International Hydrogen Ramp-up Programme – H2Uppp

Site Scoping of Renewables for Green Hydrogen Production in India

GIS mapping for development of RE with high profile complementarity

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Executive Summary 1

1 Introduction 2

1.1 Context 2

1.2 Goals and objectives 2

2 Methodology 3

2.1 General overview of the GIS methodology 3

2.1.1 Source data 3

2.1.2 Wind farm and solar park modelling 4

2.1.3 Project Opportunity Area (POA) grid 5

2.1.4 Multi-criteria analysis 6

2.2 POA attributes 7

2.2.1 Land availability factor 7

2.2.2 Average electricity generation 7

2.2.3 The Levelised Cost of Electricity (LCOE) 8

2.2.4 Distance to existing plants 11

2.2.5 Land preference 13

2.2.6 Slope gradient 15

2.2.7 Complementarity score (Wind) 16

2.3 Multi-criteria analysis of attributes 17

2.3.1 Definition of the main criteria 17

2.3.2 Pairwise comparison 18

2.3.3 Criterion weight computation 18

2.3.4 Wind AHP matrix 18

2.3.5 Solar AHP matrix 20

2.4 Constraint analysis for the land availability factor 21

2.4.1 Land cover 21

2.4.2 Elevation 22

2.4.3 Slope gradient 23

2.4.4 Surface water 23

2.4.5 Protected nature 23

2.4.6 Protected heritage 23

2.4.7 Airports 23

2.4.8 Existing plants (optional) 23

2.4.9 Combined constraint layers 24

2.4.10 Land availability factor 24

3 Results 26

3.1 POA Attributes 26

3.1.1 Average electricity generation 26

3.1.2 The Levelised Cost of Electricity (LCOE) 26

3.1.3 Distance to existing plants map 26

3.1.4 Land preference 26

3.1.5 Slope gradient 27

3.1.6 Complementarity score (Wind) 27
3.1.7 Land availability 27

3.2 POA score 28
3.2.1 Wind farms 28
3.2.2 PV 29

4 Conclusion 30

Tables

Table 1: Sourced geodata for the analysis 3
Table 2: IEC class 3 operating conditions 5
Table 3: Sourced geodata for the electricity 7
Table 4: Sourced geodata for the LCOE analysis 9
Table 5: LCOE computation parameters 11
Table 6: Sourced geodata for the proximity analysis to existing wind farms and solar parks 11
Table 7: Scoring of proximity to existing solar parks and wind farms 12
Table 8: Sourced geodata for the land preference analysis 13
Table 9: Scoring and weight of the land cover classes in the land preference attribute 14
Table 10: Land scoring based on proximity to infrastructure and its weight in the land preference attribute 14
Table 11: Sourced geodata for the slope attribute 15
Table 12: Scoring of the slope gradient per technology 15
Table 13: Random coherence index 18
Table 14: Wind AHP matrix 19
Table 15: Wind criteria weights and coherence ratio 19
Table 16: Solar AHP matrix 20
Table 17: Solar criteria weights and coherence ratio 20
Table 19: Geodata considered in the constraint analysis 21
Table 20: Sentinel-2 land cover classification 22

Figures

Figure 1: Grid of "Project Opportunity Areas" (25 km²) covering mainland India 5
Figure 2: Summary of the methodology used for site selection 6
Figure 3: Correlated wind and solar profiles 16
Figure 4: Uncorrelated wind and solar profiles 17
Figure 5: Pie chart illustrating the relative weight assigned to each POA attribute for wind projects. 19
Figure 6: Diagram of the weight assigned to each POA attribute for PV projects 20
Figure 7: Summarized constraint mask (spatial resolution of 500m) for wind projects, considering the criteria of terrain, protected areas and existing wind and PV plants. Black denotes excluded areas. 25
Figure 8: POA site suitability score distribution in India for wind farms (225 MW capacity) 28
Figure 9: POA site suitability score distribution in India for solar parks (750 MW capacity) 29

Executive Summary

In the global effort to reduce CO_2 emissions, India, being the most populated country, has a major role to play and strong renewable energy sources to rely on. These energies can be used to produce H_2 and its derivatives, among which methanol is foreseen to have a large variety of applications in the global energy transition for a local and export market.

This study is part of a pre-feasibility study that analyses the case of designing a 100% export-oriented green methanol production plant for the EU market. In this report, the most suitable locations of new wind and solar farms fitting the expected capacity of 1.5 GW to 1.75 GW are studied across the country. The framework of this project is further developed in Section 1.

To define these locations, as detailed in Section 2, the methodology divides the country into project opportunity areas (POA) which are each given a preference score. This allows to rank the best area in the country for development of wind or solar farms. The following steps have been taken:

- Country-wide Geographic Information System (GIS) data representing site suitability factors such as land use, orography, etc. was collected, processed and presented onto a uniform geographical projection and spatial resolution
- A typical wind turbine and PV plant configuration was selected as most suitable on a country level
- A POA size was defined that fits the targeted installed renewable energy capacity for the project
- Attributes to be evaluated per POA were identified. These attributes are meant to allow evaluating each POA with respect to one another
- An analytical hierarchical process matrix was elaborated for renewable sources, to give preference weights to the attributes in order to rank the different POA
- A constraint layer was created to mask the unavailable area out of the POA

The outcomes of this analysis are given in Section 3. It appears that high-score areas for wind plants are more localised geographically than for solar plants. The wind resource is relatively low even in favourably identified zones while the solar resource has a higher potential for electricity generation, lowering its levelised cost of energy (LCOE). In both cases, the most favourable regions are the northwestern states (Gujarat, Maharashtra and Rajasthan) with resource and land availability being the main drivers in terms of LCOE. This regional cross-technology overlap of high-scoring POAs provides a good opportunity to combine both technologies in those regions.

These high potential renewable sites are geographically distant from the proposed green methanol production facility in the state of Odisha. Nevertheless, although this is yet to be ascertained and confirmed as of June 2026, they might remain eligible under the European regulatory framework for renewable fuels of non-biological origin (RFNBOs), as India is operated as a single, nationally integrated electricity grid and EU legislation does not require a physical electricity flow between renewable generation assets and hydrogen (or derivative) production facilities, provided that the applicable conditions on temporal and geographical correlation are met. The results are to be used for comparative rather than quantitative basis pertaining to the uncertainties inherent to the datasets used and assumptions made.

1 Introduction

1.1 Context

The vision for India's Green Hydrogen Economy was set on 15th August 2021 (75th Independence Day) with the launch of the National Hydrogen Mission by the Prime Minister of India. In January 2023, the Indian National Green Hydrogen Mission has been approved by the Government of India with an outlay of EUR 2.25 billion until 2030. The Mission aims at making India a global hub for green H2 production, utilisation and export. India aspires to reach net zero by 2070 and has committed to reduce its emissions intensity by 45 percent in 2030 compared to the 2005 level and achieve about 50 percent cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030.

In addition to strong political commitment, India also has the potential to produce green H2 and its derivatives on a competitive basis. This is due to its low prices for RE-based electricity production, especially solar.

Activities are currently focused on green ammonia. In the future global energy transition, however, green methanol will play a key role. Methanol is needed in many industry processes, such as formaldehyde production, production of gasoline, methanol-to-olefins (MTO), MTBE, solvent applications, etc. Besides, green methanol will play a key role as a sustainable marine fuel in the future. In addition to green methanol projects for the local market, projects for the export market, where higher offtake prices are expected, can also support the general market ramp-up of green methanol projects in India as a first step. To further explore how green methanol projects can be set up in India and how they can be aligned with European regulations such as RED II, this PPP consisted in a comprehensive pre-feasibility study of a green methanol project for export.

The project has been designed as a 100% export-oriented green methanol production plant and would cater to the demand of green methanol for the shipping sector, primarily for the EU market. The project is expected to be commissioned by financial year (FY) 2028-29. The project is designed as a greenfield project with new green hydrogen and green methanol production units and new renewable energy (RE) plants (solar and wind). The location of the green hydrogen and methanol projects is fixed (Malkangiri district), while the identification of the location of the new RE plants is part of the PPP. The aim of this technical report is thus to present the methodology used to select the sites for new renewable energy plants and the outcome of the feasibility mapping.

1.2 Goals and objectives

As introduced in the previous section, a green methanol production plant is planned in the Malkangiri district in the state of Odisha with a capacity of 275 kilotons per annum (KTPA) using 50-60 KTPA of green hydrogen. This would realistically require the green hydrogen electrolyser capacity to be between 550-650 MW, fed by new renewable energy plants of a total capacity comprised between 1.5 GW to 1.75 GW. The hydrogen is to be transported to Europe after processing into methanol, which would require capture of about 400 ktpa of biogenic CO_2. Currently, the carbon is expected to be sourced from wood residues.

The objective of this study is to identify optimal sites for development of new renewable energy plants from wind and solar energy resource-rich states.

2 Methodology

This chapter describes the methodology applied to identify suitable locations in India for utility-scale renewable electricity generation to supply green hydrogen (methanol) to the European market.

The methodology is implemented in a geographic information system (GIS) environment and combines spatial constraint mapping with a structured site suitability assessment for both wind and photovoltaic development.

2.1 General overview of the GIS methodology

The bulk of the work is performed in a geo-information system (GIS), more specifically QGIS [1]. The applied methodology divides the country into a uniformly defined set of potential development zones for renewable energy plants, with each zone being defined as a "Project Opportunity Area" (POA). The spatial scale of each delineated POA should be representative of the required capacity of the renewable energy plants that will power the green hydrogen plant.

Whether a specific POA is suitable for renewable energy production depends on a number of environmental factors that impact both technical and financial project feasibility. Geodata containing spatial information about these factors, such as the proximity of existing infrastructure and environmental constraints, among other parameters such as wind and solar resource data, are gathered from varying public sources and compiled in the GIS software.

The chapter first presents the sourced geospatial datasets and how they were processed, then explains the modelling assumptions for representative wind and PV plants and the corresponding delineation of project opportunity areas, and finally, details the scoring and aggregation approach used to rank candidate areas.

2.1.1 Source data

Table 1 provides an overview of all the relevant geodata that were used for the purpose of the site suitability assessment. Sourced data includes wind and solar resource, existing infrastructure, terrain properties and environmental factors, which combined will determine site suitability for renewable energy project development.

Table 1: Sourced geodata for the analysis

Parameter	Source	Year	Data type	Description
Administrative boundary	Survey of India [2]	2020	Polygon vector (shapefile)	A shapefile of mainland India's boundary including States and Union Territories. Used to clip the available geodata to the country's outline.
Elevation	GEBCO [3]	2024	Raster (tif)	Elevation and bathymetry data at a 15 arc-second resolution.
Land cover	ESRI Impact Observatory Sentinel-2 L2A [4]	2024	Raster (tif)	Land use/land cover (LULC) derived from ESA Sentinel-2 imagery at a 10m resolution.
Surface water and waterways	OpenStreetMap (Humanitarian Data Exchange) [5]	2025	Polygon vector (shapefile)	Surface water polygons including wetlands, canals, basins, lakes, rivers, reservoirs and ponds.
Protected nature zones	Protected planet World Database on Protected Areas (WDPA) [6]	2024	Polygon vector (shapefile)	Polygons of marine protected areas, terrestrial and inland waters and conservation areas.
	OpenStreetMap Wildlife Institute of India [7]	2019	Polygon vector (shapefile)	Polygons of protected wildlife sanctuaries and national parks.

Parameter	Source	Year	Data type	Description
Protected heritage sites	UNESCO World Heritage [8]	2023	Point vector (shapefile)	Point locations of heritage sites. A buffer zone of 5 km was applied to each site in the dataset.
Roads	OpenStreetMap (Humanitarian Data Exchange) [9]	2025	Polygon vector (shapefile)	Centrelines of primary roads and highways.
Railways	OpenStreetMap (Humanitarian Data Exchange) [10]	2025	Polyline vector (shapefile)	Railway centrelines.
Airports	OpenStreetMap (Humanitarian Data Exchange) [11]	2025	Polyline vector (shapefile)	Runway outlines or airport area boundaries.
Electrical grid	OpenStreetMap (Infrageomatics) [12] [13]	2025	Polyline vector (shapefile)	Location of high-voltage powerlines
			Polygon vector (shapefile)	Location of high-voltage substations
Ports	Wikipedia [14]	2025	Polygon vector (shapefile)	Includes polygons of the cargo loading areas of the major ports: Kandla, Mundra, Jawaharlal Nehru, Mumbai, Mormugao (Goa), New Mangalore, Kochi, Tuticorin, Chennai, Ennore, Visakhapatnam, Paradip, and Haldia.
Wind farms	OpenStreetMap (Infrageomatics) [15]	2025	Point vector (shapefile)	Location of power generators including operational wind turbines
Solar parks	OpenStreetMap (Infrageomatics) [16]	2025	Polygon vector (shapefile)	Location and shape of solar parks
Wind resource	Global Wind Atlas v4.0 [17]	2025	Raster (tif)	Wind capacity factor at 100m – IEC class 3
Solar resource	Global Solar Atlas v2.12 [18][19]	2025	Raster (tif)	Specific photovoltaic power output (kWh/KWp)

The sourced data offers a wide variation in how data is geographically presented, with differences in data types and spatial resolutions. More specifically, raster files present data in pixels with a specific spatial resolution, while vector data presents geographic features with their digitised shapes, locations and attributes.

The spatial resolution of the raster datasets varies between 10 m and 500 m. As the data will be processed on the national level, all the data is downscaled to a standard 500 m spatial resolution. The available vector data is also converted to raster format with the same 500 m spatial resolution. This provides a uniform and standardised methodology that retains in part the granularity of the sourced data relative to the country-wide spatial scale of the analysis and at the same time guarantees fluid data processing.

2.1.2 Wind farm and solar park modelling

The site scoping assessment is performed for wind farms and solar parks of which the modelled technology is representative of the technology available on the Indian market. Specifically for wind farms, the analysis considers a generic wind turbine model of IEC class 3 with a nominal power of 4.5 MW, a rotor diameter of 150 m and a hub height of 100 m. Data on the performance of this wind turbine model, more specifically the capacity factor, across India was gathered from Global Wind Atlas [17] as the wind resource data for this analysis.

The class refers to the International Electrotechnical Commission (IEC) standard classification system for wind turbines. This system allows to distinguish the suitability of a given wind turbine for a set of operating conditions. In particular, the class 3 is defined for the conditions shown in Table 2. This class of wind turbine has been selected as it suits the average wind speeds observed across India, i.e. a wind regime with overall moderate wind speeds and with less extreme conditions.

Table 2: IEC class 3 operating conditions

IEC class 3	V_{REF} [m/s]	V_{AVG} [m/s]	k [-]
Value	37.5	7.5	2.0

The wind capacity factor is an indicator of the percentage of the operation of the modelled wind turbine at its full rated power over a year. It is influenced by the wind resource at a specific location and by the turbine design, helping to compare the wind farm performance at different sites.

As for solar parks, the analysis considers generic bifacial modules with a fixed structure. The solar resource data across India was gathered from Global Solar Atlas [18][19] in the form of the specific photovoltaic power output, defined in kWh/kWp. The specific photovoltaic power output represents the yearly average values of photovoltaic electricity delivered by a PV system and normalised to 1 kWp of installed capacity, considering free-standing PV system with generic crystalline silicon modules at optimum tilt [19].

In order to reach the desired renewable energy capacity of 1.5-1.75 GW, each individual plant has been estimated to reach 225 MW for a wind site and 750 MW for a solar site on a single location. Several locations can then be combined to reach the mentioned targets. The goal is to define suitable locations for the desired 225 MW of wind capacity and 750 MW of solar capacity per individual installation. For this purpose, the study considers a spatial scale of 25 km² per production plant to provide a sufficient capacity of renewable energy resources for the green hydrogen project. This translates to a power density of 9 MW per km² per wind farm and of 30 MW per km² per solar park, to be considered as a conservative approach, representative of land use for very large project sites in presence of constraints.

2.1.3 Project Opportunity Area (POA) grid

The varying data types are to be combined, processed and presented uniformly and consistently on the national level into an accessible output data format. For this purpose, the shapefile layer (polygon) containing mainland India and its administrative border was transformed into a vector grid of 5 km by 5 km cells in an equal-area projection. Each resulting grid cell is defined as a "Project Opportunity Area (POA)" for PV or wind projects and encompasses a surface area of 25 km² that, by using an equal-area projection, is consistent across the Indian mainland and representative of the desired capacity of wind and solar projects and the modelled power densities as detailed in Section 2.1.2.

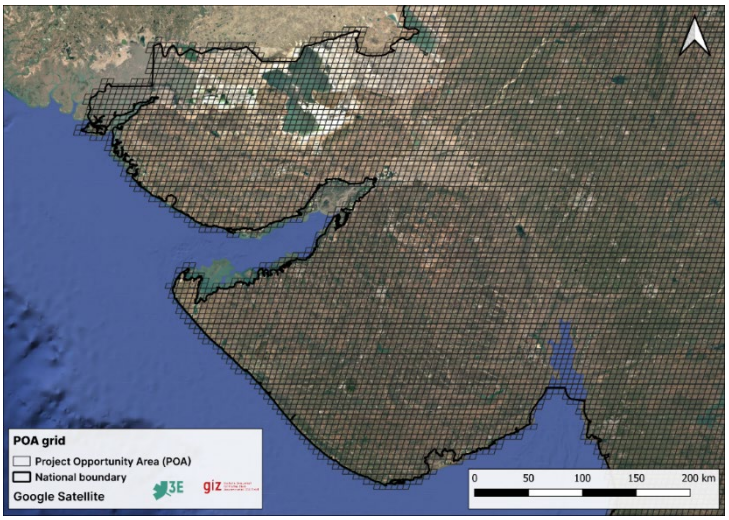


Figure 1: Grid of "Project Opportunity Areas" (25 km²) covering mainland India

2.1.4 Multi-criteria analysis

The following attributes are calculated to determine the suitability of each 25 km² POA for the installation of a modelled wind or PV plant:

- Electricity generation;
- Levelised cost of electricity (LCOE);
- Distance to existing wind and solar plants;
- Land preference;
- Slope;
- Complementarity score (wind only);
- Land availability factor.

The definition of and the methodology to calculate each individual POA attribute is further discussed in Chapter 2.2. Each attribute is calculated separately for wind and PV by combining and processing the respective sourced geodata on a nation-wide raster grid with a 500 m spatial resolution. The POA's attribute is extracted from the average of the underlying results calculated on this 500 m grid. This averaged result of each POA is subsequently normalised across the 5 km resolution POA grid into a score between 0 (unfavourable) and 1 (favourable) based on the minimum and maximum value in the POA grid. This process results in the "scored attributes" of LCOE, distance to existing plants, electricity generation, land preference, slope, and complementarity that are defined per POA, separately for wind and PV.

All these attributes, except for land availability, which is treated as a separate weighting parameter, are subsequently combined into a geometrically weighted score, meaning that if any of the individual attributes' score in a given POA equals 0, the combined POA score also returns a 0-value, thus rendering the POA entirely unfavourable as a project site.

The final attribute of land availability is used to correct the weighted attributes layer for the fraction of available land that is available for project development in each POA. More specifically, this land availability factor is derived in a separate process from an environmental constraint mapping analysis, resulting in a binary constraint mask that distinguishes strictly available land from strictly unavailable land in function of technical and regulatory constraints for the development of renewable energy projects within each POA.

This combined process results in a "project opportunity score", again a scored value defined between 0 and 1, that determines globally whether a POA is an unfavourable or a favourable site, respectively, for either wind or PV plants with the desired capacity. The diagram in **Figure** 2 presents an overview of the step-by-step GIS methodology.

25 km² that, by using an equal-area projection, is consistent across the Indian mainland and representative of the desired capacity of wind and solar projects and the modelled power densities as detailed in Section 2.1.2.

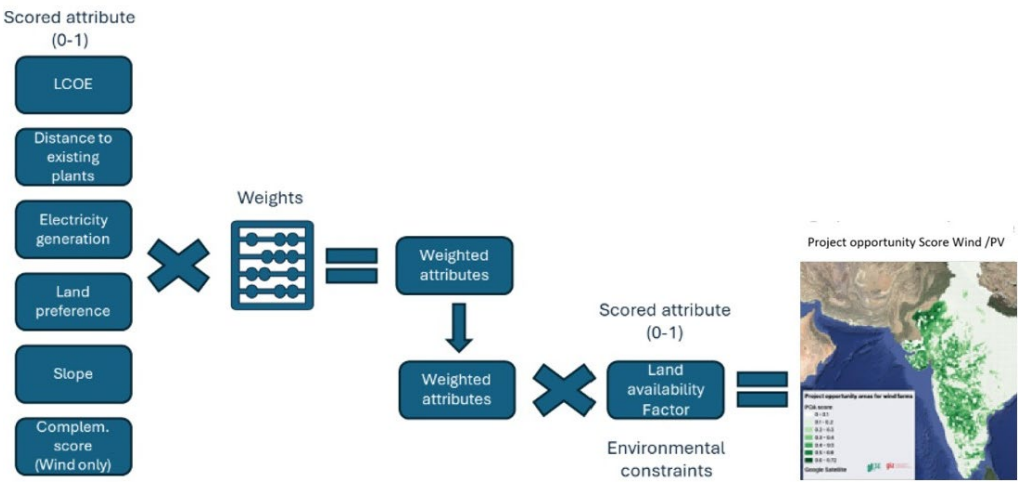


Figure 2: Summary of the methodology used for site selection

2.2 POA attributes

This section details the methodology of the calculation of each of the POA attributes for Wind and PV and the translation of their absolute values into normalised scores.

2.2.1 Land availability factor

As the land availability attribute is both derived from a detailed assessment of technical and environmental constraints for project development, and is not considered in the multi-criteria weighting analysis of the other attributes, but rather used a correcting factor on the final result, the methodology on the derivation of this final POA attribute is discussed in detail in its proper section (Section 2.4).

2.2.2 Average electricity generation

The average electricity generation is a criterion that reflects the potential annual net energy yield of a given site. The data layers shown in Table 3are used as input for the computation of this value, according to equation Eq. 1 for wind:

$$\mathbf{AEG_w = cf \times A \times p_w \times LDF \times (1 - l_w) \times 8760} \qquad \textit{Eq. 1}$$

And according to equation Eq. 2 for solar:

$$\boldsymbol{AEG_s = PV_{OUT} \times A \times p_s \times LDF \times (1 - l_s)} \qquad \textbf{Eq. 2}$$

With:

AEG_w :	Average electricity generation for wind	LDF :	Land discount factor
AEG_s :	Average electricity generation for solar	l_w :	Average production losses for wind farm
cf :	Capacity factor for wind	PV_{OUT} :	Specific photovoltaic power output
A :	Average available land area	p_s :	Land power density for solar
p_w :	Land power density for wind	l_s :	Average production losses for photovoltaic farm

Table 3: Sourced geodata for the electricity

Parameter	Source	Year	Data type	Description
Wind resource	Global Wind Atlas v4.0 [17]	2025	Raster (tif)	Wind capacity factor at 100m – IEC class 3
Solar resource	Global Solar Atlas v2.12 [18][19]	2025	Raster (tif)	Specific photovoltaic power output (kWh/KWp)

As described in Section 2.1.2, the capacity factor of a generic IEC class 3 4.5 MW wind turbine with 150 m rotor diameter and 100 m hub height was modelled from the source data of Global Wind Atlas as input for the calculation of the wind energy production at a certain location [17]. The specific photovoltaic power output, defined in kWh/kWp, from a generic free-standing bifacial PV system with generic crystalline silicon modules at optimum tilt was modelled from the source data of Global Solar Atlas [18][19]. Both wind and solar data sources are widely validated globally, also in India.

The average available land area is for now considered to be the entire POA grid cell, i.e. 25 km². A correction is performed at a later stage to account for the available land in a POA as determined by the constraint analysis (Section 2.4). The land discount factor is applied as a safety margin on the available area to account for elements that could have been missed in the geodata. Its value is set at 90%.

The production losses are estimated based on standard values in wind and solar farms. For wind farms, this typically includes wake, unavailability, performance and environmental losses and are worth 16%. For solar farms, it refers to shading, optical, module and electrical losses and is also estimated at 16%. These estimations are industry standards based 3E's international experience.

These results have subsequently been scored to obtain a value ranging from 0 (unfavourable) to 1 (favourable) by normalising the attributes to their minimum and maximum values.

2.2.3 The Levelised Cost of Electricity (LCOE)

The levelised cost of electricity (LCOE) used in this report is based on the simplified methodology of the IRENA [20]. The LCOE approach is based on a discounted cash flow analysis where the financial flows are discounted on a common basis, taking into account the time value of money.

In addition, the method chosen here does not take into account taxes, depreciation or other financial metrics. This has the advantage of making the analysis transparent and easy to understand. In addition, more detailed LCOE analyses require the formulation of many very specific assumptions which might give a misleading impression of greater precision. The main goal of this analysis remains to observe the spatial differentiation of the modelled attributes.

Thus, the formula used to calculate the LCOE of renewable energy technologies is as follows:

$$LCOE = \frac{\sum_{t=1}^{n}(I_t + M_t)/(1+r)^t}{\sum_{t=1}^{n}(E_t)/(1+r)^t} \qquad \text{Eq. 3}$$

Where:
LCOE [€/MWh] : Levelised cost of electricity
It [€] : Capital investments required in year t
Mt [€] : Operating and maintenance expenses in year t
Et [MWh] : Net electricity generated in years t
r [%] : Actual discount rate
n [y] : The lifetime of the project

The LCOE is the price of electricity required for a project where revenues would equal costs to produce a return on investment equal to the discount rate. A price of electricity above this threshold would result in a better return on capital, while a price below this threshold would result in a lower return on capital or even a loss.

While the LCOE is a widely used measure to compare renewable energy technologies with each other for modelling or policy-making purposes, it is not the only measure that can be used, and the results should be analysed with a critical eye. Importance should be given rather to the values of the LCOE and the projected revenue streams obtained at the financial close of the project by the developers, taking into account all costs and revenues and detailed financial planning.

Moreover, the LCOE should not be interpreted as an indication of the necessary feed-in tariff, as renewable energy project developers require a more detailed approach to discounted cash flows, taking into account taxation, subsidies and other incentives, to assess the profitability of actual projects. This depends on their individual situation, the market conditions, and is beyond the scope of this report.

After calculation of the LCOE in each POA, the values are normalised to a score between 0 (unfavourable) and 1 (favourable). In general, the lower the LCOE calculated in the POA, the better the score and the more favourable the site. However, any LCOE value of 100 €/MWh or higher is considered as unfavourable and hence a score of 0 was applied. Therefore, only LCOE values below 100 €/MWh were translated to a normalised score between 0 and 1.

The different parameters taken into account in its computation are detailed in the following sections and presented in Table 5. Their respective data layers are summarised in Table 4.

Table 4: Sourced geodata for the LCOE analysis

Parameter	Source	Year	Data type	Description
Roads	OpenStreetMap (Humanitarian Data Exchange) [9]	2025	Polygon vector (shapefile)	Centrelines of primary roads and highways
Railways	OpenStreetMap (Humanitarian Data Exchange) [10]	2025	Polyline vector (shapefile)	Railway centrelines
Airports	OpenStreetMap (Humanitarian Data Exchange) [11]	2025	Polyline vector (shapefile)	Runway outlines or airport area boundaries
Electrical grid	OpenStreetMap (Infrageomatics) [12] [13]	2025	Polyline vector (shapefile)	Location of high-voltage powerlines
			Polygon vector (shapefile)	Location of high-voltage substations
Ports	Wikipedia [14]	2025	Polygon vector (shapefile)	Includes polygons of the cargo loading areas of the major ports: Kandla, Mundra, Jawaharlal Nehru, Mumbai, Mormugao (Goa), New Mangalore, Kochi, Tuticorine, Chennai, Ennore, Visakhapatnam, Paradip, and Haldia
Wind resource	Global Wind Atlas v4.0 [17]	2025	Raster (tif)	Wind capacity factor at 100m – IEC class 3
Solar resource	Global Solar Atlas v2.12 [18][19]	2025	Raster (tif)	Specific photovoltaic power output (kWh/KWp)

2.2.3.1 General parameters

Several parameters for calculating the LCOE are considered common to both technologies, such as WACC, inflation rate, and project lifetime. For this study, the discount rate of the project is considered to be equal to 7%, which corresponds to the WACC chosen on the basis of analyses conducted by 3E on similar projects. The inflation rate is set at 2% and the duration of the project is 25 years.

2.2.3.2 Net energy production

The net energy production is computed for an installed capacity corresponding to 225 MW for wind plants and 750 MW for photovoltaic plants, as part of Section 2.1.1 This is based on the assumption of land use of 9 MW/km^2 and 30 MW/km^2 for wind and solar, respectively, together with the spatial resolution the POA of 25 km^2. These values are conservative but representative of land use for very large sites in presence of constraints. Average losses of 16 % were taken into account for both technologies, combining standard losses for the modelled technologies. The combination of POA can be done in order to reach the targeted renewable energy capacity.

2.2.3.3 CAPEX

The capital expenditure covers all expenses which are not recurrent and are linked to the construction of the farm. For both technologies, it considers the cost of intra park cabling, logistics from the ports, construction of new roads and of grid infrastructure such as grid high voltage lines and substation construction or connection to existing ones. For this purpose, the proximity to substations and grid voltage lines with a capacity of at least 220 kV has been considered [12][13]. Given the spatial scale of the analysis, proximity to existing infrastructure has been considered as the primary cost driver; other factors such as upgrading existing infrastructure, increasing existing capacity, or the length of existing transmission and road networks have not been included. It should be noted that a grid connection cost component is included even for sites in proximity to

existing infrastructure, thereby partially accounting for potential upgrade costs. However, site-specific grid upgrade cost variations have pragmatically not been considered, as such granularity would be beyond the scope of a country-level assessment.

The total project CAPEX also takes into account project development, management, insurance and financing costs. The numbers considered are based on several studies done by 3E. Concerning the material costs for wind, the numbers are based on values extracted from the latest NREL report [21]. It contains all the costs of the turbine components such as tower, blades, gearbox, generator, transformer and more. It also refers to the installation costs such as the construction of the foundation, the preparation of the site, etc. Concerning the material costs for solar, the figures are based on values extracted from several commercial utility-scale projects studied by 3E. It contains costs such as the photovoltaic modules, the inverters, junction boxes, transformers, meteorological stations, support structures, foundation, etc. Similarly, for wind it includes installation, development, management and financing costs.

2.2.3.4 OPEX

The operational expenditure reflects the recurring costs linked to the park operation. OPEX includes the management, maintenance and operational assurance of the park and balance of plant (BoP). Maintenance cost scales almost linearly with the number of wind turbines and modules and the installed capacity, as most maintenance operations are preventive and take place every year for all single items installed.

2.2.3.5 Decommissioning

Decommissioning costs differ between both technologies. At the end of the 25-year lifespan of wind turbines, they must either be decommissioned or reconditioned (known as "repowering"). Although both are possible depending on the context, here the wind turbines are assumed to be decommissioned and dismantled, which leads to a provision for decommissioning per wind turbine. The dismantling of the photovoltaic infrastructures has not been the subject of a complete modelling. Indeed, this cost centre is much lower for photovoltaics than for wind power and also benefits from a very high compounded discount factor.

Table 5: LCOE computation parameters

Category	Unit	Value	
		Wind	Solar
CAPEX			
• Technology and installation	k€/MW	1,193.6	457.6
• Road construction	k€/km	77.9	77.9
• Grid connection	k€/km	437.2	437.2
• Substation construction	k€/MW	45.6	45.6
• Transport from ports	k€/km	6.1	36.7
• Project-level costs	% of hard CAPEX	9.5	9.5
• Development costs	k€/MW	31.6	16.0
• Financing	% of all CAPEX	6.2	6.2
OPEX	k€/MW.y	6.6	12.8
Decommissioning	k€/MW	26.7	0
Production losses	%	16	16
Lifetime	years	25	25
WACC	%	6.25	6.25
Land capacity	MW/km2	9.0	30.0

2.2.4 Distance to existing plants

The presence of existing and operational solar parks and wind farms can be considered as an important factor for the development of new installations. In this analysis, in terms of the cost-efficiency for the construction and operation of both new solar parks and new wind farms, land in relative proximity to existing solar and wind parks is considered more favourable.

For wind specifically, available land in the more immediate vicinity of up to 15 km to existing wind farms is nevertheless considered less favourable for the development of new wind farms due to the wake effects created by the existing turbines. After 15 km, these wake effects are considered to become insignificant.

The location and properties of existing wind turbines and solar parks are gathered from the sources as presented in Table 6.

Table 6: Sourced geodata for the proximity analysis to existing wind farms and solar parks

Parameter	Source	Year	Data type	Description
Wind farms	OpenStreetMap (Infrageomatics) [15]	2025	Point vector (shapefile)	Operational wind turbines
Solar parks	OpenStreetMap (Infrageomatics) [16]	2025	Polygon vector (shapefile)	Operational solar parks

The location of existing wind farms and solar parks is gathered from OpenInfraMap, a platform that provides OpenStreetMap data of infrastructure. The wind farm data comes in the form of point vector data with the location of existing wind turbines in India, while the solar park data comes in the form of polygon vector data covering the location of existing solar farms in the country. Both datasets were converted to a raster with a spatial resolution of 500 m covering mainland India. With this operation, each wind turbine or group of wind turbines, and each solar panel field was converted to a "target pixel" or a group of "target pixels".

A proximity analysis was performed in GIS on both the rasterised wind farm and solar park maps. The proximity calculation provides for each "non-target pixel" the Euclidean distance in meters from its centre point to the centre point of the closest target pixel. The target pixel itself therefore receives a distance value of 0 m, while pixels located adjacent to target pixels but not in a diagonal direction receive a distance value of 500 m, given the spatial resolution of the raster data. This process creates two separate proximity maps, one including the calculated distances to wind farms and the other including distances solar parks.

The distance in both datasets is then given a score between 0 and 1, depending on the distance thresholds as provided in Table 7.

Table 7: Scoring of proximity to existing solar parks and wind farms

Input data	Proximity	Score
Solar parks	<= 10 km	1
	10 km < X < 500 km	linear decrease
	>= 500 km	0.5
Wind farms	<= 1 km	0
	1 km < X < 15 km	linear increase
	= 15 km	1
	15 km < X < 500 km	linear decrease
	>= 500km	0.5

Land within a proximity of up to 500 km from existing plants is generally deemed more favourable in this analysis. Note that the analysis does not provide a score lower than 0.5 to distances that are higher than 500 km. While the land in close proximity to existing plants can indeed be interpreted as being more favourable for new plants of the same kind, the order of magnitude of the considered capacities of the new plants makes it that this should not be a significant determining factor. Due to the geometric weighting of the attributes, any POA with a 0-value score for the distance criterion would become entirely unfavourable, this choice was specifically made to avoid this attribute in being a dealbreaker.

Potential land for PV that is located within 10 km from an existing solar park (target pixel) is scored with a value of 1 (favourable). All pixels further than 500 km away from a target pixel are scored with a value of 0.5. In between the thresholds, from 10 km to 500 km distance, the score decreases linearly up to the minimum score of 0.5.

Concerning potential land for wind farms, all pixels within 1 km of existing wind turbines are valued unfavourably with a value of 0 to account for significant wake effects that reduce the operational efficiency of new wind turbines. From a distance of 1 km onwards, the score increases linearly up to a distance of 15 km, after which wake effects from existing turbines can be considered negligible and the distance is scored with a value of 1 (favourably). As of 15 km onwards, the score then decreases linearly up to a distance of 500 km, after which the score is set to the minimum value of 0.5.

Finally, the scored proximity results for both wind and PV are averaged separately per POA.

2.2.5 Land preference

A "land preference" attribute is taken into account to favour locations with regards to the land use and the proximity to main infrastructure. The main guiding principle is the conservation of the socio-economic situation, where land that has high socio-economic value such as agricultural land are deemed more unfavourable for development of renewable energy projects in comparison to land of limited socio-economic value. Additionally, land in proximity to important infrastructure is deemed more favourable due to the significant pre-existing socio-economic impact of this infrastructure on its environment. The data layers as presented in Table 8 are used as input for the creation of the land preference parameter.

Table 8: Sourced geodata for the land preference analysis

Parameter	Source	Year	Data type	Description
Land cover	ESRI Impact Observatory Sentinel-2 L2A [4]	2024	Raster (tif)	Land use/land cover (LULC) derived from ESA Sentinel-2 imagery at a 10m resolution
Roads	OpenStreetMap (Humanitarian Data Exchange) [9]	2025	Polyline vector (shapefile)	Centrelines of primary roads and highways
Railways	OpenStreetMap (Humanitarian Data Exchange) [10]	2025	Polyline vector (shapefile)	Railway centrelines
Airports	OpenStreetMap (Humanitarian Data Exchange) [11]	2025	Polyline vector (shapefile)	Runway outlines or airport area boundaries
Ports	Wikipedia [14]	2025	Polygon vector (shapefile)	Includes polygons of the cargo loading areas of the major ports: Kandla, Mundra, Jawaharlal Nehru, Mumbai, Mormugao (Goa), New Mangalore, Kochi, Tuticorine, Chennai, Ennore, Visakhapatnam, Paradip, and Haldia

2.2.5.1 Land cover

The land cover data of Sentinel-2 was reclassified to assign a preference score to each class. The raster dataset on a 10 m spatial resolution includes 11 individual landcover classes and was rescaled to 500 m spatial resolution given the scale of the project area.

The land cover data is also a key factor in the environmental constraint analysis and therefore the general treatment and scoring of land cover classes is performed in agreement with the methodology of the land availability attribute (Section 2.4). In correlation with the constraint analysis, only two land use classes are considered as "available" for renewable energy project development: cropland and rangeland (all other classes are excluded). For more information on the methodology in excluding land cover classes, a more detailed description is available in Section 2.4.

In the scope of defining the land preference attribute, rangeland is favoured for project development over cropland to preserve the socio-economic value of cropland in the community. In general, the same scoring methodology is applied with values between 0 (non-favourable) and 1 (favourable). The scores that were assigned to the land cover classes and the global weight of land cover in the land preference attribute are presented in Table 9. The weight in land preference attribute use is detailed in the Land Preference Score section here below.

Table 9: Scoring and weight of the land cover classes in the land preference attribute

Input data	Reclassification (Sentinel-2 land use class)	Score	Weight in land preference attribute
Land cover	Built area (7)	0.0	0.6
	Cropland (5)	0.7	
	Rangeland (11)	1.0	
	Other classes	0.0	

All land cover classes excluded in the constraint analysis (Section 2.4) receive a score of 0. This includes the land cover class of "built area" given the spatial scale of the planned renewable energy plants. In contrast, rangeland receives the highest score of 1 in line with its more limited socio-economic value. Note that the score of croplands (0.7) is only slightly lower than for rangeland (1.0). The main reasoning being that agricultural land is the most dominant class in the land cover data while the constraint analysis by itself already is performed in a conservative manner as it considers only 2 out of 11 land cover classes as available for renewable energy projects.

2.2.5.2 Proximity to infrastructure

Aside from the land use aspect, the proximity to human infrastructure is considered as another parameter that contributes to land preference, in light of both the ease of site access as well as pre-existing environmental and socio-economic impact of the infrastructure on its neighbouring land. Four specific types of infrastructure are considered that draw significant levels of human activity, either in situ or in transit: Primary roads, railways, airports and seaports.

As for roads, only primary roads and highways are considered. Secondary, tertiary and local roads were discarded from the data. The original datasets of airports and railways were not modified. 13 major cargo ports are considered as listed in the table. These ports were polygonised manually according to the outline of the cargo loading areas.

Table 10: Land scoring based on proximity to infrastructure and its weight in the land preference attribute

Input data	Proximity	Score	Weight in land preference attribute
Distance to roads	<= 2 km	1	0.1
	2 km < X < 15 km	linear decrease	
	>= 15 km	0	
Distance to railways	<= 2 km	1	0.1
	2 km < X < 15 km	linear decrease	
	>= 15 km	0	
Distance to airports	<= 20 km	1	0.1
	20 km < X < 150 km	linear decrease	
	>= 150 km	0	
Distance to ports	<= 20 km	1	0.1
	20 km < X < 150 km	linear decrease	
	>= 150 km	0	

The vector data of the respective infrastructure types was rasterised to a 500 m resolution, after which each rasterised infrastructure map was converted to a proximity map using the GIS proximity analysis, by calculating for each pixel in the raster data the Euclidian distance to the closest infrastructure pixel. Once a proximity map was created for each infrastructure type, the distance values were scored based on distance thresholds as presented in Table 10. Land closer to these types of infrastructure are considered to have a higher preference and thus are considered more suitable for wind and PV development.

2.2.5.3 Land preference score

The scored land cover map and the 4 scored proximity maps are then combined in GIS using the raster calculator function by multiplication. The 5 individual parameters are given a weight. As land use is considered to be the dominant parameter in defining the land preference attribute, it is given a weight of 0.6, while a weight of 0.1 is applied to each of the 4 infrastructure proximity parameters. The data of the resulting 500 m resolution raster file is then averaged in the POA grid with a spatial resolution of 5 km.

2.2.6 Slope gradient

A slope map in the form of a raster image presenting the terrain's slope gradient with a spatial resolution of 500 m was derived from the General Bathymetric Chart Of The Oceans (GEBCO) digital elevation model (Table 11).

Table 11: Sourced geodata for the slope attribute

Parameter	Source	Year	Data type	Description
Elevation	GEBCO [3]	2024	Raster (tif)	Elevation and bathymetry data at a 15 arc-second resolution

While a maximum slope threshold is foreseen for both wind and PV as part of the constraint analysis to distinguish between feasible and unfeasible terrain, in addition the slope values below those maximum thresholds are given a score. The main reasoning behind this is that flat terrain will always be the most favourable type of terrain as it makes site accessibility, construction, and maintenance works easier. The scores applied to the slope parameter are provided in Table 12.

Table 12: Scoring of the slope gradient per technology

Technology	Reclassification	Score
PV	<= 5 %	1
	> 5 %	0
Wind	<= 5 %	1
	5 % > X > 20%	Linear decrease
	>= 20 %	0

The scores for the slope attribute are defined in analogy to the slope constraint in the methodology of the land availability factor (Section 2.4). The slope scores are determined based on the maximum slope threshold of 5 % for PV in the constraint analysis. As the 5 % slope threshold is already a relatively low slope value, slopes above 5 % are scored as not favourable (0-value) and slopes below 5 % are scored as favourable (1-value) for PV, in analogy to the way the slope (PV) parameter was taken into account in the constraint analysis.

For wind projects, slopes below 5 % are considered as favourable (1-value), similarly to the score for PV. In analogy with the maximum slope threshold of 20 %for wind projects in the constraint analysis, and slopes equal or higher than 20 % are therefore scored as unfavourable (0-value). Slopes between 5 % and 20 % receive a linearly decreasing score from 1 to 0, respectively.

Finally, the data of the resulting 500 m resolution raster file is then averaged in the POA grid with a spatial resolution of 5 km.

2.2.7 Complementarity score (Wind)

This metric has been computed to show the advantage of combining solar and wind production from one site area to another with respect to the objective to produce electricity for green hydrogen production plant. As a result, the flattest production profile possible would be the most suited combination for this purpose in order to maximise the electrolyser capacity factor.

For this purpose, firstly, the average wind speed and the hourly-versus-monthly cross table (12 x 24 matrix) wind speed index and total power output have been extracted at 219 points spaced equally across India from the Global Wind Atlas [17] and the Global Solar Atlas [18] .

The power production table for solar considers a fixed ground mounted photovoltaic plant of 1,000 kWp installed capacity. The power production cross table for wind has been calculated by multiplying the obtained matrix by the wind speed at site then extracting the power corresponding to the resulting power from the power curve of a generic IEC class 3 turbine with rated power 4.5MW and rotor diameter of 150 m.

To enable a meaningful comparison between the local wind profile and any photovoltaic profile, an average solar profile is required. This is possible as the solar resource profile does not show large variations. Hence, an average hourly-versus-monthly cross table has been built for the solar profile, by averaging all downloaded matrices. The complementarity value is then computed as the correlation coefficient between these two matrices. This yields a value between -1 and 1 depending on the complementarity of an average daily solar profile and the grid point's local wind profile.

Each POA of the 5x5km grid is then assigned a weighted average value depending on the distance of the 4 closest downloaded points. This methodology is justified by the relatively regionally consistent daily wind profiles, further validated by the relatively small geographical variability of the correlation coefficients.

Finally, the values are normalised such that a score between 0 and 1 is obtained with 0 corresponding to correlation values close to 1 and with 1 corresponding to correlation values close to -1. Indeed, a highly correlated profile as in Figure 3 results in the lowest capacity factor for the electrolyser, while the opposite happens for completely decorrelated profiles as in Figure 4.

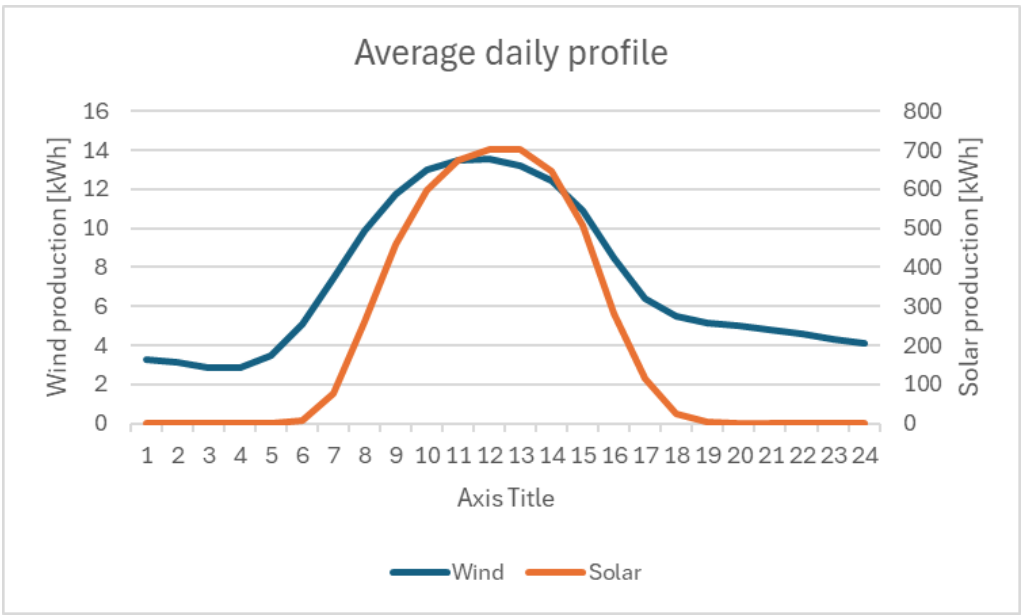


Figure 3: Correlated wind and solar profiles

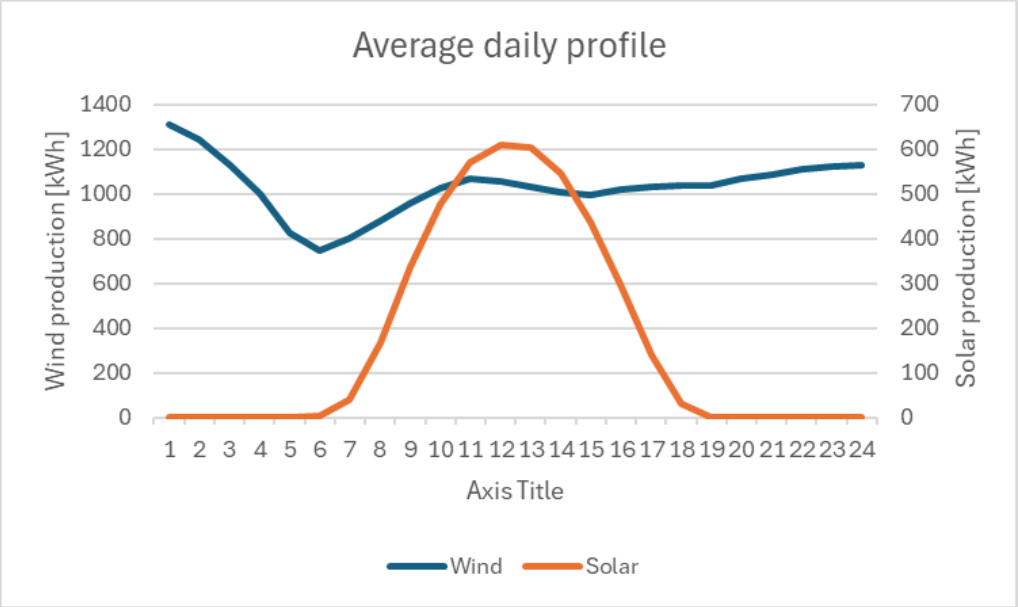


Figure 4: Uncorrelated wind and solar profiles

2.3 Multi-criteria analysis of attributes

The analytic hierarchy process (AHP) [22] has been used to compute the relative preference weights to attribute to each layer taken into account into the final score of a zone. This technique is based on a pairwise comparison between each of the criteria, ordered as rows and columns of a matrix. The different steps of its implementation are presented here below.

2.3.1 Definition of the main criteria

The attributes as presented in the previous sections reflect various aspects that each have a specific impact on site selection. They have been chosen such that they are independent from one another and can help to select site according to different scenarios. The selection criteria were determined on the basis of the participating parties' prior experience in analogous projects, as well as findings derived from a comprehensive desktop analysis. The evaluated parameters have been presented in the last sections. The reasoning behind their selection is detailed below:

- The levelised cost of energy is key to evaluate to financial value of a site
- The distance to existing plants reflects the impact of wake due to neighbouring turbines which could decrease the wind farm production up to a vicinity of 10 km but also highlights the advantages in terms of operational cost to build a new park nearby others for both photovoltaic and wind. Indeed, these two aspects cannot be monetised easily such that including them into the LCOE could not be done.
- The average electricity generation illustrates mainly the capacity factor of a given site. Decoupling this attribute from the LCOE allows putting the emphasis on energy production only since both attributes are important for prioritisation to find both large sites with a low LCOE, in the scope of this study.
- The land preference is a parameter used to give preference to zones based on the land use type and proximity to large infrastructure, with focus on favouring land of lower socio-economic value.
    - The slope criterion allows to discriminate zones based on their terrain complexity. This is indeed also difficult to take into account in the LCOE calculation but is crucial to consider. Indeed, slopy terrain increases the project complexity and hence its cost.
    - The complementarity score is exclusively used for the wind farm site selection. This can help to select locations with good complementary resources between wind and solar.

2.3.2 Pairwise comparison

These criteria are then compared in a matrix by using preference scores. The AHP method uses a scale from 1 to 9 and their reciprocal (1 to 1/9) to establish the relative preference of a criterion with respect to another. These have to be understood as follows:

- 1 indicates an equal importance between both criteria
- 3 indicates a moderate importance of the line criterion with respect to the one in the column
- 5 indicates a strong preference of the line criterion with respect to the one in the column
- 7 indicates a very strong preference of the line criterion with respect to the one in the column
- 9 indicates an extreme preference of the line criterion with respect to the one in the column
- 2,4,6,8 are intermediate value
- The reciprocals (i.e. 1/2, 1/3, 1/5, etc.) indicate that the column criterion is more important than the line

When filling the matrix, for each line criterion, a pairwise comparison is performed with all criteria in the columns yielding as many score as there are columns. The selection of the preference has been determined based on the final objective this study, being to develop renewable energy plants for green methanol production plant.

For example, if LCOE is highly preferred compared to the distance to existing plants, a value of 5 can be attributed to the cell corresponding to the line "LCOE" and the columns "distance to existing plants". On the other hand, the reciprocal value of 1/5 will be attributed to the cell corresponding to the line "distance to existing plants" and the column "LCOE". If a criteria is compared to himself, a value of 1 is automatically given (i.e. on the matrix diagonal).

2.3.3 Criterion weight computation

Once the matrix has been built, a normalisation process is performed. This is done by summing the matrix values along its columns, to obtain a total value per criterion. Each cell of each column is then divided by the resulting column total. Each line is then averaged to compute the relative weight of each criterion which is referred to as the priority vector. In parallel, a coherence ratio is computed to quantify the coherence of the weights attributed to each criterion. Computing the coherence ratio consists in the following steps:

- Compute the coherence vector by multiplying the initial matrix by the priority vector, then dividing each element by its corresponding value in the priority vector
- Compute the maximal eigenvalue λ_{max} by averaging all values in the coherence vector
- Compute the coherence index IC as $IC = \frac{\lambda_{max}-n}{n-1}$ with n, the number of criteria
- Compute the coherence ratio CR by dividing the coherence index IC by the random coherence index IR, which is a standard value depending on n, the number of criteria, as in Table 13.

The random coherence index IR is predefined vector from the AHP methodology. If the CR is below 0.1, the matrix is considered coherent while if is higher, it is necessary to revise the comparison to improve the coherence of the weighting.

Table 13: Random coherence index

N	1	2	3	4	5	6	7	8	9
IR	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.46

2.3.4 Wind AHP matrix

This section presents the AHP matrix built for the wind site selection. The reasoning is mainly based on putting high importance to LCOE, electricity generation and complementarity. This is done is light of the main objective to produce green hydrogen from new sources of renewable energy in a competitive market. Hence, low energy prices both from renewable and from hydrogen production are the main drivers, such that the capacity factor of the electrolyser has to be optimised by aiming for the flattest renewable energy production profiles.

Table 14: Wind AHP matrix

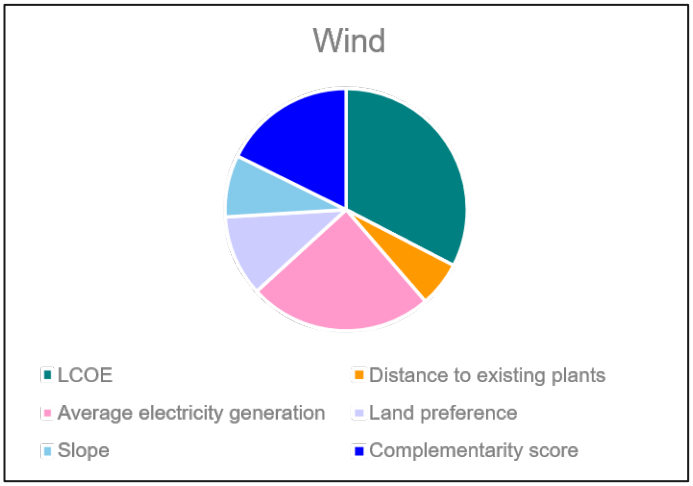
Category	LCOE	Distance to existing plants	Average electricity generation	Land preference	Slope	Complementarity score
LCOE	1	3	2	3	3	3
Distance to existing plants	1/3	1	1/4	1/2	1/2	1/4
Average electricity generation	1/2	4	1	3	3	2
Land preference	1/3	2	1/3	1	2	1/2
Slope	1/3	2	1/3	1/2	1	1/3
Complementarity score	1/3	4	1/2	2	3	1

The resulting weights and coherence ratio are given in Table 15. The coherence ratio shows that the preferences have been assigned in coherently , with 3 main criteria being indeed LCOE, average electricity generation and the complementarity between wind and PV, while still leaving some importance to the average slope and land preference.

Table 15: Wind criteria weights and coherence ratio

Category	Unit	Score
LCOE	[%]	32.6
Distance to existing plants	[%]	6.0
Average electricity generation	[%]	24.6
Land preference	[%]	10.8
Slope	[%]	8.3
Complementarity score	[%]	17.7
Coherence ratio	[-]	0.04

Figure 5: Pie chart illustrating the relative weight assigned to each POA attribute for wind projects.



2.3.5 Solar AHP matrix

This section presents the AHP matrix built for the solar site selection. The reasoning is mainly based on putting an emphasis on LCOE and electricity generation.

Table 16: Solar AHP matrix

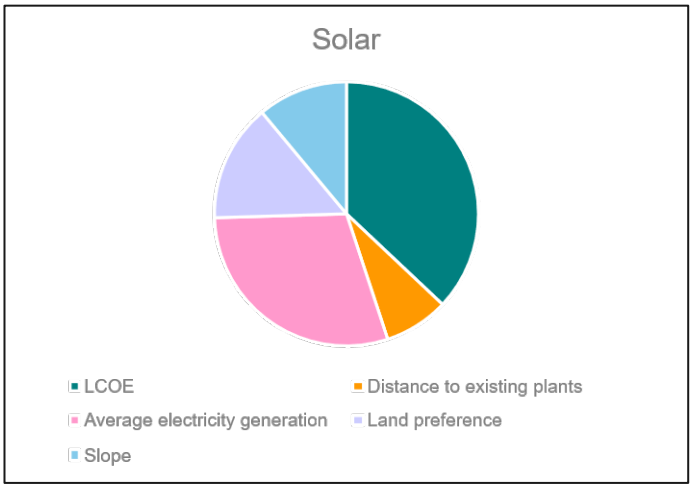
Category	LCOE	Distance to existing plants	Average electricity generation	Land preference	Slope
LCOE	1	3	2	3	3
Distance to existing plants	1/3	1	1/4	1/2	1/2
Average electricity generation	1/2	4	1	3	3
Land preference	1/3	2	1/3	1	2
Slope	1/3	2	1/3	1/2	1

The resulting weights and coherence ratio are Table 17:

Table 17: Solar criteria weights and coherence ratio

Category	Unit	Score
LCOE	[%]	37.0
Distance to existing plants	[%]	7.9
Average electricity generation	[%]	29.6
Land preference	[%]	14.4
Slope	[%]	11.1
Complementarity score	[%]	0.04

Figure 6: Diagram of the weight assigned to each POA attribute for PV projects



Again, the coherence ratio shows that the preferences have been assigned coherently, this time with only 2 main criteria being indeed LCOE and average electricity generation.

2.4 Constraint analysis for the land availability factor

The land availability attribute presents the fraction of land that is *a priori* suitable and available for the development of wind farms and solar parks based on environmental constraints. It is derived from the country's territory corrected for the constraints as detailed in Table 19. The constraints represent land that is excluded for the development of wind farms and solar parks.

Table 18: Geodata considered in the constraint analysis

Parameter	Data type	Description	Constraint threshold
Elevation	Raster (tif)	Elevation and bathymetry data at a 15 arc-second resolution.	Elevations above 1,500 m and below sea level are considered excluded
Land cover	Raster (tif)	Land use/land cover (LULC) derived from ESA Sentinel-2 imagery at a 10m resolution.	9 out of 11 landcover classes are considered as excluded area. See section on land cover
Surface water and waterways	Polygon vector (shapefile)	Surface water polygons including wetlands, canals, basins, lakes, rivers, reservoirs and ponds.	Polygons with a surface area equal to or greater than 50% of a 500 m pixel size are considered as excluded area
Protected nature zones	Polygon vector (shapefile)	Polygons of marine protected areas, terrestrial and inland waters and conservation areas.	Holes within the polygons were deleted so the whole area within the outline of the polygon are considered excluded.
	Polygon vector (shapefile)	Polygons of protected wildlife sanctuaries and national parks.	Holes within the polygons were deleted so the whole area within the outline of the polygon are considered excluded
Protected heritage sites	Point vector (shapefile)	Point locations of heritage sites.	A buffer zone of 5 km was applied to each site in the dataset, and which is considered an excluded area.
Airports	Polyline vector (shapefile)	Runway outlines or airport area boundaries.	A buffer zone of 15 km, henceforth considered as an excluded area for wind development, is created from the runway or airport outlines
Wind farms (optional)	Point vector (shapefile)	Location of power generators including operational wind turbines	Turbine centre points are rasterised to exclusion pixels of 500m spatial resolution
Solar parks (optional)	Polygon vector (shapefile)	Location and shape of solar parks	Panel field polygons are rasterised to exclusion pixels of 500m spatial resolution

2.4.1 Land cover

The landcover dataset of Sentinel-2 was used to distinguish available land from unavailable land for wind and PV development based on the existing land use. The raster dataset on a 10 m resolution includes 11 individual landcover classes, as presented in Table 20. The landcover data is used to exclude land on which development is either technically difficult or impossible, such as on surface water, wetlands, etc., or (while technically feasible) not acceptable, such as on built area or on forested area.

Excluding built area and forested area provides a conservative approach with the conservation of both the natural and human environment in mind, mainly the (permanent) habitats of humans, fauna and flora. In the meantime, the exploitation of solar parks and wind farms can be combined with existing agricultural activities, and therefore cropland and rangeland are included as available land for development, even though those landcover classes can also be considered an important part of the human environment. To consider this potential socio-economic impact on the human environment, the land preference attribute was introduced into the analysis in Section 2.2.5.

In summary, 2 landcover types are considered as available land: cropland (5) and rangeland (11). All other classes are thus considered an excluded area, either due to technical restrictions for construction in these areas, for environmental conservation purposes, or a combination of both reasons.

For this purpose, the raster data was reclassified to a binary mask layer (raster format), designating a value of 0 to unavailable landcover classes and a value of 1 to available landcover classes. The resolution of the raster data was lowered from 10 m to 500 m to improve computational efficiency in GIS and clipped to the national boundaries given the spatial scale of the analysis on the country level.

Table 19: Sentinel-2 land cover classification

Value	Name	Description
1	Water	Areas where water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built up features like docks; examples: rivers, ponds, lakes, oceans, flooded salt plains.
2	Trees	Any significant clustering of tall (~15 feet or higher) dense vegetation, typically with a closed or dense canopy; examples: wooded vegetation, clusters of dense tall vegetation within savannas, plantations, swamp or mangroves (dense/tall vegetation with ephemeral water or canopy too thick to detect water underneath).
4	Flooded vegetation	Areas of any type of vegetation with obvious intermixing of water throughout a majority of the year; seasonally flooded area that is a mix of grass/shrub/trees/bare ground; examples: flooded mangroves, emergent vegetation, rice paddies and other heavily irrigated and inundated agriculture.
5	Crops	Human planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, fallow plots of structured land.
7	Built Area	Human made structures; major road and rail networks; large homogenous impervious surfaces including parking structures, office buildings and residential housing; examples: houses, dense villages / towns / cities, paved roads, asphalt.
8	Bare ground	Areas of rock or soil with very sparse to no vegetation for the entire year; large areas of sand and deserts with no to little vegetation; examples: exposed rock or soil, desert and sand dunes, dry salt flats/pans, dried lake beds, mines.
9	Snow/Ice	Large homogenous areas of permanent snow or ice, typically only in mountain areas or highest latitudes; examples: glaciers, permanent snowpack, snow fields.
10	Clouds	No land cover information due to persistent cloud cover.
11	Rangeland	Open areas covered in homogenous grasses with little to no taller vegetation; wild cereals and grasses with no obvious human plotting (i.e., not a plotted field); examples: natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures. Mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within dense forests that are clearly not taller than trees; examples: moderate to sparse cover of bushes, shrubs and tufts of grass, savannas with very sparse grasses, trees or other plants.

2.4.2 Elevation

Land at an altitude below sea level and above 1,500 meters is deemed either inaccessible or not favourable for developing wind farms and solar parks. The elevation data from General Bathymetric Chart Of The Oceans (GEBCO) is available in raster format on a 15 arc-second resolution. This data was reclassified into a binary mask layer (raster format), excluding data pixels with an altitude either below 0 m or above 1,500 m and clipped to the national boundaries of mainland India.

2.4.3 Slope gradient

The elevation data from GEBCO was used to create a slope map, generating slopes between 0° and about 55° within the spatial range of the analysis and on the same resolution as the elevation data. Areas with an elevation below sea level where disregarded for this purpose. A slope threshold was introduced to distinguish between favourable and unfavourable terrain for project development, being 20% (roughly 11°) for wind farms and 5% (roughly 3°) for solar parks. The slope data was then reclassified into a binary mask layer (raster format), excluding raster pixels with a slope value higher than these thresholds. Therefore, two slope constraint maps with excluded areas for development were produced, one for wind farms and one for solar parks.

2.4.4 Surface water

In addition to the surface water class available in the landcover data, OpenStreetMap provides a vector data layer with polygonised rivers, wetlands, canals, basins, lakes, reservoirs and ponds. All surface water located on mainland India is considered as an excluded area for renewables. The bulk of the data encompasses small polygons representing smaller lakes, ponds and water reservoirs with a surface area that is insignificant on a 500 m resolution. Given the size of the dataset (number of individual polygons) and the resolution on which the analysis is performed in this stage (500 m), all polygons with a surface area lower than half the surface area of one 500 m by 500 m pixel are deleted from the dataset. The remaining polygons with a surface area above this threshold are considered as excluded areas for wind and PV development. The vector data of the excluded areas was rasterised to a binary mask layer with a 500 m spatial resolution, with the excluded areas being designated a value of 0 and the available land a value of 1.

2.4.5 Protected nature

Areas of protected nature located on mainland India are considered as exclusion zones for wind and PV development. The exclusion zones are sourced from two databases: the World Database on Protected Areas (WDPA) and the Wildlife Institute of India. The prior database includes polygons of marine protected areas, terrestrial and inland waters and conservation areas. The latter database includes polygons of protected wildlife sanctuaries and national parks.

Holes within the polygons were deleted to prevent development potential within the boundaries of these protected natural areas. The vector data of the excluded areas was rasterised to a binary mask layer with a 500 m resolution, with the excluded areas being designated a value of 0 and the available land a value of 1.

2.4.6 Protected heritage

Areas within 5 km of a UNESCO World Heritage site located on mainland India were considered as an exclusion, both for wind farms and solar parks. The point vector layer including all protected sites in India that are compiled in the UNESCO database were polygonised with a 5 km buffer for this purpose. The vector data of the excluded areas was rasterised to a binary mask layer with a 500 m resolution, with the excluded areas being designated a value of 0 and the available land a value of 1.

2.4.7 Airports

Areas within 15 km from airports located on mainland India were considered as an exclusion zone for wind development as a representation of aviation and radar restrictions for large wind turbines. The polyline vector layer with airfield runways from OpenStreetMap was polygonised with a 15 km buffer for this purpose. The vector data of the excluded areas was rasterised to a binary mask layer with a 500 m resolution, with the excluded areas being designated a value of 0 and the available land a value of 1.

2.4.8 Existing plants (optional)

Whether existing wind farms and solar parks are to be included as constraints for the development of new projects, depends mainly on matters such as the financial preferences of the project developer and plant ownership. Whether a developer prefers to opt for the construction of new plants entirely or whether they also want to keep the option open for the replacement of existing plants is entirely situational.

Considering the preservation of existing plants can be seen as the easiest approach, especially if lack of space for new developments and operational restrictions is not an issue. In contrast, considering a “tabula rasa” approach in which existing

plants are not preserved instead provides opportunities for repowering existing and potentially outdated renewable energy plants with new wind farms or solar parks.

Therefore, 2 constraint map versions where created, one with both types of existing plants being considered as a constraint, and the other without taking existing plants into account. In the prior version, the available vector geodata with the location of existing wind turbines and solar panel fields where rasterised to a spatial resolution of 500 m (at the same time providing an additional buffer in between existing and new constructions) and combined with the other constraints.

2.4.9 Combined constraint layers

The following constraint layers with excluded areas for wind farm development were combined into a single mask layer (raster format) using the raster calculator functionality within GIS:

- Land cover
- Elevation
- Slope (20 % threshold for wind)
- Surface water
- Protected nature
- Protected heritage sites
- Airports (15 km buffer)
- Existing wind farms and solar parks (optional)

The following constraint layers with excluded areas for PV development were combined into a single mask layer (raster format) using the raster calculator functionality within GIS:

- Land cover
- Elevation
- Slope (5 % threshold for PV)
- Surface water
- Protected nature
- Protected heritage sites
- Existing wind farms and solar parks (optional)

Each individual constraint layer is a binary mask layer in raster format with a pixel resolution of 500 m, in which a pixel of unavailable land is designated a value of 0 and a pixel of available land is designated a value of 1. The constraint layers are combined by multiplication using the raster calculator, where the values of intersecting pixels across the constraint layers are multiplied with one another. Therefore, if any of the individual constraint layers presents a pixel as unavailable land (0-value), the pixel will be designated as unavailable land in the combined constraint layer as well. Only if all individual constraint layers assign a pixel as available land (1-value), will it also be assigned as such in the combined constraint layer.

Important to note is that the analysis excludes internationally disputed territories, considering that not all sourced geodata is available for those regions in international databases as well as to avoid the risks of development of critical infrastructure in those regions.

2.4.10 Land availability factor

The land availability score is calculated per 5 km by 5 km POA using the zonal statistics functionality in GIS by overlaying the combined constraint layer of both wind and PV by the national grid and by calculating the ratio of 1-value pixels within each 5 km by 5 km grid cell. As this procedure is performed on two versions of the constraint analysis, one including and the other excluding existing plants as a constraint, this procedure results in 4 land availability maps with a spatial resolution of 5 km, with each cell assigned a score between 0 and 1, where 0- value cells indicate that only excluded areas are present within the boundaries of that cell and hence no project development is feasible in that area, and where 1-values indicate that the cell does not contain any restricted areas for project development.

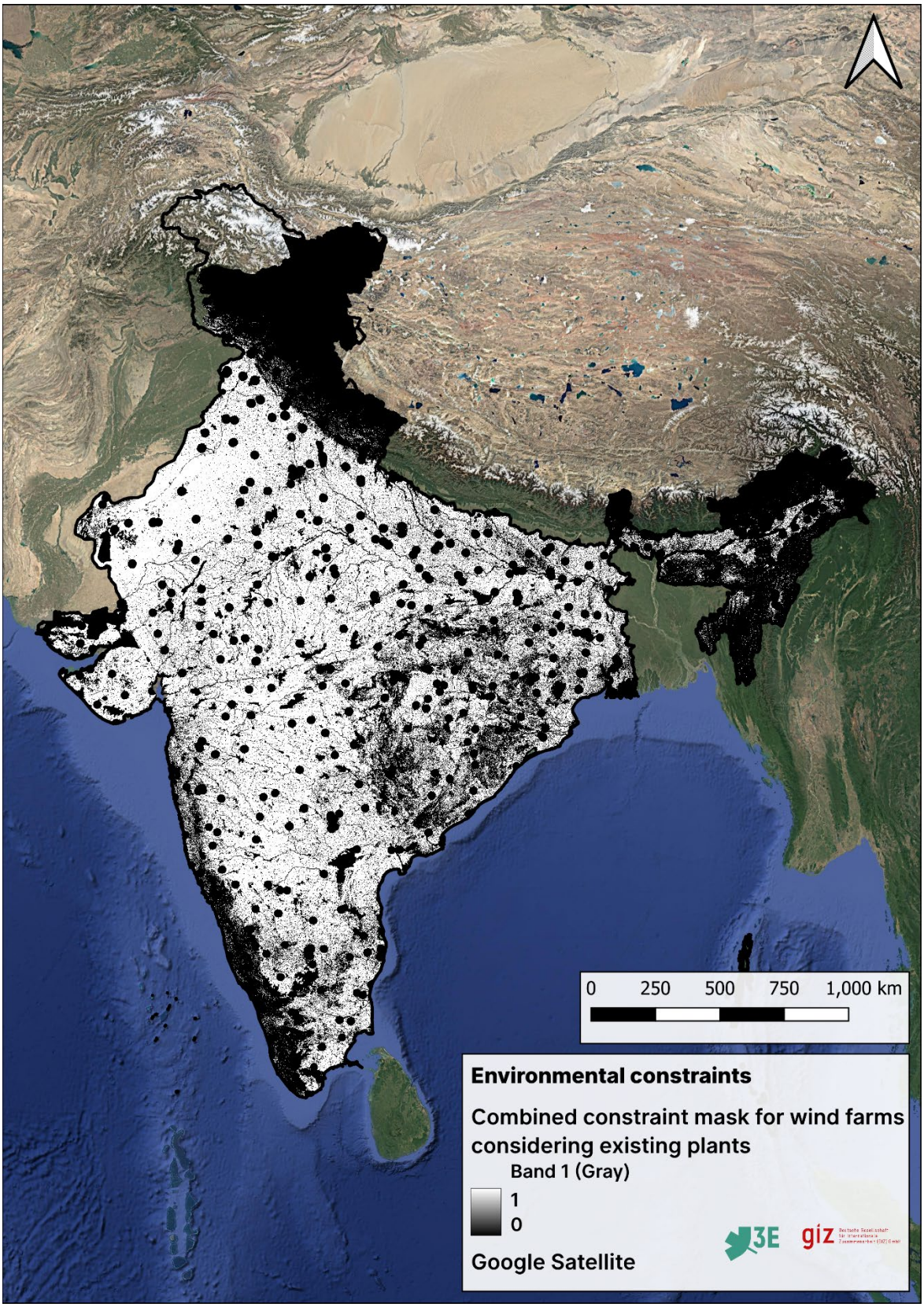


Figure 7: Summarized constraint mask (spatial resolution of 500m) for wind projects, considering the criteria of terrain, protected areas and existing wind and PV plants. Black denotes excluded areas.

3 Results

The POA attributes are discussed in Section 3.1, while the final POA score maps for both wind and PV are presented in Section 3.2.

3.1 POA Attributes

The respective maps of the individual POA attributes are presented in ANNEX A.

3.1.1 Average electricity generation

The high scores for wind are mainly concentrated in the western states (Gujarat, Maharashtra, and Rajasthan) and southern states (Andhra Pradesh, Karnataka, Tamil Nadu, and Telangana). The production values for a POA zone are distributed around 200 TWh with a minimum close to 670 MWh and a maximum close to 1,100 TWh.

Concerning solar production, most of the country POA produce between 800 TWh and 900 MWh with minimal values around 485 TWh and maximal values around 1,000 TWh. The highest production values are located in Rajasthan, Gujarat, Maharashtra and Madhya Pradesh.

3.1.2 The Levelised Cost of Electricity (LCOE)

Concerning the results obtained for the costs of production from wind energy, it appears that the favourable zones are concentrated on the western side of the country, and mainly in the state of Gujarat and partly in Rajasthan. The state of Tamil also shows good opportunity zones but on less extended areas. This can be explained by the existence of road and grid infrastructure as well as good wind energy resource. It appears that the northern territories are also zones where the LCOE is relatively low. Those areas will nevertheless be excluded by the constraint mask. The LCOE highest values are located in the most remote places in the country.

In comparison, the average electricity generation maps show a similar trend as those of the levelised cost of electricity. This shows that the LCOE is mainly driven by the resource availability rather than proximity to ports, roads and grid infrastructures.

Regarding solar analysis, the resource is largely more profitable than wind, as most of the country shows relatively low and less variable LCOE. However, it appears that the best sites are also concentrated in the western and northern parts of the country. This is positive considering the potential of mutualising the cost of development of wind and solar projects close to one another.

3.1.3 Distance to existing plants map

Concerning the wind map, a buffer of 10 km has been taken from every plant to account for the impact of wake on wind turbine net energy yield. It appears from the map that the existing plants extensively populate quite logically the most favourable zones in the country. However, as the final weight attributed to it in the AHP is relatively low, the impact of this criterion on the overall POA score remains small. Concerning the solar map, no buffer is foreseen and it can be seen that most of the country is already populated with solar farms quite homogeneously.

3.1.4 Land preference

The two dominant land cover classes are cropland and rangeland, which are also the two only classes that were not excluded in the analysis. However, while the analysis favours rangeland slightly over cropland, the surface area of cropland is more than twice that of rangeland. The lower score assigned to cropland does therefore reduce the favourability of cropland significantly.

Proximity to infrastructure plays a more limited role when compared to the land use factor, but while rangeland is often more remote compared to cropland, the infrastructure proximity does negatively affect this land cover type as opposed to rangeland which is generally less remote.

The state of Rajasthan is particularly noticeable for its higher land preference scores, mainly because the state is home to the most extensive rangeland found in India because of its more arid and semi-arid environments.

3.1.5 Slope gradient

The analysis and the results for the slope attribute indicate that most of the Indian mainland (about 80% of the total surface area) has an altitude gradient of 2% or lower. The slope threshold is more restrictive for PV as wind turbines have a smaller footprint than solar panel fields. Nevertheless, the associated sores are relatively high for both technologies due to the large availability of simple terrain across India. Obvious low-scoring zones are the mountain ranges in the north of the country, but also the southwestern coastline and forested areas in the more central areas of the country.

3.1.6 Complementarity score (Wind)

This map, only used for the ranking of preferred sites for wind farms, shows that the most favourable regions in terms of complementary of the two renewable sources are located in the central areas of the country. Hence, it overlaps with most preferred zones in terms of LCOE and electricity generation areas for both wind and solar. This allows to locate all new wind and solar sites in similar areas, reducing the combined LCOE for both resources.

3.1.7 Land availability

In general, the terrain restrictions in elevation and slope play the largest role in defining land availability, while with regards to land cover, only forested areas and surface water (lakes and river systems) provide significant restricted areas across the mainland. As protected heritage and nature sites are present in a more dispersed manner, they play a less significant role in the analysis.

For wind projects, restrictions with respect to radar systems and airfields play a significant role, while the slope gradient threshold for wind is less restrictive than for solar. However, mainland India consists in majority of relatively flat terrain, with the main exceptions being the mountainous regions in the northern parts of the country and the coastal areas in the southwest. The results of land availability for wind and PV are therefore rather similar.

3.2 POA score

3.2.1 Wind farms

The POA scores representing site suitability for wind projects present a clear divide between unfavourable zones in the northeast and favourable zones in the southwest of India. The final result aligns closely with the individual scored results of the electricity generation and LCOE, with the highest concentration of highly favourable sites being located in the northwest and the western areas of India being more favourable in general. The highest scoring POAs are located in Rajasthan's (semi-)arid regions.

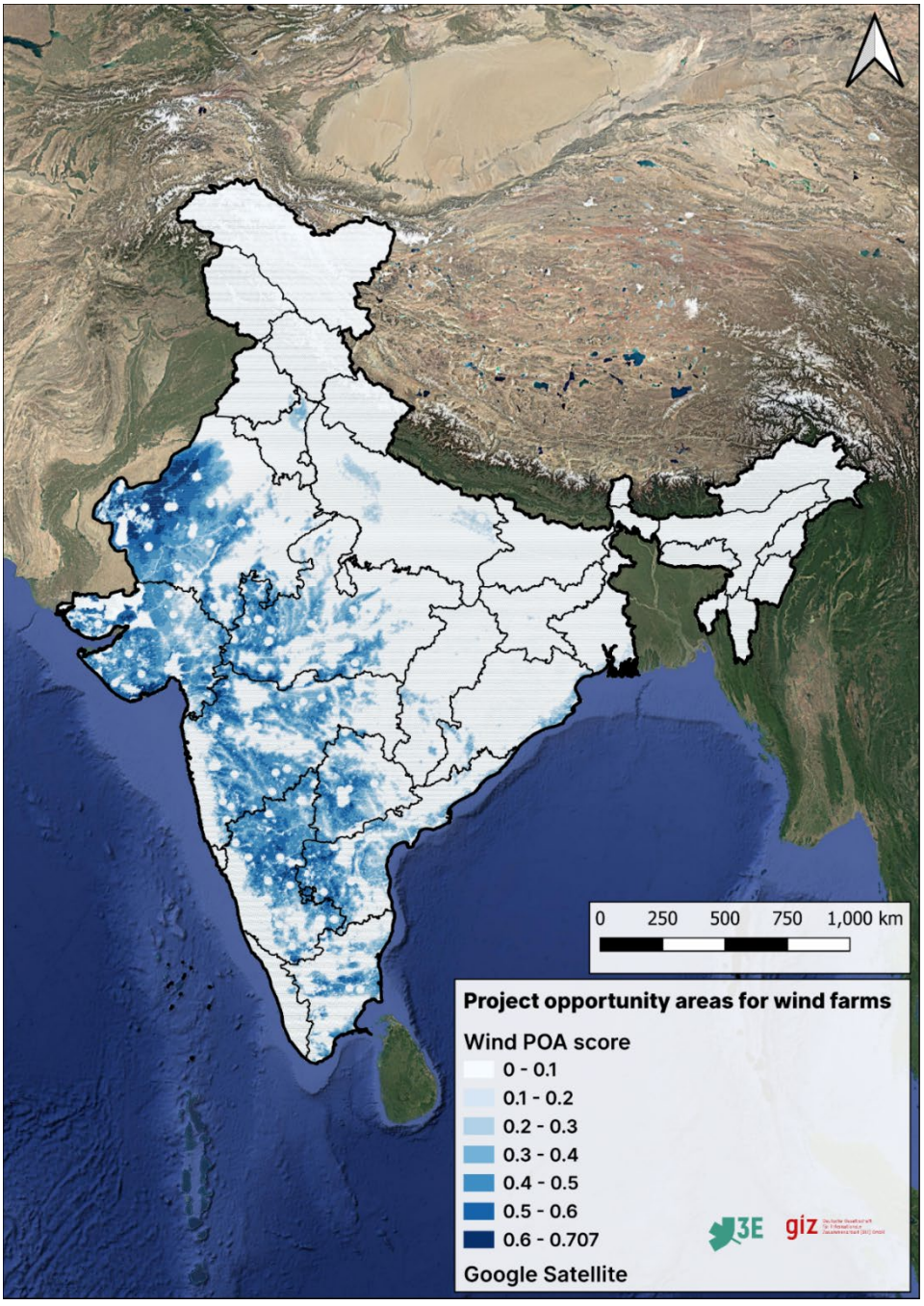


Figure 8: POA site suitability score distribution in India for wind farms (225 MW capacity)

3.2.2 PV

The POA scores representing site suitability for PV projects are in general more favourable across the nation as the solar resource shows less geographical variation than the wind resource. The final result therefore aligns closely with the land availability score, as the environmental constraints (and more specifically land use constraints) tend to play a more significant role than the resource. The highest scoring POAs are located in Rajasthan's (semi-)arid regions.

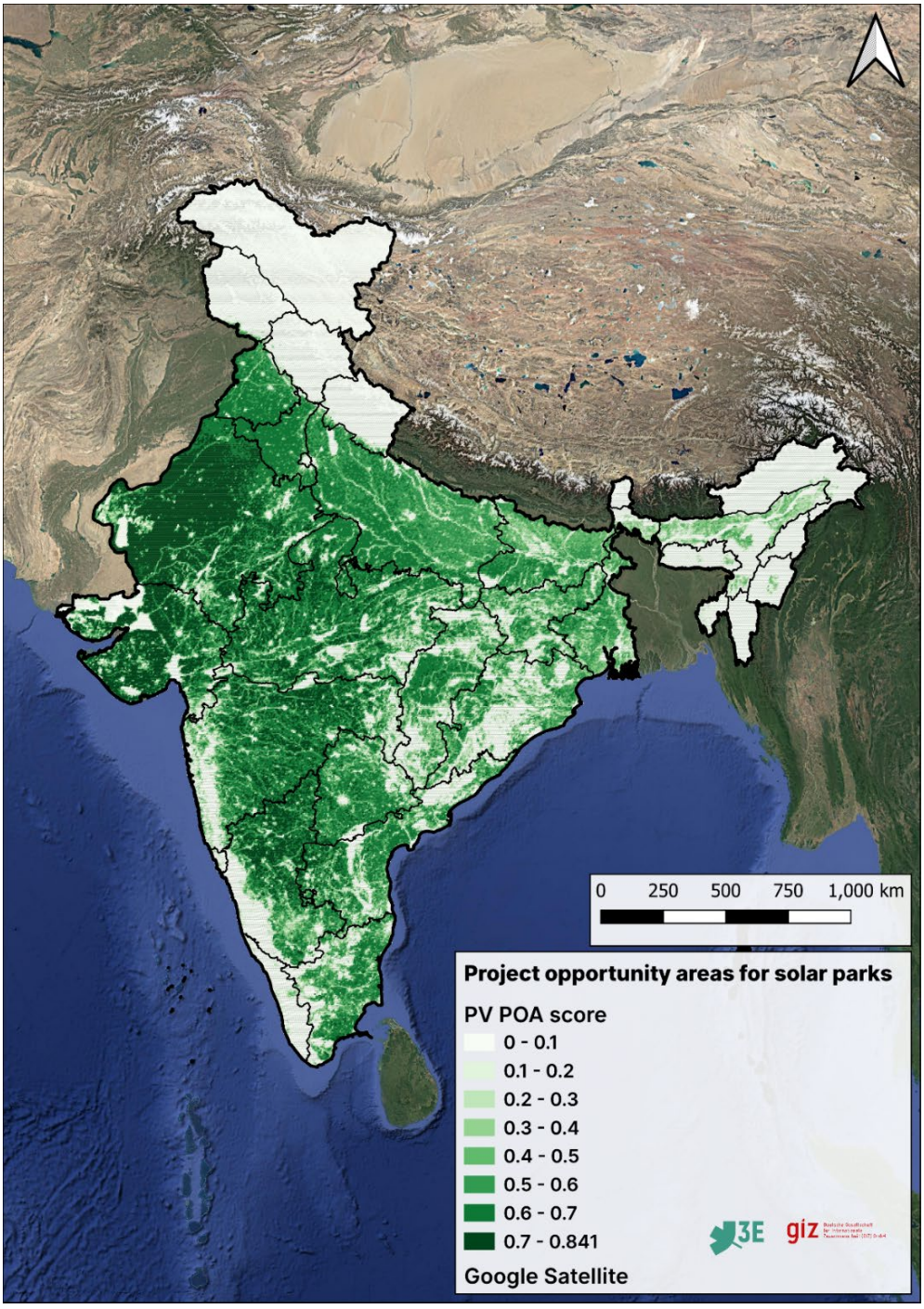


Figure 9: POA site suitability score distribution in India for solar parks (750 MW capacity)

4 Conclusion

Following this analysis, it appears that highly suitable areas are more localised for wind plants than for solar plants. This results in more heterogeneity in terms of LCOE for wind than for solar. Moreover, the wind resource is relatively low even in favourably identified zones while the solar resource has a higher potential for electricity generation, lowering its LCOE. In both cases, the most favourable regions are the northwestern states (Gujarat, Maharashtra and Rajasthan) with resource and land availability being the main drivers in terms of levelised cost of energy (LCOE) in zones not excluded by the constraints mapping. Indeed, in terms of electricity generation only, the eastern part of the territory above the Himalayan chain shows high values but the high slopes, altitudes and difficulty of access forbid the use of this land for the construction of utility-scale wind and solar farms.

The regional cross-technology overlap of high-scoring POAs in the northwestern states provides a good opportunity to combine both technologies in those regions. The most favourable locations are thus located on the opposite side of the selected location for the methanol production site planned in the state of Odisha. However, in the hypothesis of single grid operation for India, the geographical proximity of the new renewable energy sites with respect to the methanol production site is not a necessity. This hypothesis must be respected when developing large renewable energy projects as the spatial unevenness of the renewable energy resources requires transmission lines transporting the electricity across the country to share the energy and make it reliable to use large amount of renewable energy despite their variability.

Additionally, most of the favourable zones are located on agricultural land, which could result in social friction but would allow diversifying the use of the land. This could be solved by policies encouraging wind development through incentives such as land leasing and revenue sharing.

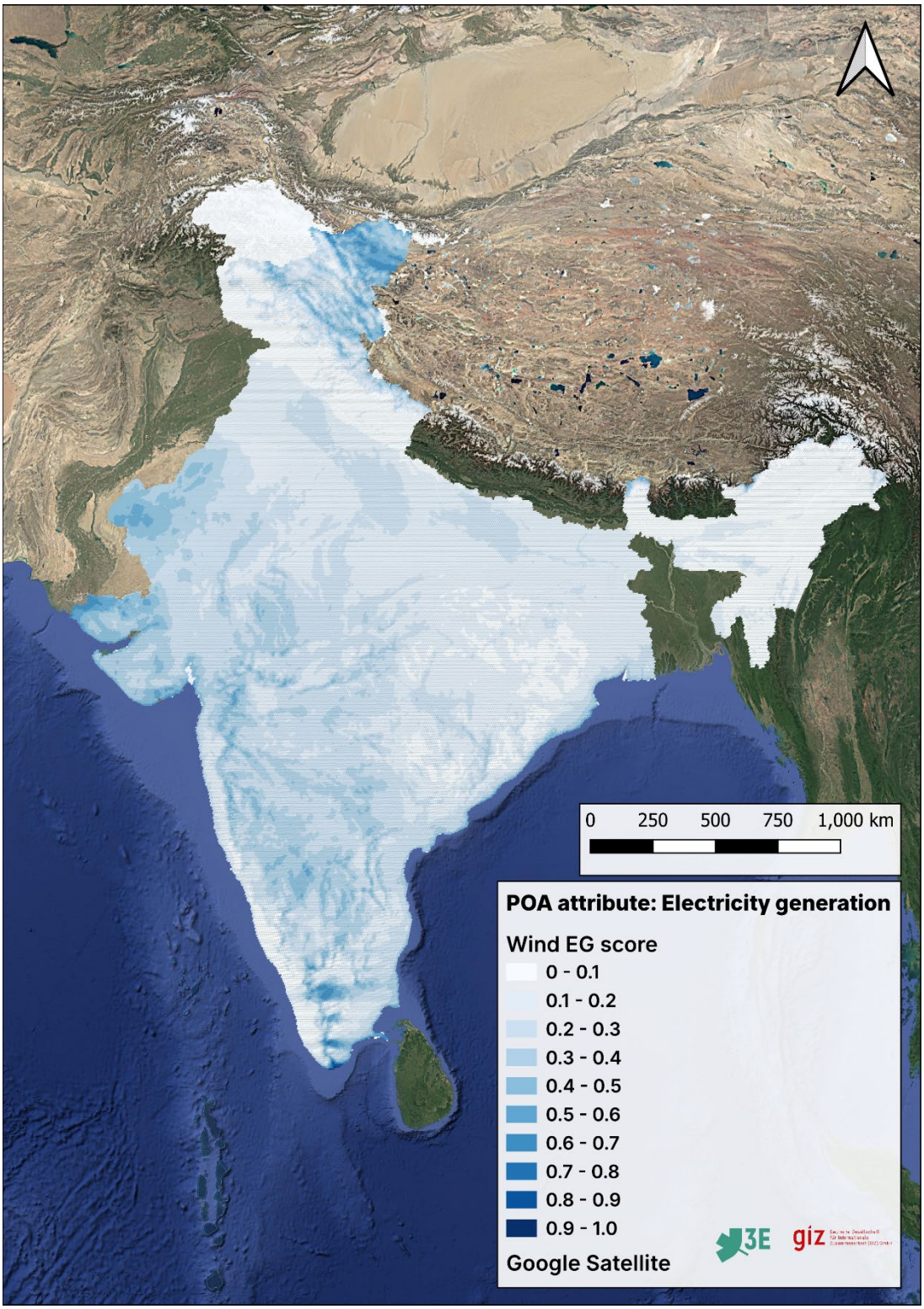
The results are limited by the uncertainties associated with the input data in terms of resolution and accuracy and by the generic hypotheses made in terms of technological choice and for the pairwise preference weights of all selected attributes. These maps are aimed to be integrated into a web user interface that allows users to identify the attributes of the different zones. As the methodology at this stage is purely the result of internal stakeholder discussions, it should therefore be further optimised through consultations of external stakeholders, e.g. in the fields of green hydrogen, renewables and grid experts, especially regarding the prioritisation or weighting of the different observed criteria.

References

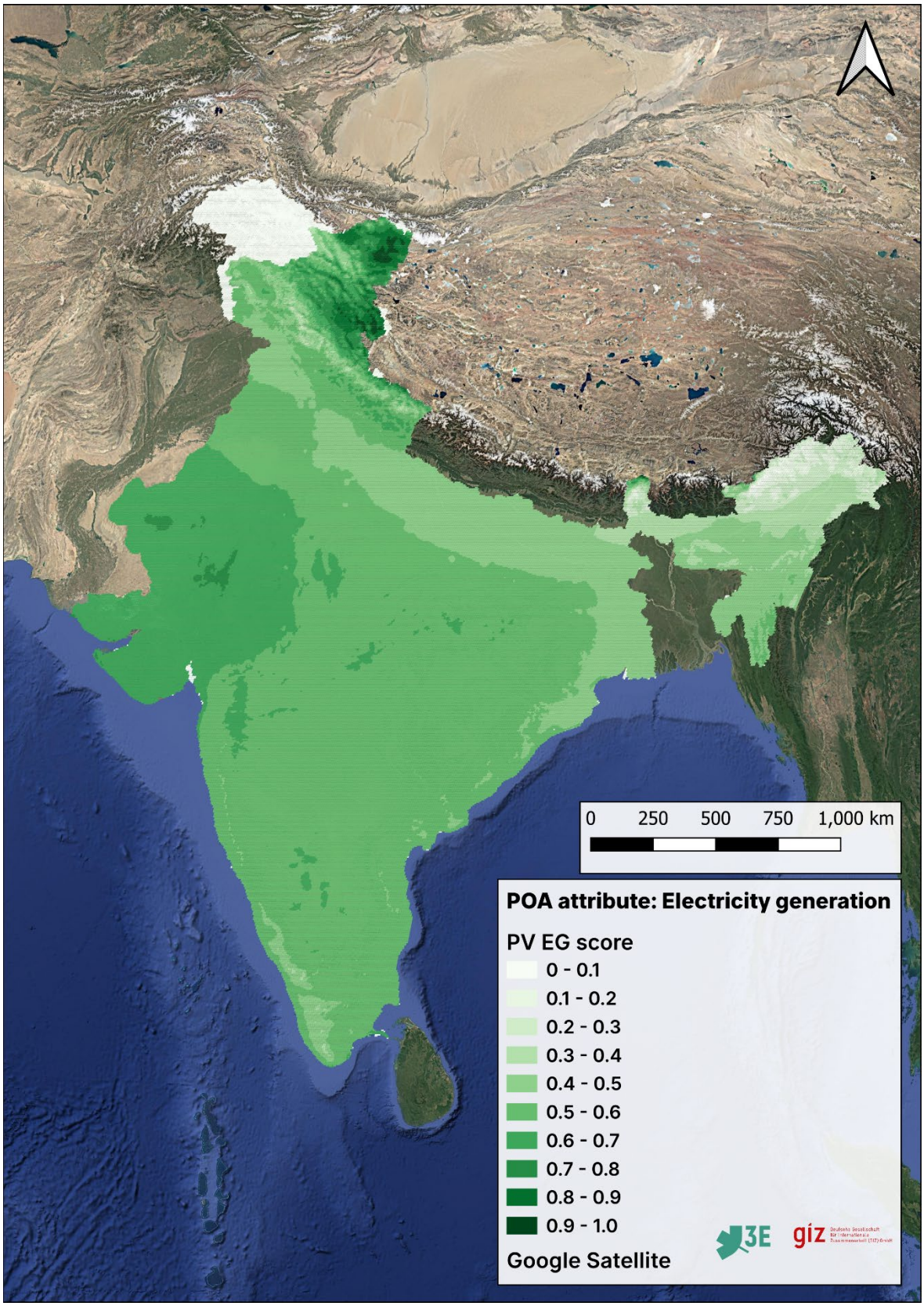
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ANNEX A POA attribute maps

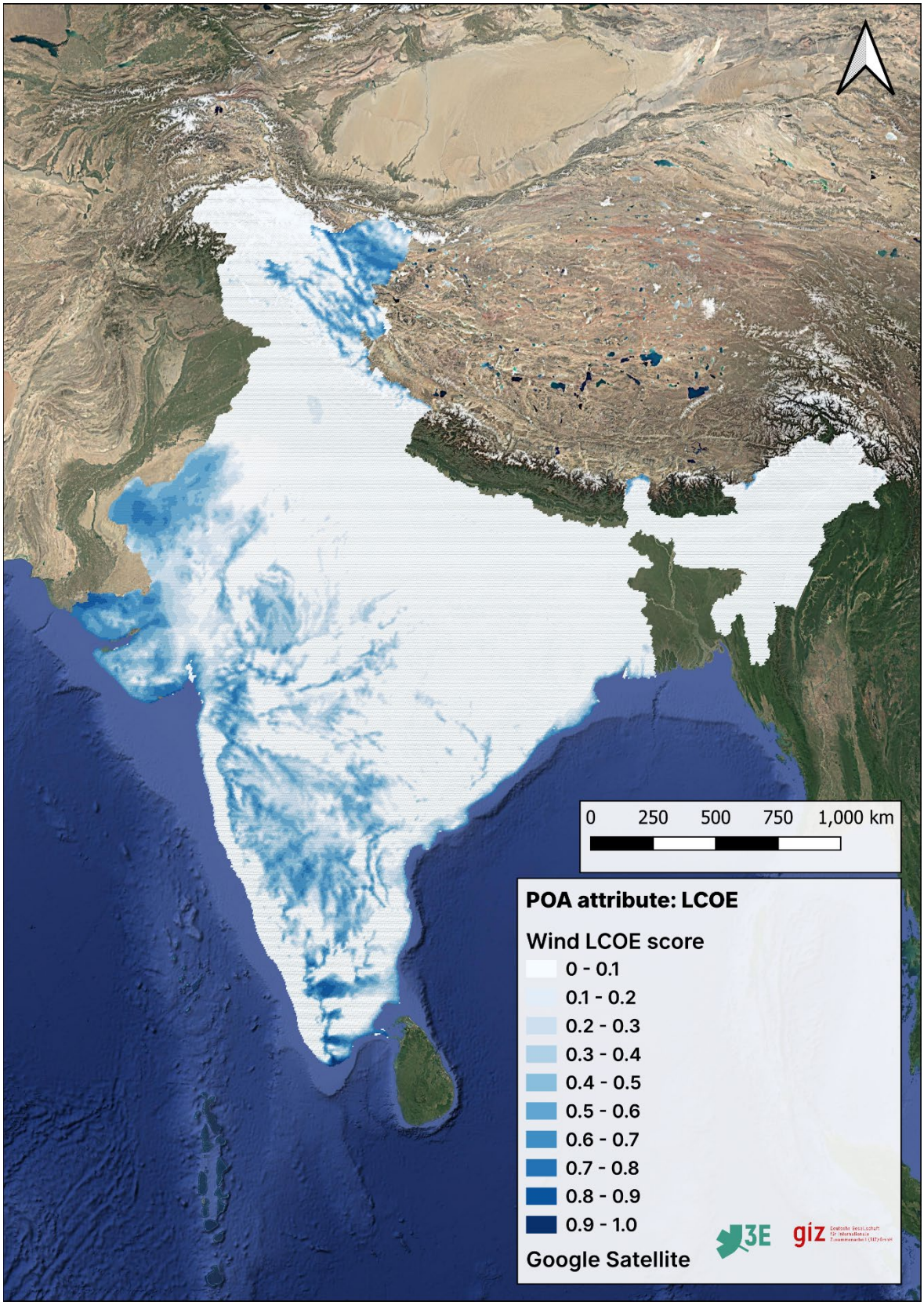
Average electricity generation – Wind



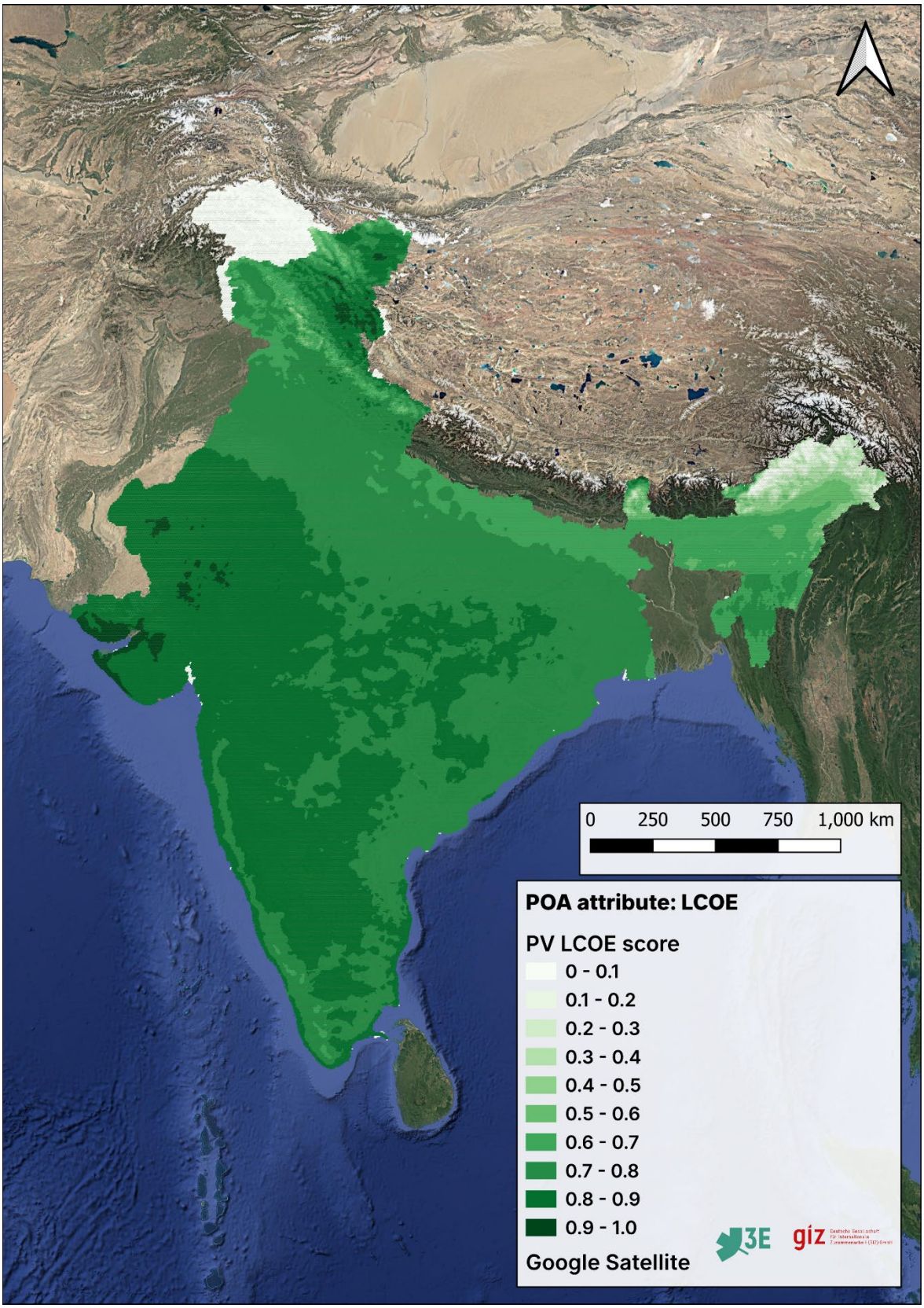
Average electricity generation – PV



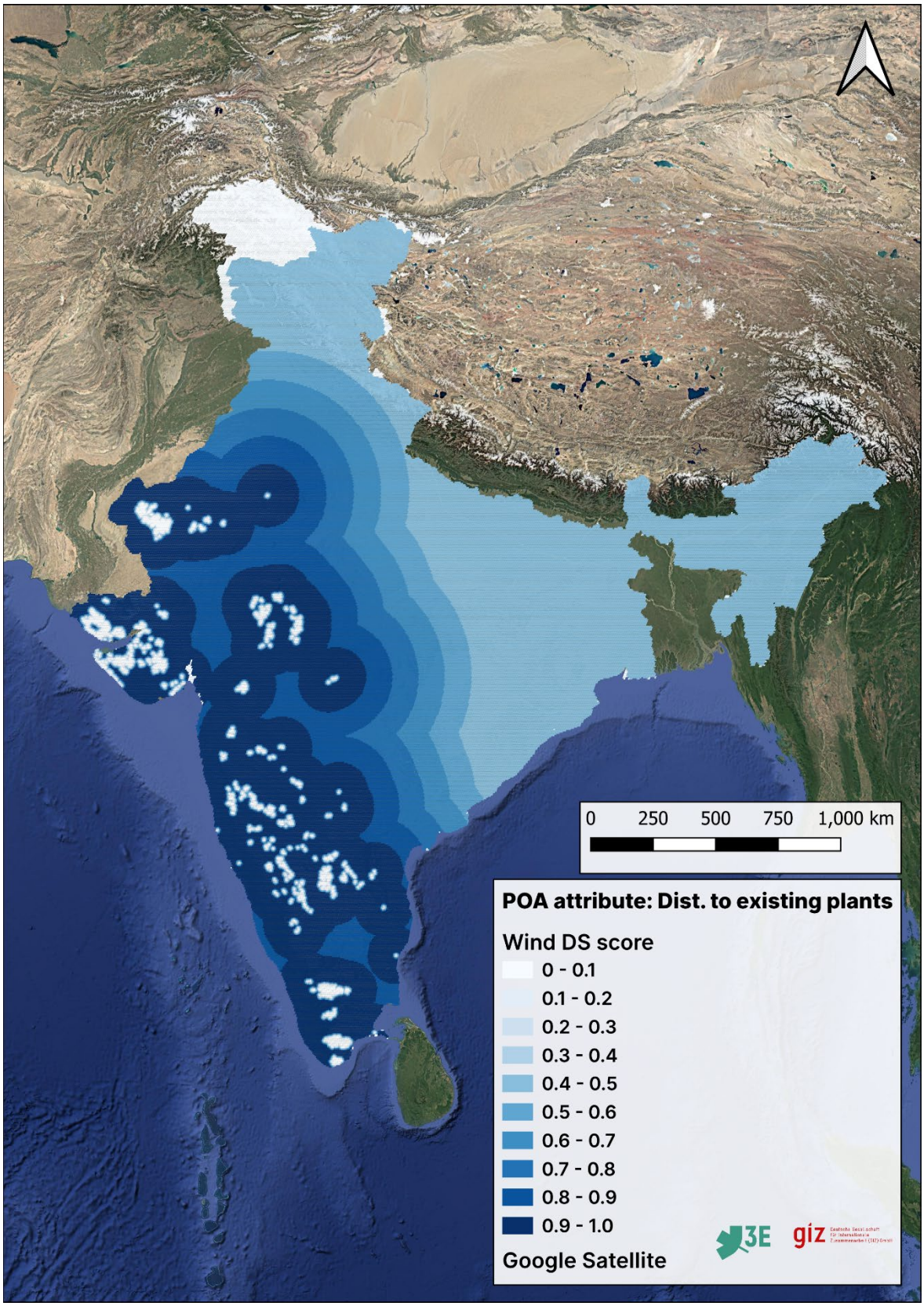
LCOE – Wind


0 250 500 750 1,000 km
POA attribute: LCOE
Wind LCOE score
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
Google Satellite
3E
giz

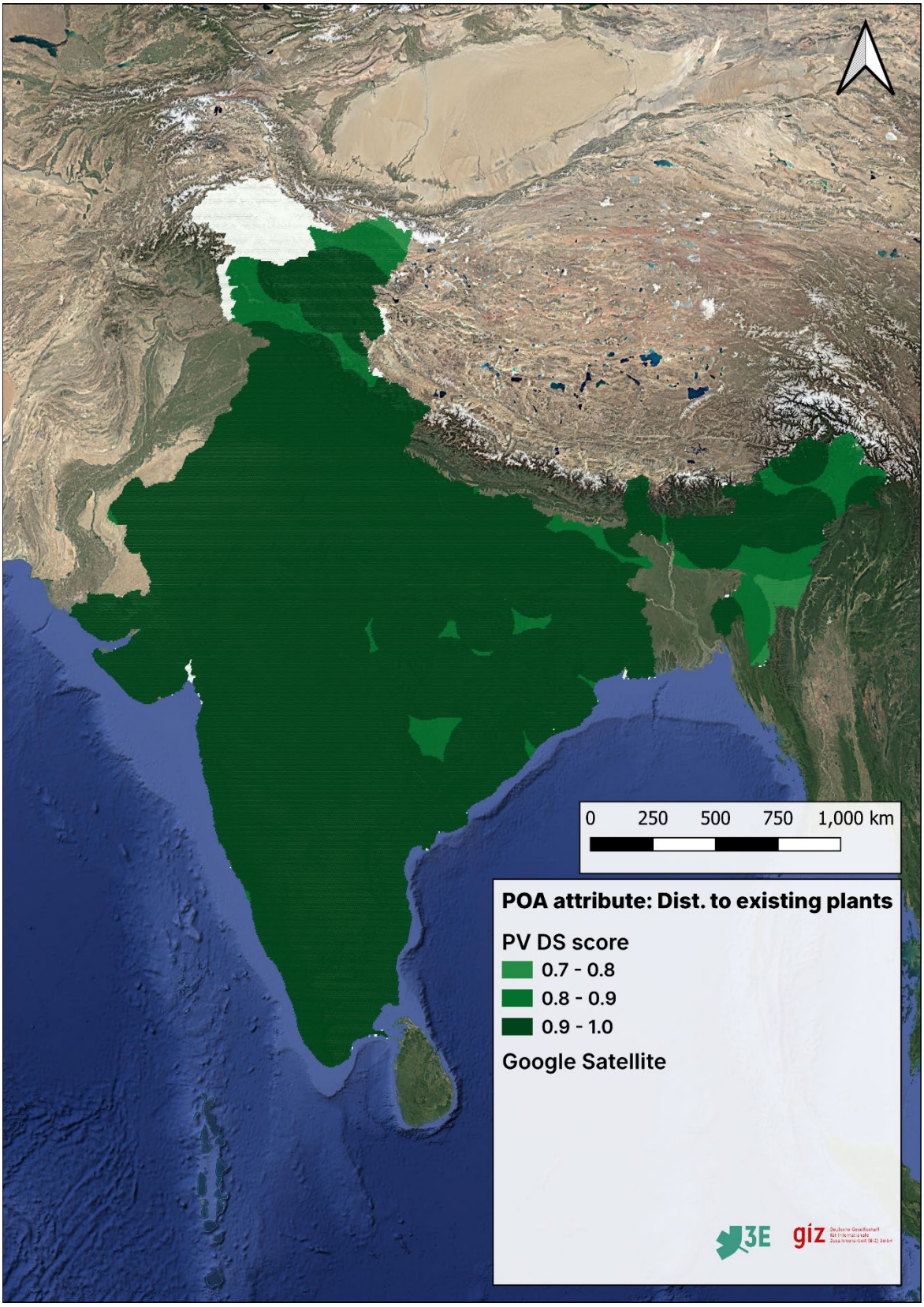
LCOE – PV


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POA attribute: LCOE
PV LCOE score
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
Google Satellite

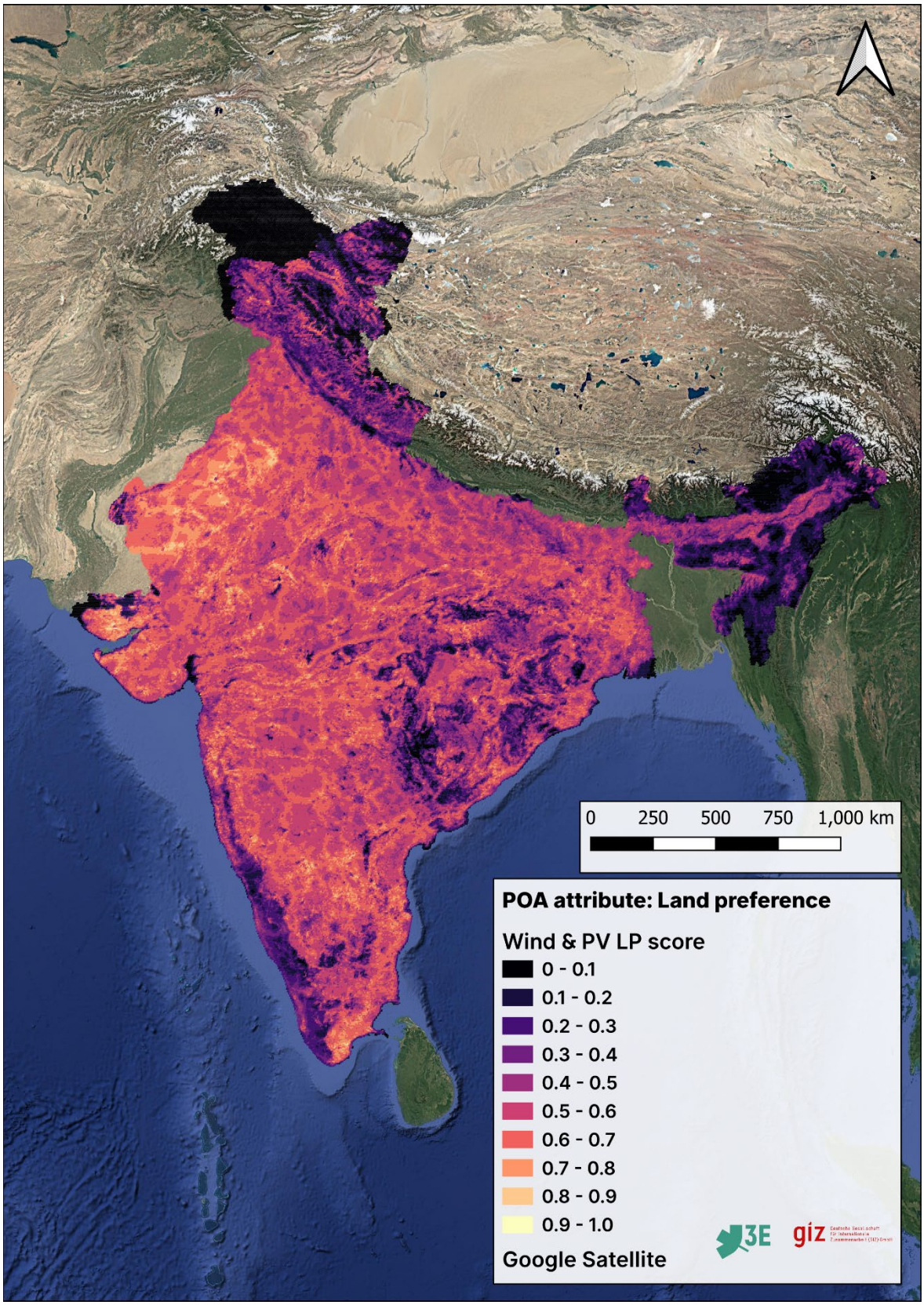
Distance to existing plants – Wind



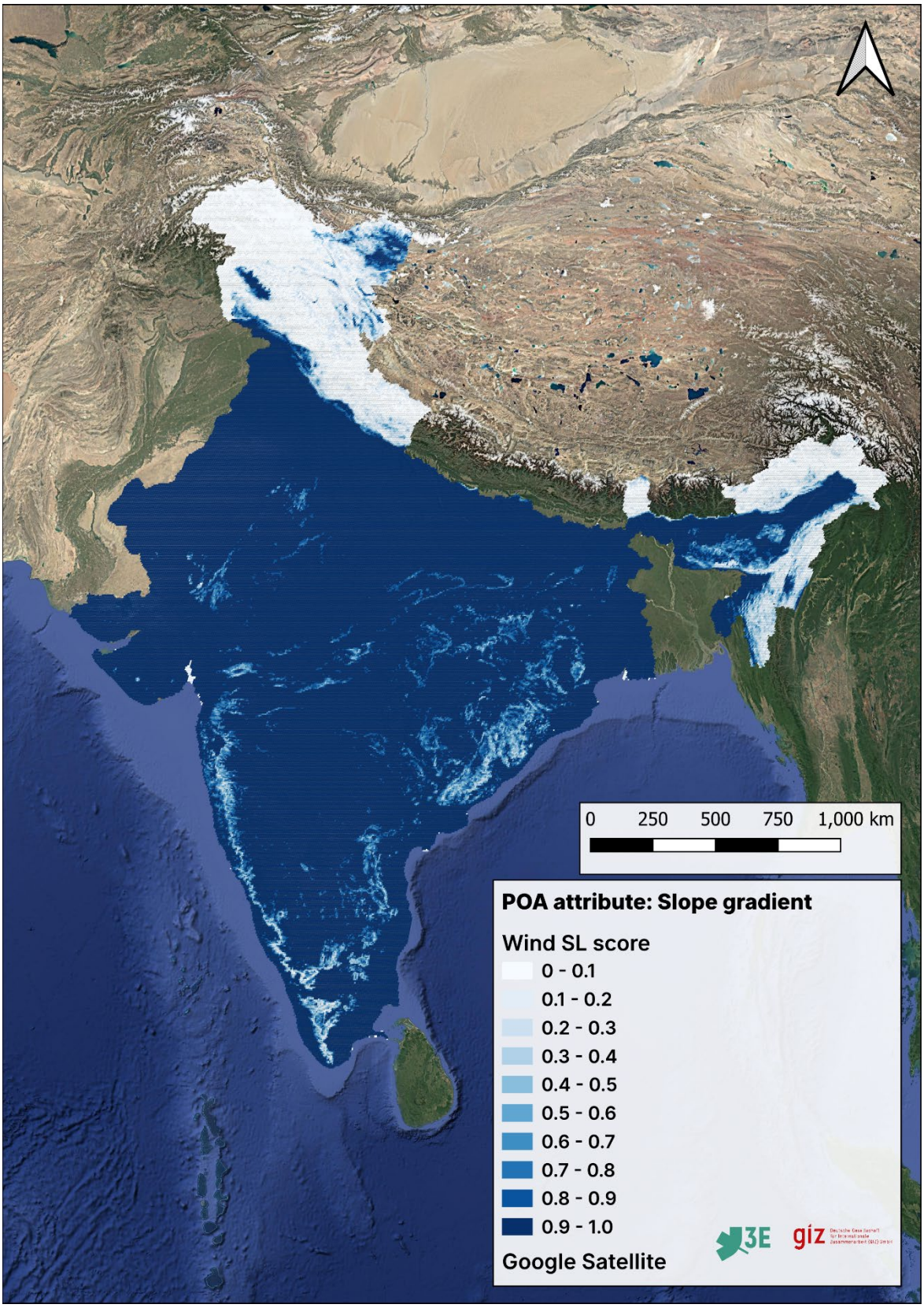
Distance to existing plants – PV



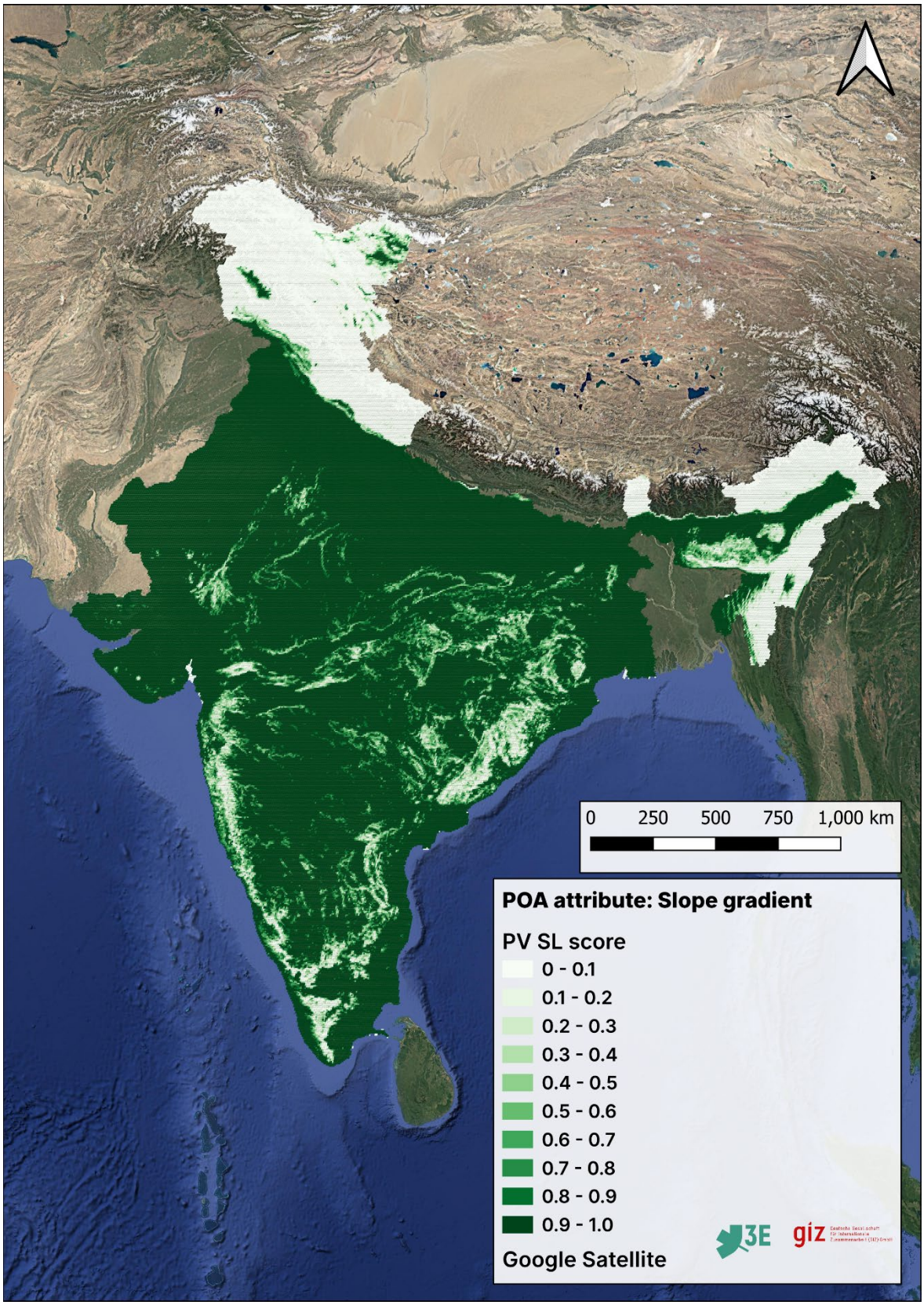
Land preference



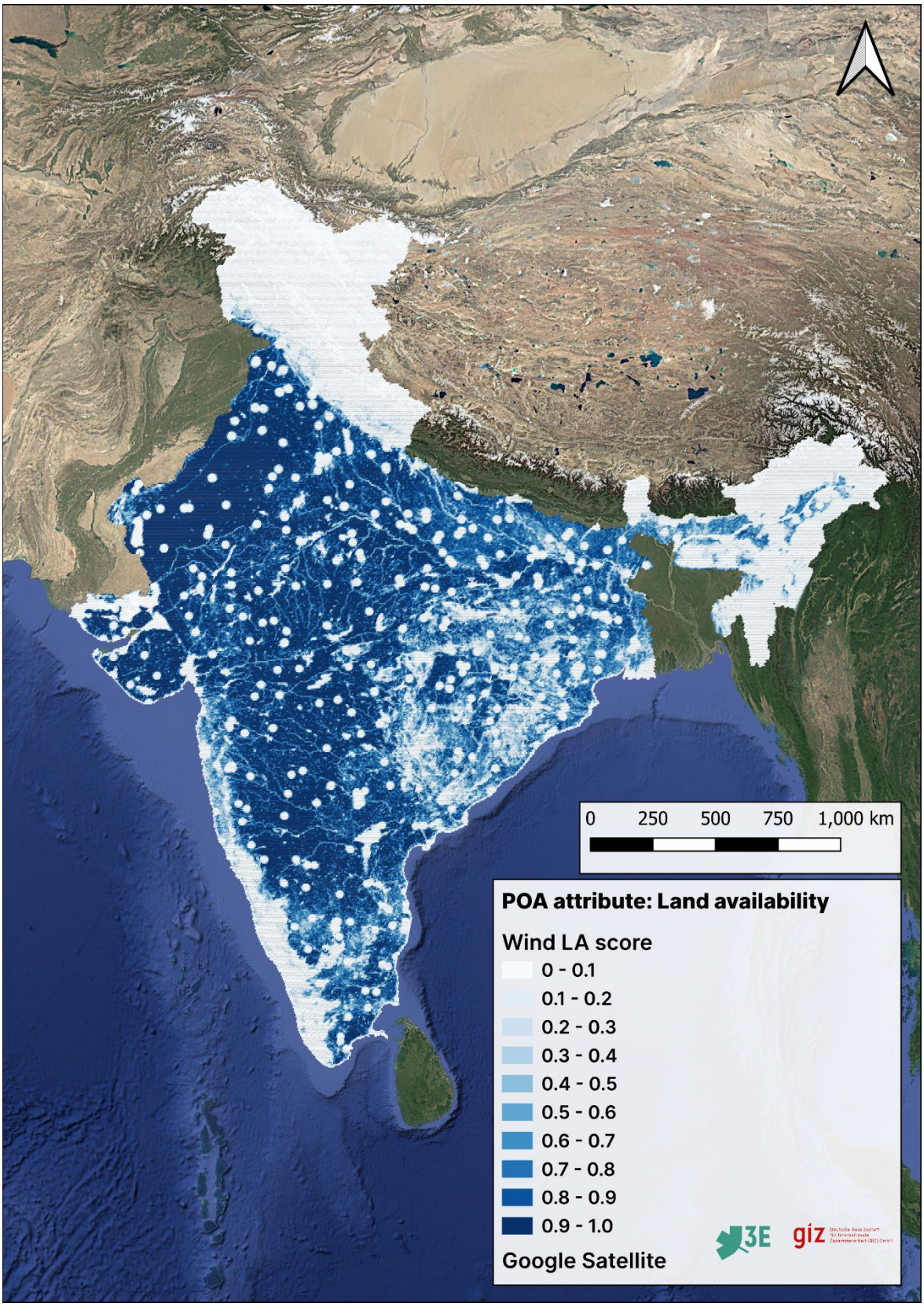
Slope – Wind


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POA attribute: Slope gradient
Wind SL score
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0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
Google Satellite
3E
giz

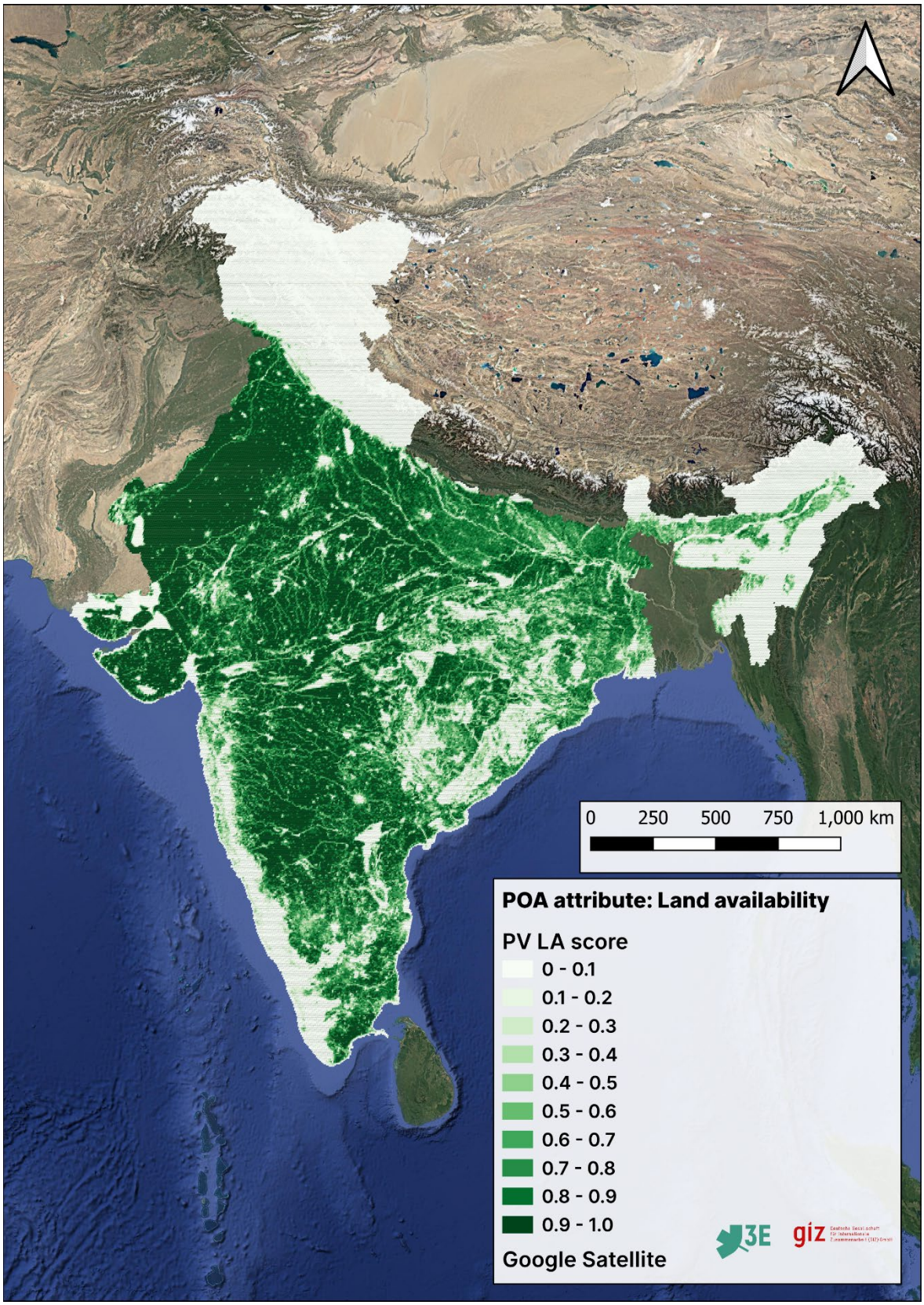
Slope – PV


0 250 500 750 1,000 km
POA attribute: Slope gradient
PV SL score
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0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
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0.7 - 0.8
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0.9 - 1.0
Google Satellite

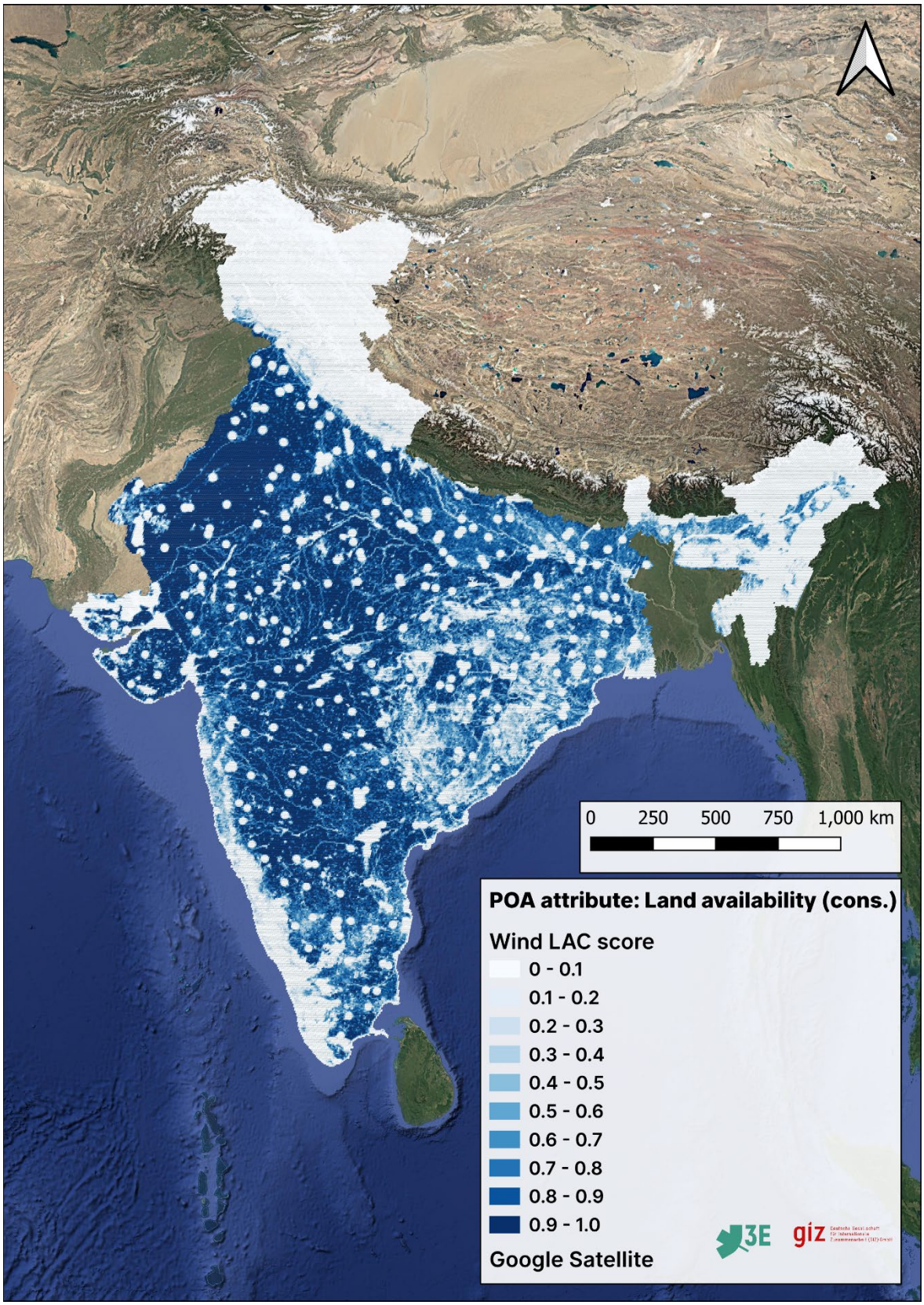
Land availability factor – Wind



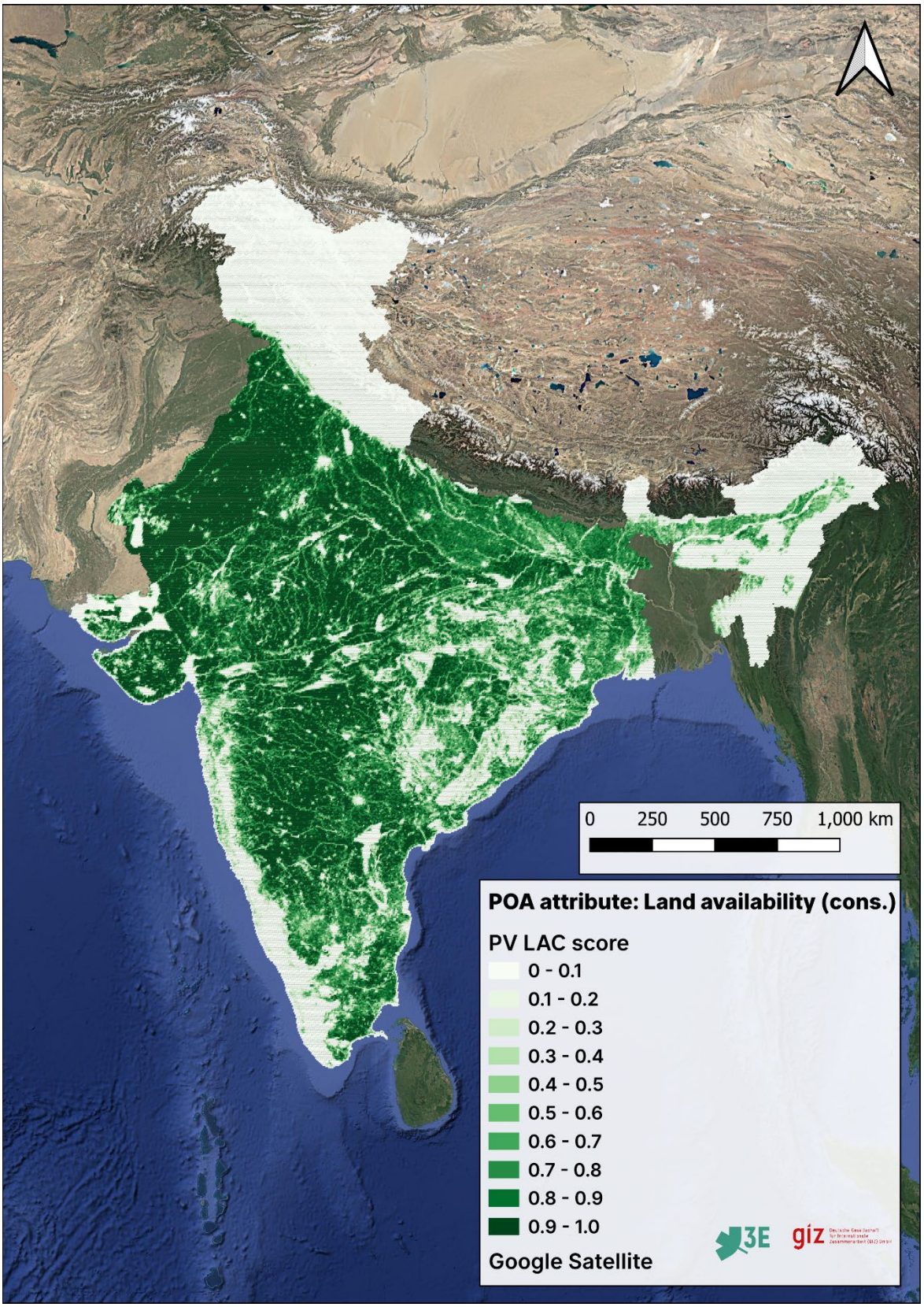
Land availability factor – PV



Land availability factor – incl. existing plants – Wind (conservative)



Land availability factor – incl. existing plants – PV (conservative)





The International Hydrogen Ramp-up Programme (H2Uppp) is supporting entrepreneurial engagement in the ramping-up of hydrogen in the Global South and is a funding programme of the:

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Zusammenarbeit (GIZ) GmbH