

Article

Associated Gas Recovery Integrated with Solar Power for Produced Water Treatment: Techno-Economic and Environmental Impact Analyses

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Abstract: Excess associated gas from unconventional wells is typically flared while excess produced water is injected underground. In this work, flare gas recovery is integrated with produced water desalination and a solar pre-heater. The solar module with a beam splitter preheats the produced water. Aspen Plus process modeling, economic analysis, and greenhouse gas analysis were performed. The solar flare gas recovery desalination (Solar-FGRD) process can conserve water resources and reduce the brine injection by 77%. The accompanying solar farm results in excess solar electricity for exporting to the grid. The process burner combustion efficiency (CE) is 99.8%, with a destruction and removal efficiency (DRE) of 99.99% for methane as opposed to a flare CE of 80–98% (and a methane DRE of 91–98%). The greenhouse gas (GHG) emissions for CO₂ and methane, in terms of CO₂ equivalent (CO₂e), can be reduced by 45% for US North Dakota and Texas flaring and 13% for North Sea flaring by employing the Solar-FGRD process. Comprehensive financial analysis demonstrates the financial–economic feasibility of the investment project with or without tax credits. Best-case and worst-case scenarios provide a realistic range that investors can consider before making investment decisions.

Keywords: economic feasibility; tax credits; produced water; desalination; flare gas recovery; brine disposal; photovoltaic cell; solar thermal collector



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1. Introduction

The flaring of associated gas results in wasted energy and raw materials in addition to atmospheric emission of greenhouse gases, which intensifies climate change. Consequently, flare gas recovery (FGR) is a priority for regulatory agencies and the oil and gas (O&G) industry [1–13]. Furthermore, the disposal of untreated produced water, a waste byproduct of natural gas production wells, in evaporation ponds and/or subsurface injection sites remains under scrutiny due to the shortage of disposal sites and the scarcity of fresh water. The call for produced water treatment for recycling and reuse is becoming louder. A cost-effective, integrated solution that promotes the reuse of treated produced water with captured flare gas not only reduces greenhouse gas emissions and generates a revenue-generating water stream but also improves a company's environmental, social, and governance (ESG) performance. In previous studies, the FGR-thermal vapor compression (FGR-TVC) processes (compressor-based or ejector-based) for produced water desalination were demonstrated to be technically viable [14–25]. The rapid advancement of solar energy technology coupled with high solar insolation in the US Southwest makes a compelling argument to utilize solar energy in O&G operations [26–31]. The solar flare gas recovery desalination (Solar-FGRD) process seeks to reduce operating and utility costs by improving

heat integration and decreasing reliance on a power grid to operate the desalination plant. The objective of the Solar-FGRD process is to maximize potable water and minimize waste streams, including brine and burner flue gas hydrocarbons. Unlike previous works, which only dealt with operating costs analysis, comprehensive economic analysis and greenhouse gas (GHG) analysis are carried out in this study. The Solar-FGRD process integrates solar thermal and photovoltaic technology to desalinize produced water with recovered flare gas [14,16,29,31]. The process modeling, economic feasibility, and environmental impact were evaluated and compared to a produced water brine injection disposal baseline process without flare gas recovery (FGR) and without produced water desalination [32–40].

2. Literature Review

2.1. Associated Gas Flaring and Greenhouse Gas Emissions

In 1983, McDaniel conducted a controlled flare study sponsored by USEPA, which established the benchmark combustion efficiency (CE) and destruction removal efficiency (DRE) of 98% [8]. In the controlled flare tests Allen and Torres conducted in Tulsa, Oklahoma, in 2010, however, substantially lower CE and DRE values were observed for low-heating-value and stand-by-mode flares than the commonly assumed 98% [1]. Recent flare studies by Alphones et al., Chen and Alphones, Damodara et al., and Singh et al. [2–4,11] also support this view based on a large collection of industrial flare data. The low CE and DRE and the related air pollution issues from open-air flaring have been widely publicized, such as in the World bank and IPCC reports [7,12]. The under-reported methane emission issue from flaring in US onshore and offshore oil and gas productions were observed by satellites measurements and reported by Tran et al. [13] and in a series of publications from the University of Michigan group [5–7,9]. Shaw et al. indicated that the flaring operation in North Sea O&G production is more efficient [10].

2.2. Produced Water Reuse and Disposal

After a well begins to produce oil and associated gas, in the case of fracking, flowback water is observed during the first few weeks, after which the produced water continues to flow throughout the life of the well (or for an extended period of time). The total dissolved solids (TDS) in the produced water varies from 10,000 to 300,000 mg/L [18–21]. Figure 1 [18] shows the flow rate of produced water for a well. In this project, 52.2 bbl/h of produced water was assumed. Figure 2 illustrates the TDS content in typically produced water samples from unconventional reservoirs in the US [19–22,24]. In this study, 130,000 mg/L was considered as the average TDS content of produced water. Based on Chen et al.'s work [14], the TDS composition was assumed to be 28.9% Na⁺, 9.6% Ca²⁺, and 61.5% Cl[−]. The Solar-FGRD process captures this stream and converts 76.8% of the volume to potable water (<500 mg/L), which municipalities can use for irrigation, cleaning, household use, and drinking water. Chen et al. [14] reported a potable water recovery of 36% (62.9 bbl/h of potable water), with 669.2 bbl/h of waste streams (113.2 bbl/h brine and 556 bbl/h of cooling water). The process intake is 720 bbl/h. The potable water revenue is USD 4,628,433/yr, and the waste disposal cost is USD 10,258,836/yr. The ejector-based FGR-TVC (thermal vapor compression) process was reported in Seefeldt and Hoon's work and later adapted by Mazumder et al. [16]. The FGR-TVC process could save about 33% capital cost and 16% operating cost per year, compared with the compressor-based FGR-TVC process. In this paper, Aspen Plus process modeling was performed by simplifying Mazumder et al.'s flowsheets to maximize potable water recovery and reduce burner flue gas emissions [25]. Dinani et al. [15] reported an optimization of the natural gas liquid (NGL) product plus the outlet gas (mainly methane) utilization (after FGR) for South Iran oil and gas fields. They concluded that the best approach would be 93% of the methane gas going to enhanced oil recovery and 7% used for power generation. However, their paper addresses a different scope of work, and the results cannot be directly compared to this study.

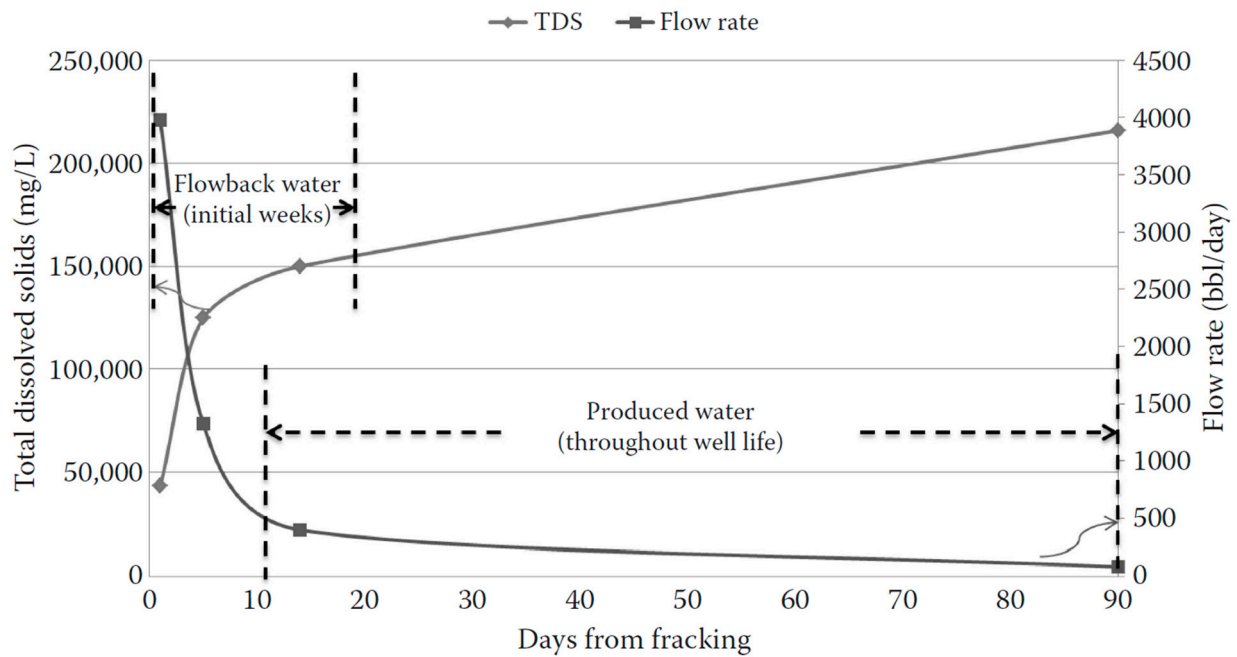


Figure 1. Produced water flow rate throughout well life (or an extended period of time) [18].

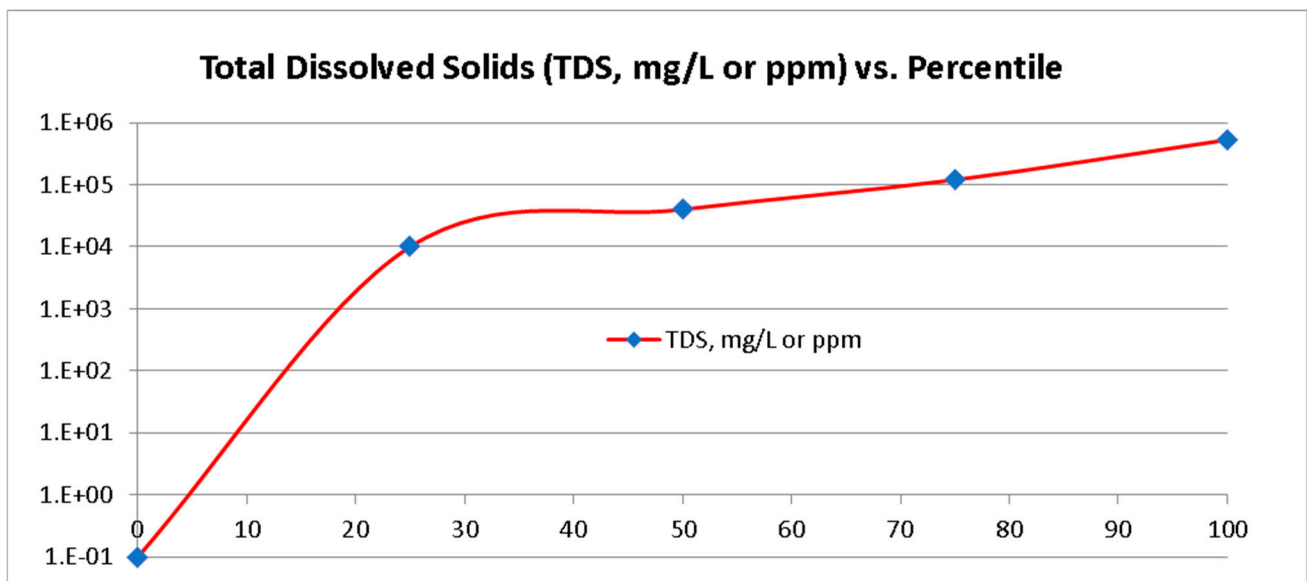


Figure 2. Total dissolved solids (TDS, mg/L or ppm) vs. sample percentile in typical produced water samples [19–22].

2.3. Photovoltaic–Thermal Systems

The theoretical solar photovoltaic efficiency limits (up to 47% at 1 sun) vs. actual photovoltaic efficiencies (15–30%) were discussed in Alharbi et al. [26] and Elsheniti et al. [27]’s papers. Jiang et al. [29] described a parabolic trough concentrating photovoltaic thermal system with a spectral beam splitter. Huang et al. [28] reported that the efficiency limits of solar photovoltaic–thermal (PV-T) systems can reach as high as 70–87% (with a 40% thermal efficiency and the balance electrical efficiency), depending on the beam splitter, semiconductor, operating temperature, solar collecting efficiency, etc. The solar insolation maps, data, and PVWatts calculator are available from the US National Renewable Energy Laboratory websites [30,31].

2.4. Techno-Economic Analysis

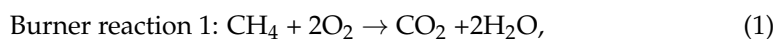
The economic analysis is based on the capital and operating costs generated by the Aspen Process Economic Analysis (APEA) tool [32]. The potable water rate used was the West Texas prevailing tap water rate [17]. Al-Ani [33], Longmore [38], and Zis et al. [40] discussed the use of the payback period (PBP) as a useful tool for investment evaluations. Fernando [34] explained the concept of discount cash flow, which serves as a basis for calculating the net present value (NPV) at the end of a given project period as discussed in Fernando [35], Gallo [36], Ling [37], and San Ong and Thum [39].

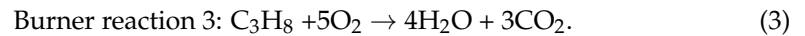
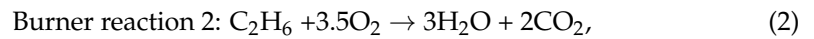
3. Methodology

3.1. Process Description

The Solar-FGRD process, as shown in Figure 3 and Table 1, was modeled with Aspen Plus Version 11 [25] and is summarized as follows:

- A feed (INTAKE) of 52 bbl/h pretreated produced water (metals and sludge removed) at 60 °F and 0 psig containing 131,260 mg/L TDS with 28.9% Na⁺, 9.6% Ca²⁺, and 61.5% Cl⁻ is pumped (P1) at 30 psig (via stream INTAKE1) into a brine cooler (COOLER), which heat exchanges and raises the temperature of the feed to 110 °F.
- The stream (PREHEAT) exits the COOLER at 110 °F and is further pre-heated through a solar-powered heater (SOLAR) to 145 °F. The solar heat input is 600,000 Btu/h. The pre-heated stream exits the SOLAR as FEED1.
- The 52 bbl/h preheated produced water (FEED1) flows through an evaporator (HX1B), which generates a two-phase stream (FEED) of 59 mol% vapor at 291 °F. The HX1B exchanger heat input (Q3) is 13,000,000 Btu/h.
- The FEED stream is further heated via a second evaporator (EVAP), which increases the temperature of the FEED from 291 °F to 310 °F and increases the vapor fraction from 59 mol% to 74 mol%. The heated two-phase stream exits the EVAP as WATERHOT.
- Then, a separator (SEPARATR) flashes the WATERHOT stream into a 100% vapor stream (POTABLEV). This stream is free of TDS and is considered pure water. The separator also generates a 100% liquid stream BRINEHOT, which contains TDS.
- The liquid stream exiting the separator (BRINEHOT) is at 310 °F and contains 503,268 mg/L TDS with 28.9% Na⁺, 9.6% Ca²⁺, and 61.5% Cl⁻. The stream is cooled to 80 °F via the COOLER and then the cooled stream (BRINE1) is pumped to storage via pump P3 at 30 psig. The produced water intake is used to cool the hot brine stream. The final waste brine liquid stream BRINE comprises 29.8 wt% of the produced water feed. This waste stream will need to be disposed of at a subsurface injection site.
- The pure water vapor stream (POTABLEV) at 310 °F is condensed to 99.91 mol% liquid at 212 °F via exchanger HX1A. Q1 represents the 13,000,000 Btu/h of heat removed. The heat removed from the potable water vapor is used to preheat the produced water feed stream in HX1B. The condensed potable water (POTABLEL) is further cooled to 70 °F via an air-cooler (AIRCOOL), which removes 3,270,934 Btu/h of heat (Q2). The cooled potable water stream (POTABLE1) is pumped to storage via pump P2 at 30 psig. The final product stream POTABLE is distilled water without TDS for sale and comprises 70.2 wt% of the produced water feed.
- The primary heat source for the desalination is stream FUELGAS, which is the recovered gas from the production well at 150 lb/h, 60 °F, and 50 psig, and consists of 65.3 wt% methane, 24.8% ethane, 9.01% propane, 0.575% nitrogen, and 0.226% carbon dioxide. A VALVE is used to drop the pressure to 20 psig. The stream LP-GAS is fed to a burner COMBUST, which is modeled as an equilibrium reactor based on Gibbs free energy minimization. Excess air (35%) at 60 °F, 5 psig, and 3507 lb/h, consisting of 21% oxygen, 78% nitrogen, and 1% argon, is fed to the burner via stream AIR.
- The COMBUST combustion reactions are given below:





- The burner outlet stream HOTGAS is heated to 2904 °F and contains combustion gases. This stream is fed to the evaporator (EVAP) and transfers heat such that the flue gas stream (FLUEGAS) releases into the atmosphere at 320 °F.
- The flue gas waste stream flow is 3657 lb/h (11.43 wt% carbon dioxide, 8.45 wt% water, 72.22 wt% nitrogen, 6.27 wt% oxygen, 0 wt% carbon monoxide, 0 wt% nitrous oxide, 0 wt% nitrogen dioxide, 0.29 wt% nitric oxide, 0 wt% methane, 0 wt% ethane, and 0 wt% propane).
- The modeled destruction efficiency for the flue gas is ~100% methane, ~100% ethane, and ~100% propane.
- The heat for exchanger SOLAR is provided via solar energy through a solar collector module. The solar heat input is 600,000 Btu/h. The Solar-FGRD process utilizes a novel solar beam splitter that can split sunlight into photovoltaic ($500 < \lambda < 900 \text{ nm}$), infrared ($\lambda > 900 \text{ nm}$), and higher-energy ($\lambda < 500 \text{ nm}$) spectra. Figure 4 illustrates the novel two-stage solar beam splitter technology.

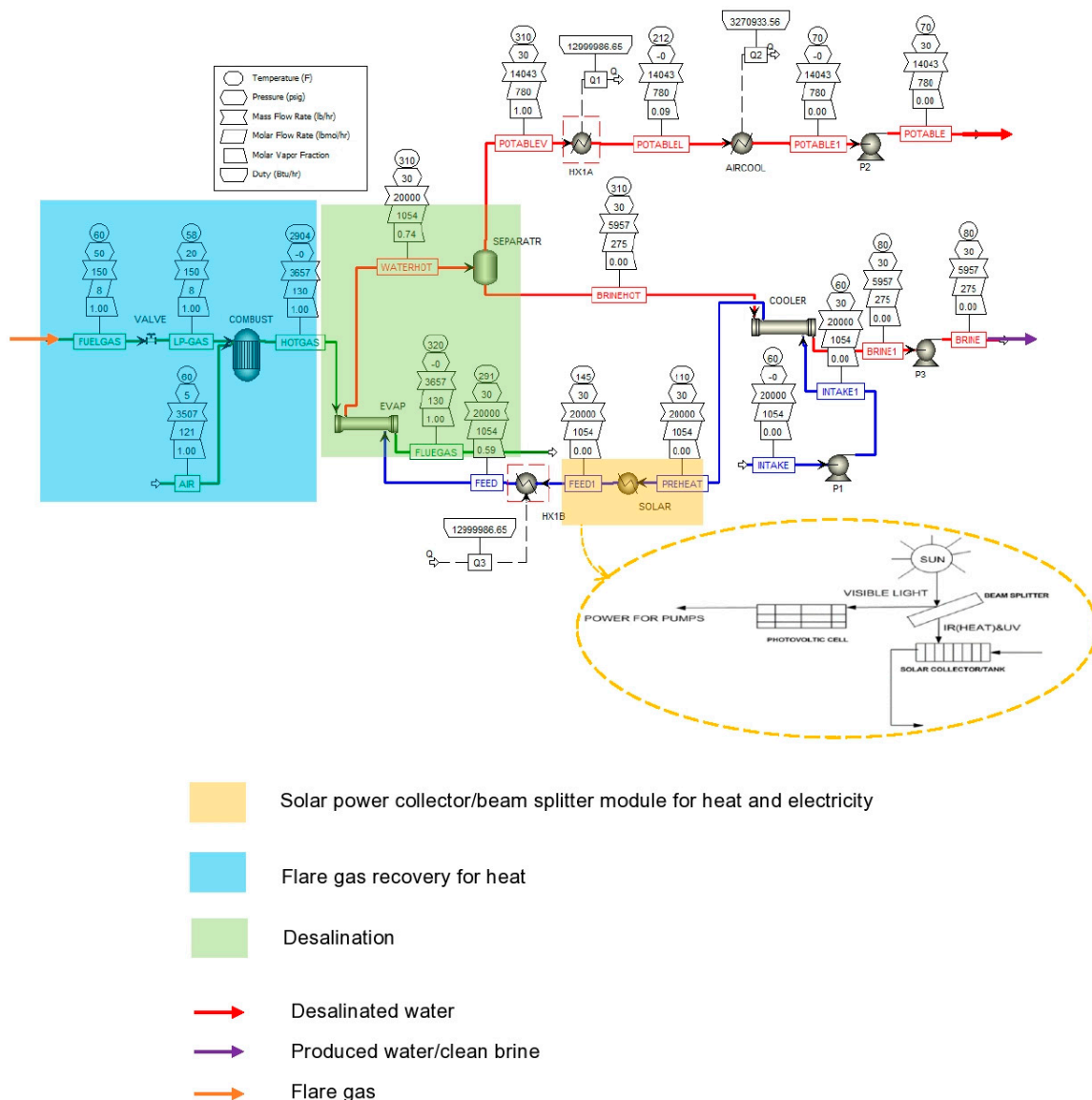
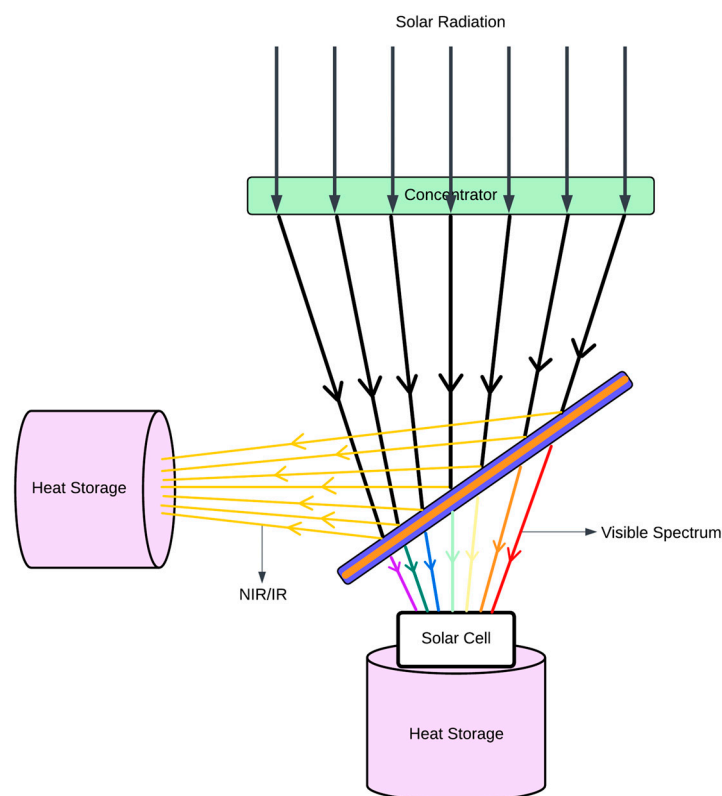


Figure 3. Aspen Plus simulation for the Solar-FGRD process with improved heat integration.

Table 1. Heat and material balance of the Solar-FGRD process.

Stream	Temperature	Pressure	Enthalpy Flow	Mass Flow	Volume Flow	Mole Vapor Fraction
	F	psig	Btu/h	lb/h	bbl/h	
AIR	60.0	5	−14,804	3507.1	-	1.000
BRINE	80.0	30	−31,680,818	5956.7	12.5	0.000
BRINE1	80.0	30	−31,680,818	5956.7	12.5	0.000
BRINEHOT	309.8	30	−30,830,429	5956.7	13.6	0.000
FEED	291.4	30	−113,325,111	20,000.0	-	0.589
FEED1	144.6	30	−126,325,087	20,000.0	53.2	0.000
FLUEGAS	320.0	0	−3,148,450	3657.1	-	1.000
FUELGAS	60.0	50	−257,062	150.0	-	1.000
HOTGAS	2904.1	0	−271,866	3657.1	-	1.000
INTAKE	60.0	0	−127,777,647	20,000.0	52.2	0.000
INTAKE1	60.0	30	−127,775,476	20,000.0	52.2	0.000
LP-GAS	57.7	20	−257,062	150.0	-	1.000
POTABLE	70.0	30	−95,886,918	14,043.3	40.1	0.000
POTABLE1	70.0	0	−95,888,587	14,043.3	40.1	0.000
POTABLEL	212.0	0	−92,617,653	14,043.3	6356.8	0.093
POTABLEV	309.8	30	−79,617,653	14,043.3	-	1.000
PREHEAT	109.6	30	−126,925,087	20,000.0	52.7	0.000
WATERHOT	309.8	30	−110,448,527	20,000.0	-	0.739

**Figure 4.** The solar photovoltaic-thermal system with a solar concentrator and a beam splitter for the utilization of the full solar spectrum.

3.2. Financial and Economic Feasibility Analysis

3.2.1. Aspen Process Economic Analyzer (APEA)

The Aspen Process Economic Analyzer (APEA) was used to evaluate total capital cost, total operating cost, total raw material cost, and total product sales [32]. Several investment evaluation tools—cash flow, net present value (NPV), and payback period (PBP)—were further investigated [33–40].

3.2.2. Cash Flow

Cash flow tables were constructed for a project period of 20 years. Cash flows are determined from design capacity, sales, capital costs, working capital, total operating cost, taxes, and interest payments. These tables also present cumulative cash flow, present value, and present worth factor [34].

3.2.3. Net Present Value (NPV)

The NPV measures the profitability of a project or investment by assessing the difference between the present value of expected cash inflows and the present value of cash outflows over the investment's time horizon. A positive NPV, as shown in Equation (4), indicates a potentially profitable investment, while a negative NPV suggests that the investment may not be financially viable [35,36,39].

$$NPV = \sum_{t=0}^n \frac{R_t}{(i+1)^t} \quad (4)$$

where R_t = Net cash flow (in–out flows) during a single period t ;

i = discount rate;

t = number of time periods.

3.2.4. The Payback Period (PBP)

The PBP method is an important method for capital budgeting or investment decision-making as it gives a more accurate approximation even with the non-uniform future cash flows, which is more likely in the real business world [33,38,40]. The PBP is the point in time when the cumulative net cash flow becomes positive:

1. The cumulative net cash flow is calculated for each year. The net cash flow is summed up for that year starting from the beginning of the project.
2. The latest year is denoted as “ n ”, when the cumulative net cash flow becomes positive. This year is when the investment has been fully recovered.
3. The exact point in the latest year n is determined when the remaining original investment is paid back using the formula as given in Equation (5):

$$\text{Exact Time in Year } n = \frac{\text{Original Investment} - \text{Cumulative Net Cash Flow at the end of Year } n - 1}{\text{Net Cash Flow in Year } n} \quad (5)$$

3.3. Greenhouse Gas Analysis

The Solar-FGRD process has a high hydrocarbon combustion efficiency (CE) and methane destruction removal efficiency (DRE) compared to conventional open-air flaring. CE is defined as the hydrocarbon conversion to CO_2 :

$$\text{Combustion Efficiency (CE \%)} = \frac{\text{Mass of carbon converted to } \text{CO}_2}{\text{Mass of carbon fed as fuel}} \quad (6)$$

Another representation of the flare efficiency is the destruction and removal efficiency (DRE) as defined by each hydrocarbon species flared, such as methane and ethane. DRE should refer to a particular parent compound in the fuel. For methane,

$$\text{DRE\% (CH}_4\text{)} = \frac{\text{Amount of CH}_4 \text{ fed} - \text{Amount of CH}_4 \text{ in flue gas}}{\text{Amount of CH}_4 \text{ fed to the flare}}. \quad (7)$$

4. Results

4.1. Solar Heater Integration

To preheat the feed-produced water stream by 35 °F (from 110 °F to 145 °F), the thermal energy required is 175.8 kW. Assuming an average solar insolation of 6.37 kWh/m²/day in the US Southwest [30] and a solar energy heat recovery of 40%, the total solar collector area required is 1656 m². The Solar-FGRD process requires 20 kW to power the facility, and the solar photovoltaic module assumes a 15% efficiency. While the photovoltaic module with beam splitter captures the visible spectrum for power generation, the thermal module captures the rest of the spectrum (~40%) for intake water pre-heating. The photovoltaic module area will match the solar collector area of 1655.9 m². The total excess photovoltaic electricity generated is 0.035 MW, which can be sold to the power grid as a revenue stream. The Solar-FGRD process requires 0.614 acres of the total area to install the plant and associated solar modules. Table 2 summarizes the solar thermal and photovoltaic calculations.

Table 2. Solar thermal and photovoltaic calculations.

Solar Insolation Permian Basin	
Total Solar Insolation (kWh/m ² /day)	6.37
Total Solar Insolation (kWh/m ² /year)	2325.05
Solar Collector/Water Heater	
Solar Preheater ΔT (°F)	35
Water Flow Rate (bbl/day)	1254
Solar Preheater Thermal Energy Required (kW)	176
Solar Preheater Thermal Energy Required (kWh/yr)	1,540,008
Solar Energy Heat Recovery	40%
Thermal Solar Insolation (kWh/m ² /yr)	930
Solar Collector Efficiency	40%
Solar Collector Area Required (m ²)	1656
Solar Farm Area	
Gross Area Required (m ²)	2484
Gross Area Required (acres)	0.61
Photovoltaic Module	
Electrical Energy Required (kW)	20
Electrical Energy Required AC (kWh/yr)	175,200
Photovoltaic Module Efficiency	15%
Electrical Solar Insolation (kWh/m ² /year)	2325
Photovoltaic Module Area (m ²)	1656
Inverter DC/AC Ratio	1.2
Photovoltaic Electricity Generated DC (kWh/yr)	577,503
Photovoltaic Electricity Generated AC (kWh/yr)	481,253
Excess Photovoltaic Electricity Generated AC (kWh/yr)	306,053
Excess Photovoltaic Electricity Generated AC (MW)	0.03

4.2. Salt Sensitivity Analysis

The base-case water TDS concentration is 131,260 mg/L, with 28.9% Na⁺, 9.6% Ca²⁺, and 61.5% Cl⁻. The base case TDS concentration results in 76.8% potable water recovery by volume. The TDS concentration varied according to Figure 2, which illustrates the typical variance in produced water salinity. Table 3 and Figure 5 below demonstrate the capability of the Solar-FGRD process in handling various TDS concentrations, as well as the resulting potable water recovery, which varies between 75.7 and 77.7%. The TDS range and distribution shown in Table 3 were based on data from USGS and industrial reports [18–24].

Table 3. Potable water recovery as a function of produced water TDS concentration.

Produced Water Feed				Potable Water Stream			Brine			Potable Water Recovery
Density	TDS	Mass Flow	Volume Flow	Density	Mass Flow	Volume Flow	Density	Mass Flow	Volume Flow	
kg/m ³	mg/L	kg/h	bbl/h	kg/m ³	kg/h	bbl/h	kg/m ³	kg/h	bbl/h	
1021.27	30,000	8481.5	52.2374796	998.18	6443.5	40.603	1074.642	2628.4	15.384	77.73%
1056.82	80,000	8776.7	52.2374796	998.18	6417.0	40.436	1211.498	2654.8	13.784	77.41%
1092.32	131,260	9071.6	52.2374796	998.18	6370.0	40.140	1362.269	2701.9	12.475	76.84%
1111.92	160,000	9234.4	52.2374796	998.18	6335.4	39.922	1450.398	2736.4	11.867	76.42%
1138.90	200,000	9071.8	52.2374796	998.18	6274.1	39.536	1574.194	2797.8	11.179	75.68%

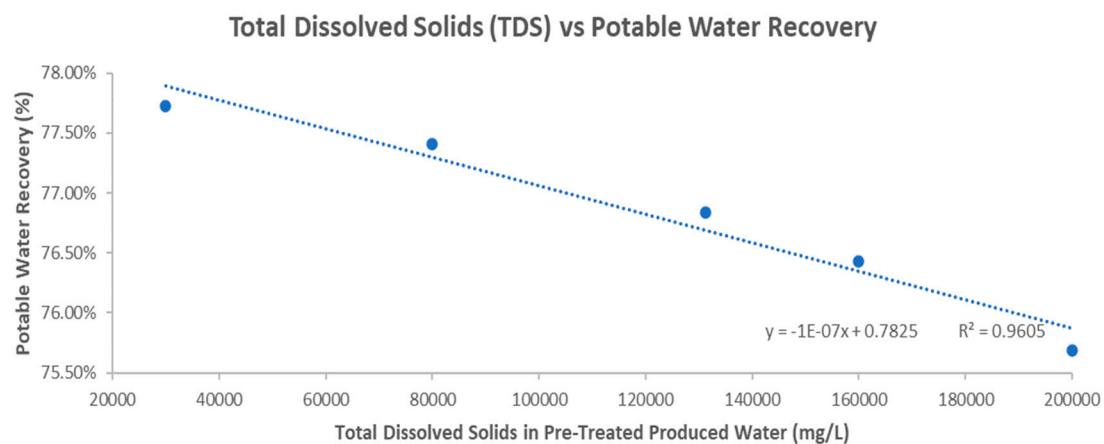


Figure 5. Percentage of potable water recovery via the Solar-FGRD process for various TDS concentrations.

4.3. Financial and Economic Evaluation

In this section, the financial–economic feasibility of investment was demonstrated by providing a comprehensive financial analysis, including the best-case, base-case, and worst-case scenarios (Tables 4 and 5). Assumptions of the base case financial model include total investment of USD 5,099,096 (40% equity and 60% loan), 0% down payment on loan, 6% interest rate, USD 0.1/gal distilled water sales price, USD 0.06/kWh electricity sales price, and USD 1.75/bbl brine water disposal cost. Table 6 highlights multiple cases (base case, worst case, and best case) for consideration.

The cash flow and payback period are also determined by the capital cost and annual operating cost, which have been estimated in the financial model. The best-case scenario of cash flows and the payback period is demonstrated in Table 7.

Table 4. The Solar-FGRD process financial model—base case.

Assumptions		
Capital Cost	USD 5,000,000.00	
Working Capital	USD 99,095.67	
Total Investment	USD 5,099,095.67	
Loan	USD 3,059,457.40	60%
Equity	USD 2,039,638.27	40%
Annual Interest Rate	6%	
Loan Payback Years	20	
Annual Loan Payment	USD 263,026.84	
Down payment	0%	
Payments per Year	12	
Operating Cycle	1	months
Revenue		
Produced Water Volume	1254	bbl/day
Distilled Water Recovery	76.84%	
Distilled Water Volume	963.34	bbl/day
Distilled Water Sales Price	USD 0.10	USD/gal
Distilled Water Sales	USD 1,476,804.94	USD/yr
Solar Electricity Generated	306,052.5	kWh/yr
Electricity Sales Price	USD 0.06	USD/kWh
Electricity Sales	USD 18,363.15	USD /yr
Total Annual Revenue	USD 1,495,168.09	
Tax Credits	USD 0.00	USD/yr
Cost		
Produced Water Volume	1254	bbl/day
Distilled Water Recovery	76.84%	
Brine Water Volume	290.36	bbl/day
Brine Water Disposal Unit Cost	USD 1.75	USD/bbl
Brine Water Disposal Total Cost	USD 185,465.48	USD/yr
Solar Area Required	0.614	acre
Solar Farm Area Lease (1 acre)	500	USD/month
Solar Farm Lease Cost	USD 3682.57	USD/yr
Operating Cost	USD 1,000,000.00	USD/yr
Total Annual Cost	USD 1,189,148.05	

Table 5. The Solar-FGRD process cash flows—base case.

Cash Flows				
Year Count	Cash Flow	Present Value	Present Worth Factor	Cumulative Cash Flow
0	(USD 2,039,638.27)	(USD 2,039,638.27)	1	(USD 2,039,638.27)
0	USD 0.00	USD 0.00	1	(USD 2,039,638.27)
1	USD 42,993.20	USD 40,559.63	0.943396226	(USD 1,996,645.06)
2	USD 42,993.20	USD 38,263.80	0.88999644	(USD 1,953,651.86)
3	USD 42,993.20	USD 36,097.92	0.839619283	(USD 1,910,658.65)
4	USD 42,993.20	USD 34,054.65	0.792093663	(USD 1,867,665.45)
5	USD 42,993.20	USD 32,127.02	0.747258173	(USD 1,824,672.24)

Table 5. Cont.

Cash Flows				
Year Count	Cash Flow	Present Value	Present Worth Factor	Cumulative Cash Flow
6	USD 42,993.20	USD 30,308.51	0.70496054	(USD 1,781,679.04)
7	USD 42,993.20	USD 28,592.94	0.665057114	(USD 1,738,685.83)
8	USD 42,993.20	USD 26,974.47	0.627412371	(USD 1,695,692.63)
9	USD 42,993.20	USD 25,447.61	0.591898464	(USD 1,652,699.43)
10	USD 42,993.20	USD 24,007.18	0.558394777	(USD 1,609,706.22)
11	USD 42,993.20	USD 22,648.28	0.526787525	(USD 1,566,713.02)
12	USD 42,993.20	USD 21,366.31	0.496969364	(USD 1,523,719.81)
13	USD 42,993.20	USD 20,156.89	0.468839022	(USD 1,480,726.61)
14	USD 42,993.20	USD 19,015.94	0.442300964	(USD 1,437,733.40)
15	USD 42,993.20	USD 17,939.56	0.417265061	(USD 1,394,740.20)
16	USD 42,993.20	USD 16,924.12	0.393646284	(USD 1,351,746.99)
17	USD 42,993.20	USD 15,966.15	0.371364419	(USD 1,308,753.79)
18	USD 42,993.20	USD 15,062.40	0.350343791	(USD 1,265,760.58)
19	USD 42,993.20	USD 14,209.81	0.33051301	(USD 1,222,767.38)
20	USD 42,993.20	USD 13,405.48	0.311804727	(USD 1,179,774.17)
NPV@Yr 20		(USD 1,546,509.60)		
Payback Period		>20		years

Table 6. The Solar-FGRD process financial sensitivity study.

	Base Case	Worst Case	Best Case
Capital Cost	USD 5,000,000	USD 7,000,000	USD 3,000,000
Annual Interest Rate	6%	7%	5%
Loan/Equity	60%/40%	60%/40%	60%/40%
Annual Loan Payment	USD 263,026.84	USD 396,282.33	USD 147,259.15
Distilled Water Sales Price (USD /gal)	USD 0.10	USD 0.024	USD 0.20
Brine Water Disposal Cost (USD /bbl)	USD 1.75	USD 1.75	USD 1.75
Without Tax Credit			
Annual Tax Credit	USD 0.00	USD 0.00	USD 0.00
Annual Cash Flow	USD 42,993.20	(USD 1,212,634.05)	USD 1,635,565.83
20-Year NPV	(USD 1,546,509.60)	(USD 15,686,300.66)	USD 19,143,127.17
Pay Back Period	-	-	0.80
With Tax Credits (NPV = 0 for the base case)			
Annual Tax Credit	USD 134,831.75	USD 134,831.75	-
Annual Cash Flow	USD 177,824.96	(USD 1,077,802.30)	-
20-Year NPV	USD 0.00	-	-
Pay Back Period	11.95	-	-
With Tax Credits (NPV = 0 for the worst case)			
Annual Tax Credit	USD 1,480,675.81	USD 1,480,675.81	-
Annual Cash Flow	USD 1,523,669.01	USD 268,041.76	-
20-Year NPV	USD 15,436,725.24	USD 0.00	-
Pay Back Period	1.34	11.25	-

Table 7. The Solar-FGRD process cash flows—best case.

Cash Flows				
Year Count	Cash Flow	Present Value	Present Worth Factor	Cumulative Cash Flow
0	(USD 1,239,638.27)	(USD 1,239,638.27)	1	(USD 1,239,638.27)
0	USD 0.00	USD 0.00	1	(USD 1,239,638.27)
1	USD 1,635,565.83	USD 1,557,681.75	0.952380952	USD 395,927.56
2	USD 1,635,565.83	USD 1,483,506.42	0.907029478	USD 2,031,493.40
3	USD 1,635,565.83	USD 1,412,863.26	0.863837599	USD 3,667,059.23
4	USD 1,635,565.83	USD 1,345,584.06	0.822702475	USD 5,302,625.06
5	USD 1,635,565.83	USD 1,281,508.63	0.783526166	USD 6,938,190.90
6	USD 1,635,565.83	USD 1,220,484.41	0.746215397	USD 8,573,756.73
7	USD 1,635,565.83	USD 1,162,366.10	0.71068133	USD 10,209,322.56
8	USD 1,635,565.83	USD 1,107,015.33	0.676839362	USD 11,844,888.39
9	USD 1,635,565.83	USD 1,054,300.32	0.644608916	USD 13,480,454.23
10	USD 1,635,565.83	USD 1,004,095.54	0.613913254	USD 15,116,020.06
11	USD 1,635,565.83	USD 956,281.47	0.584679289	USD 16,751,585.89
12	USD 1,635,565.83	USD 910,744.26	0.556837418	USD 18,387,151.73
13	USD 1,635,565.83	USD 867,375.48	0.530321351	USD 20,022,717.56
14	USD 1,635,565.83	USD 826,071.89	0.505067953	USD 21,658,283.39
15	USD 1,635,565.83	USD 786,735.13	0.481017098	USD 23,293,849.23
16	USD 1,635,565.83	USD 749,271.55	0.458111522	USD 24,929,415.06
17	USD 1,635,565.83	USD 713,591.96	0.436296688	USD 26,564,980.89
18	USD 1,635,565.83	USD 679,611.39	0.415520655	USD 28,200,546.72
19	USD 1,635,565.83	USD 647,248.94	0.395733957	USD 29,836,112.56
20	USD 1,635,565.83	USD 616,427.56	0.376889483	USD 31,471,678.39
NPV		USD 19,143,127.17		
Payback Period		0.80	years	

4.4. Environmental Impacts

The environmental impacts of the Solar-FGRD process are given in terms of greenhouse gases and wastewater streams reduction.

4.4.1. Greenhouse Gases (GHG)

The Solar-FGRD process burner combustion efficiency is 99.8%, in contrast with the typical well-maintained flare combustion efficiency (CE) of 98% (e.g., North Sea) and a CE of 80% observed in the Texas/North Dakota oil and gas fields. [7,8]. With the Solar-FGRD's burner design and well-controlled operating temperatures, DRE of 99.99% can be achieved for methane, ethane, and propane. Table 8 summarizes the speciated greenhouse gas emissions of these three scenarios: Solar-FGRD vs. open-air flaring in the North Sea and the US.

The greenhouse gas (GHG) emissions for CO₂ and unburnt hydrocarbons in terms of CO₂ equivalent (CO₂e) are given in Table 9. CO₂e changes from 2442 metric tons per year (T/yr., North Dakota and Texas, USA) and 1545 T/yr (North Sea) to 1351 T/yr for the Solar-FGRD process. This represents a 45% and 13% CO₂e reduction. Figure 6 shows the methane (line) and CO₂e (column) emissions for the three above-mentioned scenarios.

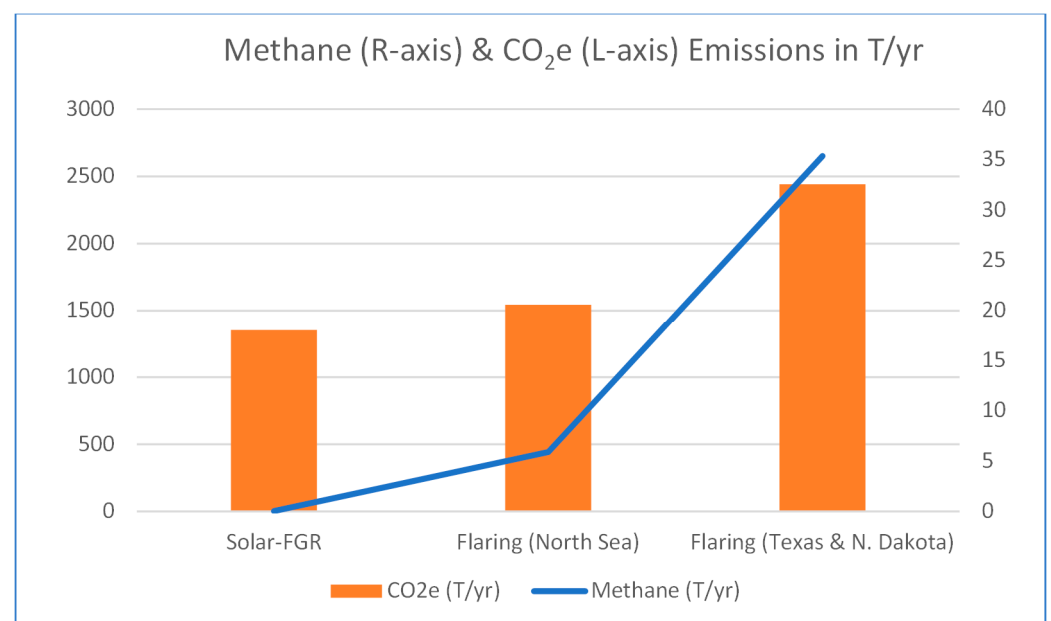
Table 8. Speciated GHG emissions: Solar-FGRD vs. flaring scenarios.

	Produced Water to Potable				Gas Flaring (North Sea)			Gas Flaring (N. Dakota & Texas)			
	IN	OUT	DRE	CO ₂ e	OUT	DRE	CO ₂ e	OUT	DRE	CO ₂ e	100-Y GWP
	lb/h	lb/h		lb/h	lb/h		lb/h	lb/h		lb/h	
Methane	98.9	0.01	0.9999	0.3	1.5	0.99	41.5	8.9	0.91	249.1	28.0
Ethane	37.2	0.00	0.9999	0.0	0.8	0.98	8.0	3.3	0.91	34.1	10.2
Propane	13.6	0.00	0.9999	0.0	0.4	0.97	3.9	1.2	0.91	11.6	9.5
Carbon Dioxide	0.3	339.55	-	339.6	332.2		332.2	273.6		273.6	1.0
Carbon Monoxide	0.0	0.50	-		1.7		3.3	23.0		46.0	2.0
Nitrous Oxide	0.0	0.00	-		0.0			0.0			
Nitric Oxide	0.0	10.61	-		10.6			10.6			
Nitrogen Dioxide	0.0	0.00	-		0.0			0.0			
Total	150.0			339.9			388.8			614.5	
CE		0.998			0.976			0.804			

Table 9. Comparison of methane, carbon dioxide, and CO₂ equivalent for the Solar-FGRD, North Sea flaring, and US flaring.

	Solar-FGRD	Flaring (North Sea)	* Flaring (Texas & N. Dakota)
Methane (T/yr)	0.04	5.89	35.35
CO ₂ (T/yr)	1349.21	1319.81	1087.28
CO ₂ e (T/yr)	1350.52	1545.05	2441.88
% Reduction		13	45

* Flaring data from Texas and North Dakota Fields is used as the baseline.

**Figure 6.** Comparison of methane and GHG (CO₂e) emissions.

4.4.2. Potable Water Recovery and Brine Reduction

The Solar-FGRD process also recovers 77% of produced water as potable water for sale or reuse (Table 10). Without flare gas recovery, 52.2 bbl/h of produced water would need to

be disposed of underground versus 12.1 bbl/h with the Solar-FGRD process. In comparison, the prior FGR-TVG and FGR-ETVG processes reduce brine disposal by 36% [11,13].

Table 10. Water recovery and brine reduction from the Solar-FGRD process.

	IN	OUT	Water Recovery/Brine Reduction
	bbl/h	bbl/h	
Brine/Produced Water	52.2	12.1	76.8%
Potable Water	0	40.1	76.8%

5. Discussion

5.1. Photovoltaic–Thermal Efficiency

In this work, the photovoltaic module recovers ~55% of solar insolation with 15% photovoltaic efficiency for electricity generation, and 40% is recovered as thermal energy to pre-heat the produced water feed. The process eliminates reliance on the power grid for plant operations by generating excess for-sale solar power, which serves as a revenue stream. In theory, the photovoltaic–thermal module can go up to 70–87% depending on the beam splitter, operating temperature, collecting efficiency, etc. [26–29].

5.2. Economic Analysis

As shown in Table 4, the base-case Solar-FGRD process generates USD 1,495,168/yr revenue through sales of potable/distilled water and excess solar electricity. Since the 20-year net present value (NPV) is –USD 1,546,510, a tax credit is required for the base case for the project to be considered feasible to pursue. The annual cash flow is USD 42,993. As shown in Table 5, the NPV at year 20 is negative, and the payback period for the project exceeds 20 years.

Table 6 highlights multiple cases (the base case, worst case, and best case) for consideration. A higher potable water recovery percentage leads to greater revenue, in terms of potable water sales, and lower costs, in terms of third-party brine disposal costs. The financial model in Table 4 assumes a sales price of USD 0.1/gal for distilled water for drinking out of city drinking fountains or bottled consumption. This distilled water sales stream is dependent on demand for an additional volume of water to add to a municipality’s current water supply. It is also likely that this sales price may be discounted if the water stream is used for general tap use at USD 0.024/gal (Current Water and Sewer Rates, 2024), such as for irrigation or cleaning (worst-case scenario), instead of for drinking. For the best-case scenario, the assumed sales price is USD 0.2/gal for distilled drinking water. A market analysis of distilled water in the southwestern USA is being conducted to quantify the risk of receiving a discounted sales price for distilled water intended for drinking.

Depending on project cash flows, revenues, and expenses, tax credits may or may not be needed for project feasibility. The tax credit is not needed for the best-case but has to be provided for the base-case and the worst-case scenarios. For the base case, USD 134,831.75/yr tax credit is provided for the proposed process; this is equivalent to 0.175 cent/kg for water conservation, 0.226 cent/kg for flare gas reduction, or USD 54.3/m²/yr. for solar panel installation.

5.3. Greenhouse Gas Analysis

DRE of 98% for hydrocarbons can be realized for the same light hydrocarbons by flares operated under conditions representative of good industrial operating practices [6]. However, the open-air flaring in oil and gas fields is often unassisted and unattended and often results in a lower DRE. For example, the University of Michigan F3UEL project sampled flares in the Permian Basin, the Eagle Ford Shale, and the Bakken Formations from a Scientific Aviation Mooney aircraft; the DRE of methane was found to be 91% on average. Contributing factors include inefficient flaring (as low as ~60% DRE caused by windy conditions, insufficient air mixing, or malfunction), or even unlit flares (3–5%) [5–7,9].

6. Conclusions

The solar flare gas recovery desalination (Solar-FGRD) process can desalinate pre-treated produced water with TDS between 30,000 and 200,000 mg/L. The process can achieve 76–78% potable water recovery with 0 mg/L TDS, which is a revenue-generating distilled water product for drinking as well as irrigation, cleaning, and household use. As such, it reduces brine disposal volume by 77% (from 52.2 bbl/h to 12.1 bbl/h) compared to Chen et al. and Mazumder et al.'s previous works (36%).

The photovoltaic module recovers ~55% of solar insolation with 15% photovoltaic efficiency for electricity generation and recovers 40% as thermal energy to pre-heat the produced water feed by 35 °F. The process eliminates reliance on the power grid for plant operations by generating excess solar power for sale, which serves as a revenue stream. In theory, the photovoltaic–thermal module can go up to 70–87% depending on the beam splitter, semiconductor, operating temperature, solar collecting efficiency, etc.

The process burner combustion efficiency (CE) is 99.8%, in contrast with the well-maintained flare CE of 98% and some observed flare CE of 80%. In terms of the destruction and removal efficiency (DRE), the FGR burner has 99.99% DRE for light hydrocarbons, such as methane, whereas in flaring, it can vary from $98 \pm 1\%$ for well-maintained flares to ~91% for poorly maintained flares. The greenhouse gas (GHG) emissions for CO₂ and unburnt hydrocarbons (i.e., methane), in terms of CO₂ equivalent (CO₂e), changes from 2442 metric ton per year (T/yr., North Dakota and Texas) or 1545 T/yr (North Sea) to 1351 T/yr for the Solar-FGRD process. This represents a 45% and 13% CO₂e reduction.

The comprehensive base-case financial analysis demonstrates the financial–economic feasibility of the investment project. Best-case and worst-case scenarios provide a realistic range that investors can consider before making investment decisions. The cash flow and payback period are also determined by the capital cost and annual operating cost. Depending on project cash flows, revenues, and expenses, tax credits may or may not be needed for project feasibility. The tax credit is not needed for the best case, which has a payback period of 0.8 year. Tax credit must be provided for the base case and the worst-case scenarios. For the base case, USD 134,831.75/yr tax credit is required at the minimum for the proposed process, with a payback period of 11.95 year.

The theoretical implications of this work are as follows: (1) a framework to recover the flare gas to make use of the plentiful sunshine in the southwest United States or any other sunbelts in the world is provided by the proposed integrated design; (2) it is possible to reduce the carbon footprint, water footprint, and waste disposal at the same time. The practical implications are as follows: (1) the Solar-FGRD system can be profitable if the local potable water, electricity, brine disposal prices, equity-to-loan ratio, and interest rate are favorable (e.g., if the potable water can be sold as bottled water or as indicated in Tables 6 and 7) in comparison to our base case, as detailed in Section 4.3; (2) the Solar-FGRD system can be profitable if adequate carbon, water, and brine waste reduction incentives are provided by the policy makers, as shown in Table 6. The limitations of this design include the following: (1) the proposed design clearly cannot be deployed profitably where the petroleum and solar resources are lacking; (2) the capital and operating costs are based on AspenTech's APEC; these numbers should be double checked with the Chemical Engineering Plant Cost Index (CEPCI), manufacturer catalogs, or actual vendors' quotes. For future research, the solar heating provided by the Solar-FGRD system is relatively small (<1%) in comparison to the flare gas heating. Obviously, the fuel gas flow can be significantly reduced to enhance the use of solar heating in an optimized system. Further, a case study can be performed based on the tax credits provided by the government (e.g., the Inflation Reduction Act in the US) for the reduction of carbon, water, and waste footprints and the utilization of renewable energy.

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ware, validation, visualization, writing—original draft; G.S., funding acquisition, methodology, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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