Client: Adani Green Energy Limited

Title: Life Cycle Assessment of Solar-Wind Hybrid Electricity

On behalf of Sphera Solutions, Inc., and its subsidiaries

Document prepared by

Arun Shaji
Consultant
AShaji@sphera.com

Ramjee Chaudhary
Associate Consultant
RChaudhary@sphera.com

Quality assurance by

Ritesh Agrawal
Director, Consulting
RAgrawal@sphera.com

Under the supervision of

Dr. Rajesh Kumar Singh
Sr. Director, Consulting
rsingh@sphera.com

Summary

Adani Group is an Indian multinational conglomerate with diversified businesses in key industry verticals like Resources - Coal mining and management; Logistics - Airport operations, Shipping and Rail; Energy - Renewable and Thermal Power Generation, Power Transmission and Distribution; Solar PV Cell and Module Manufacturing as well as Agro Commodities; Defence & Aerospace and other ancillary industries.

Adani Green Energy Limited (AGEL) is one of the largest companies in the field of renewable energy productions in India, with a current project portfolio of 13,990 MW. AGEL, incorporated in 2015 and promoted by Adani Enterprises Ltd., is spearheading the renewable energy initiatives of Adani Group with an operational Solar Project portfolio of 2238 MW and operational Wind projects of 397 MW.

AGEL is committed to a sustainable roadmap in contributing to one of the world's largest renewable energy expansion programmes along with catering to India's Climate Change goals. On 15th October 2019, AGEL became one of the privileged signatories to the United Nations Global Impact. Ever since its inception, AGEL has been constantly striving in the arena of sustainability and proved to be a pace setter with broad strategic planning. One of the reasons for its excellent performance is, indeed, the incorporation of ingenious sustainable approach in all of its operations.

As a contribution to the decarbonisation strategy of India's Power Sector, AGEL has invested in renewable power projects, including the 1,690MW project in Jaisalmer, Rajasthan with a capital outlay of USD ~1.8 billion, funded in collaboration with 12 international banks and through the internal resources of AGEL. AGEL has also recently completed the acquisition of SB Energy, a 5 GW renewable portfolio in India with a capex outlay of USD 3.5 billion. In total, this translates to a USD 5.3 billion in investments in green power and decarbonization, out of its USD 20 billion pledge to invest in green infrastructure.

A Solar-Wind hybrid (390 MW) project is set up in Jaisalmer, Rajasthan and implemented by Adani Hybrid Energy Jaisalmer One Limited (AHEJ1L) which is the subsidiary of AGEL. The Project Company has entered into Power Purchase Agreement (PPA) with Solar Energy Corporation of India (SECI) through a competitive bidding process on 'Build, Own, Operate' basis for the purchase of Solar-Wind hybrid power for a period of 25 years.

AGEL is further interested to evaluate the environmental impacts of the 390 MW Solar-Wind hybrid electricity generation over the entire life cycle from the production of photovoltaic (PV) panels and Wind turbines (raw materials supply, upstream transportation, manufacturing process), Installation and Commissioning, Use including maintenance and End of life stages (decommissioning, downstream transportation, metal recycling and landfill). Thinkstep Sustainability Solutions Pvt Limited, a Sphera company, has been entrusted to carry out the Life Cycle Assessment (LCA) as per ISO 14040/44 standards.

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Methodology

- Goal: To evaluate the environmental impacts of 390 MW Solar-Wind Hybrid Electricity generation in Jaisalmer district of Rajasthan, India
- Scope:
  - System Boundary - Cradle to Grave (over the entire life cycle from the production of PV panels and Wind turbines including raw materials supply, upstream transportation, manufacturing process; Installation and Commissioning; Use including maintenance; and End of Life (EoL) stages covering decommissioning, downstream transportation, metal recycling and landfill)
  - Functional Unit (FU) - 1 MWh of electricity delivered to the grid from Solar-Wind Hybrid project with operational life of 25 years
  - Time Coverage for Data collection - FY 2021-22
- Geographical Coverage - AGEL's 390 MW Solar-Wind Hybrid plant is commissioned in Jaisalmer, India. The Solar project is spread over 1530 acres, whereas Wind turbines cover an area of 115 acres. This site receives the ground level wind speed (predominantly southwest direction) in range 0.9-5.0 m/s. The datasets coverage of this study pertains to the production of Solar PV modules in China and the Wind Turbines in Pune, India.
- Software and database - The LCA model was created using GaBi 10 Software system for life cycle engineering developed by Sphera Solutions Inc. The GaBi 2021 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

Identification of Relevant Findings

This study covered the Cradle to Grave approach for LCA of 1 MWh Solar-Wind Hybrid Electricity generation. The results are shown for life cycle stage-wise as well as for the source-wise. The hotspots are identified at the life cycle stages, component level, source level and finally at the material level.

An overview of the Cradle to Grave LCIA results is given in Table 1.

Table 1: Cradle to Grave LCIA Results for 1 MWh of Solar-Wind Hybrid Electricity Generation

Environmental Indicator	Total	Solar PV System	Wind Turbine System	Installation Phase	Use Phase	EoL Disposal	EoL Credits
Abiotic Depletion (ADP elements) [kg Sb eq.]	6.07E-03 (100%)	6.36E-03 (105%)	2.89E-04 (5%)	7.73E-07 (0%)	3.36E-10 (0%)	8.06E-07 (0%)	-5.89E-04 (-10%)
Abiotic Depletion (ADP fossil) [MJ]	511.89 (100%)	294.81 (57.6%)	245.82 (48%)	8.57 (1.7%)	0.09 (0%)	25.02 (4.9%)	-62.43 (-12%)
Acidification Potential (AP) [kg SO2 eq.]	2.08E-01 (100%)	1.90E-01 (91.3%)	3.17E-02 (15.2%)	1.30E-02 (6.3%)	2.27E-05 (0%)	1.24E-02 (6%)	-3.93E-02 (-19%)
Eutrophication Potential (EP) [kg Phosphate eq.]	1.83E-02 (100%)	1.14E-02 (62.3%)	3.24E-03 (17.7%)	2.98E-03 (16.3%)	1.32E-06 (0%)	2.65E-03 (14.5%)	-2.02E-03 (-11%)
Global Warming Potential (GWP 100 years) [kg CO_2 eq.]	31.54 (100%)	23.24 (73.7%)	8.95 (28.4%)	2.51 (8%)	0.00 (0%)	3.31 (10.5%)	-6.47 (-21%)
Global Warming Potential (GWP 100 years), excluding biogenic carbon [kg CO_2 eq.]	31.53 (100%)	23.32 (74%)	8.96 (28.4%)	2.42 (7.7%)	0.00 (0%)	3.32 (10.5%)	-6.48 (-21%)
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	9.43E-11 (100%)	6.76E-11 (71.7%)	2.04E-11 (21.6%)	2.08E-13 (0.2%)	2.47E-15 (0%)	3.16E-12 (3.4%)	2.96E-12 (3%)
Photochemical Ozone Creation Potential (POCP) [kg Ethene eq.]	5.76E-03 (100%)	5.41E-03 (93.9%)	2.21E-03 (38.4%)	1.17E-03 (20.3%)	1.82E-06 (0%)	-1.08E-03 (-18.8%)	-1.95E-03 (-34%)

Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	606.29 (100%)	382.83 (63.1%)	266.11 (43.9%)	8.97 (1.5%)	0.10 (0%)	26.88 (4.4%)	-78.60 (-13%)
USEtox 2.12, Ecotoxicity (recommended only) [CTUe]	5.15E-02 (100%)	3.54E-02 (68.7%)	1.29E-02 (25%)	2.98E-04 (0.6%)	1.19E-05 (0%)	6.97E-03 (13.5%)	-4.09E-03 (-8%)
USEtox 2.12, Human toxicity, cancer (recommended only) [CTUh]	5.10E-07 (100%)	2.88E-09 (1%)	5.12E-07 (100%)	6.97E-10 (0%)	7.64E-14 (0%)	8.83E-11 (0%)	-4.96E-09 (-1%)
USEtox 2.12, Human toxicity, non-canc. (recommended only) [CTUh]	1.15E-10 (100%)	4.43E-11 (38.5%)	2.45E-11 (21.3%)	5.13E-11 (44.6%)	6.25E-15 (0%)	2.18E-12 (1.9%)	-7.12E-12 (-6%)
Blue water consumption [kg]	309.70 (100%)	127.32 (41.1%)	139.49 (45%)	10.23 (3.3%)	5.60 (2%)	4.61 (1.5%)	22.45 (7%)

Overall LCIA Results across Cradle to Grave

- The total GWP is 31.53 kg CO_2 eq. with major contribution from the Solar PV system (23.3 kg CO_2 eq.) followed by the wind turbine system (8.96 kg CO_2 eq.). This is majorly due to the usage of metal parts, glass and plastics in the manufacturing of the components for Solar PV system and the Wind turbine. Additionally, the emissions due to the usage of electricity and the fuels during the manufacturing of the components is also contributing to the GWP. A credit of 6.47 kg CO2 eq. is taken at the EoL for recycling of metals and, finally the credits for electricity and thermal energy from the incineration of wastes.
- Abiotic Depletion (ADP elements) is 6.07E-03 kg Sb eq. with major contribution from Solar PV system (6.36E-03 kg Sb eq.) followed by Wind Turbine system (2.88E-04 kg Sb eq.). This is due to the usage of metals in the fabrication of the solar PV and the wind turbine. A credit of 5.89E-04kg Sb eq. is taken at the EoL for recycling of metals and, finally the credits for electricity and thermal energy from the incineration wastes.
- Abiotic Depletion (ADP fossil) is 511.89 MJ with major contribution from solar PV system (295 MJ) followed by Wind Turbine system (239 MJ). This is due to the usage of fossil fuels in the production of the solar PV modules and the wind turbine. A credit of 62.43 MJ is taken at the EoL for recycling of metals and, finally the credits for electricity and thermal energy from the incineration wastes.
- Acidification Potential (AP) is 2.08E-01 kg SO_2 eq. with major contribution from Solar PV system (1.90E-01 kg SO_2 eq.) followed by Wind Turbine system (3.14E-02 kg SO_2 eq.). This is due to SO_X and NO_X emissions during the manufacturing. A credit of 3.93E-02 kg SO2 eq. is taken at the EoL for recycling of metals and, finally the credits for electricity and thermal energy from the incineration wastes.
- Photochemical Ozone Creation Potential (POCP) is 5.76E-03 kg Ethene eq. with major contribution from the solar PV system (5.41E-03 kg Ethene eq.) followed by the wind turbine system (1.97E-03 kg Ethene eq.). A credit of 1.95E-03 kg Ethene eq. is taken at the EoL for recycling of metals and, finally the credits for electricity and thermal energy from the incineration wastes.
- Primary Energy Demand from ren. and non-ren. Resources (net calorific value) is 606.29 MJ with major contribution from Solar PV system (383 MJ) followed by Wind Turbine system (260 MJ). A credit of 78.60 MJ is taken at the EoL for recycling of metals and, finally the credits for electricity and thermal energy from the incineration wastes.
- Blue water consumption is 309.70 kg with major contribution from Solar PV system (127 kg) followed by Wind Turbine system (139.49 kg).

LCIA Results excluding EoL

- The total GWP is 34.7 kg CO_2 eq., the major contributor is the Solar PV modules used in the facility (21 kgCO_2 eq.) followed by the wind turbine system (8.27 kg CO_2 eq.). This is majorly due to the usage of metal parts, glass, and plastics in the manufacturing of the components of solar PV modules and wind turbines. Additionally, emissions due to the usage of electricity and fuels during the manufacturing of the components is also contributing to GWP.
- Abiotic Depletion (ADP elements) is 6.65E-03 kg Sb eq. with major contribution from Solar PV modules (5.93E-03 kg Sb eq.). This is due to the glass, metals and plastics used in the PV modules manufacturing.

- Abiotic Depletion (ADP fossil) is 549.29 MJ with major contribution from the solar PV modules (261.37 MJ) followed by the wind turbine system (236.65 MJ). This is due to the usage of fossil fuels in the production of the solar PV modules and the wind turbine.
- Acidification Potential (AP) is 2.34E-01 kg SO_2 eq. with major contribution from the solar PV modules (1.70E-01 kg SO_2 eq.). This is due to the SOX and NOX emissions during the manufacturing.
- Photochemical Ozone Creation Potential (POCP) is 8.79E-03 kg Ethene eq. with the major contribution from the solar PV modules (4.81E-03 kg Ethene eq.). This is due to the VOC emissions during the PV modules manufacturing.
- Primary Energy Demand from ren. and non-ren. Resources (net calorific value) is 658.00 MJ with major contribution from Solar PV modules (342.34 MJ) followed by Wind Turbine system (256.89 MJ).
- Blue water consumption is 282.64 kg with major contribution from the wind turbine system (139.42 kg) followed by the solar PV system (109.77 kg).

Source Wise LCIA Results for Solar PV System

- The total GWP is 23.32 kg CO_2 eq., the major contributor is the Solar PV system is the fuel/energy requirement (13.35 kgCO_2 eq.) followed by the raw materials (8.91 kg CO_2 eq.). The impact from the raw materials is majorly due to the usage of metal parts, glass, and plastics in the manufacturing of solar PV system components. Additionally, the emissions due to the usage of electricity and the fuels during the manufacturing of the components is also contributing to the GWP.
- Abiotic Depletion (ADP elements) is 6.36E-03 kg Sb eq. with major contribution from the raw materials. This is due to the glass, metals, and plastics during the manufacturing of solar PV system components.
- Abiotic Depletion (ADP fossil) is 294.81 MJ with major contribution from the fuel/energy requirement (164 MJ) followed by the raw materials (118 MJ). This is due to the usage of fossil fuels the manufacturing of solar PV system components.
- Acidification Potential (AP) is 1.90E-01 kg SO_2 eq. with major contribution from the fuel/energy requirement (9.66E-02 kg SO_2 eq.) followed by the raw materials (8.37E-02 kg SO_2 eq.). This is due to the SO_X and NO_X emissions during the manufacturing of solar PV system components.
- Photochemical Ozone Creation Potential (POCP) is 5.41E-03 kg Ethene eq. with the major contribution from the fuel/energy requirement (4.88E-03 kg Ethene eq.). This is due to the VOC emissions during the components of the solar PV system manufacturing.
- Primary Energy Demand from ren. and non-ren. Resources (net calorific value) is 382.83 MJ with major contribution from fuel/energy requirement (203.72 MJ) followed by raw materials (165.33 MJ).
- Blue water consumption is 127.04 kg with major contribution from the raw materials.

Considering the Solar PV system, majority of GWP impacts from raw materials are from PV modules (7.28 kg CO_2 eq.). The contributions from raw materials for Mono PV, Multi PV and Thin Film (CdTe) are 2.68 kg CO_2 eq. (Figure 1(a)), 2.69 kg CO_2 eq. and 1.91 kg CO_2 eq. (Figure 1(b)) respectively. For Mono and Multi PV modules, the aluminium extrusion profile followed by the glass are the hotspots in the raw materials. In case of Thin Film (CdTe) PV modules, float flat glass is the hotspot in the raw materials.

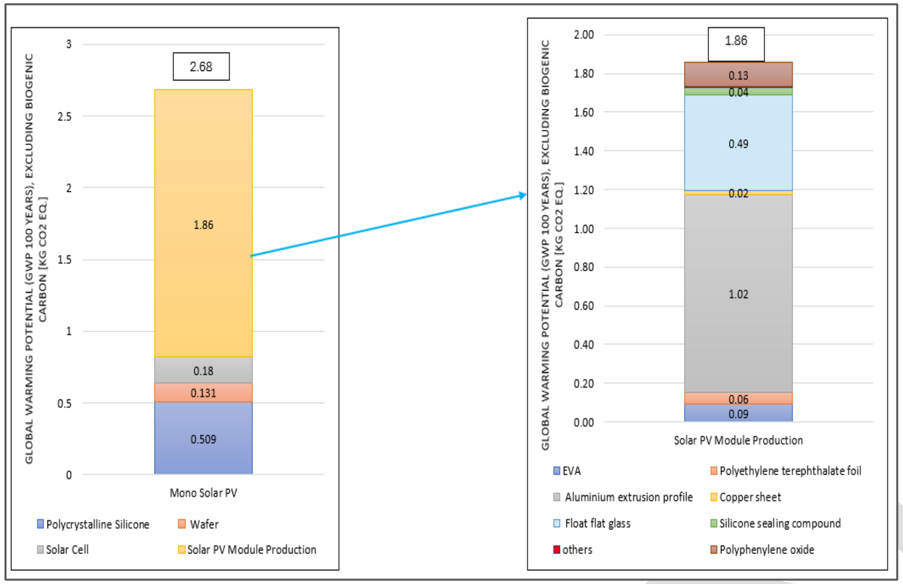

Figure 1(a): Detailed break-up for GWP of raw materials for Mono Solar PV module

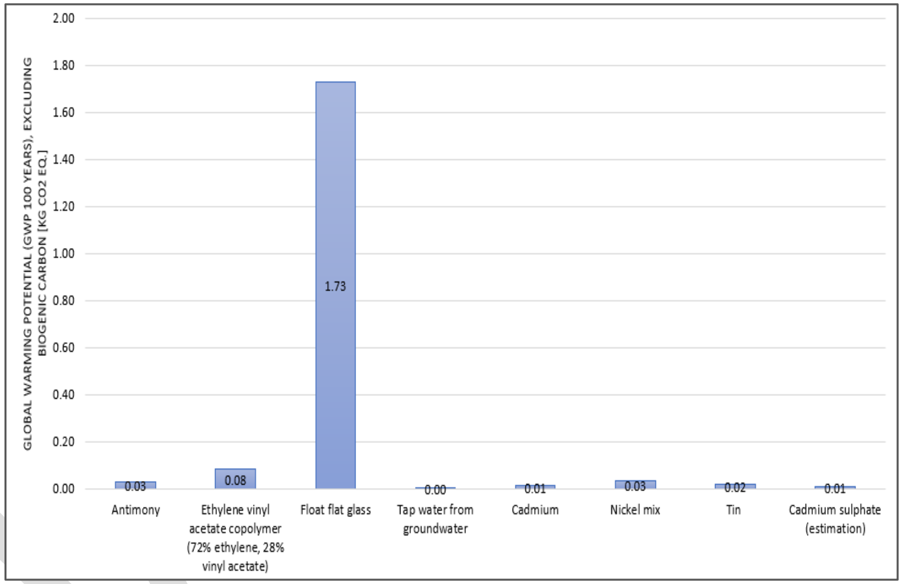

Figure 1(b): Detailed break-up for GWP of raw materials for Thin Film (CdTe) PV module

Source Wise LCIA Results for Wind Turbine System

- The total GWP is 8.96 kg CO_2 eq., the major contributor is the raw materials (6.72 kg CO_2 eq.) followed by the fuel/energy requirement (1.56 kg CO_2 eq.). The impact from the raw materials is majorly due to the usage of metal parts, glass, and plastics in the manufacturing of the components solar PV modules. Additionally, the emissions due to the usage of electricity and the fuels during the manufacturing of the components is also contributing to the GWP.
- Abiotic Depletion (ADP elements) is 2.89E-04 kg Sb eq. with major contribution from the raw materials (2.89E-04 kg Sb eq.). This is due to the glass, metals, and plastics during the manufacturing of wind turbine system components.
- Abiotic Depletion (ADP fossil) is 245.82 MJ with major contribution from the fuel/energy requirement (141.56 MJ) followed by the raw materials (95.09 MJ). This is due to the usage of fossil fuels during the manufacturing of wind turbine system components.
- Acidification Potential (AP) is 3.17E-02 kg SO_2 eq. with major contribution from the raw materials (2.41E-02 kg SO_2 eq.) followed by the fuel/energy requirement (2.57E-03 kg SO_2 eq.). This is due to the SO_X and NO_X emissions during the manufacturing of wind turbine system components.
- Photochemical Ozone Creation Potential (POCP) is 2.21E-03 kg Ethene eq. with the major contribution from the raw materials (2.33E-03 kg Ethene eq.). This is due to the VOC emissions during the manufacturing of wind turbine system components.
- Primary Energy Demand from ren. and non-ren. Resources (net calorific value) is 266.11 MJ with major contribution from fuel/energy requirement (145.04 MJ) followed by raw materials (111.84 MJ).
- Blue water consumption is 139.49 kg with major contribution from the raw materials (136.82).

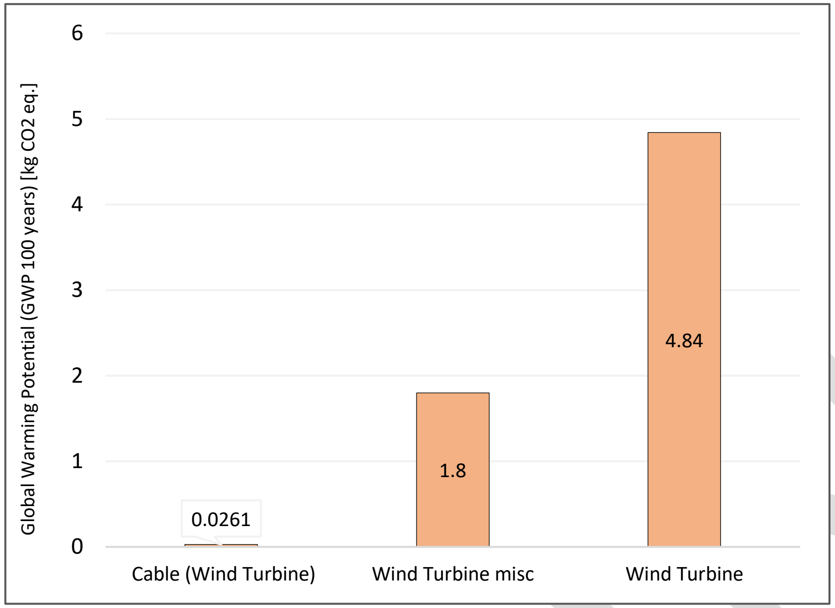

Figure 2(a): Detailed break-up of GWP of raw materials for Wind Turbine System

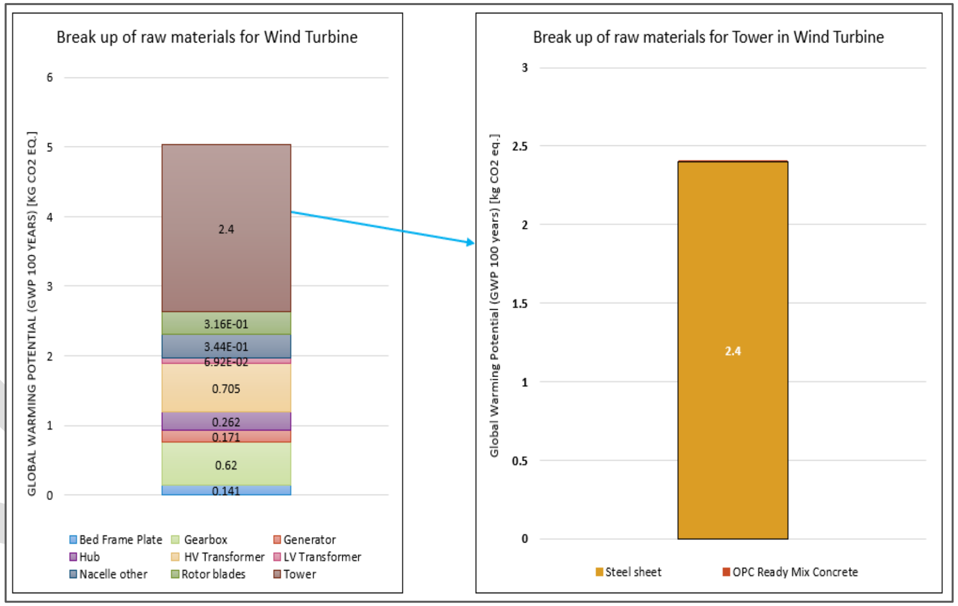

Figure 2(b): Detailed break-up for GWP of raw materials for Wind Turbine and Tower

Figures 2(a) and 2(b) show the further break up of GWP of raw materials consumed in Wind Turbine system. Steel sheet used in Tower is the major GWP hotspot. The contribution of the OPC ready mix concrete is very negligible.

Benchmarking GWP Results

As per EU Taxonomy's 100g emissions threshold[1] for a power plant operating below 100g CO_2 eq./kWh over its lifetime is making a substantial contribution to reaching Paris Agreement targets. The overall GWP value of the AGEL Solar -Wind Hybrid facility is 30.2g CO_2 eq./kWh of electricity generation. A comparison of AGEL Solar-Wind Hybrid facility with other similar technologies for Solar-based and Wind-based electricity generation is given in Table 2 for the purpose of benchmarking carbon footprints.

[1]In March 2020, the EU Technical Expert Group on Sustainable Finance (TEG) published its recommendations for an EU Taxonomy for Sustainable Activities. A key feature of the recommendations around electricity generation was a "substantial contribution" emissions threshold of 100g CO2 eq./kWh. It's the limit on the intensity of greenhouse gas (GHG) emissions produced from the generation of electricity, heat and power from hydropower, geothermal energy or gaseous and liquid fuels. A power plant operating below 100g CO2 eq./kWh over its lifetime is making a substantial contribution to reaching Paris Agreement targets. *EUTaxonomy_100g_7points.pdf (ecostandard.org)*

Table 2: Comparison of Carbon Footprints for different electricity generation technologies

Electricity generation technology	Carbon footprint ($g\ CO_2$-eq./kWh)	Reference
Solar PV	20-81	M.J.(Mariska) de Wild-Scholten (2013)
	31.5-41.8	Kim et al. (2013)
	60.1-87.3	Hou et al. (2015)
Wind Turbine	5.1	VESTAS LCA Study[2]
Solar-Wind Hybrid (AGEL)	30.2	AGEL

Conclusion

This study establishes the baseline environmental impacts for generation of 1 MWh Solar-Wind hybrid electricity from 390 MW plant commissioned by AGEL in Jaisalmer district of Rajasthan, India. The hotspots are identified at the life cycle stages- component level, source level and finally at the material level. Across the various life cycle stages, the major contributor to GWP is manufacturing of Solar PV system followed by Wind turbine system. In Solar PV system, photovoltaic (PV) modules i.e., Thin Film (CdTe), mono crystalline and multi crystalline PVs contribute to GWP. For Thin Film PV, float flat glass is hotspot for GWP in the raw materials category. For Multi and Mono PV modules, aluminium extrusion profile followed by glass are major contributors to GWP. Additionally, the usage of electricity and fuel source (Thermal energy) for the fabrication of PV modules are also contributing to GWP. For the Wind turbine system, main components of Wind Turbine are major contributors to GWP. Among the main components, the tower is the major contributor GWP. In the tower, steel is contributing majorly to GWP.

[2]*https://www.vestas.com/content/dam/vestas-com/global/en/sustainability/reports-and-ratings/lcas/0075-0998_V01%20-%20LCA%20of%20Electricity%20Production%20from%20an%20onshore%20V116-2.0%20MW%20Wind%20Plant_120718_v1.1.pdf.coredownload.inline.pdf*