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**Appendix**

# Appendix: Techno-Economic Modeling of Diverse Renewable Energy Sources Integration: Achieving Net-Zero CO2 Emissions

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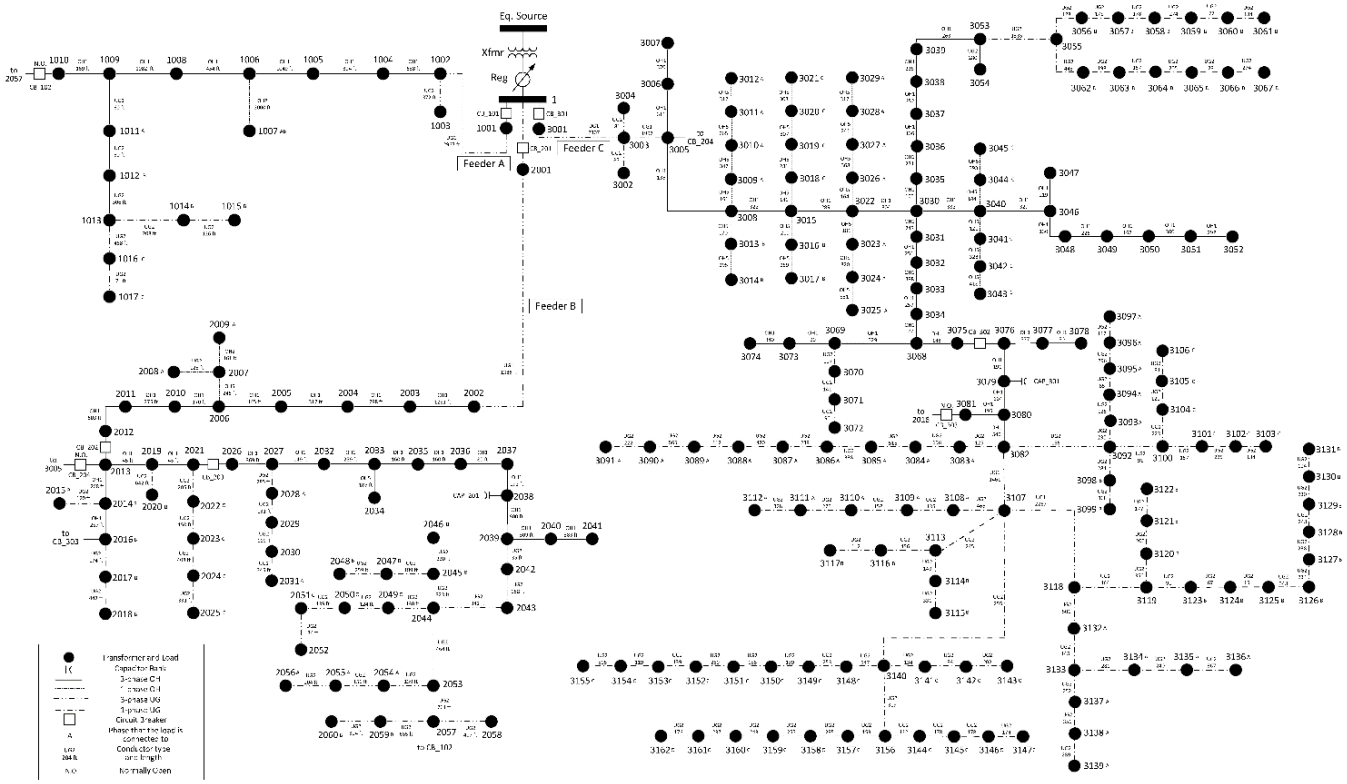


Fig. 1. Single line diagram of the fully observable Iowa 240-Bus power system in the Midwest U.S (Source: Bu F, Yuan Y, Wang Z, Dehghanpour K, Kimber A. A Time-Series Distribution Test System Based on Real Utility Data. 2019 North Am. Power Symp. NAPS, Iowa, USA: Iowa State University; 2019, p. 1–6. https://doi.org/10.1109/NAPS46351.2019.8999982).

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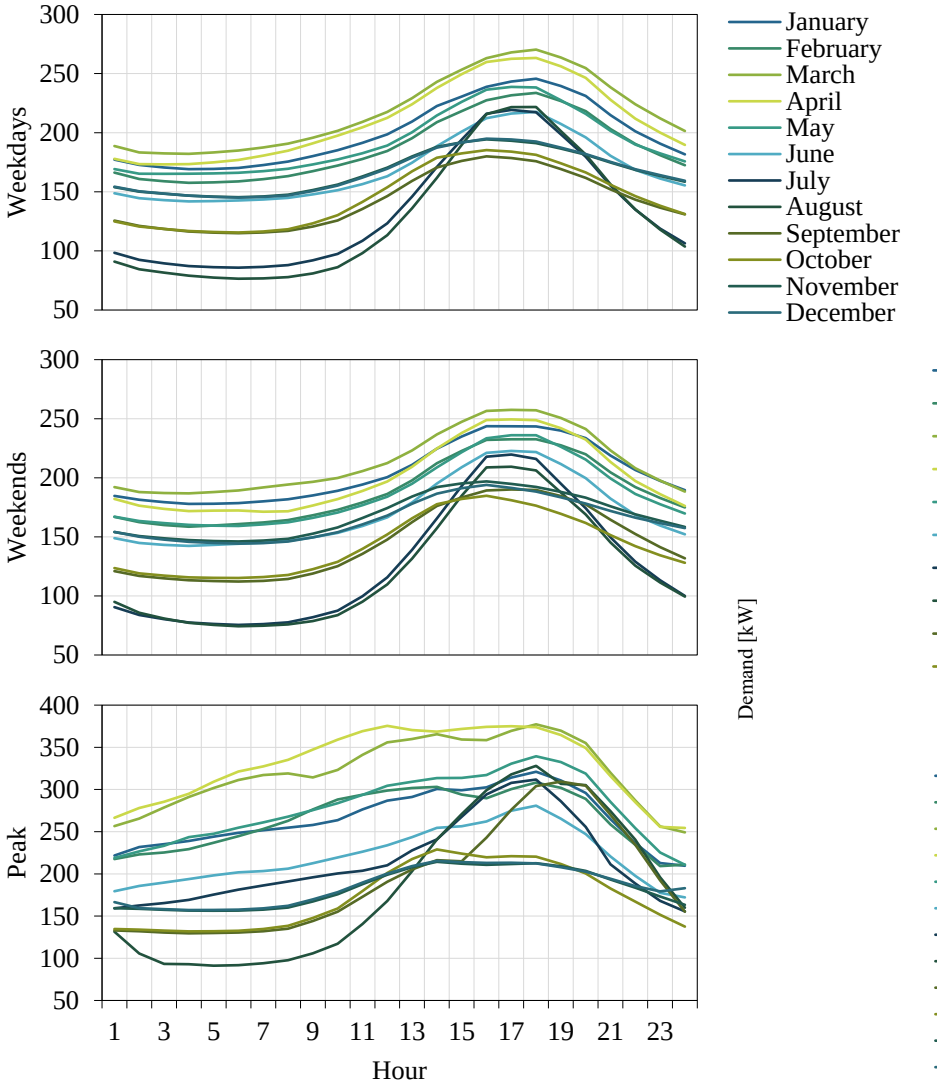


Fig. 2. Load demand profile distinguished by weekdays, weekends, and peak loads.

Table 1. The Case Study Technical and Financial Specifications

| Technical Specifications | |
|---|---|
| Voltage at PCC (Point of common coupling) | 13.8 kV |
| 3-Phase short circuit | 4,000 MVA |
| Voltage operating set point | 1 |
| Annual consumption | 1.5 GWh |
| Peak demand | 377.2 kW |
| Operating capacity percentage | - % |
| Designated amount | - kW |
| Designated amount | - kW |
| Maximum power export | - kW |
| Maximum power import | - kW |
| **Financial Specifications** | |
| Install cost | $10,000 |
| Annual maintenance costs | $2,000 |
| Lifetime | 15 years |

Table 2. Solar Farm Technical and Financial Specifications

| | |
|---|---|
| **Technical Specifications** | |
| Type of panel technology | Standard panel 19% efficiency |
| Array Type | Fixed ground-mounted array |
| System losses | 14.08% |
| Inverter efficiency | - % |
| Array tilt angle | 42.0 ° |
| Pointing | South |
| Solar farm performance kWdcoutput/ kWdcinstalled | Computed data 2.2 km, given in Fig. 4. |
| **Financial Specifications** | |
| Type of panel technology | Standard panel 19% efficiency |
| Array Type | Fixed ground-mounted array |
| System losses | 14.08% |
| Inverter efficiency | - % |
| Array tilt angle | 42.0 ° |
| Pointing | South |
| **Incentives** | |
| Investment tax credit | 30% |
| Amount depreciable | 85% |
| Modified accelerated cost recovery system | 5 years |
| Production tax credit | 0 /kWh |

Table 3. Grid-tied Inverter Technical and Financial Specifications

| | |
|---|---|
| **Connection** | |
| Primary: Utility grid | Secondary: Solar farm |
| **Financial Specifications** | |
| Installation cost per unit | 300 /kW |
| Lifetime | 10 years |
| Fixed monthly maintenance | 0 /kW/month |
| Discrete module size | 1 kW |
| Power Factor | 95% |
| **Incentives** | |
| Investment tax credit | 30% |
| Amount depreciable | 85% |
| Modified accelerated cost recovery system | 5 years |
| Production tax credit | 0 /kWh |

Table 4. Storage System Technical and Financial Specifications

| | |
|---|---|
| **Energy Conversion** | |
| Inverter cost | 250 /kW |
| Power Factor | 95% |
| Charging Efficiency | 90% |
| Charging rate | 0.3 |
| Max SoC | 100% |
| Discharging efficiency | 90% |
| Discharge rate | 0.3 (3.3 Hours duration) |
| Min SoC | 5 |
| Discrete module size | - kWh |
| Maximum annual cycle | - |
| Min annual cycle | - |
| Emergency Min SoC | 5% |
| Reserve SoC | 0% |
| **Storage System** | |
| Installation cost per unit | 300 /kWh |
| Lifetime | 10 years |

| | |
|---|---|
| Fixed monthly maintenance | 546 / kWh / month |
| Fixed install fees | 0 |
| Incentives | |
| Investment tax credit | 30% |
| Amount depreciable | 85% |
| Modified accelerated cost recovery system | 5 years |
| Charge from the utility | 100% |

Table 5. Wind Farm Technical and Financial Specifications

| | |
|---|---|
| Technical Specifications | |
| Model | 100 kW XANT M21 |
| Rated size | 100 kW |
| Hub height | 38 m |
| Power factor | 100% |
| Investment Specifications | |
| Installation cost per unit | 300,000 /Unit |
| Lifetime | 20 years |
| Fixed monthly maintenance | 400 / turbine / month |
| Maintenance of annual variable | 0.015 /kWh / year |
| Incentives | |
| Investment tax credit | 30% |
| Amount depreciable | 0% |
| Modified accelerated cost recovery system | 5 years |
| Production tax credit | 0 /kWh |

Table 6. Fuel Cell Technical and Financial Specifications

| | |
|---|---|
| *Technical Specifications* | |
| *Rated size* | *100 kW* |
| *Nameplate efficiency* | *60%* |
| *Temperature derating* | *100 % (-35 °C to 45 °C)* |
| *Heat-to-power ratio* | *0.3* |
| *Fuel type* | *Hydrogen* |
| *Investment Specifications* | |
| *Installation cost per unit* | *230000 /Unit* |
| *Lifetime* | *20 years* |
| *Fixed monthly maintenance* | *0 /kWh / year* |
| *Runtime maintenance* | *0 /kWh / year* |
| *Maintenance of annual variable* | *0.0185 /kWh / year* |
| *Incentives* | |
| *Investment tax credit* | *30%* |
| *Amount depreciable* | *0%* |
| *Modified accelerated cost recovery system* | *5 years* |
| *Production tax credit* | *0 /kWh* |

Table 7. Hydrogen Energy Technical and Financial Specifications

| | |
|---|---|
| Technical Specifications | |
| Power factor | 100% |
| Nameplate efficiency | 46.6% |
| Type of hydrogen technology | Green |
| Investment Specifications | |
| Installation cost per unit | 32.85 /kg/hour |
| Lifetime | 20 years |
| Fixed installation fee | 0 |
| Fixed monthly maintenance | 0 /kg/month |

| Incentives | |
|---|---|
| Investment tax credit | 0% |
| Amount depreciable | 0% |
| Modified accelerated cost recovery system | - years |
| Production tax credit | 3 /kg |

Table 8. Hydrogen Storage Technical and Financial Specifications

| Technical Specifications | |
|---|---|
| Filling efficiency | 90% |
| Max filling rate | 0.5 |
| Max stored capacity | 100% |
| Emptying efficiency | 90% |
| Max emptying rate | 0.5 (2 hours duration) |
| Min stored capacity | 0% |
| Monthly access fee | 0 |
| Emission factor | 0 kgCO2/kWh |
| Fee | 13.99 /kg |
| Annual limit | - kg |
| Maximum annual cycles | - |
| Min annual cycles | - |
| **Financial Specifications** | |
| Installation cost per unit | 0.5 /kg |
| Lifetime | 30 years |
| Fixed installation fee | 0 |
| Fixed monthly maintenance | 0 /kg/month |

Table 9. Controller Technical and Financial Specifications

| Financial Specifications | |
|---|---|
| Installation cost per unit | 10,000 /Unit |
| Lifetime | 15 years |
| Annual support | 3,000 / year |
| Miscellaneous | 2,000 /Cycle |
| **Financial Specifications** | |
| Investment tax credit | 0% |
| Amount depreciable | 0% |
| Modified accelerated cost recovery system | - years |
| Production tax credit | 3 /kg |

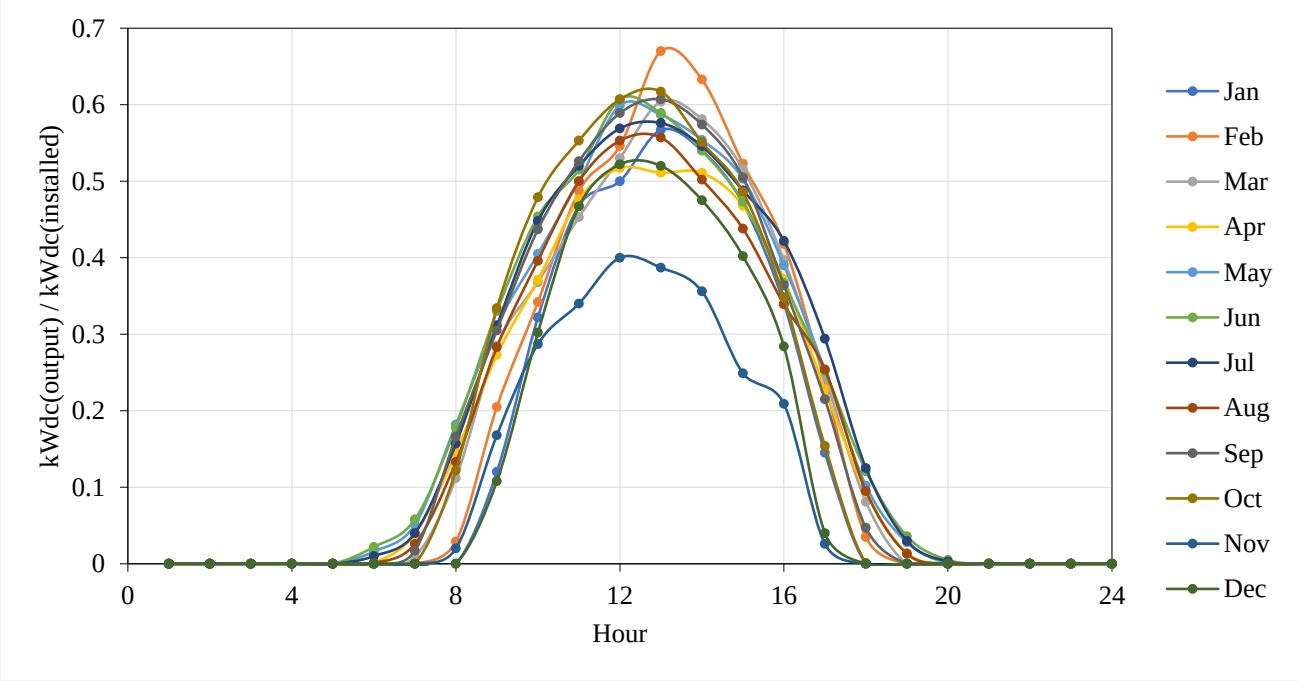


Fig. 3. Performance ratio of solar farm for tracking and benchmarking for forecast validation and economic assessment.

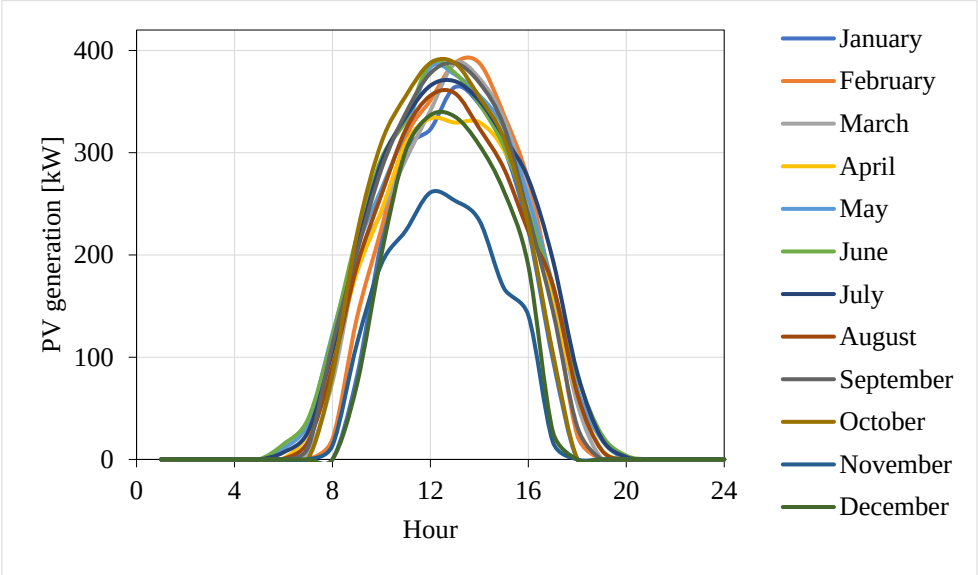


Fig. 4. Seasonal and diurnal variations of solar farm generation.

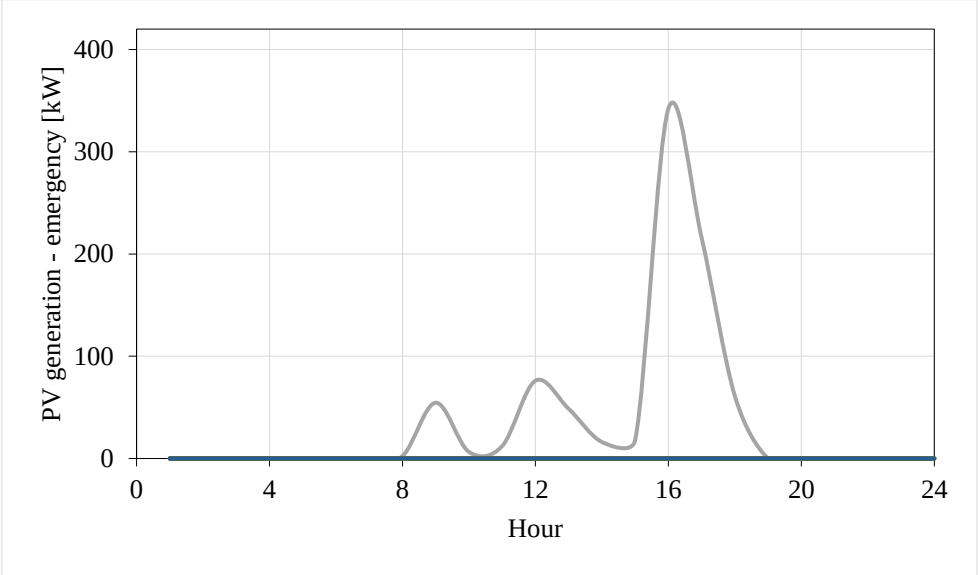


Fig. 5. Solar farm response to sudden load profile changes and resilience requirements in March.

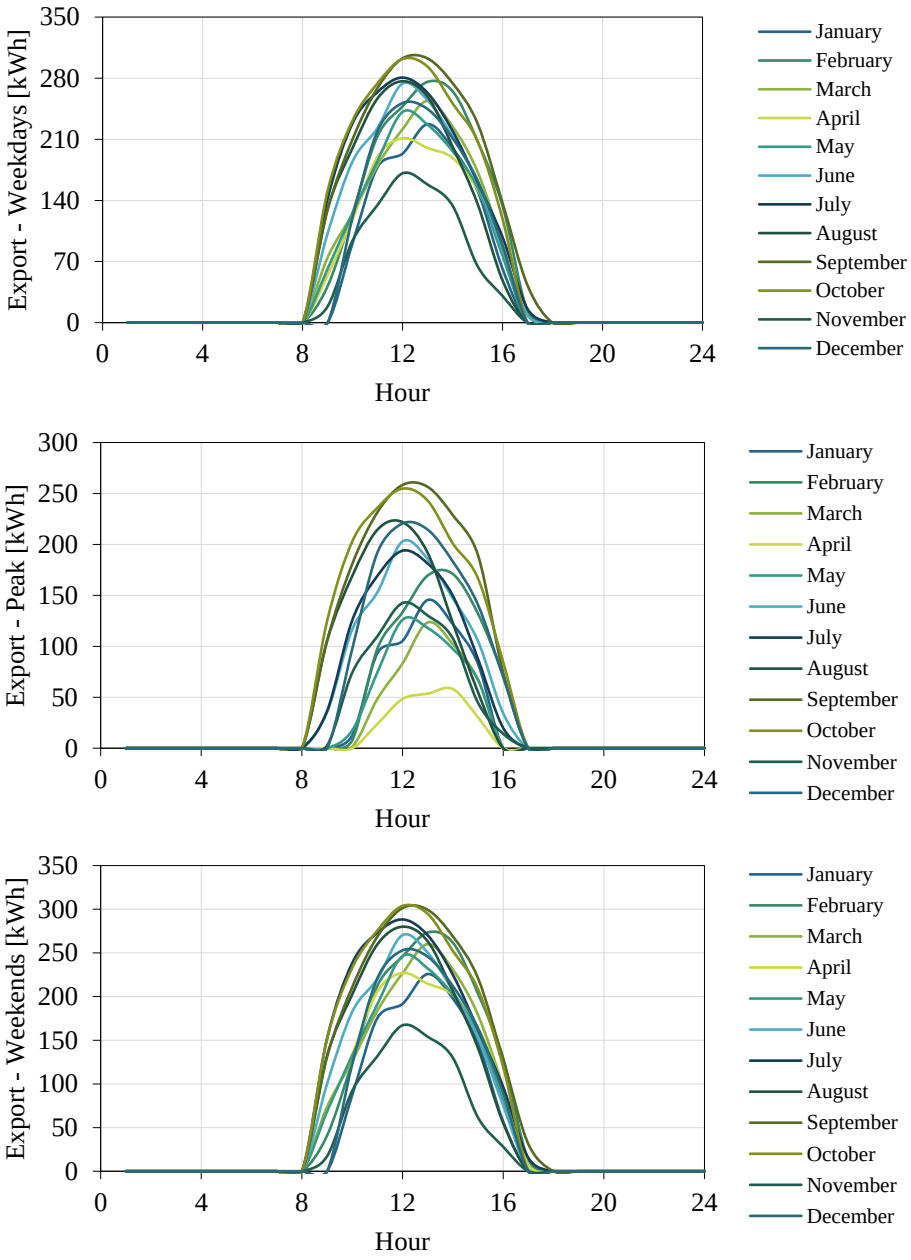


Fig. 6. Daily and seasonal solar farm electricity export patterns by hour, week, and month, demonstrating maximum output during warmer months and consistency between weekdays and weekends.

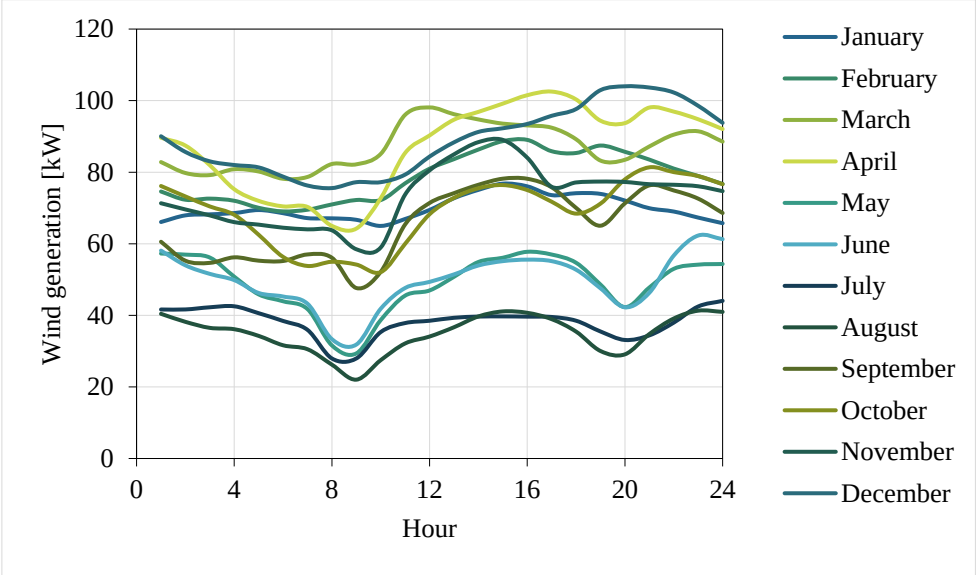


Fig. 7. Monthly and hourly wind farm power generation profile.

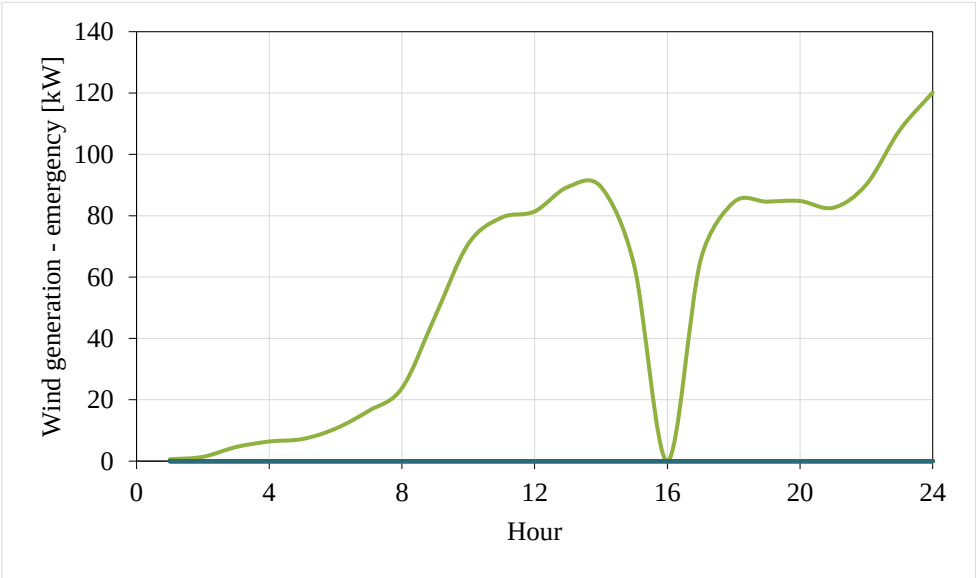


Fig. 8. Emergency response to system load and status changes in March – ensuring resilience and stability of the system.

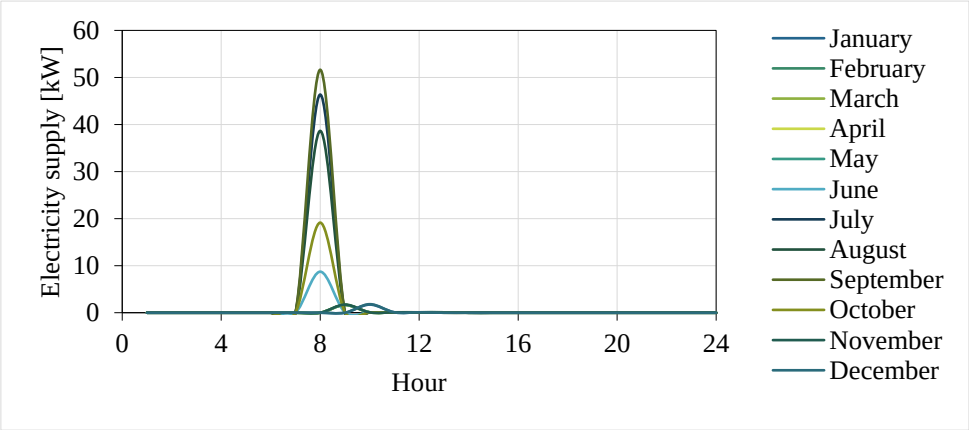


Fig. 9. Monthly and hourly distribution of photovoltaic electricity supply to a hydrogen electrolyzer

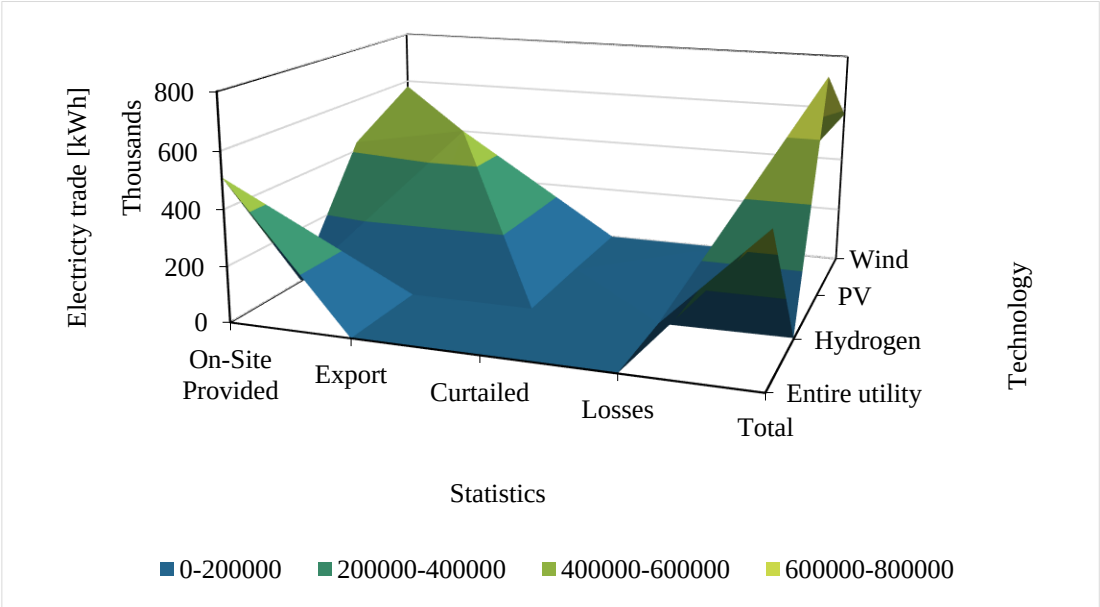


Fig. 10 . Share of multiple energy sources in the power system supply.

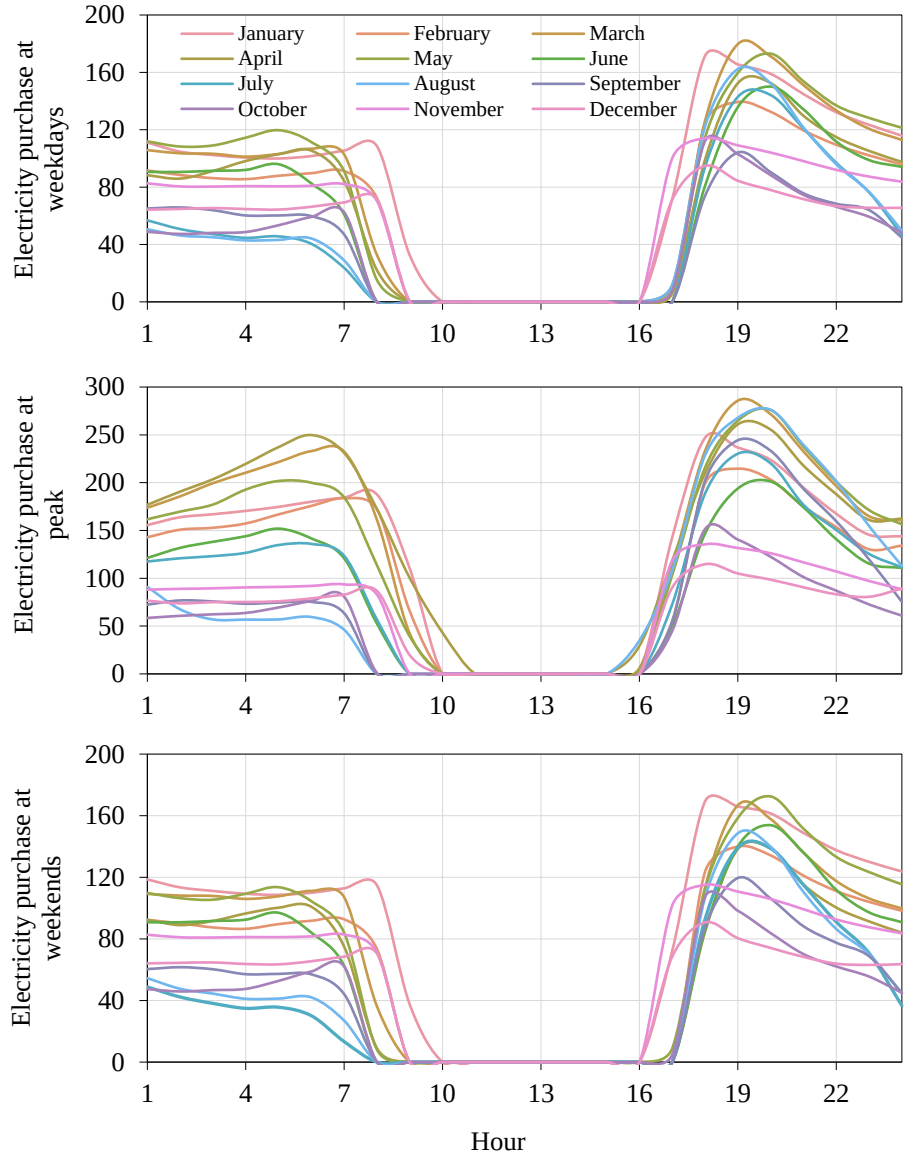


Fig. 11. Analysis of hourly and monthly variations in electricity purchases - highlighting seasonal impact on peak, weekday, and weekend consumption patterns.

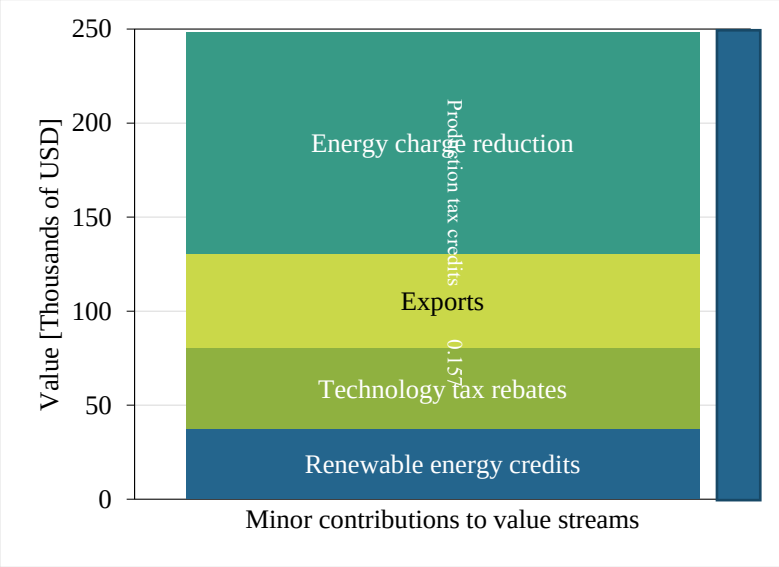


Fig. 12 Distribution of renewable energy financial sources highlighting the predominance of energy charge reductions and exports, supported by technology tax rebates and renewable energy credits.

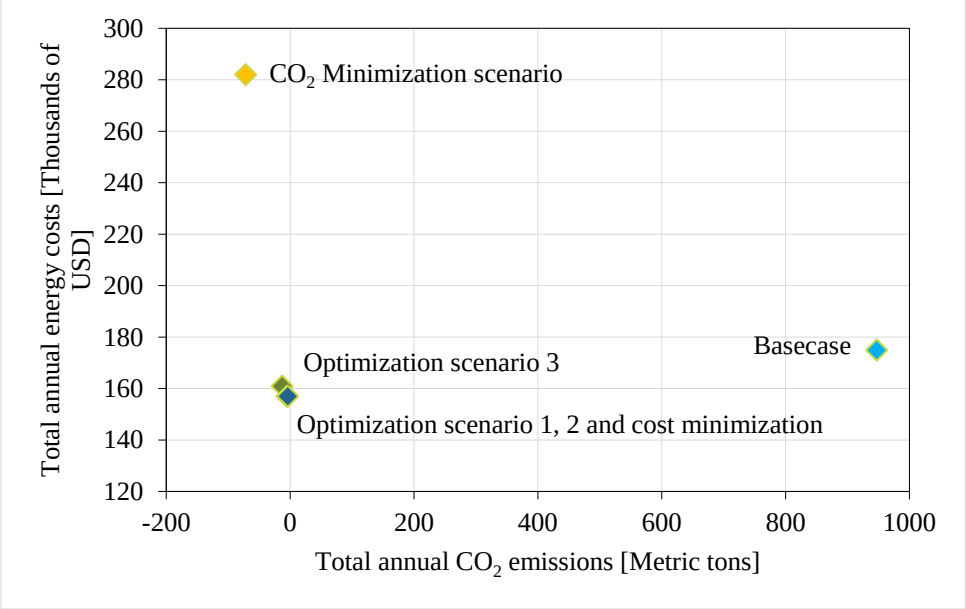


Fig. 13. Comparison of different optimization scenarios, highlighting the alignment of cost minimization, carbon reduction, and system resilience.

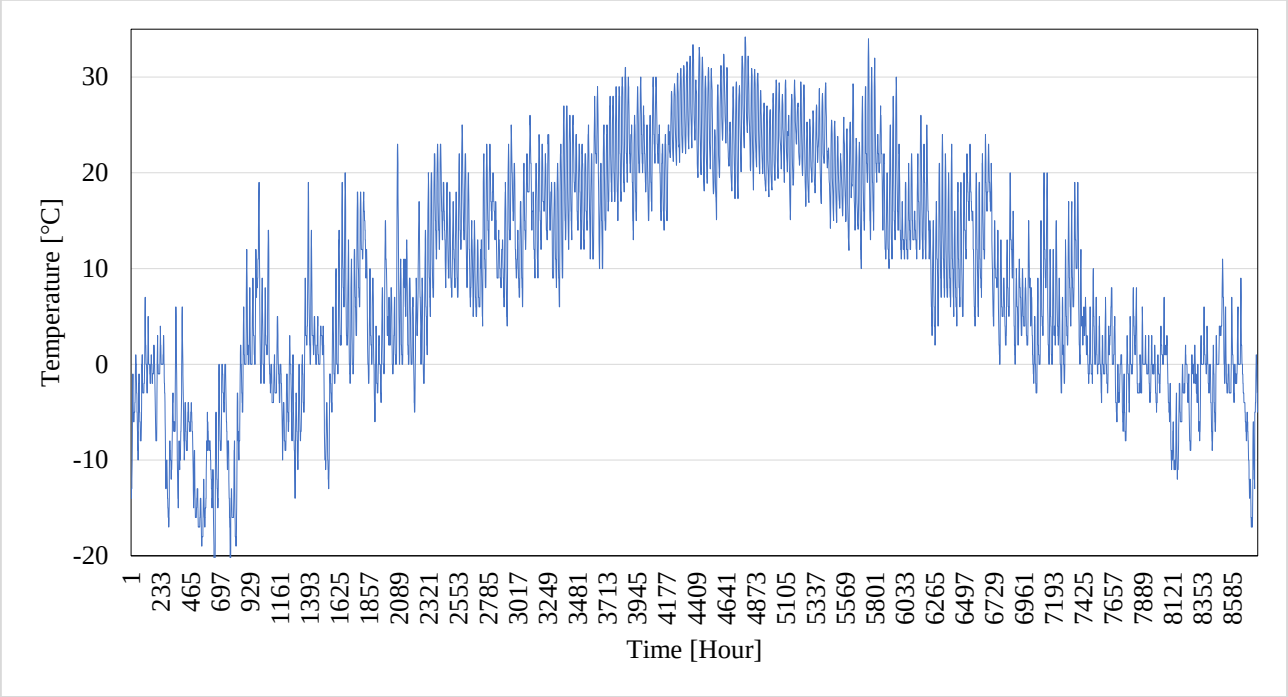


Fig. 14 . Ambient Hourly Temperature of the proposed case study location.

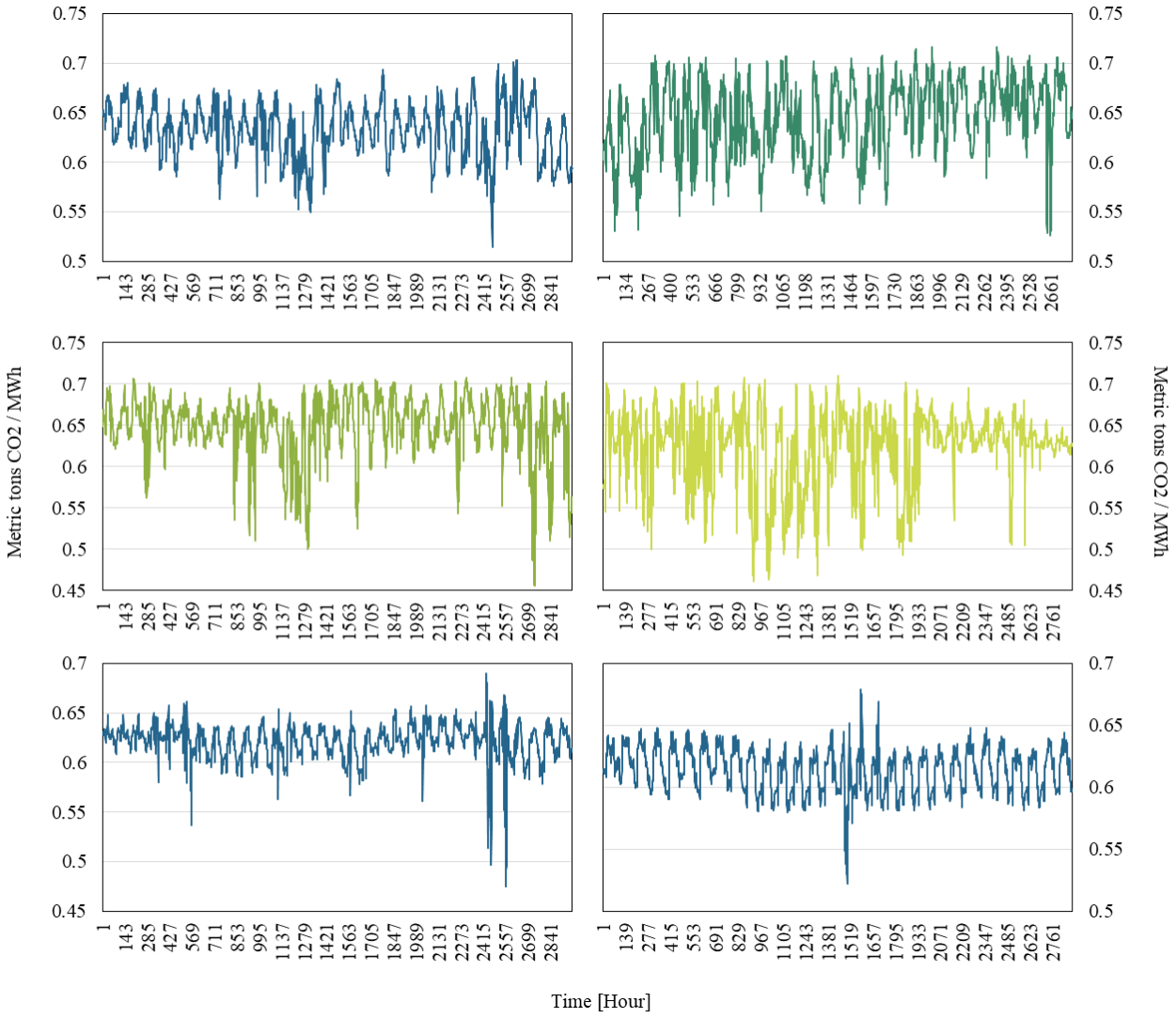


Fig. 15. Marginal $CO_2$ emissions from January to June, respectively.

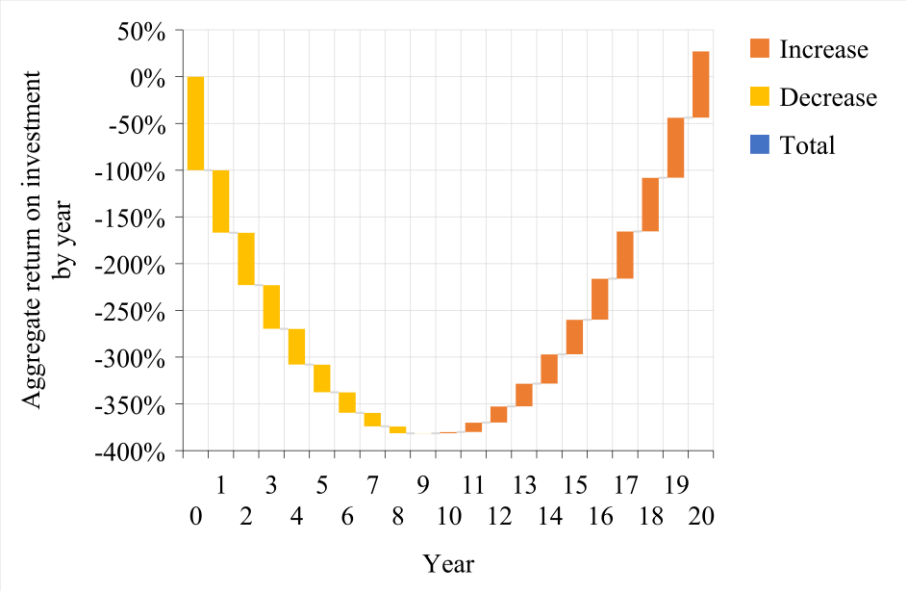


Fig. 16. The 20-year forecast of project's return on investment (ROI) indicating long-term profitability.

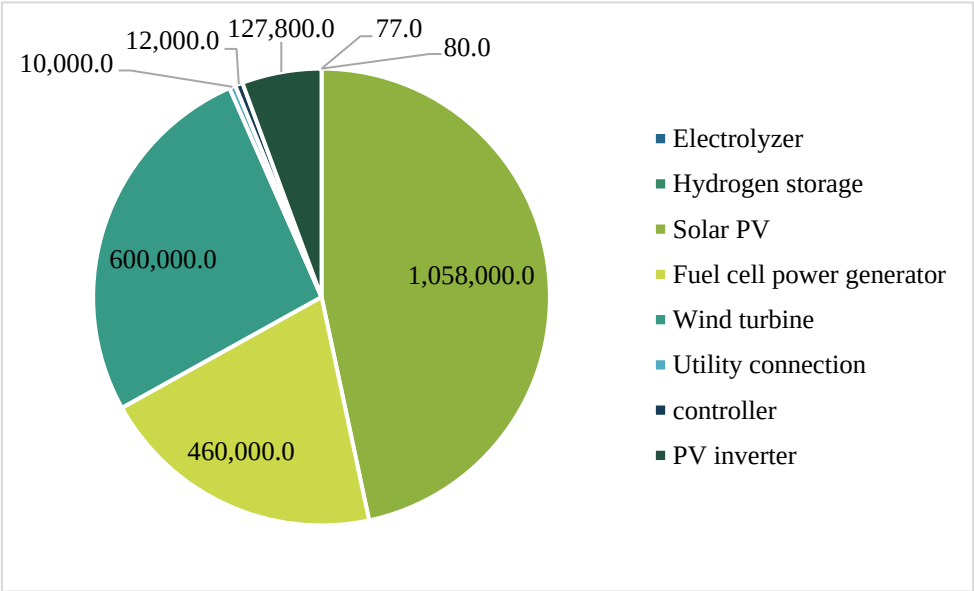


Fig. 17. Distribution of investment costs across various renewable energy system components.

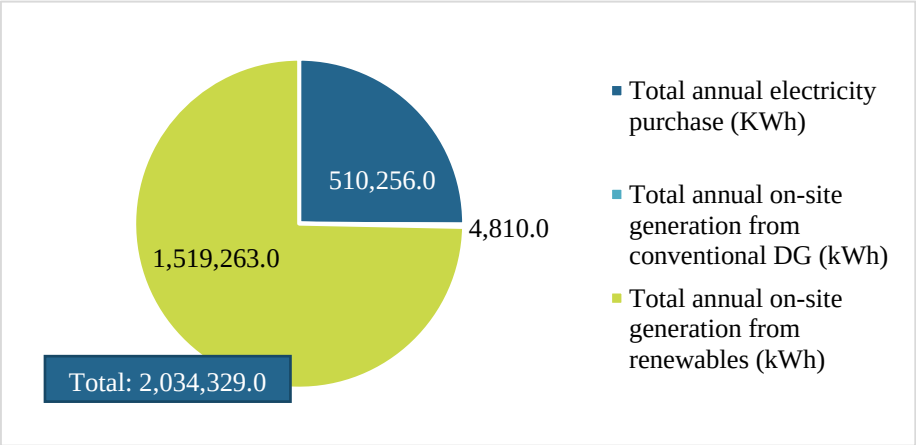


Fig. 18. Energy balancing of contributions from electricity purchases, hydrogen energy, and onsite renewable generation.

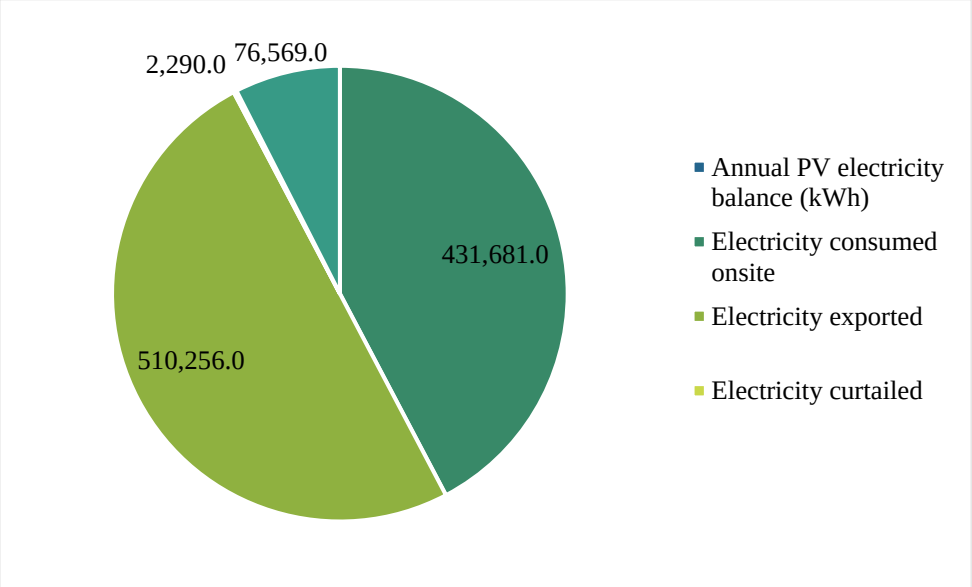


Fig. 19. Annual PV electricity balance of onsite consumption, export, curtailment, and inverter losses.

TABLE 10. Detailed cash flow: Cost (Thousands of USD).

| | Year 0 | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electricity sales | 0 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| Utility energy charges | 0 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 | -57 |
| DER maintenance costs | 0 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 |
| Total OPEX costs | 0 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 | -49 |
| CAPEX for hydrogen electrolyzer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CAPEX for hydrogen storage | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CAPEX for solar farm | 0 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 |
| CAPEX for fuel cell | 0 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 |
| CAPEX for wind farm | 0 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 |
| CAPEX for utility connection | 0 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| CAPEX for controller | 0 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| CAPEX for PV inverter - default | 0 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 |
| Total CAPEX costs | 0 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 |
| Federal ITC credit | 0 | 536 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 38 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Federal MACRS depreciation | 0 | 50 | 81 | 48 | 29 | 29 | 15 | 0 | 0 | 0 | 0 | 5 | 9 | 5 | 3 | 3 | 2 | 0 | 0 | 0 | 0 |
| Renewable energy credits | 0 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 |
| Production tax credits | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total incentives | 0 | 624 | 119 | 86 | 67 | 67 | 53 | 38 | 38 | 38 | 38 | 81 | 46 | 43 | 41 | 41 | 39 | 38 | 38 | 38 | 38 |
| Net annual cost (*Non-discounted*) | 0 | 386 | -119 | -151 | -171 | -171 | -185 | -200 | -200 | -200 | -200 | -156 | -192 | -195 | -197 | -197 | -199 | -200 | -200 | -200 | -200 |
| Cumulative cost (*Non-discounted*) | 0 | 386 | 267 | 116 | -55 | -226 | -411 | -611 | -811 | -1,011 | -1,211 | -1,367 | -1,559 | -1,754 | -1,951 | -2,148 | -2,347 | -2,547 | -2,747 | -2,948 | -3,148 |

TABLE 11. Detailed cash flow: Savings (Thousands of USD).

| | Year 0 | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue increase: electricity sales | 0 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| Savings: utility energy charges | 0 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 | 118 |
| Savings: DER maintenance costs | 0 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 | -42 |
| Total OPEX savings | 0 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 |
| CAPEX difference for hydrogen electrolyzer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CAPEX difference for hydrogen storage | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CAPEX difference for solar farm | 0 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 | -85 |
| CAPEX difference for fuel cell | 0 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 |
| CAPEX difference for wind farm | 0 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 | -48 |
| CAPEX difference for utility connection | 0 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| CAPEX difference for controller | 0 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| CAPEX difference for PV inverter - default | 0 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 | -17 |
| Total CAPEX difference | 0 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 | -189 |
| Federal ITC credit | 0 | 536 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 38 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Federal MACRS depreciation | 0 | 50 | 81 | 48 | 29 | 29 | 15 | 0 | 0 | 0 | 0 | 5 | 9 | 5 | 3 | 3 | 2 | 0 | 0 | 0 | 0 |
| Renewable Energy credits | 0 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 |
| Production tax credits | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total incentives difference | 0 | 624 | 119 | 86 | 67 | 67 | 53 | 38 | 38 | 38 | 38 | 81 | 46 | 43 | 41 | 41 | 39 | 38 | 38 | 38 | 38 |
| Net annual cash flow (*Non-discounted*) | 0 | 562 | 56 | 24 | 5 | 5 | -10 | -24 | -24 | -24 | -24 | 19 | -16 | -20 | -22 | -22 | -23 | -25 | -25 | -25 | -25 |
| Cumulative cash flow (*Non-discounted*) | 0 | 562 | 618 | 642 | 647 | 651 | 641 | 617 | 592 | 568 | 544 | 563 | 546 | 527 | 505 | 483 | 460 | 435 | 411 | 386 | 361 |