r,jr}$	Minimum production capacity to consider the installation of variable renewable technologies, MW
$CMAXRENOW_{r,jr}$	Maximum production capacity to consider the installation of variable renewable technologies, MW
$CMINESS_{r,i}$	Minimum storage capacity for consideration of the installation of electric power storage, MW
$CMAXESS_{r,i}$	Maximum storage capacity to be considered for the installation of electric energy storage, MW
$CAPDESC_{r,i}$	Percentage of capacity that can be discharged by energy storage
$CMIN_{r,h}^{elect}$	Minimum capacity to consider electrolyzer installation, MW
$CMAX_{r,h}^{elect}$	Maximum capacity for electrolyzer installation to be considered, MW
$CMIN^{EHS}$	Minimum capacity to be considered for the installation of hydrogen storage, $tonH_2$
$CMAX^{EHS}$	Maximum capacity to consider the installation of hydrogen storage, $tonH_2$
CT	Transmission link capacity from one region to another, MWh
$CPROD_{jt}$	Variable cost of production in conventional technologies, \$/MWh
$CPROD_{jrt}$	Variable cost of production in renewable technologies, \$/MWh
$CTRANS_{r,r'}$	Unit cost of power transmission from one region to another, \$/MWh
$EALM_{r,i}^{0}$	Energy contained in energy storages at time zero, MWh
$EDEM$	Electricity demand, MWh

$EMIS_{jc}$	Emission factor of CO_2 emissions equivalents generated into the atmosphere by the amount of fuel oil used, $tonCO_{2eq}$/ton of fuel oil
$EMIS_{jg}$	Emission factor of CO_2 emissions equivalents generated into the atmosphere per amount of natural gas used, $tonCO_{2eq}$/ton of natural gas
FC_i^{ESS}	Unit cost of installing electric power storage, \$/MW
FC_h^{elect}	Unit cost of electrolyzer installation, \$/MW
FC_g^{EHS}	Unit cost of installing hydrogen storage, \$/$tonH_2$
FC_{jr}^{renow}	Unit cost of installation of variable renewable technologies, \$/MW
K^{inv}	Factor used to annualize the equipment investment
$LHVC$	Low calorific value of fuel oil, GJ/ton of fuel oil
$LHVH$	Low calorific value of hydrogen, GJ/$tonH_2$
$LHVG$	Low calorific value of natural gas, GJ/ton of natural gas
$M_{r,0,g}^{EHS}$	Amount of hydrogen contained in the storage at the initial time, $tonH_2$
$MAXPROD_{r,jt,t}$	Maximum production capacity of conventional technologies, MW
$MINPROD_{r,jt,t}$	Minimum production capacity of conventional technologies, MW
PV_h^{elect}	Unit sale price of green hydrogen in each of the electrolyzers, \$/$tonH_2$
$RDMAX_{jt}$	Fraction of installed capacity that can be reduced over a period
$RUMAX_{jt}$	Fraction of installed capacity that can be increased over a period
$UC_i^{ess-CV-O\&M}$	Variable operation and maintenance cost in energy storage, \$/MWh
$UC_i^{ess-CF-O\&M}$	Fixed operation and maintenance cost in energy storage, \$
UC_h^{elect}	Unit operating cost of electrolyzers, \$/$tonH_2$
UC_g^{EHS}	Unit operating cost of hydrogen storage, \$/$tonH_2$
U^{UMDEMT}	Unit tax on unsupplied energy, \$/MWh
U^{CUT}	Unit tax on unused energy, \$/MWh
$U^{CARBONTAX}$	Environmental tax on emissions of CO_2 equivalents, \$/$tonCO_{2eq}$
η_i^{car}	Load efficiency in electrical energy storage systems
η_i^{des}	Discharge efficiency in electrical energy storage systems
η^{trans}	Electricity transmission efficiency
η_h^{elect}	Efficiency of electrolyzers
$\eta_{jc}^{convotr}$	Thermal efficiency of fuel oil to electricity
$\eta_{jg}^{convgas}$	Thermal efficiency from natural gas to electricity
$\eta_{jg}^{convH_2}$	Thermal efficiency from hydrogen to electricity

References

1. Nepal, R.; Paija, N. Energy security, electricity, population and economic growth: The case of a developing South Asian resource-rich economy. *Energy Policy* **2019**, *132*, 771–781. [CrossRef]
2. Li, F.; Zhang, D.; Zhang, J.; Kou, G. Measuring the energy production and utilization efficiency of Chinese thermal power industry with the fixed-sum carbon emission constraint. *Int. J. Prod. Econ.* **2022**, *252*, 108571. [CrossRef]
3. Komarnicka, A.; Murawska, A. Comparison of consumption and renewable sources of energy in European Union countries—Sectoral indicators, economic conditions and environmental impacts. *Energies* **2021**, *14*, 3714. [CrossRef]
4. Brunner, T.; Axsen, J. Oil sands, pipelines and fracking: Citizen acceptance of unconventional fossil fuel development and infrastructure in Canada. *Energy Res. Soc. Sci.* **2020**, *67*, 101511. [CrossRef]
5. Brockway, P.E.; Owen, A.; Brand-Correa, L.I.; Hardt, L. Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. *Nat. Energy* **2019**, *4*, 612–621. [CrossRef]
6. Serrano-Areválo, T.I.; Lira-Barragán, L.F.; El-Halwagi, M.M.; Ponce-Ortega, J.M. Strategic planning for optimal management of different types of shale gas wastewater. *ACS Sustain. Chem. Eng.* **2022**, *10*, 1451–1470. [CrossRef]
7. Brauers, H.; Oei, P.Y. The political economy of coal in Poland: Drivers and barriers for a shift away from fossil fuels. *Energy Policy* **2020**, *144*, 111621. [CrossRef]
8. Martins, F.; Felgueiras, C.; Smitkova, M.; Caetano, N. Analysis of fossil fuel energy consumption and environmental impacts in European countries. *Energies* **2019**, *12*, 964. [CrossRef]
9. Ahmad, T.; Zhang, D. A critical review of comparative global historical energy consumption and future demand: The story told so far. *Energy Rep.* **2020**, *6*, 1973–1991. [CrossRef]
10. Holladay, J.D.; Hu, J.; King, D.L.; Wang, Y. An overview of hydrogen production technologies. *Catal. Today* **2009**, *139*, 244–260. [CrossRef]
11. Megía, P.J.; Vizcaíno, A.J.; Calles, J.A.; Carrero, A. Hydrogen production technologies: From fossil fuels toward renewable sources. A mini review. *Energy Fuels* **2021**, *35*, 16403–16415. [CrossRef]

12. Wang, S.; Lu, A.; Zhong, C.J. Hydrogen production from water electrolysis: Role of catalysts. *Nano Converg.* **2021**, *8*, 4. [CrossRef] [PubMed]
13. Bhattacharyya, R.; Misra, A.; Sandeep, K.C. Photovoltaic solar energy conversion for hydrogen production by alkaline water electrolysis: Conceptual design and analysis. *Energy Convers. Manag.* **2017**, *133*, 1–13. [CrossRef]
14. Esposito, D.V. Membraneless electrolyzers for low-cost hydrogen production in a renewable energy future. *Joule* **2017**, *1*, 651–658. [CrossRef]
15. Rivard, E.; Trudeau, M.; Zaghib, K. Hydrogen storage for mobility: A review. *Materials* **2019**, *12*, 1973. [CrossRef]
16. Dawood, F.; Anda, M.; Shafiullah, G.M. Hydrogen production for energy: An overview. *Int. J. Hydrog. Energy* **2020**, *45*, 3847–3869. [CrossRef]
17. Karayel, G.K.; Javani, N.; Dincer, I. Green hydrogen production potential for Turkey with solar energy. *Int. J. Hydrog. Energy* **2022**, *47*, 19354–19364. [CrossRef]
18. Kojima, H.; Nagasawa, K.; Todoroki, N.; Ito, Y.; Matsui, T.; Nakajima, R. Influence of renewable energy power fluctuations on water electrolysis for green hydrogen production. *Int. J. Hydrog. Energy* **2023**, *48*, 4572–4593. [CrossRef]
19. Maggio, G.; Nicita, A.; Squadrito, G. How the hydrogen production from RES could change energy and fuel markets: A review of recent literature. *Int. J. Hydrog. Energy* **2019**, *44*, 11371–11384. [CrossRef]
20. Praveenkumar, S.; Agyekum, E.B.; Ampah, J.D.; Afrane, S.; Velkin, V.I.; Mehmood, U.; Awosusi, A.A. Techno-economic optimization of PV system for hydrogen production and electric vehicle charging stations under five different climatic conditions in India. *Int. J. Hydrog. Energy* **2022**, *47*, 38087–38105. [CrossRef]
21. Moelling, D.S.; Femiana, E.; Burns, D.K. Flexible Use of Hydrogen Fueled Duct Burners in Combined Cycle Power Plant HRSGs. In Proceedings of the ASME 2022 Power Conference, Pittsburgh, PA, USA, 18–19 July 2022; ASME: New York, NY, USA, 2022. [CrossRef]
22. Öberg, S.; Odenberger, M.; Johnsson, F. The value of flexible fuel mixing in hydrogen-fueled gas turbines–A techno-economic study. *Int. J. Hydrog. Energy* **2022**, *47*, 31684–31702. [CrossRef]
23. Öberg, S.; Odenberger, M.; Johnsson, F. Exploring the competitiveness of hydrogen-fueled gas turbines in future energy systems. *Int. J. Hydrog. Energy* **2022**, *47*, 624–644. [CrossRef]
24. Koohi-Fayegh, S.; Rosen, M.A. A review of energy storage types, applications and recent developments. *J. Energy Storage* **2020**, *27*, 101047. [CrossRef]
25. Tan, K.M.; Babu, T.S.; Ramachandaramurthy, V.K.; Kasinathan, P.; Solanki, S.G.; Raveendran, S.K. Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration. *J. Energy Storage* **2021**, *39*, 102591. [CrossRef]
26. Chen, T.; Jin, Y.; Lv, H.; Yang, A.; Liu, M.; Chen, B.; Xie, Y.; Chen, Q. Applications of lithium-ion batteries in grid-scale energy storage systems. *Trans. Tianjin Univ.* **2020**, *26*, 208–217. [CrossRef]
27. da Silva Lima, L.; Quartier, M.; Buchmayr, A.; Sanjuan-Delmás, D.; Laget, H.; Corbisier, D.; Mertens, J.; Dewulf, J. Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems. *Sustain. Energy Technol. Assess.* **2021**, *46*, 101286. [CrossRef]
28. Razmjoo, A.; Kaigutha, L.G.; Rad, M.V.; Marzband, M.; Davarpanah, A.; Denai, M. A Technical analysis investigating energy sustainability utilizing reliable renewable energy sources to reduce CO_2 emissions in a high potential area. *Renew. Energ.* **2021**, *164*, 46–57. [CrossRef]
29. Namahoro, J.P.; Wu, Q.; Zhou, N.; Xue, S. Impact of energy intensity, renewable energy, and economic growth on CO_2 emissions: Evidence from Africa across regions and income levels. *Renew. Sust. Energ. Rev.* **2021**, *147*, 111233. [CrossRef]
30. Praveenkumar, S.; Agyekum, E.B.; Kumar, A.; Velkin, V.I. Thermo-enviro-economic analysis of solar photovoltaic/thermal system incorporated with u-shaped grid copper pipe, thermal electric generators and nanofluids: An experimental investigation. *J. Energy Storage* **2023**, *60*, 106611. [CrossRef]
31. PraveenKumar, S.; Agyekum, E.B.; Kumar, A.; Velkin, V.I. Performance evaluation with low-cost aluminum reflectors and phase change material integrated to solar PV modules using natural air convection: An experimental investigation. *Energy* **2023**, *266*, 126415. [CrossRef]
32. Ding, S.; Zhang, M.; Song, Y. Exploring China's carbon emissions peak for different carbon tax scenarios. *Energy Policy* **2019**, *129*, 1245–1252. [CrossRef]
33. Yuyin, Y.; Jinxi, L. The effect of governmental policies of carbon taxes and energy-saving subsidies on enterprise decisions in a two-echelon supply chain. *J. Clean. Prod.* **2018**, *181*, 675–691. [CrossRef]
34. Serrano-Arévalo, T.I.; Juárez-García, M.; Ponce-Ortega, J.M. Optimal planning for satisfying future electricity demands involving simultaneously economic, emissions, and water concerns. *Proc. Integ. Optim. Sustain.* **2020**, *4*, 379–389. [CrossRef]
35. Liu, Y.; Du, J.L. A multi criteria decision support framework for renewable energy storage technology selection. *J. Clean. Prod.* **2020**, *277*, 122183. [CrossRef]
36. Rezaei, M.; Akimov, A.; Gray, E.M. Economics of solar-based hydrogen production: Sensitivity to financial and technical factors. *Int. J. Hydrog. Energy* **2022**, *47*, 27930–27943. [CrossRef]
37. Tovar-Facio, J.; Guerras, L.S.; Ponce-Ortega, J.M.; Martin, M. Sustainable energy transition considering the water–energy nexus: A multiobjective optimization framework. *ACS Sustain. Chem. Eng.* **2021**, *9*, 3768–3780. [CrossRef]

38. Al-Shahri, O.A.; Ismail, F.B.; Hannan, M.A.; Lipu, M.S.H.; Al-Shetwi, A.Q.; Begum, R.A.; Al-Muhsen, N.F.O.; Soujeri, E. Solar photovoltaic energy optimization methods, challenges and issues: A comprehensive review. *J. Clean. Prod.* **2021**, *284*, 125465. [CrossRef]
39. Hu, D.; Ryan, S.M. Stochastic vs. deterministic scheduling of a combined natural gas and power system with uncertain wind energy. *Int. J. Electr. Power Energy Syst.* **2019**, *108*, 303–313. [CrossRef]
40. Moretti, L.; Astolfi, M.; Vergara, C.; Macchi, E.; Pérez-Arriaga, J.I.; Manzolini, G. A design and dispatch optimization algorithm based on mixed integer linear programming for rural electrification. *Appl. Energy* **2019**, *233*, 1104–1121. [CrossRef]
41. Feng, Z.K.; Niu, W.J.; Cheng, C.T. Optimizing electrical power production of hydropower system by uniform progressive optimality algorithm based on two-stage search mechanism and uniform design. *J. Clean. Prod.* **2018**, *190*, 432–442. [CrossRef]
42. Kong, J.; Skjelbred, H.I.; Fosso, O.B. An overview on formulations and optimization methods for the unit-based short-term hydro scheduling problem. *Electr. Power Syst. Res.* **2020**, *178*, 106027. [CrossRef]
43. Singh, B.; Knueven, B. Lagrangian relaxation based heuristics for a chance-constrained optimization model of a hybrid solar-battery storage system. *J. Glob. Optim.* **2021**, *80*, 965–989. [CrossRef]
44. National Secretariat of Energy (SENER). National Electric System Development Program 2018–2032 "PRODESEN". 2018. Available online: https://www.gob.mx/cms/uploads/attachment/file/331770/PRODESEN-2018-2032-definitiva.pdf (accessed on 1 May 2022).
45. National Institute of Ecology and Climate Change (INECC). Technology Roadmap and Mitigation Potential for Utility-Scale Electricity Storage in Mexico. 2020. Available online: https://www.gob.mx/inecc/documentos/hoja-de-ruta-tecnologica-y-potencial-de-mitigacion-del-almacenamiento-de-electricidad-a-escala-de-servicios-publicos-en-mexico (accessed on 1 May 2022).
46. Preuster, P.; Alekseev, A.; Wasserscheid, P. Hydrogen Storage Technologies for Future Energy Systems. *Annu. Rev. Chem. Biomol. Eng.* **2017**, *8*, 445–471. [CrossRef] [PubMed]
47. Chi, J.; Yu, H. Water electrolysis based on renewable energy for hydrogen production. *Chin. J. Catal.* **2018**, *39*, 390–394. [CrossRef]
48. van den Broek, R.; van den Burg, T.; van Wijk, A.; Turkenburg, W. Electricity generation from eucalyptus and bagasse by sugar mills in Nicaragua: A comparison with fuel oil electricity generation on the basis of costs, macro-economic impacts and environmental emissions. *Biomass Bioenergy* **2000**, *19*, 311–335. [CrossRef]
49. İlbaş, M.; Karyeyen, S. A numerical study on combustion behaviours of hydrogen-enriched low calorific value coal gases. *Int. J. Hydrog. Energy* **2015**, *40*, 15218–15226. [CrossRef]
50. Renner, S. Poverty and distributional effects of a carbon tax in Mexico. *Energy Policy* **2018**, *112*, 98–110. [CrossRef]
51. De Sisternes Jimenez, F.; Webster, M.D. *Optimal Selection of Sample Weeks for Approximating the Net Load in Generation Planning Problems*; Massachusetts Institute of Technology: Cambridge, MA, USA, 2013; Available online: http://hdl.handle.net/1721.1/102959 (accessed on 8 February 2023).
52. GAMS Development Corporation. *General Algebraic Modelling System (GAMS)*; GAMS Development Corporation: Fairfax, VA, USA, 2020.
53. Energy Alliance between Mexico and Germany. Green Hydrogen in Mexico: The Potential of Transformation. 2021. Available online: https://www.energypartnership.mx/fileadmin/user_upload/mexico/media_elements/reports/Hidro%CC%81geno_AE_Tomo_IV.pdf (accessed on 1 June 2022).
54. Secretary of Environment and Natural Resources (SEMARNAT). Emission Factor of the National Electricity System 2020. 2020. Available online: https://www.gob.mx/cms/uploads/attachment/file/630693/Aviso_FEE_2020.pdf (accessed on 1 July 2022).
55. Fan, Z.; Xiao, W. Electrochemical splitting of methane in molten salts to produce hydrogen. *Angew. Chem. Int. Ed.* **2021**, *60*, 7664–7668. [CrossRef]
56. Kleinberg, R.L.; Paltsev, S.; Ebinger, C.K.E.; Hobbs, D.A.; Boersma, T. Tight oil market dynamics: Benchmarks, breakeven points, and inelasticities. *Energy Econ* **2018**, *70*, 70–83. [CrossRef]
57. Kavadias, K.A.; Kosmas, V.; Tzelepis, S. Sizing, optimization, and financial analysis of a green hydrogen refueling station in remote regions. *Energies* **2022**, *15*, 547. [CrossRef]
58. Moradpoor, I.; Syri, S.; Santasalo-Aarnio, A. Green hydrogen production for oil refining–Finnish case. *Renew. Sust. Energ. Rev.* **2023**, *175*, 113159. [CrossRef]
59. Keck, F.; Lenzen, M.; Vassallo, A.; Li, M. The impact of battery energy storage for renewable energy power grids in Australia. *Energy* **2019**, *173*, 647–657. [CrossRef]