

Sustainable Energy Week Yerevan. June 2017



Solar resource assessment for PV applications in Armenia



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The Consortium



irsolav



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The Project



2. The Project. Objective

RFP NO.: SPP-CS-1/2015 "SOLAR RESOURCE MAPPING AND SITE SELECTION FOR SOLAR PV POWER PLANTS: ARMENIA"

- **What:** Improvement of solar resource knowledge for Armenia.
- **How:** Elaboration of Solar Atlas and identification of suitable sites for solar power plants.
- **Why:** Strengthening of Armenian Government to make decisions on the solar energy sector. Enhance bankability of solar projects.



2. The Project. Planning

1. Inception

Previous knowledge on solar resource

Necessity to produce updated and validated solar atlas

Methodology for satellite estimation of solar resource

Methodology for PV potential estimation

Methodology for site selection to install ground measurement stations

Task 3 Implementation plan

Recommendations for O&M of ground measurement stations

Methodology for solar map update

Methodology for site selection for PV power plants

2. Preliminary Solar Map

3. Ground-based data collection

4. Validated Solar Atlas

5. Site Selection for PV plants



2. The Project. Schedule

Task	Months															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1: Inception																
2: Preliminary Map																
3: Measurement Campaign																
4: Validated Atlas																
5: PV sites selection																
Capacity Building																

Task	Beginning Date	Accomplishment Date
1: Inception	Mid November 2015	Mid December 2015
2: Preliminary Map	Mid November 2015	Mid January 2016
3: Measurement Campaign	Mid May 2016	Mid May 2017
4: Validated Atlas	Mid May 2016	Mid February 2017
5: PV sites selection	Mid November 2016	Mid March 2017

- 5 Tasks
- 16 Months: end of project by **March 2017**
- 4 months delay in beginning of Measurement Campaign



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The Project. Task 1: Inception



2. The Project. Task 1: Inception

Previous available information: Satellite Data

PVGIS (JRC)



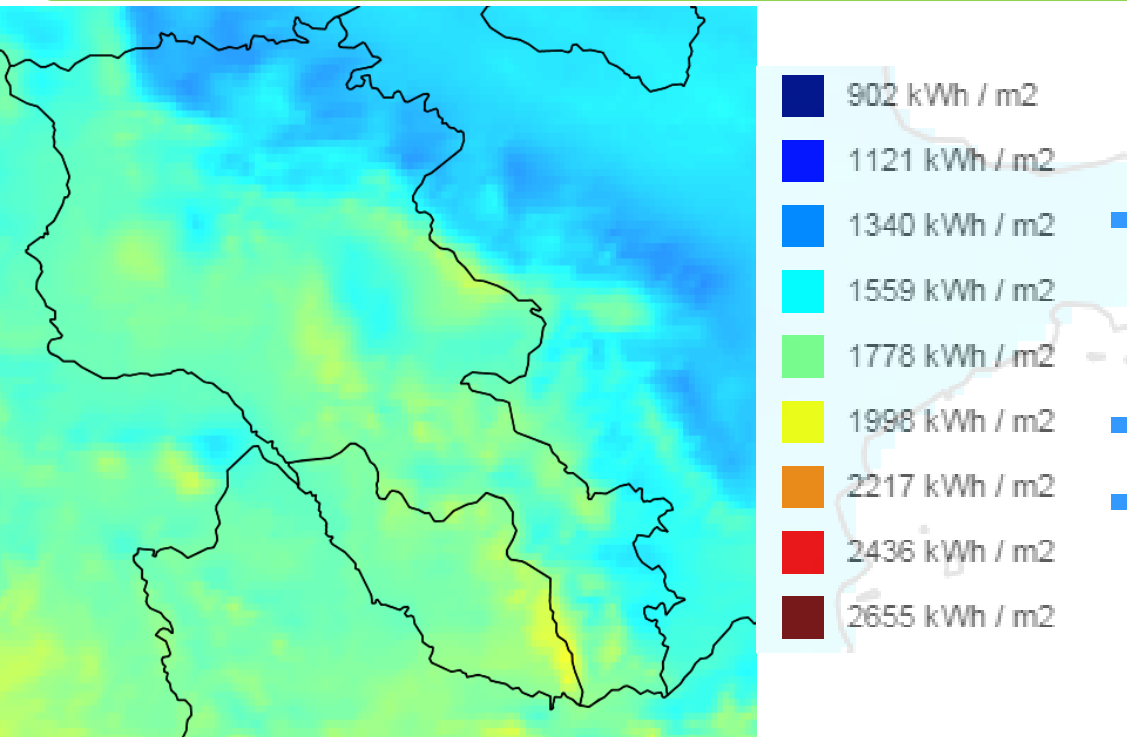
- Web-based tool:
<http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa&lang=en#>
- 1985-2004
- 5km spatial resolution
- GHI, GTI (not DNI).



2. The Project. Task 1: Inception

Previous available information: Satellite Data

Helioclim 3



*Global Wind and Solar Atlas
from IRENA*

(<http://irena.masdar.ac.ae/>)

■ GHI. 2005

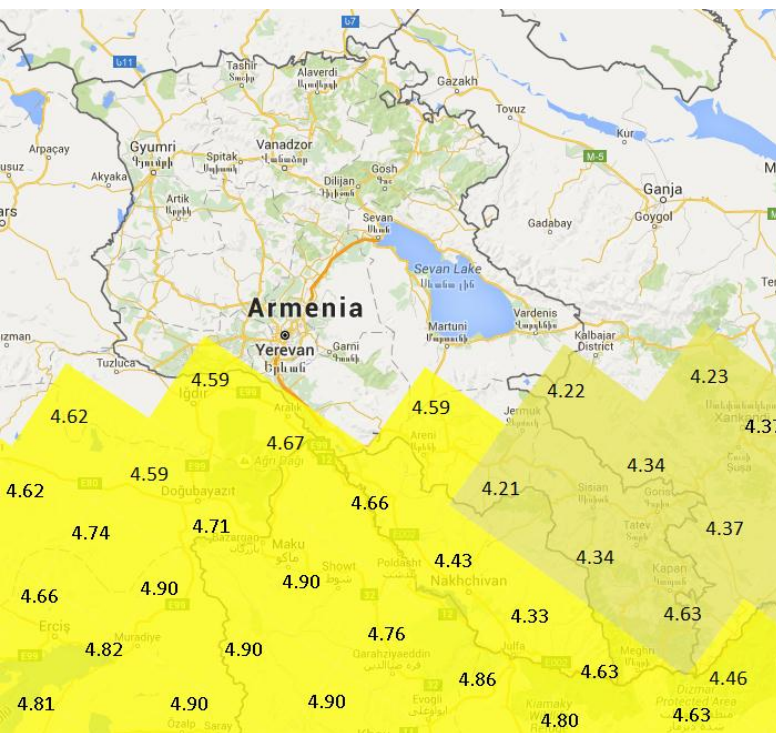
■ 30km spatial resolution



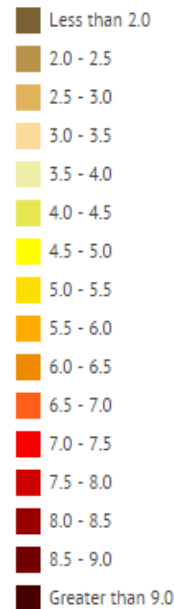
2. The Project. Task 1: Inception

Previous available information: Satellite Data

NREL



GHI NREL Moderate Resolution
(kWh/m sq. per day)



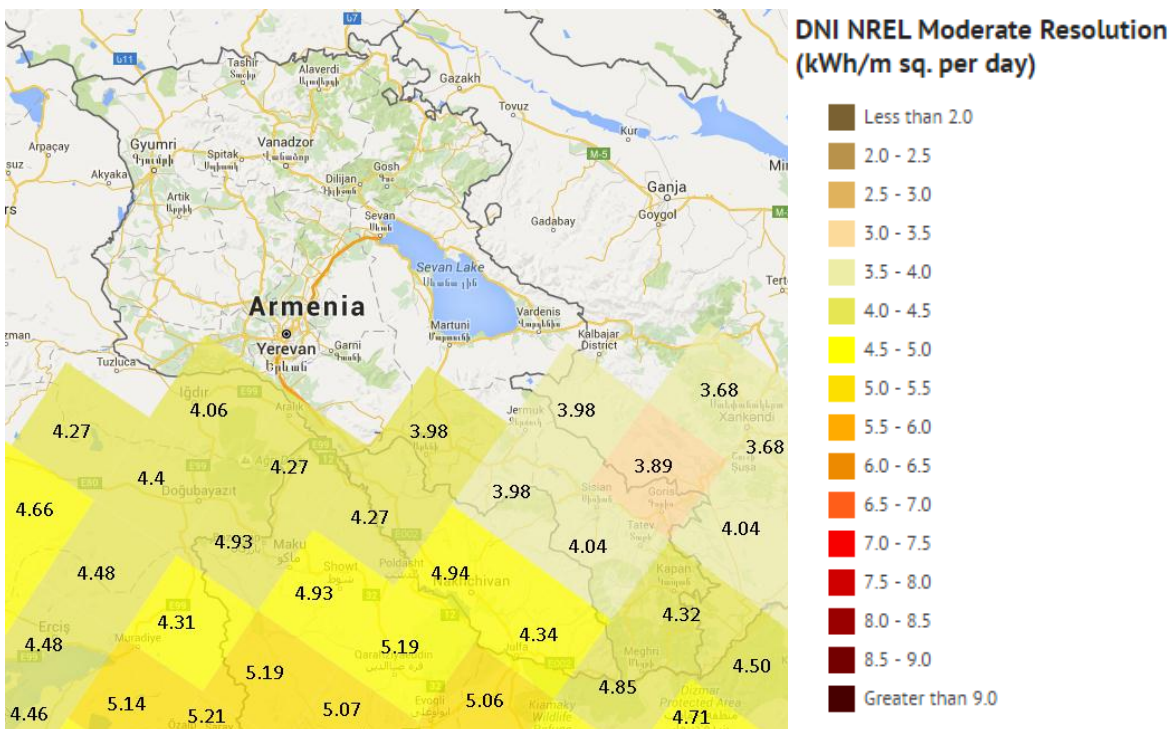
- **SWERA:**
<http://maps.nrel.gov/swera>
- **GHI. Yearly Mean**
- **1985-1992**
- **40km spatial resolution**



2. The Project. Task 1: Inception

Previous available information: Satellite Data

NREL



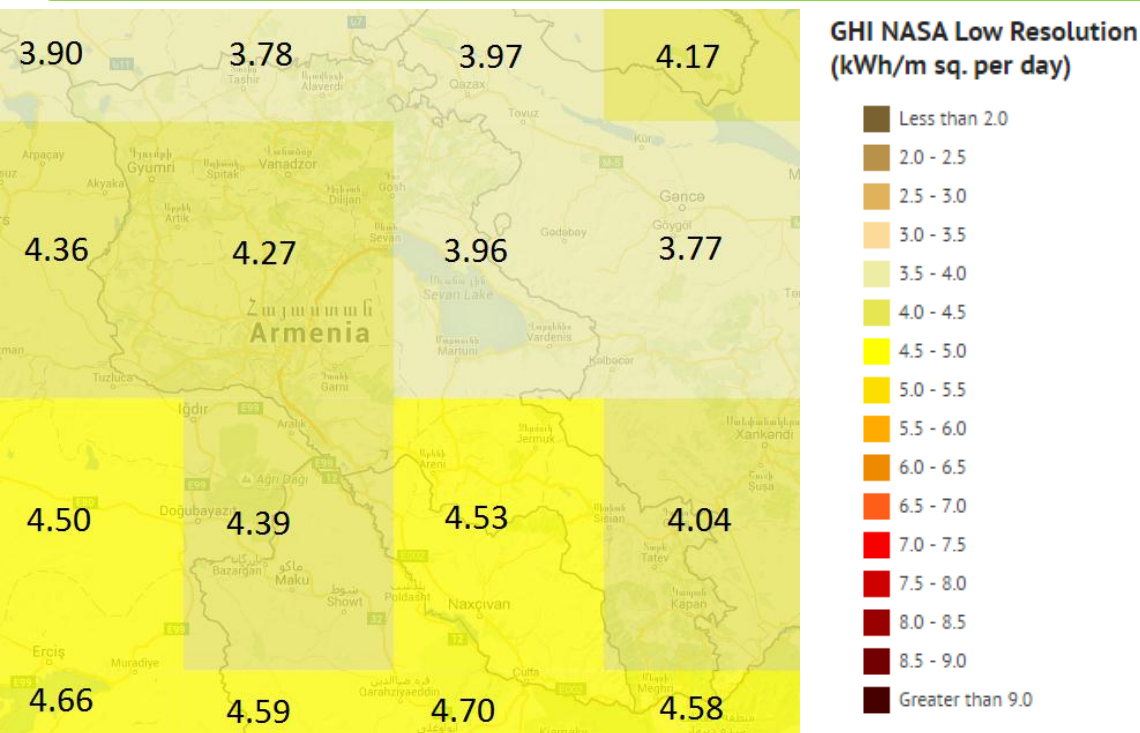
- **SWERA:**
<http://maps.nrel.gov/swera>
- **DNI. Yearly Mean**
- **1985-1992**
- **40km spatial resolution**



2. The Project. Task 1: Inception

Previous available information: Satellite Data

NASA



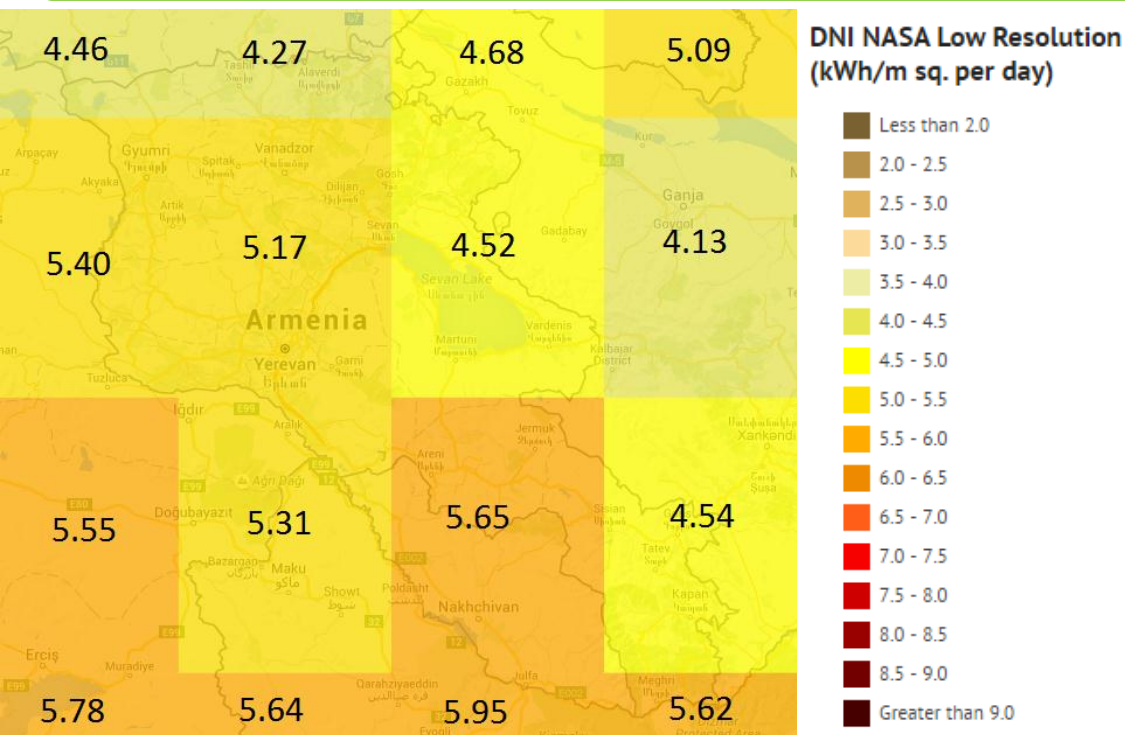
- **SWERA:**
<http://maps.nrel.gov/swera>
- **GHI. Yearly Mean**
- **1983-2005**
- **100km spatial resolution**



2. The Project. Task 1: Inception

Previous available information: Satellite Data

NASA



- **SWERA:**
<http://maps.nrel.gov/swera>
- **DNI. Yearly Mean**
- **1983-2005**
- **100km spatial resolution**

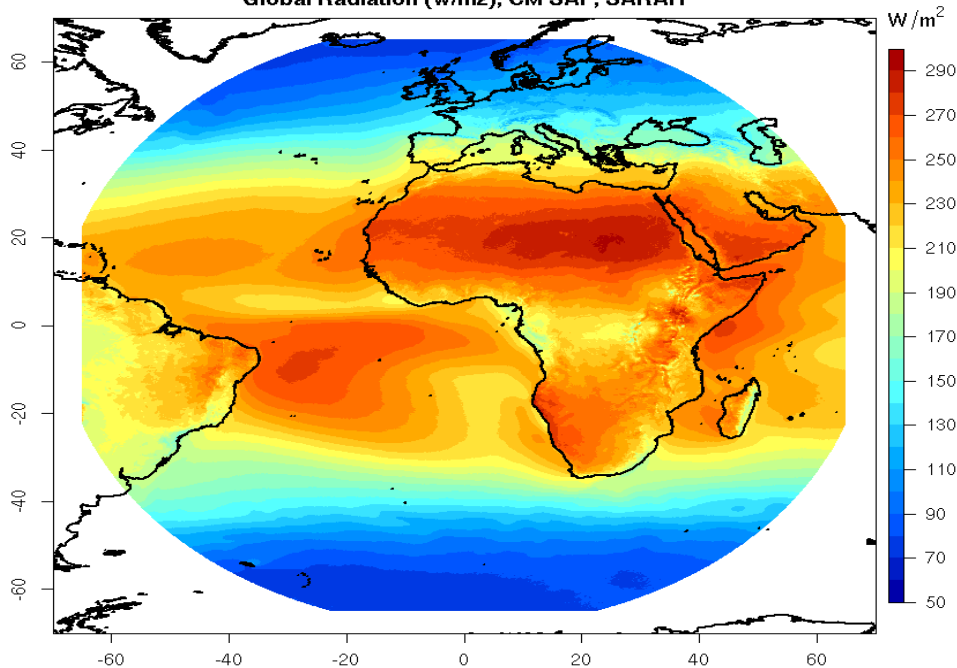


2. The Project. Task 1: Inception

Previous available information: Satellite Data

CMSAF (Eumetsat)

Global Radiation (W/m²), CM SAF, SARAH



- <http://www.cmsaf.eu/>
- GHI, DNI. Hourly Mean
- 1983-2015
- ~5km spatial resolution

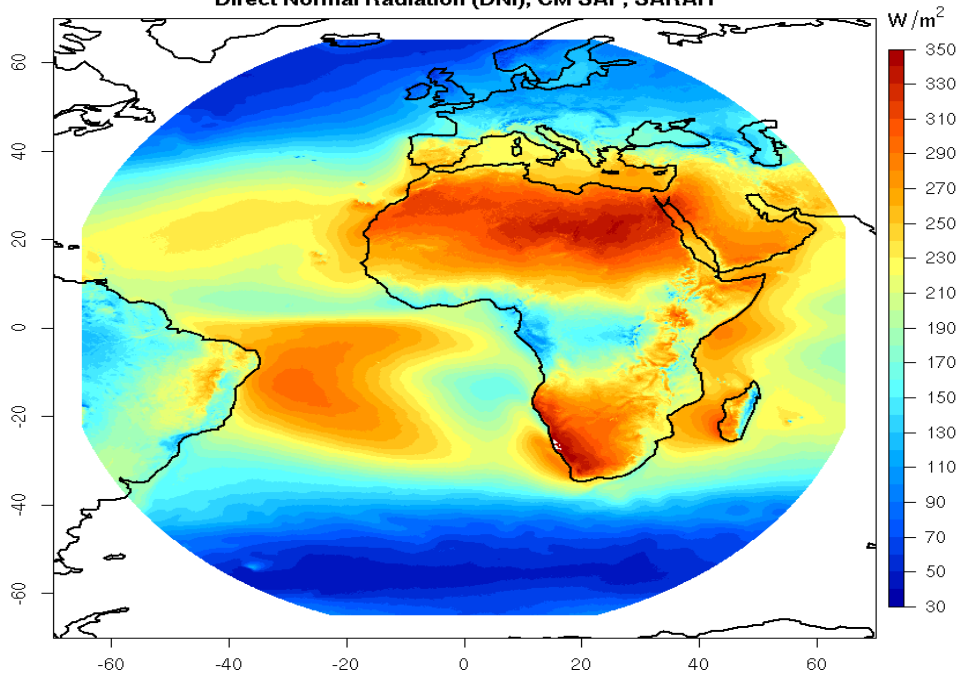


2. The Project. Task 1: Inception

Previous available information: Satellite Data

CMSAF (Eumetsat)

Direct Normal Radiation (DNI), CM SAF, SARAH



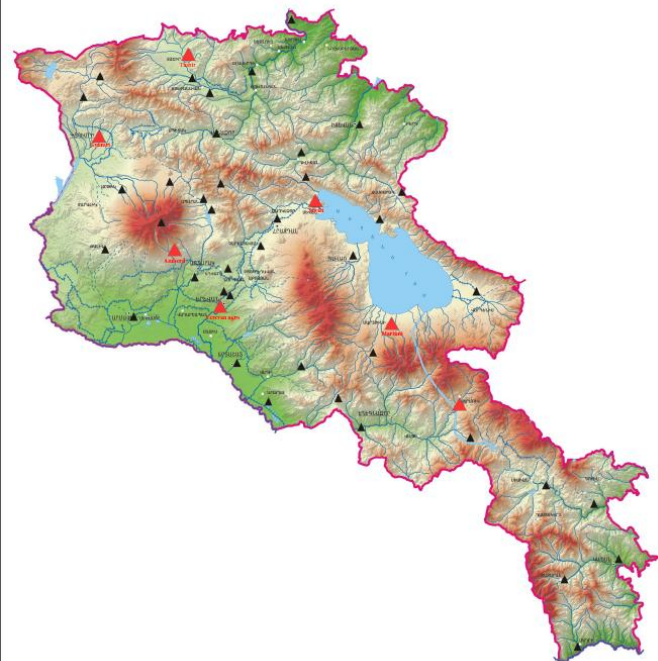
- <http://www.cmsaf.eu/>
- GHI, DNI. Hourly Mean
- 1983-2015
- ~5km spatial resolution



2. The Project. Task 1: Inception

Previous available information: Ground-based measurements

Hydromet



N	Point name	Latitude	Longitude	Altitude	Available since
1	Yerevan Agro (Merdavan village)	40°11'	44°24'	942	1953
2	Sevan	40°34'	45°00'	1917	1954
3	Martuni	40°09'	45°18'	1943	1957
4	Tashir	41°07'	44°17'	1507	1963
5	Gyumri	40°47'	43°50'	1529	1954
6	Amberd	40°23'	44°15'	2071	2009



2. The Project. Task 1: Inception

Previous available information: Ground-based measurements

Hydromet

- GHI, DNI, DHI
- Monthly Means
- Available period: 2005-2014





2. The Project. Task 1: Inception

Limitations of existing datasets

- Either solar radiation derived from satellite images with **low spatial** resolution;
- Or updated hourly and minute data **not available**;
- Or no existing observations equipped with high precision radiometric equipment. Solar Resource map **uncertainty cannot be assessed**;
- Or no data available for:
 - Direct Normal Irradiance (DNI)
 - Diffuse Horizontal Irradiance (DHI)
- Or **no local conditions** taken into account for solar mapping in Armenia.



2. The Project. Task 1: Inception

Conclusions: Necessary steps

Preliminary Solar
Resource Map
(Task 2)

Ground Measurements
Campaign
(Task 3)

Production of Updated and
Validated Solar Atlas
(Task 4)

Selection of PV sites
(Task 5)



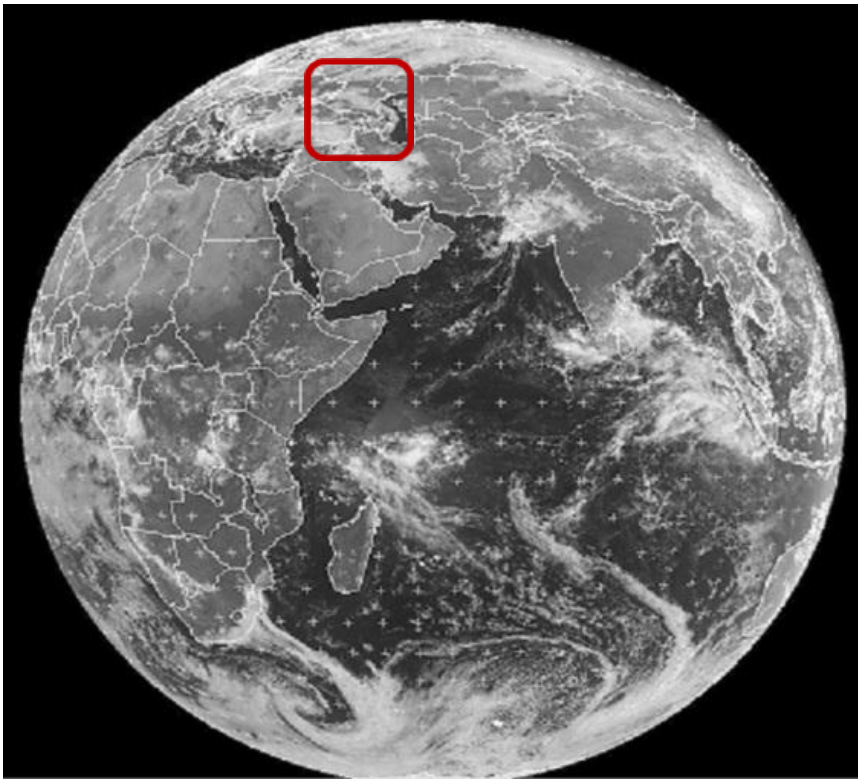


2 The Project. Task 2: Preliminary Solar Resource Map



2. The Project. Task 2: Preliminary Solar Resource Map

IrSOLaV Methodology for satellite estimations



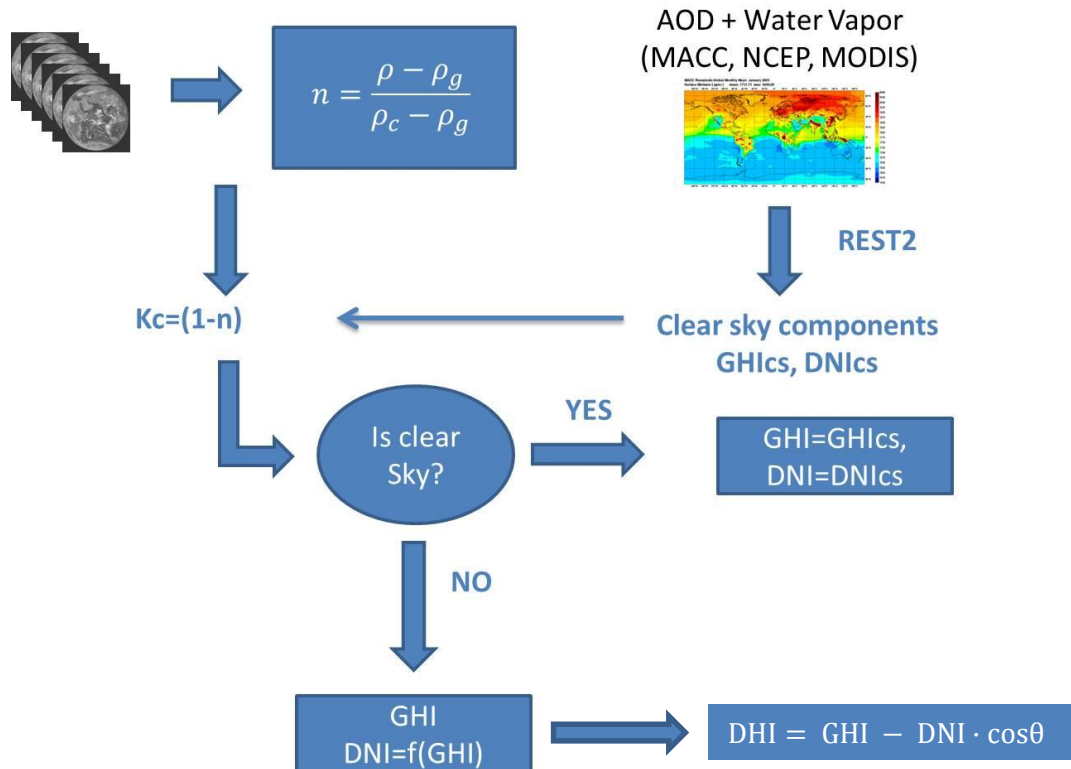
Meteosat First Generation satellite over India:

- MFG-5:
 - 99-07
 - 0.05x0.05
 - 63°E
- MFG-7:
 - 07-14
 - 0.05x0.05
 - 57°E
- Database: 1999 to present.



2. The Project. Task 2: Preliminary Solar Resource Map

IrSOLaV Methodology for satellite estimations: GHI, DNI, DHI

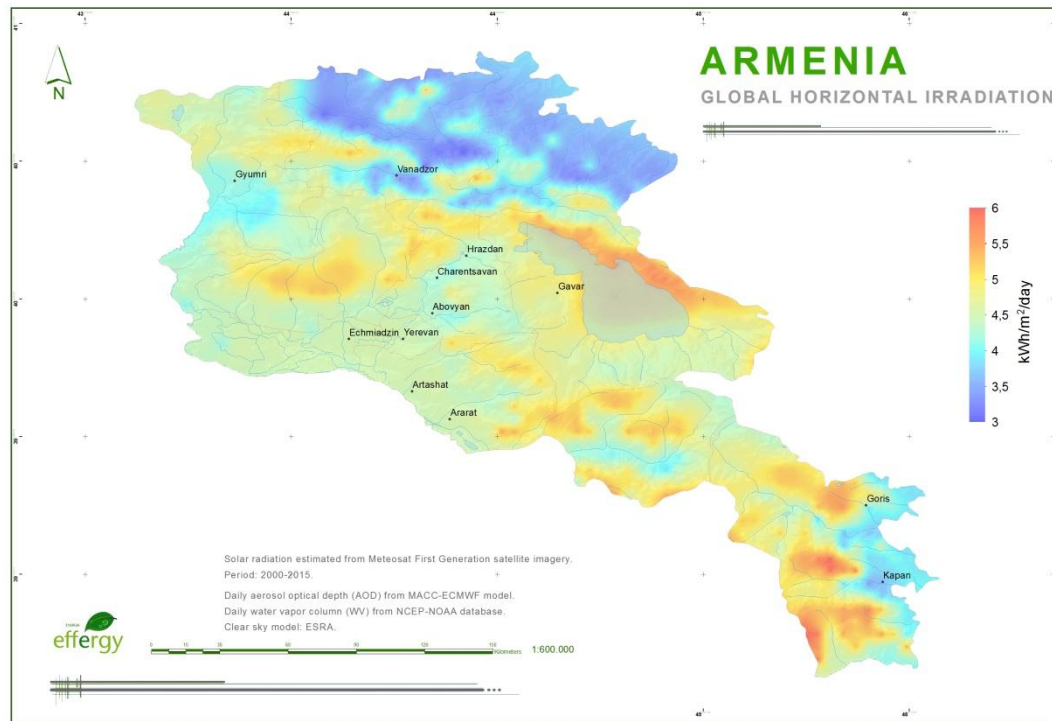


- Modified Heliosat-2
 - Own estimation of ground and cloud albedo (*Polo et al., 2012, 2013*).
- Own model for selection of clear sky conditions (*Polo et al., 2009*).
- Flexibility in:
 - Transmittance models: REST2, ESRA, SOLIS
 - Climatologic database for atmospheric attenuation agents: MACC, MODIS, MISR, NCEP, Aeronet.
 - DNI estimation: Louche, DirInt, DirIndex.



2. The Project. Task 2: Preliminary Solar Resource Map

Preliminary Maps: GHI

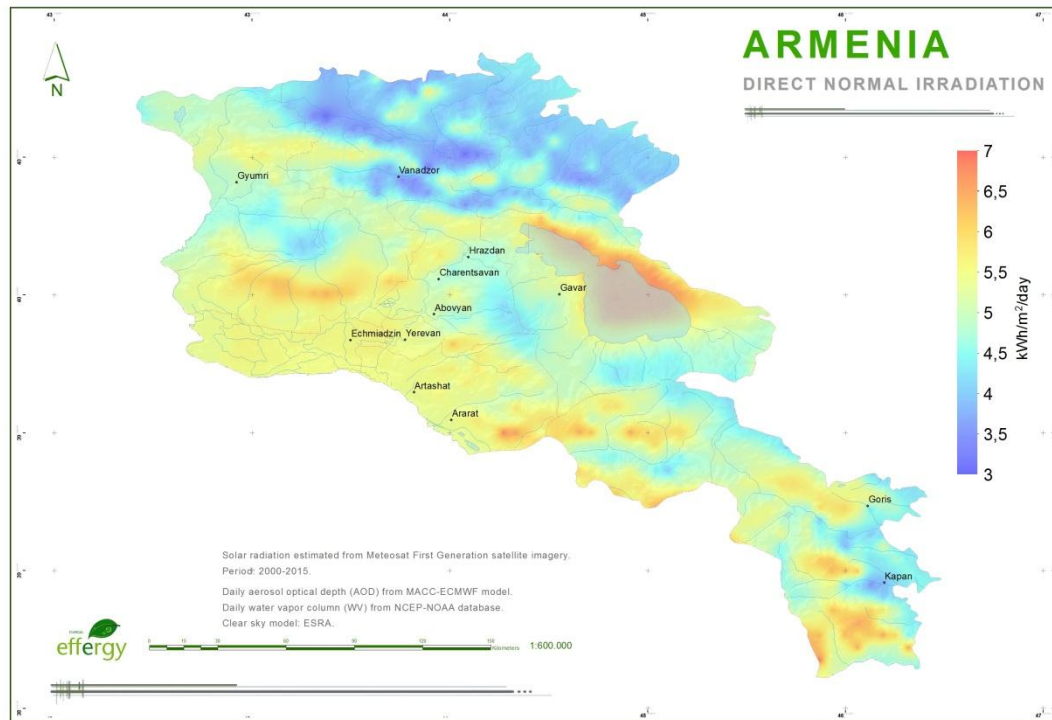


- Mean Yearly Values
 - 2000-2015 period.
- Highest:
 - 5.5-6 kWh/m²/day
 - 2000-2200 kWh/m²/year
 - Eastern strip Sevan Lake
 - Aragats Mount
 - Southern part



2. The Project. Task 2: Preliminary Solar Resource Map

Preliminary Maps: DNI

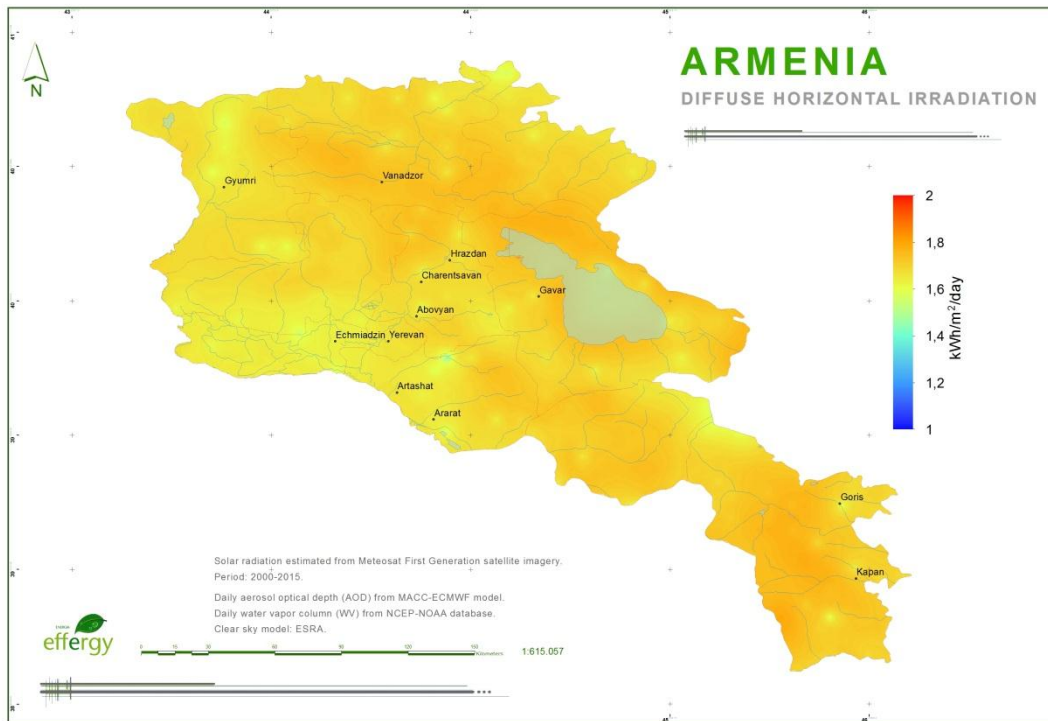


- Mean Yearly Values
 - 2000-2015 period.
- Highest:
 - 6.5 kW/m²/day
 - 2375kW/m²/year
 - Eastern strip Sevan Lake
 - Aragats Mount
 - Southern part



2. The Project. Task 2: Preliminary Solar Resource Map

Preliminary Maps: DHI



- Mean Yearly Values
 - 2000-2015 period.
- Lowest:
 - 1.5 kWh/m²/day**
 - 550kWh/m²/year**
 - Eastern strip Sevan Lake
 - Aragats Mount
 - Southern part

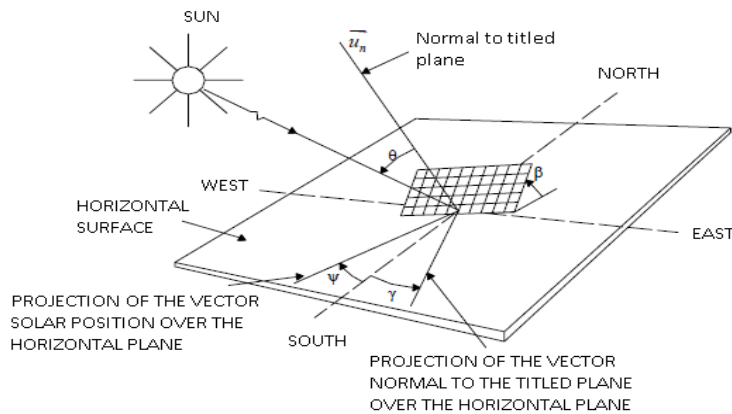


2. The Project. Task 2: Preliminary Solar Resource Map

Methodology for satellite estimations: GTI

$$GTI = \frac{1}{2} \cdot \rho_{daily} \cdot [1 - \cos\beta] \cdot GHI + RB \cdot DNI \cdot \cos\theta + \frac{1}{2} \cdot DHI \cdot [1 + \cos\beta]$$

$$RB = \frac{\cos\beta \cdot \cos\theta + [\cos\varphi \cdot \cos\gamma - \sin\varphi \cdot \sin\gamma] \cdot \sin\beta \cdot \sin\theta}{\cos\theta}$$



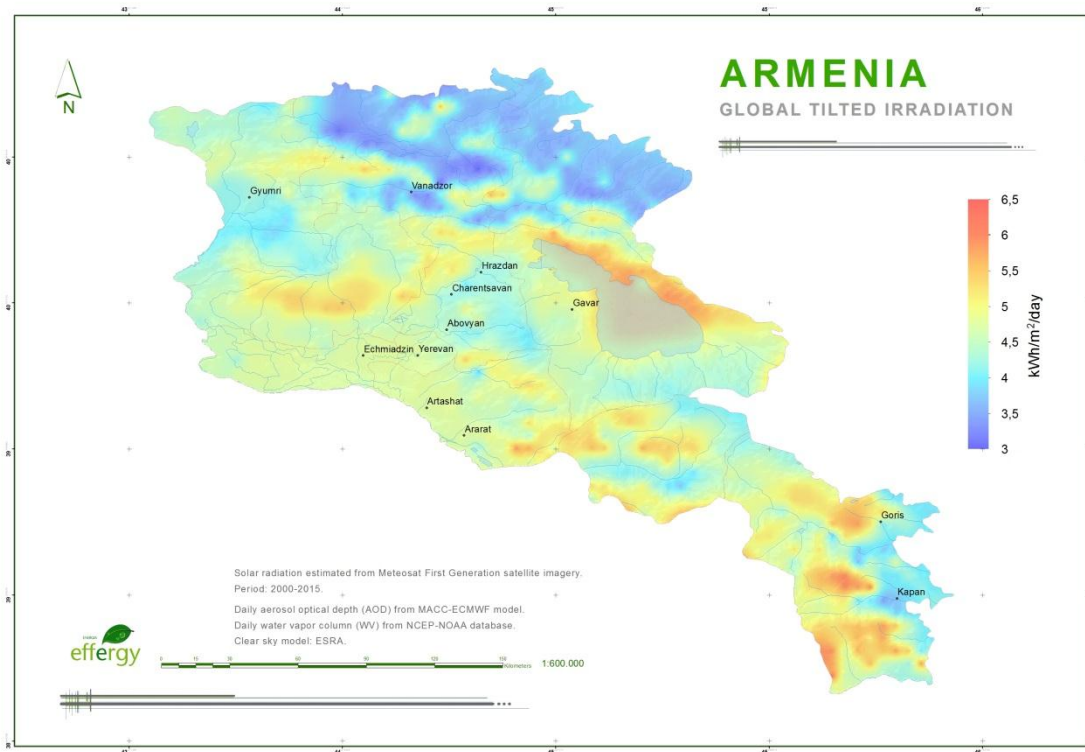
ρ_{daily} : daily ground albedo

β : tilt angle. Optimized to **35°** for Armenia



2. The Project. Task 2: Preliminary Solar Resource Map

Preliminary Maps: GTI

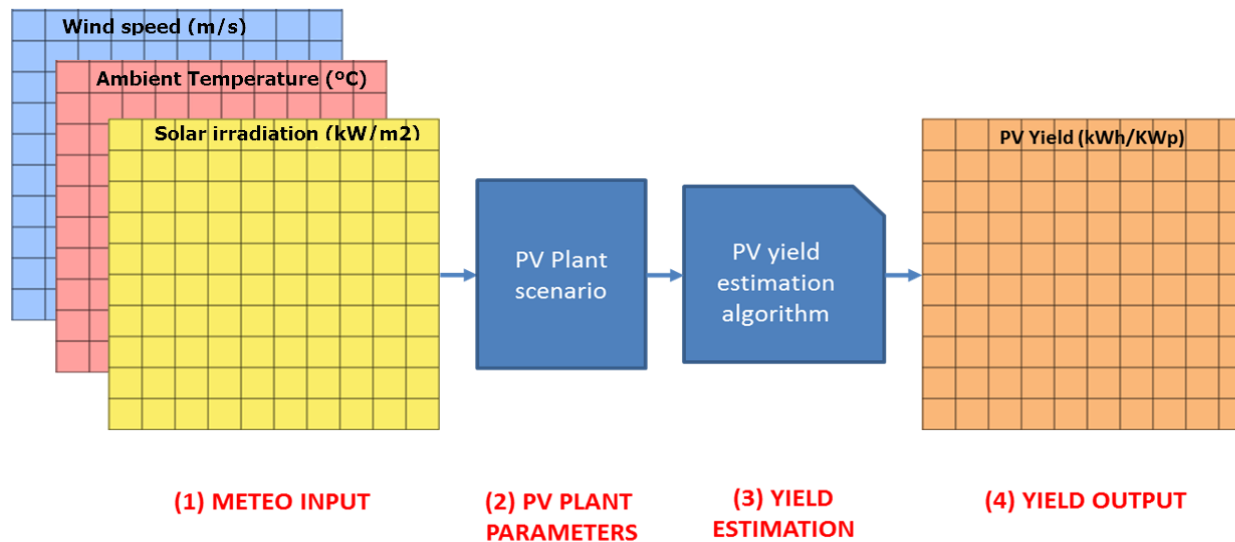


- Mean Yearly Values
 - 2000-2015 period.
- Optimal Tilt angle: **35°**.
- Highest:
 - 5.5-6 kWh/m²/day**
 - 2000-2200 kWh/m²/year**
 - Eastern strip Sevan Lake
 - Aragats Mount
 - Southern part

2. The Project. Task 2: Preliminary Solar Resource Map

Methodology for PV potential

PV Yield is the specific energy that a PV system produce per kWp installed.





2. The Project. Task 2: Preliminary Solar Resource Map

Methodology for PV potential

1. METEO INPUT

Typical Meteorological Year: 8760 hourly values for each cell of the map grid (0.05°).

- **GTI, Temperature, Wind**

2. PV PLANT PARAMETERS

- **PV Generator:** PV Si-c modules (REC Peak Energy 72, 310Wp)
- Mounting: static tilt angle **35°**
- Inverter vs PV Peak Power Ratio: 1.2
- **PV Inverter:** 1MW SMA Sunny Central MPVS-100 (94.4% European Efficiency)
- LV/MV Transformer: Commercial 1.2 MW capacity (SMA SC1000-CPXT)
- **Losses:**
 - **Dust:** 2%, Maximum Peak Power **Tracking:** 2%, **Electrical** (due to cables, fuses, and other electrical components): 2%, **Shadows:** 1%.
 - Total losses factor: **7%**



2. The Project. Task 2: Preliminary Solar Resource Map

Methodology for PV potential

3. PV YIELD ESTIMATION

$$E_{annual} = \int P_{AC}(G, T) dt = \int P_{DC}(G, T) \cdot \eta_{Inv} \cdot \eta_T dt$$

- Output power of the PV Generator:

$$P_{DC} = P^* \frac{G}{G^*} \cdot \frac{\eta}{\eta^*}$$

- Power efficiency of the inverter:

$$\eta_{Inv} = \frac{P_{AC}}{P_{DC}} = \frac{p_{DC} - (k_0 + k_1 \cdot p_{DC} + k_2 \cdot p_{DC}^2)}{p_{DC}}$$

- Power efficiency of the LV/MV transformer:

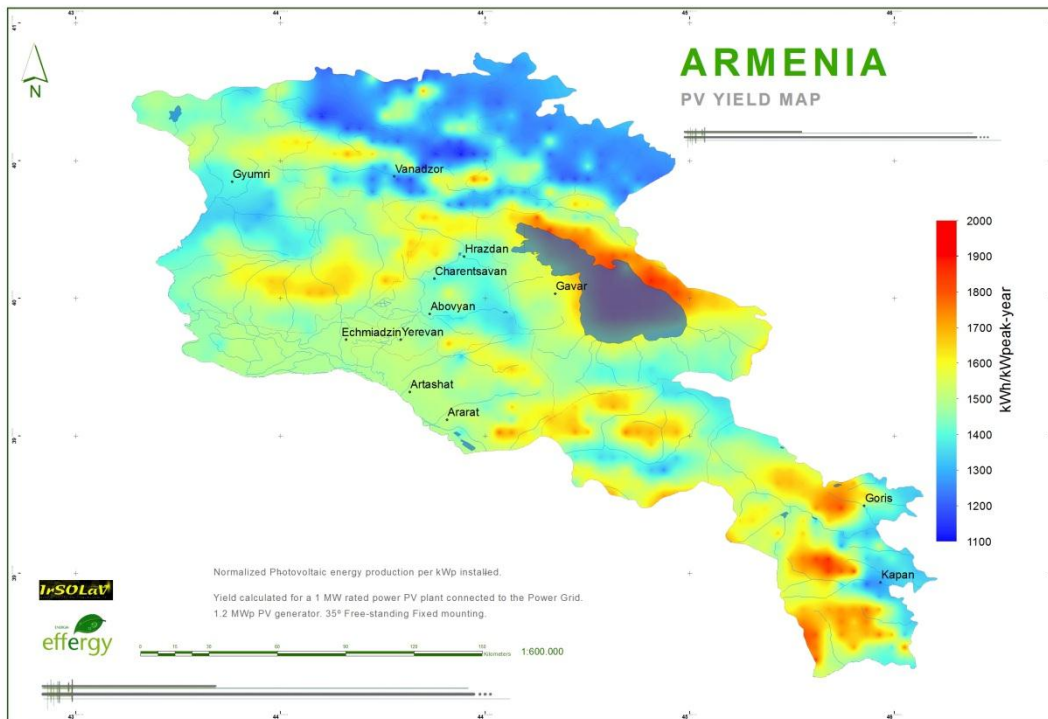
$$\eta_T = \frac{P_{out}}{P_{AC}} = \frac{P_{out}}{P_{out} + P_{Core} + P_{Cu}}$$

- Further details found in Deliverable 5 of the Project.



2. The Project. Task 2: Preliminary Solar Resource Map

Preliminary Maps: PV Yield

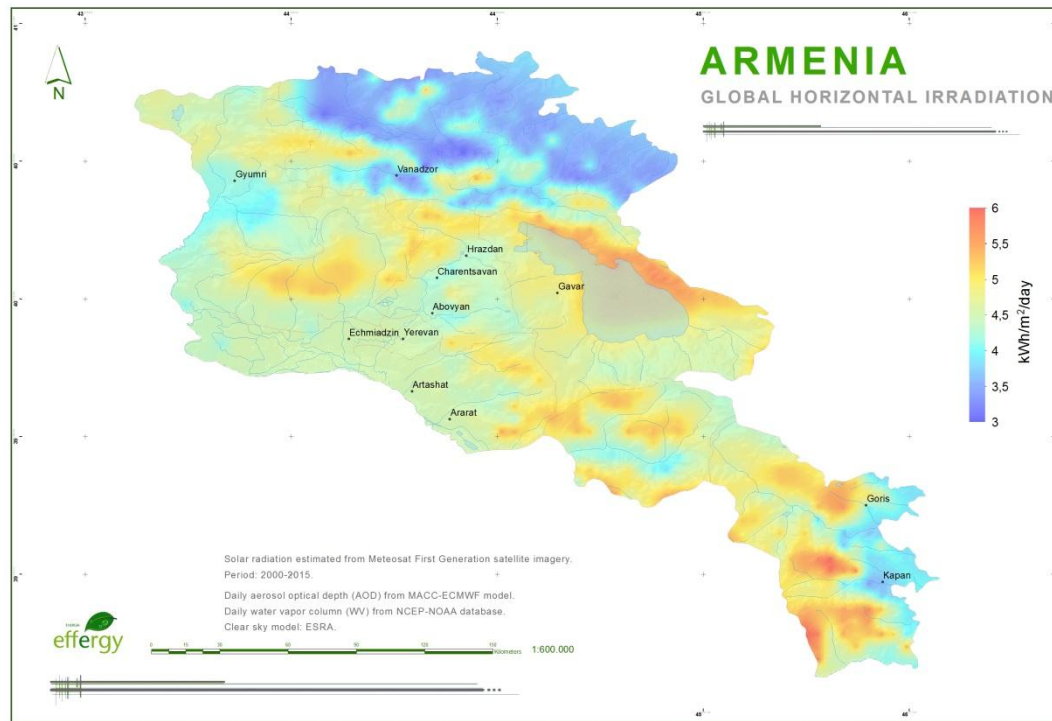


- TMY
- Highest: **1900kWh/kWp**
 - Eastern strip Sevan Lake
 - Aragats Mount
 - Southern part
- Yerevan: **1500kWh/kWp**
- Vayots' Dzor and Syunik Provinces: **1700kWh/kWp**



2. The Project. Task 2: Preliminary Solar Resource Map

Candidate Site Selection for Solar Monitoring Network in Armenia



- **OBJECTIVE:**

Setup a solar monitoring network that minimize uncertainty of solar resource map.

- **RATIONALE:**

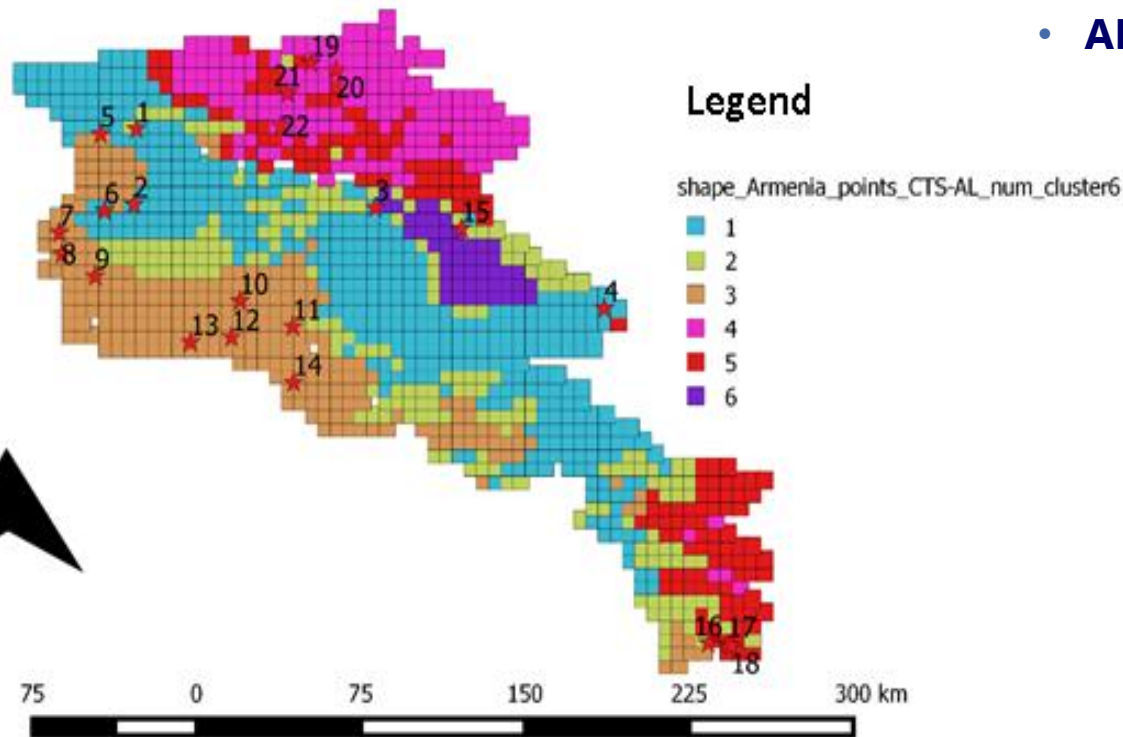
Characterization of solar resource spatial and temporal distribution minimizing number of locations that represent:

- Zones with potentially commercially exploitable solar resources.
- Different local climate and / or topographical conditions.



2. The Project. Task 2: Preliminary Solar Resource Map

Candidate Site Selection for Solar Monitoring Network in Armenia



- **AREA SELECTION**

- **Clustering**

- GHI Monthly Time Series
 - Cluster ensemble approach (Hornik, 2005)
 - **6 clusters selected**

- **Selection of Areas**

- Ranking:
 - Representativeness
 - Size of area
 - Spatial variability
 - Restrictive issues
 - GHI



2. The Project. Task 2: Preliminary Solar Resource Map

Candidate Site Selection for Solar Monitoring Network in Armenia

SPECIFIC SITE SELECTION

Avoidance Criteria: Rivers, lakes, conservation areas



(A) Rivers



(B) Conservation areas

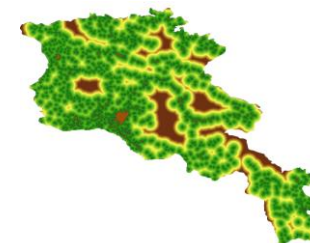


(C) Lakes

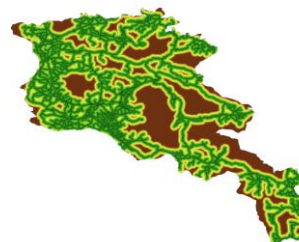
Proximity Criteria: Transmission system, cities, road and railway network



(A) Transmission system



(B) Cities/towns



(C) Road networks



(D) Railways



2. The Project. Task 2: Preliminary Solar Resource Map

Candidate Site Selection for Solar Monitoring Network in Armenia

LOGLIST SITE SELECTION

Id	Cluster #	Longitude°	Latitude°	Altitude meters	Nearest city
1	1	43.97	40.882320	2354	Krashen
2	1	43.96	40.596490	1930	Artik
3	1	44.95	40.583340	2309	Sevan
4	1	45.891180	40.201830	2069	Sotk
5	1	43.839780	40.572480	1836	Maralik
6	2	46.317980	38.930840	905	Araksashen
7	3	43.822760	40.863890	1701	Mayisyan
8	3	43.654300	40.489260	1491	Norshen
9	3	43.801380	40.324000	1283	Arteni
10	3	44.395700	40.229740	1054	Proshyan
11	3	44.612800	40.132820	1401	Hatsavan
12	3	44.360890	40.092000	829	Hovtashat
13	3	44.192470	40.073290	843	Yeraskhahun
14	3	44.615570	39.921000	834	Taperakan
15	3	43.664310	40.408490	1437	Tilk
16	4	44.686050	41.133620	1670	Madan
17	4	44.789820	41.104960	1633	Teghut
18	4	44.591550	41.018790	1362	Ardvi
19	4	44.564300	40.893460	1198	Vahagnadzor
20	5	46.398280	38.927470	724	Shvanidzor
21	5	46.412490	38.920330	1089	Nrnadzor
22	6	45.305630	40.505090	2012	Shorzha



2. The Project. Task 2: Preliminary Solar Resource Map

Final Site Selection for Solar Monitoring Network in Armenia

- **OBJECTIVE:**

Selection of four locations for the installation of ground radiometric stations from the longlist.

- **RANKING METHODOLOGY:**

#	Item	Weight
1	South Obstacle height, °	0.7
2	West Obstacle height, °	0.8
3	North Obstacle height, °	0.5
4	East Obstacle height, °	0.8
5	Distance from lakes, km	0.5
6	Availability of maintenance personnel	0.8
7	Availability during the winter period	1
8	Mobile data connection availability	1
9	AC power availability	0.5
10	Area of visibility surface, km ²	0.4
11	Responsible (covering) surface area, km ²	1
12	Solar resource in the area, GHI component	1

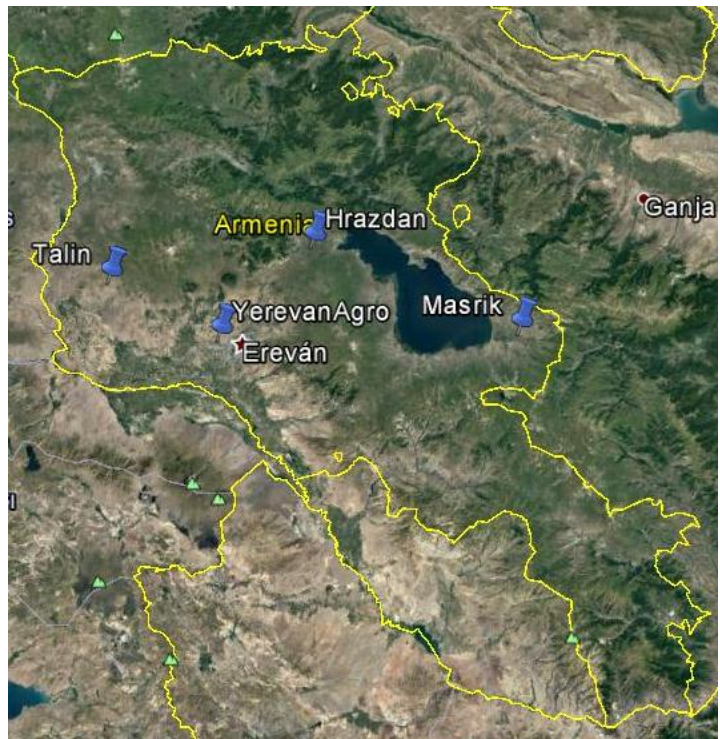
Secondary items

- Min surface 10m²
- Firm and flat soil
- Permitted fence
- Avoid risk of flood or heavy rains, reflecting surfaces
- Avoid polluted sites (industrial, airports, crowded roads)
- Avoid animal populations

2. The Project. Task 2: Preliminary Solar Resource Map

Final Site Selection for Solar Monitoring Network in Armenia

AWARDED SITES:



Id	Region #	Longitude (°)	Latitude (°)	Altitude (m)	Nearest city
8	1	44,823	40,5116	1944	Masrik
11	1	45,7645	40,2077	1845	Hrazdan
15	2	43,8927	40,3863	1641	Talin
28	3	44,3976	40,1887	946	Yerevan

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