Evaluation of Rooftop Solar Potential in Chernihiv and Lviv, Ukraine, and Efficacy of High-Resolution 3D Data Digital Twins

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Summary

This analysis evaluates rooftop solar photovoltaic (PV) siting opportunities in the cities of Chernihiv and Lviv, Ukraine, leveraging very-high-resolution 3D elevation data to calculate technical potential. The study assessed total rooftop solar capacity and annual energy production. The study also assessed the feasibility of adapting this methodology on a national scale using either simulated digital surface models (DSMs) or a digital twin approach.

Rooftop Solar Technical Potential
The total estimated rooftop solar capacity and annual energy production for both cities is presented in direct current (DC) and alternating current (AC). This accounting provides a clear estimate of the potential rooftop solar installations that could be realized under optimal conditions, considering both technical constraints and the geographic distribution of available rooftop space.

- **Chernihiv**:
  - **DC Capacity**: 332 MW | **AC Capacity**: 259 MW
  - **Annual Energy Production**: 376,197 MWh_{DC}/year
- **Lviv**:
  - **DC Capacity**: 873 MW | **AC Capacity**: 682 MW
  - **Annual Energy Production**: 995,530 MWh_{DC}/year

Building Count and Descriptions
In Chernihiv and Lviv, 116,503 buildings were analyzed for their rooftop solar potential. The buildings in the study areas include a mixture of residential, commercial, and industrial buildings, characterized by diverse roof shapes and sizes.

Summary *(continued)*

Building Count and Descriptions *(continued)*
In Lviv, the study area covers a combination of historic and modern architecture, while Chernihiv presents a more complex set of challenges in evaluating roof suitability due to damage from the war.

Feasibility of a Digital Twin for Nationwide Analysis
The study explored the differences between using high-resolution DSMs and a simulated DSM, or digital twin, as a cost-effective alternative for scaling the workflow nationwide. While the very-high-resolution DSM provided more precise results, the simulated DSM demonstrated reasonable accuracy for broader applications in modeling aggregated distributed solar supply. The feasibility of using a digital twin for Ukraine's national rooftop solar potential is considered promising, with certain limitations in areas with highly variable building stock and heavy war damage.

Impact of the Russia's Full-Scale Invasion
Russia's invasion of Ukraine has resulted in significant destruction of buildings throughout Ukraine. This destruction directly impacts the technical potential for rooftop solar in the region. NREL estimates a loss of 2,754 buildings, 20.15 MW_{DC} of capacity, and 22,869 MWh_{DC} of annual energy production lost to the war in Chernihiv as well as a loss of 1,316 buildings, 34.49 MW_{DC} of capacity, and 39,369 MWh_{DC} of annual energy production lost to the war in Lviv.

Value of the Data and Applications
This analysis highlights the critical value of high-resolution siting data in assessing rooftop solar siting opportunities. The findings may be instrumental for municipal planners, solar developers, and policymakers as they assess Ukraine's renewable energy potential. The study also provides a foundation for expanding technical potential analyses to the national level, supporting Ukraine's transition toward a more resilient and sustainable energy future.

DATA INPUTS

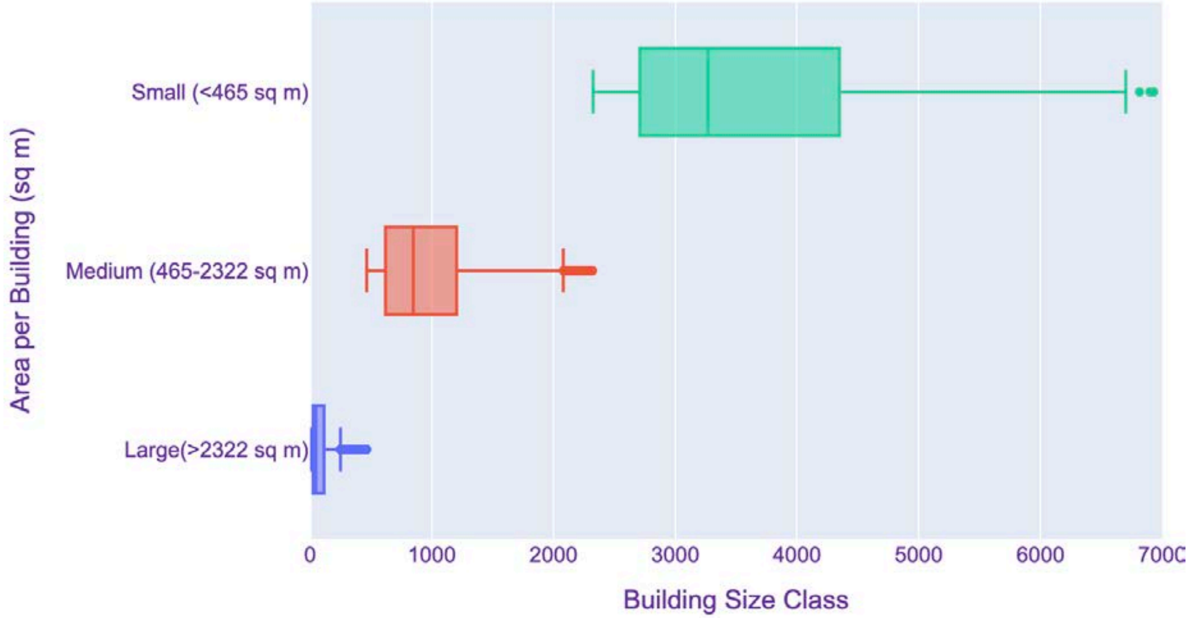
- Buildings and Damage
- Surface Models
- Solar Resource

Buildings: Chernihiv

OpenStreetMap Buildings

- OpenStreetMap (OSM) building footprints are polygon vector data depicting the planimetric envelope of a building. They do not indicate building area but encapsulate potential PV-developable roof surfaces.
- OSM building footprints are created through crowdsourced mapping and automated imports from public sources.
  - OSM data can be inconsistent in coverage and accuracy, as it relies on community contributions. Urban areas are often well-mapped, but rural or remote regions may have incomplete or outdated data. Quality can vary based on the availability of high-resolution imagery and the activity of local contributors. Zoning used throughout this analysis, as such, is only partially available.

Statistic	**Small** *0–464 m^2*	**Medium** *464–2,322 m^2*	**Large** *>2,322 m^2*
Count	60,366	3,426	288
Mean	80	923	6,186
Standard Deviation	77	411	13,045
Minimum	10	465	2,327
25%	26	603	2,690
50%	50	733.	3,331
75%	115	1,126	4,888
Maximum	464	2,322	165,512



OpenStreetMap. "OpenStreetMap Building Footprints." OpenStreetMap, 2024. https://www.openstreetmap.org.

Buildings: Lviv

OSM Buildings

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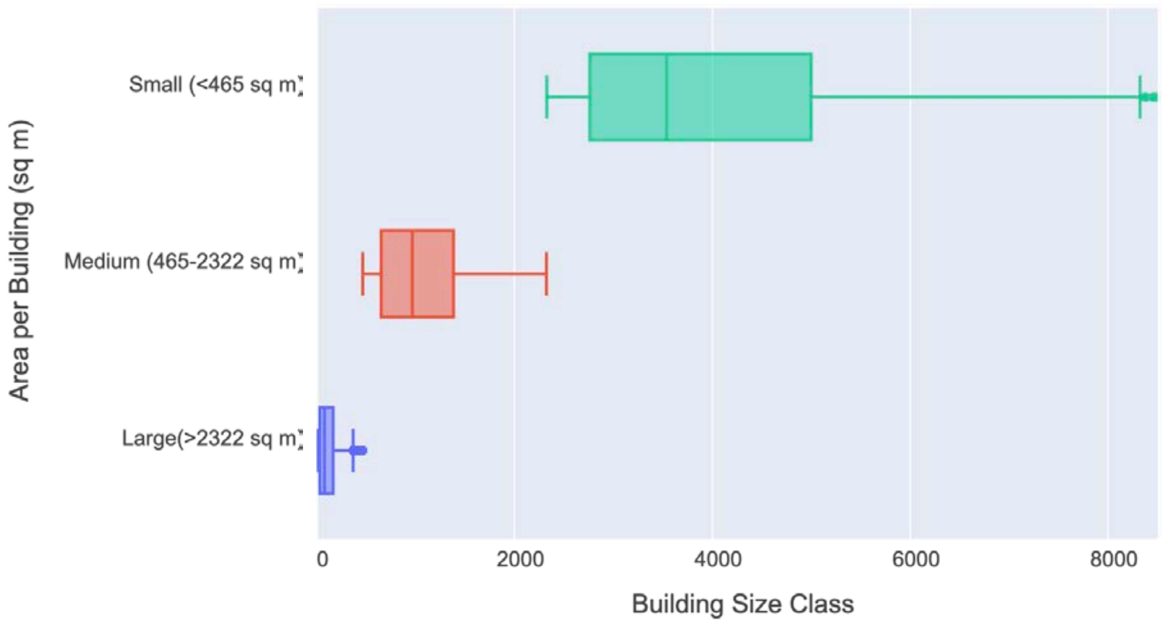
Statistic	**Small** *0–464 m^2*	**Medium** *464–2,322 m^2*	**Large** *>2,322 m^2*
Count	42,947	5,642	1,386
Mean	111	1,070	4,714
Standard Deviation	100	487	3,873
Minimum	10	465	2,325
25%	30	651	2,760
50%	78	965	3,537
75%	165	1,382	4,994
Maximum	463	2,321	47,394



OpenStreetMap. "OpenStreetMap Building Footprints." OpenStreetMap, 2024. https://www.openstreetmap.org.

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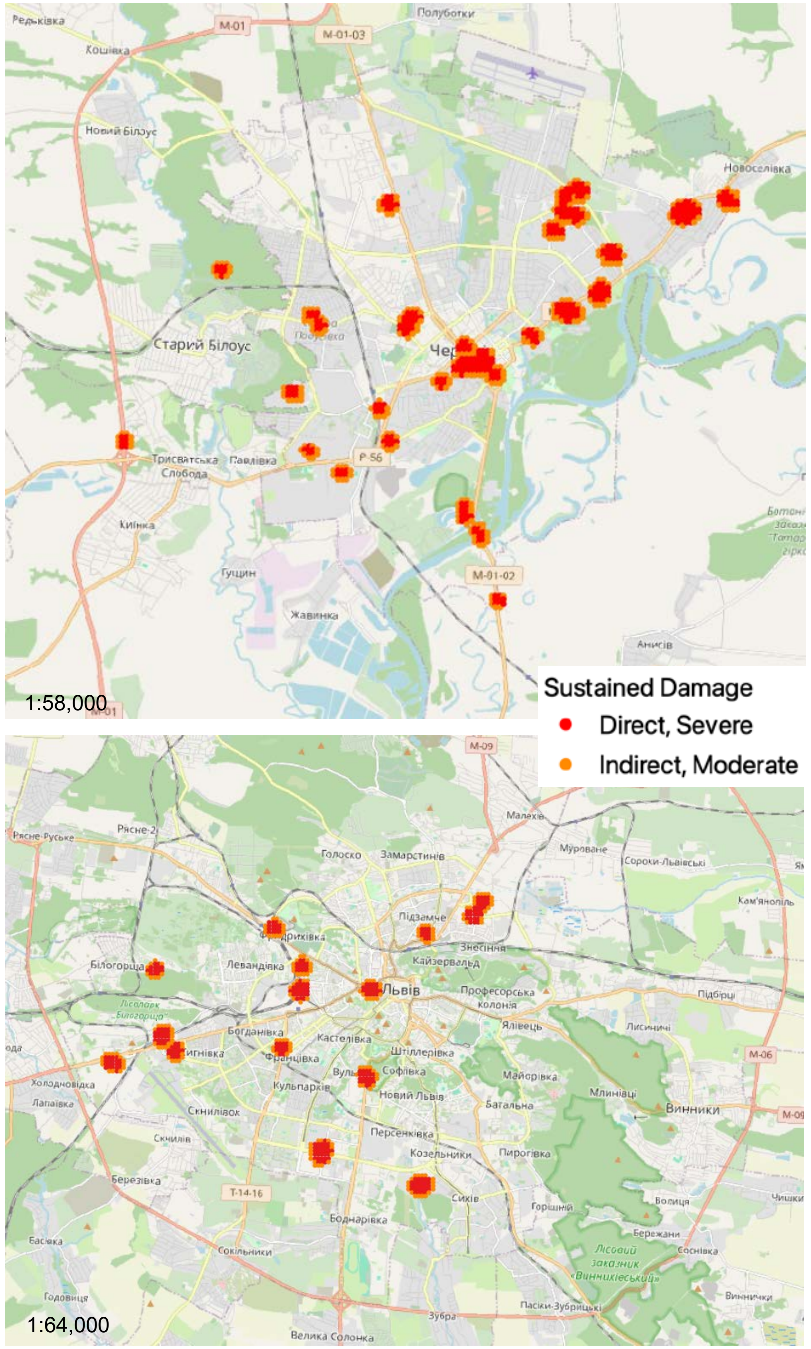
Areas Damaged by War

Center for Information Resilience

- The Center for Information Resilience (CIR) documents and analyzes areas damaged by war through geospatial data, satellite imagery, and open-source intelligence. Their work focuses on identifying and verifying damage to infrastructure, buildings, and civilian areas in conflict zones. CIR tracks destruction in near-real time.
- CIR events from bombing or explosions, civilian infrastructure damage, ground battles, and military infrastructure damage were included in this analysis.
  - Areas within 100 meters of events are considered to have severe damage, while areas within 200 meters of events are considered to have moderate damage based on damage extents reported with ordnance used during the 2022 invasion of Ukraine.

	Severe Damage			Moderate Damage		
City	*Commercial Buildings*	*Residential Buildings*	*Other Buildings*	*Commercial Buildings*	*Residential Buildings*	*Other Buildings*
Chernihiv	6	372	1,233	6	252	885
Lviv	2	206	577	6	242	283



Center for Information Resilience. "Areas Damaged by War – Conflict Mapping and Geolocation." CIR, 2023. https://www.info-res.org.

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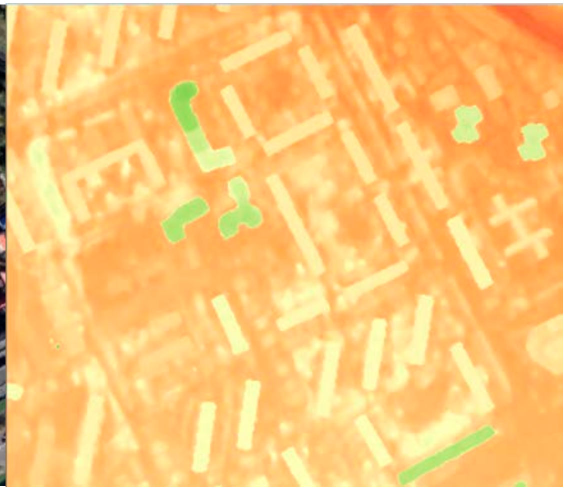
Built Environment: DSMs

Maxar Precision 3D DSM Data

- Photogrammetric DSM provided by Maxar's Precision 3D (previously known as Vricon).
- Precision 3D uses high-resolution satellite image composites through stereophotogrammetry to create submeter surface models. The fully automated technology is sensor-agnostic and does not require ground control points.

City	First Acquisition Date	Latest Acquisition Date
Chernihiv	2011-03-21	2023-05-05
Lviv	2007-11-19	2022-02-14

Google Earth Satellite



Precision 3D DSM

Lviv
49.825°, 23.972°

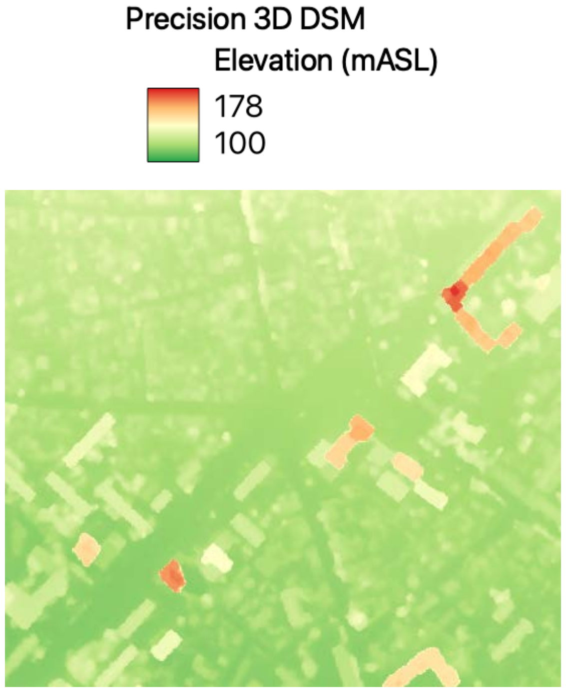
Built Environment: Simulated DSMs

Open and Licensed Data Products Composite

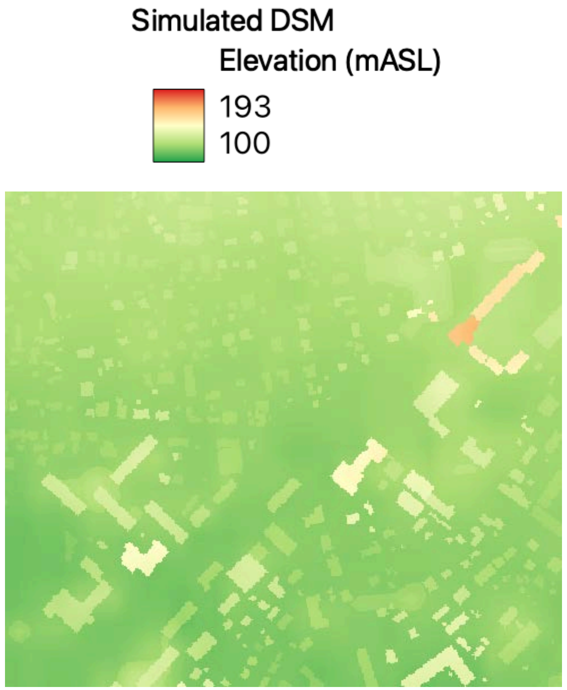
A 2-meter resolution DSM was simulated by combining available common surface features geospatial data and adding to existing digital elevation models. These data represent a cost-effective option for simulated very-high-resolution 3D data-derived surface models. Some interpolation to smooth non-break edges was required.

Compiled datasets include:

- Buildings with heights (ONEGEO)
- 30-meter digital elevation model (Copernicus)
- Tree canopy cover (Landsat).



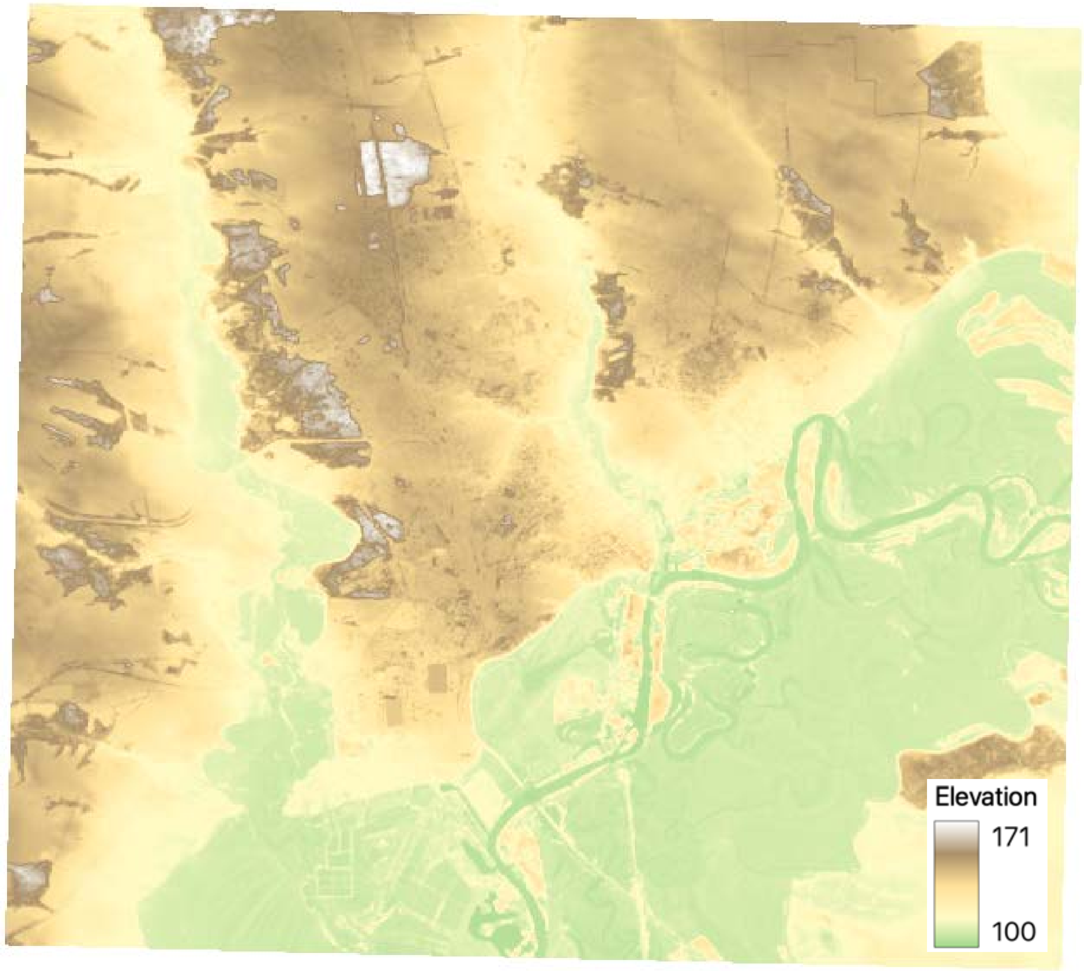
Precision 3D DSM



Simulated DSM

Red Square, Chernihiv
49.825°E 23.972°N

Terrain: Digital Elevation Model

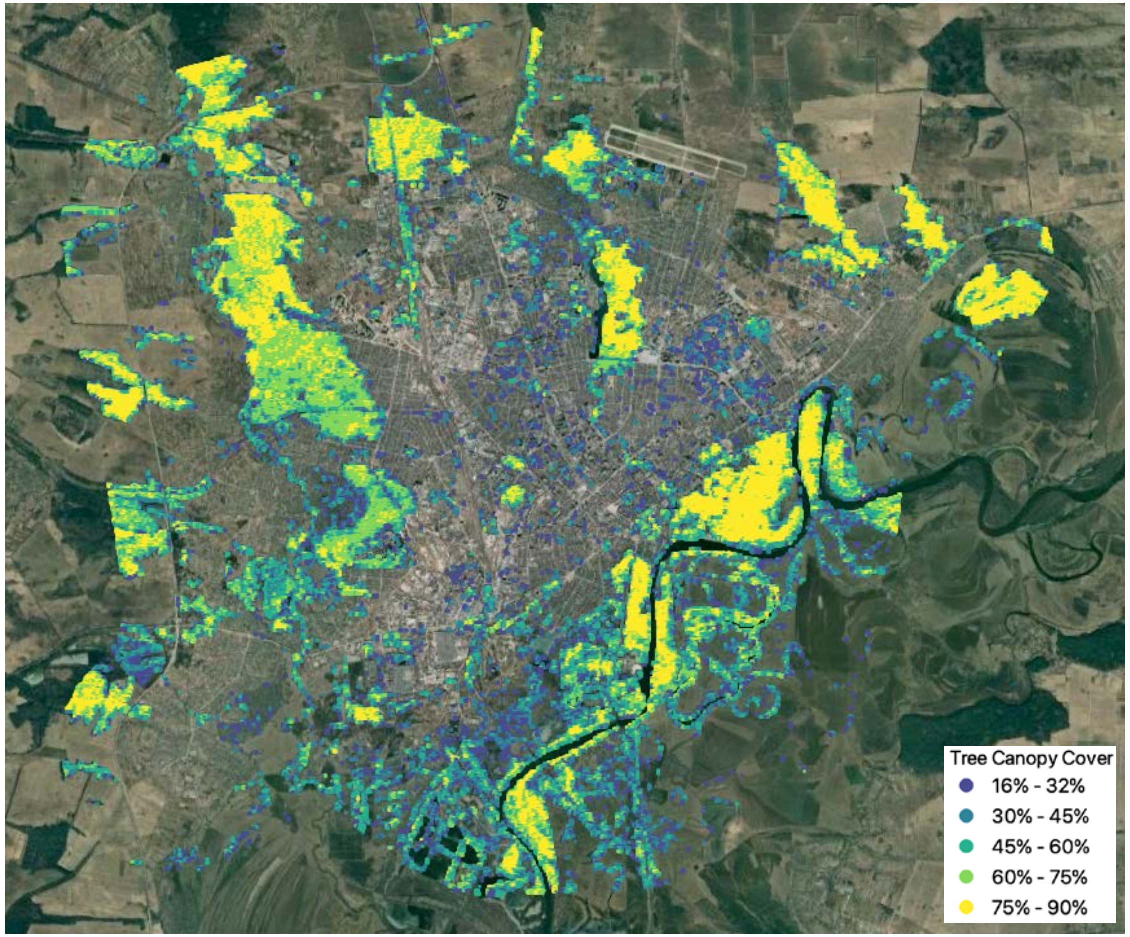


[3] Copernicus Global Land Service. "Copernicus Global Digital Elevation Model (GLO-DEM)." European Union, 2021. Data available from: Copernicus Land Monitoring Service.

Copernicus Global Digital Elevation Model (GLO-DEM):

- The Copernicus GLO-DEM offers two primary resolutions:
    - **30 meters (GLO-30)**: Provides detailed elevation data for global coverage.
    - **90 meters (GLO-90)**: A coarser version for users needing less detail.
- The model is derived from multiple sources, including radar data from the TanDEM-X mission, offering consistent global coverage.
- While the 30-meter product provides high resolution, it is not a very-high-resolution product comparable to photogrammetric data products, like Precision 3D. This model does not capture fine topographical details in highly dynamic areas like waterways or regions with heavy vegetation.

Tree Canopy Cover



[1] Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. "High-Resolution Global Maps of 21st-Century Forest Cover Change." *Science*, vol. 342, no. 6160, 2013, pp. 850-853.

Global Forest Watch Tree Cover:

- Tree cover is defined as all vegetation taller than 5 meters in height as of 2015. The tree cover data was sourced from Global Forest Watch at 30-meter resolution.[1]
  - In this case, tree cover is the biophysical presence of trees and may take the form of natural forests or plantations existing over a range of canopy densities.

Copernicus Global Land Cover—Forest Type:

- Forest-type values were sourced from the Copernicus Global Land Cover project, which provides a harmonized and high-resolution classification and mapping of land cover types across the globe.[2]
  - Scots pine (*Pinus sylvestris*), English oak (*Quercus robur*), silver birch (*Betula pendula*), and aspen (*Populus tremula*) vary in height from 20-40 meters.
  - High tree cover correlates with 1x tree height, while gradient was applied on tree cover margins.

[2] Copernicus Global Land Service. "Land Cover 100m: Collection 3: Epoch 2015: Globe." European Union, 2017. Data available from: Copernicus Land Monitoring Service.

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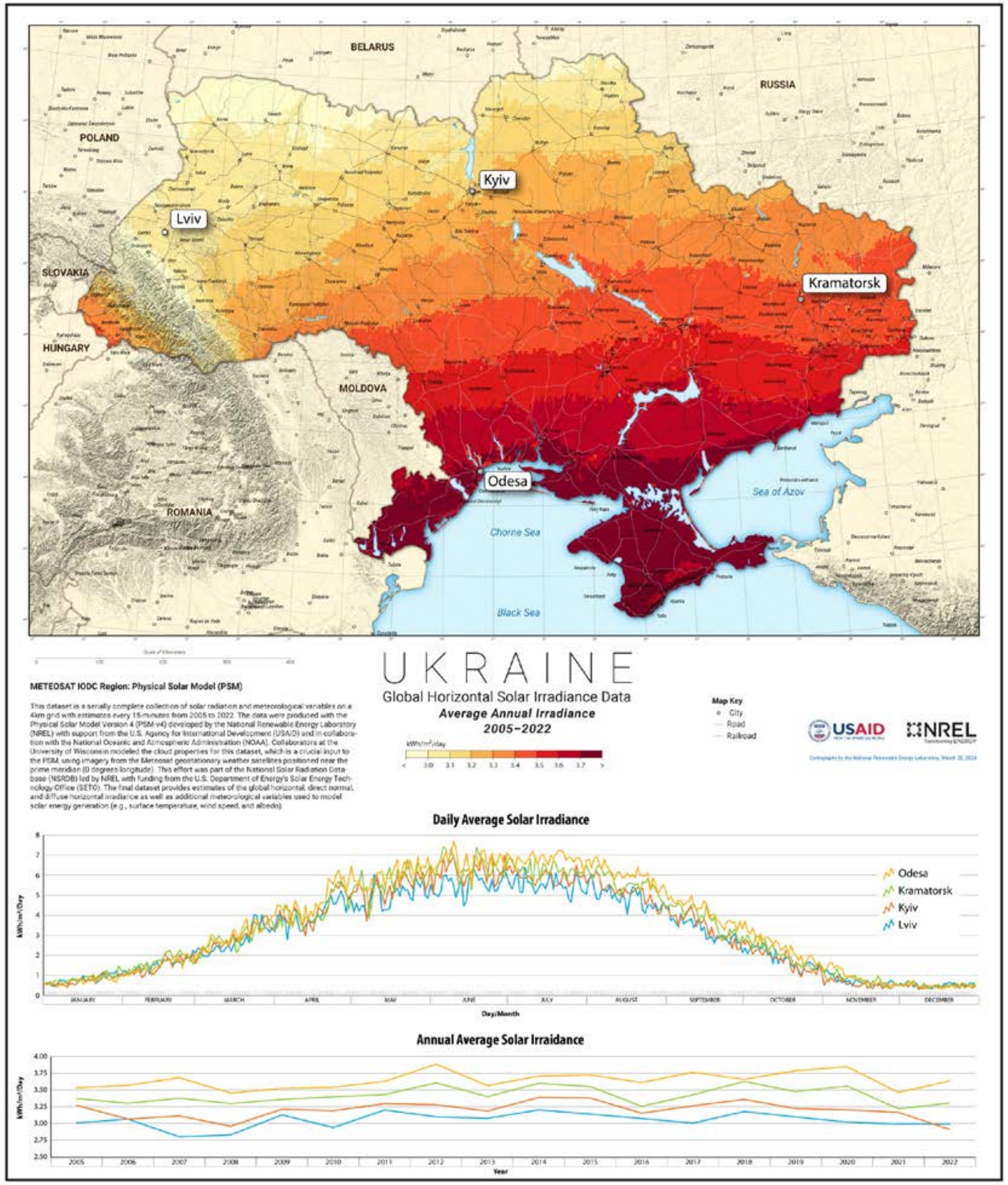
Solar Resource Data

Meteosat Second Generation

- The dataset is a serially complete collection of solar radiation and meteorological variables on a 4-km grid at 15-minute intervals spanning 2005–2022.
- The data was produced with the Physical Solar Model V4 (PSM-v4) developed by NREL with support from USAID and National Oceanic and Atmospheric Administration.
- The data is available through the RE Explorer.
- Includes global horizontal, direct normal, and diffuse horizontal irradiance, as well as other meteorological variables (e.g., surface temperature, wind speed, and albedo).



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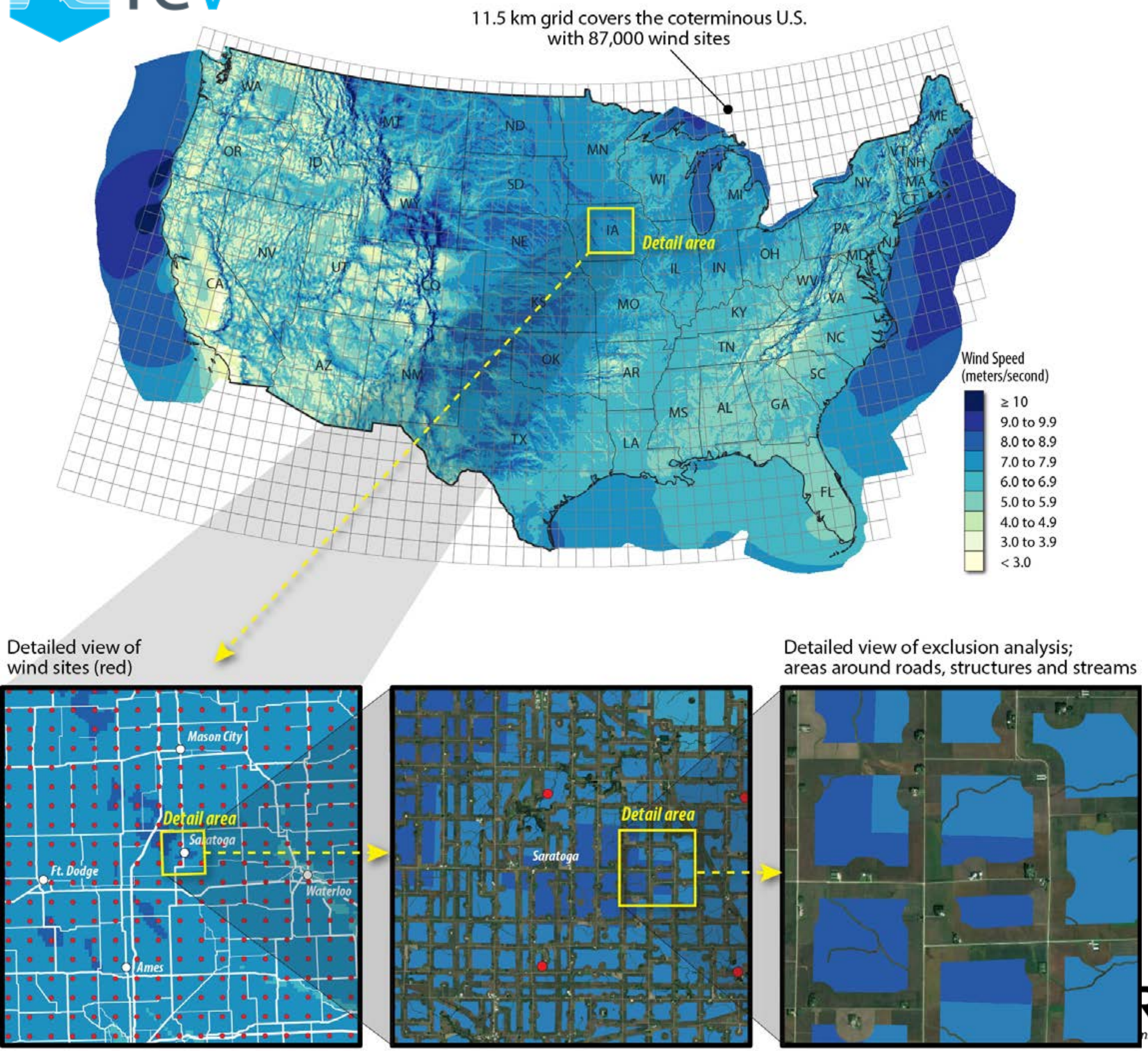
TOOLS

- ❖ Renewable Energy Potential Model
- ❖ PV Rooftop Model

A Best-in-Class Model for Estimating Renewable Energy Supply



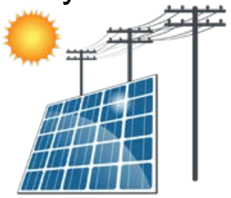
Technologies Modeled

Land-Based Wind

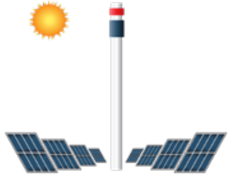
Offshore Wind

Rooftop PV

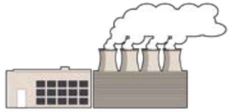
Utility-Scale PV



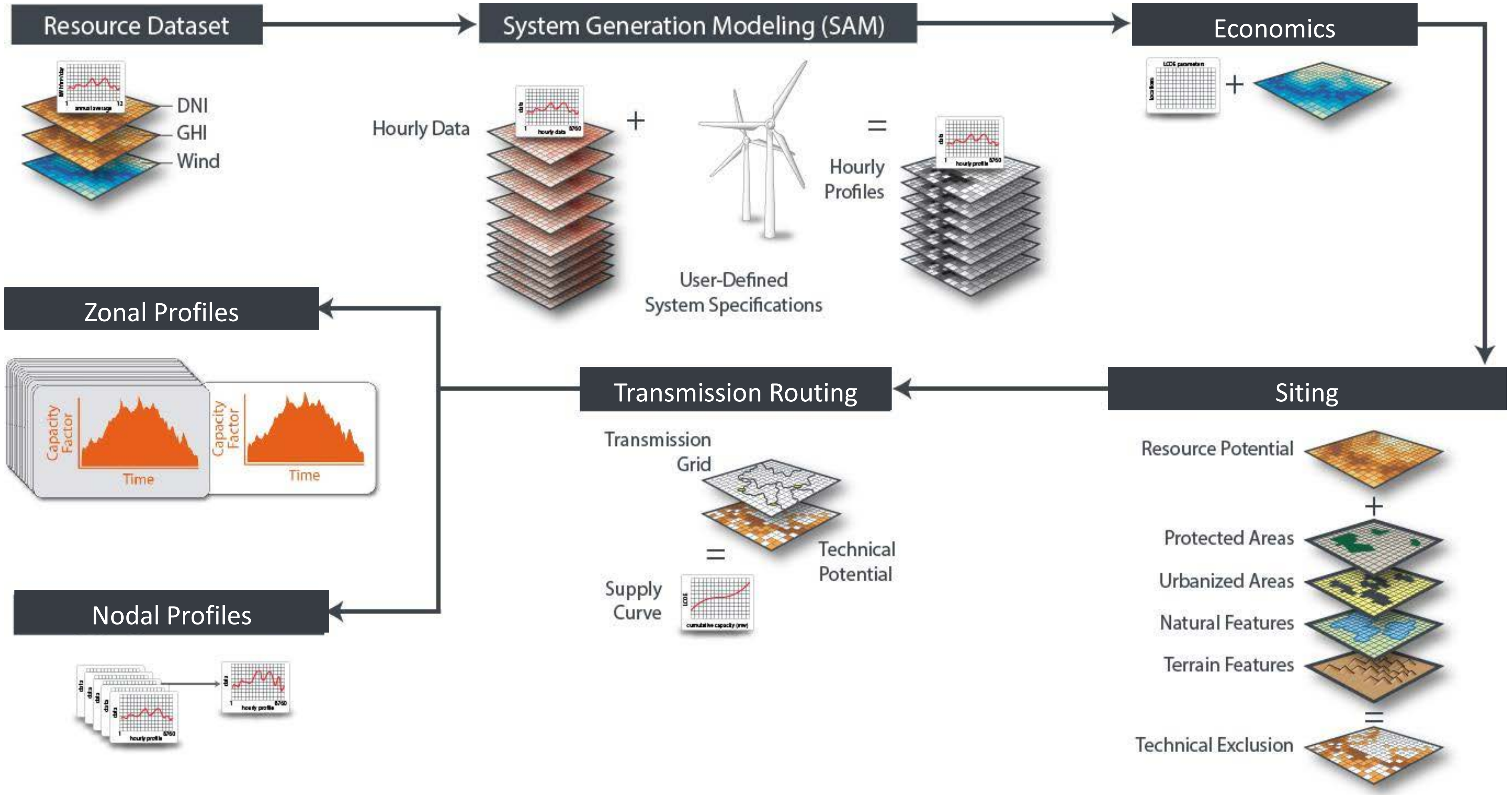
Concentrating Solar Power



Geothermal



reV Modular Workflow



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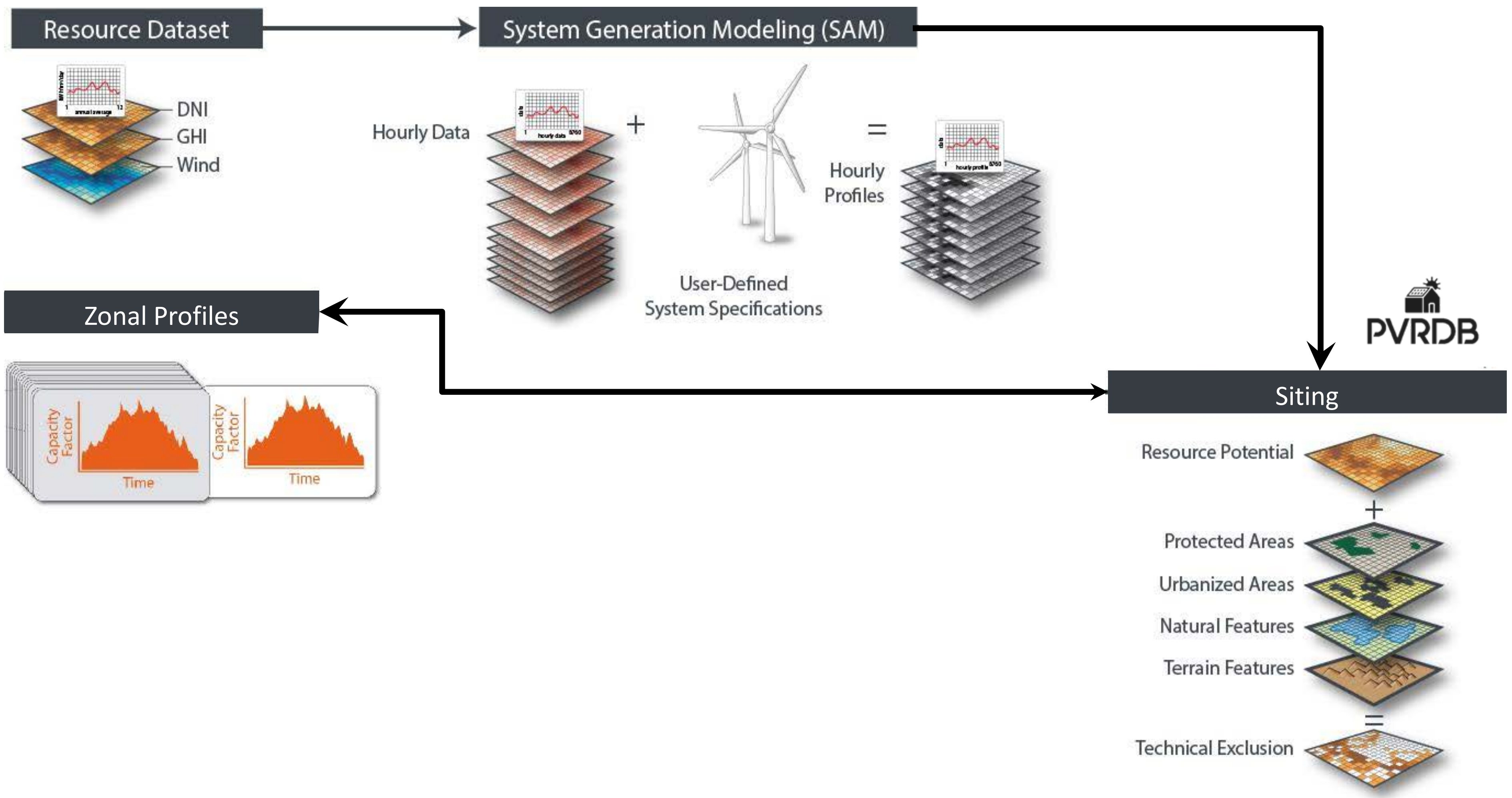
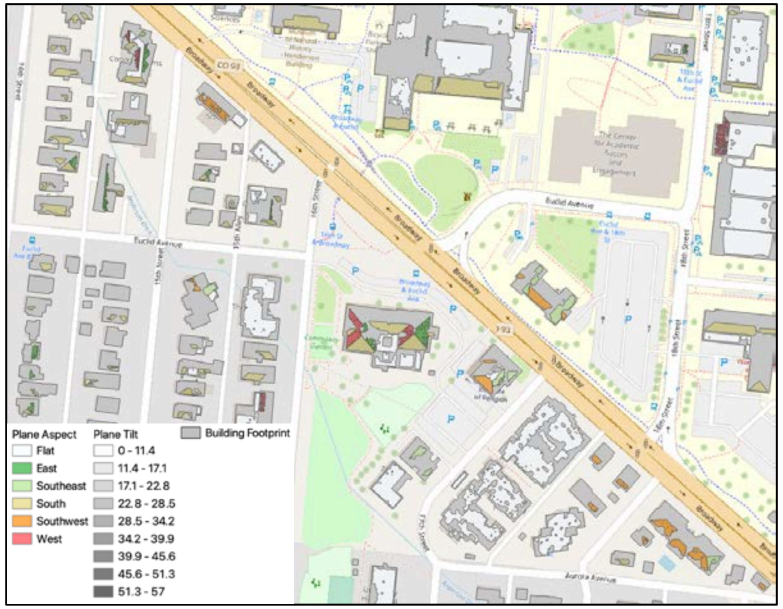
Study Workflow



Capabilities and Limits:

- Identifies obstructions to array placement and shading at submeter scale
- Handles customized array configurations per plane or building
- Does not assess roof condition, roof material, or code compliance.



PV Rooftop Model

PV Rooftop Database

LiDAR or photogrammetric DSMs are used to delineate **roof planes suitable for PV array installation**. Suitable planes are combined with outputs from NREL's Renewable Energy Potential (reV) model to create rooftop PV data products.

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Shading Assessment

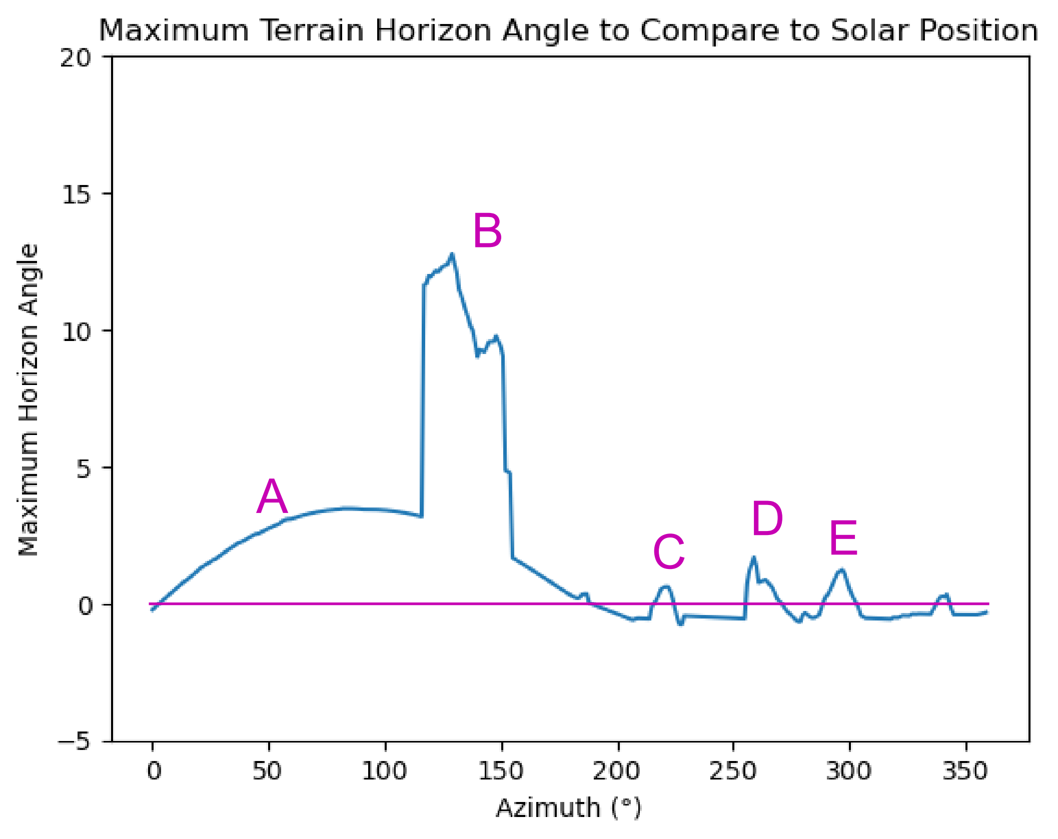
PV Rooftop computes illumination and converts it to a binary shading classification based on seasonal thresholds.

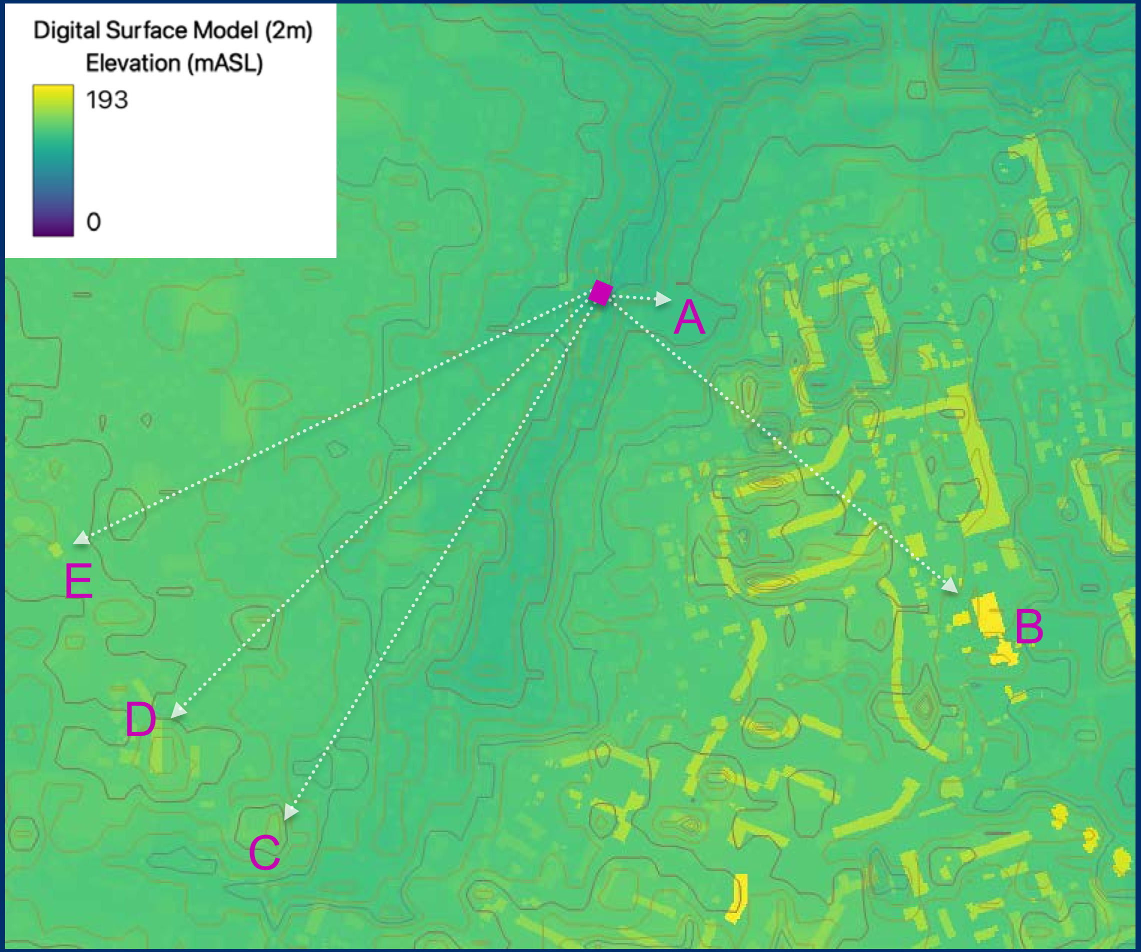
- A pixel is considered excessively shaded if its cumulative time in shade exceeds 20% of overall daylight time throughout a year.

Parameters:

- Dynamic search distance based on maximum feature height in raster
- Temporal resolution, sample dates.

Shading Method

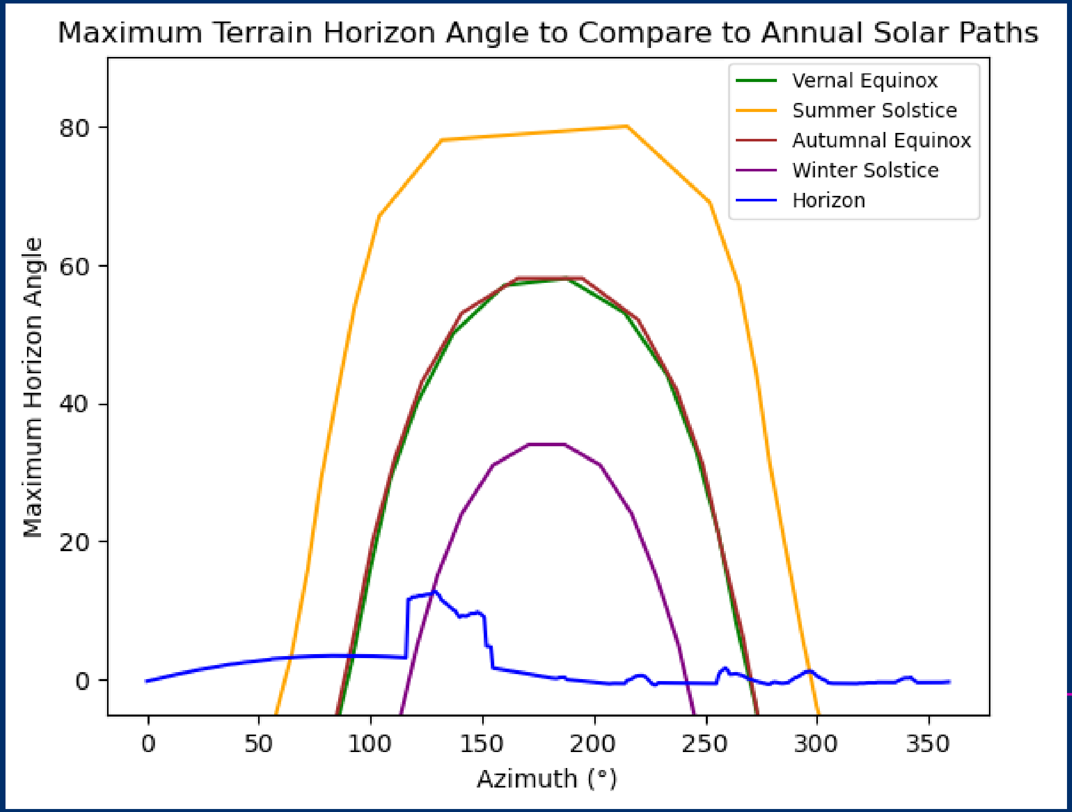




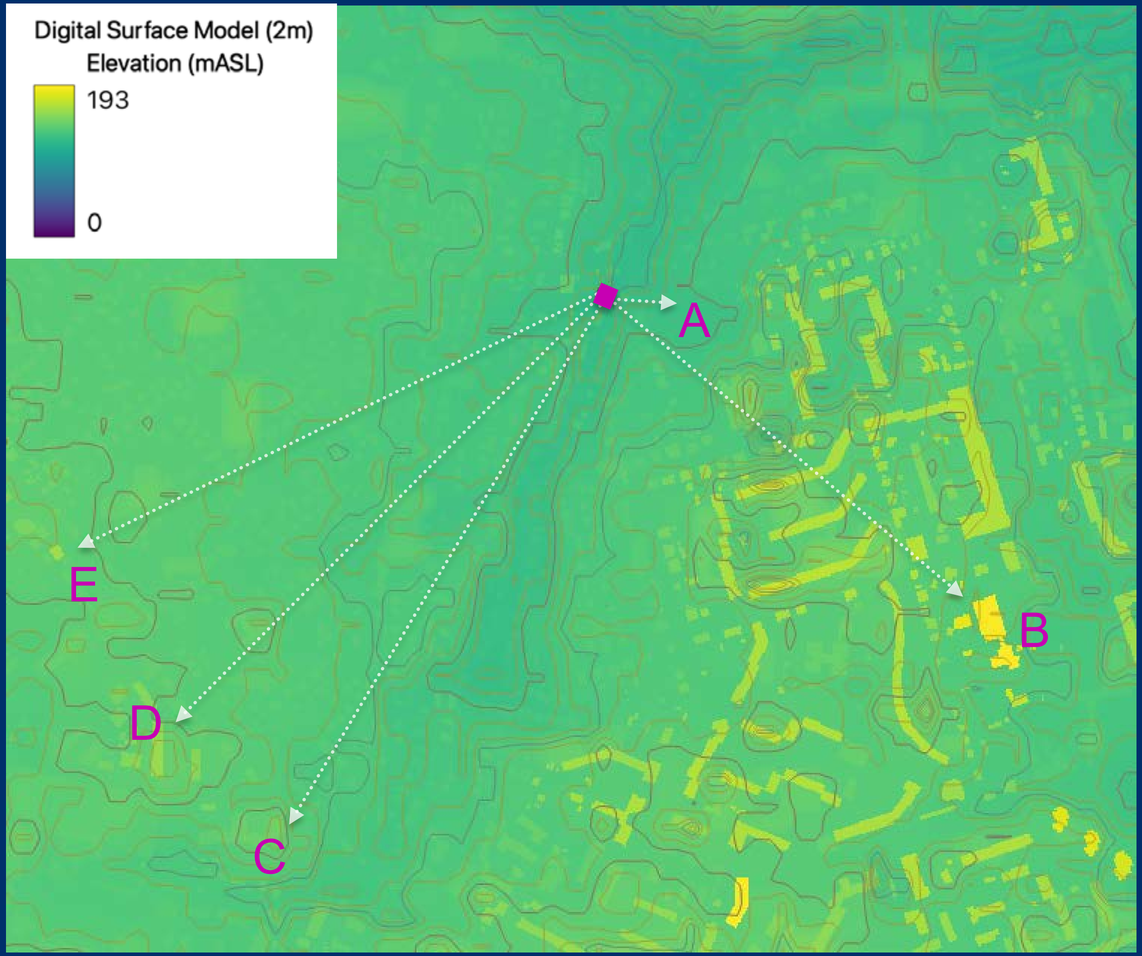
Horizon profiles are constructed using a DSM.

31.27479°E, 51.50646°N

Shading Method

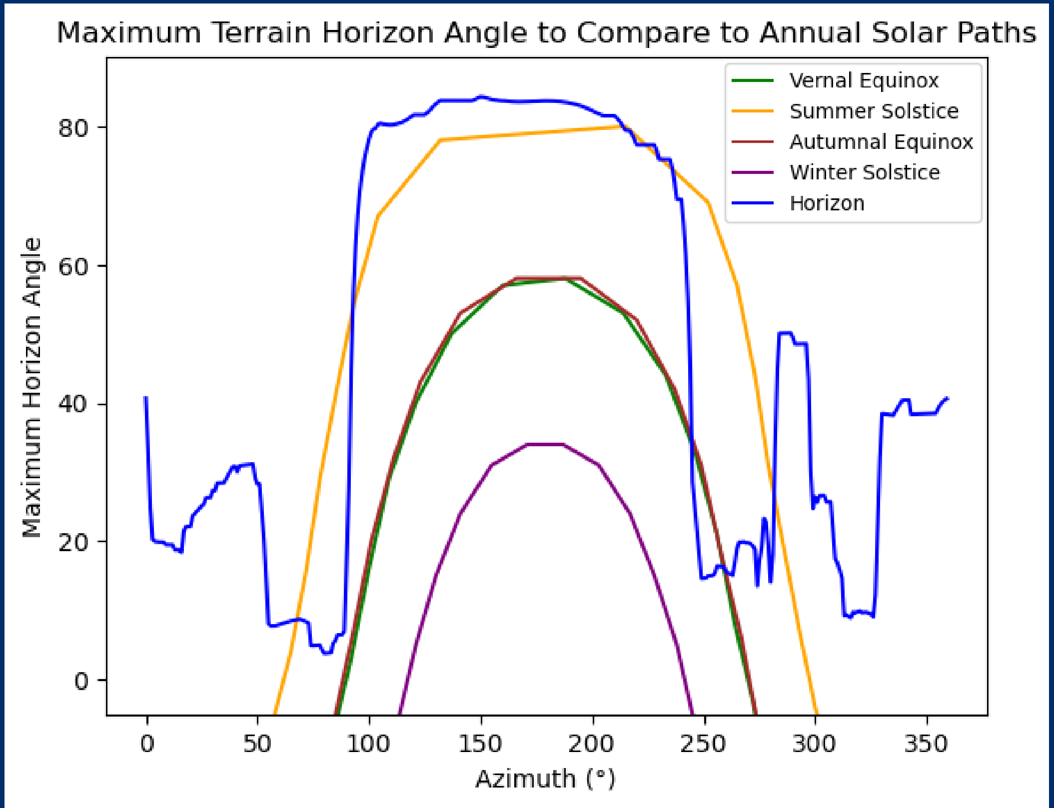


Horizon profile is compared to solar position throughout the year.

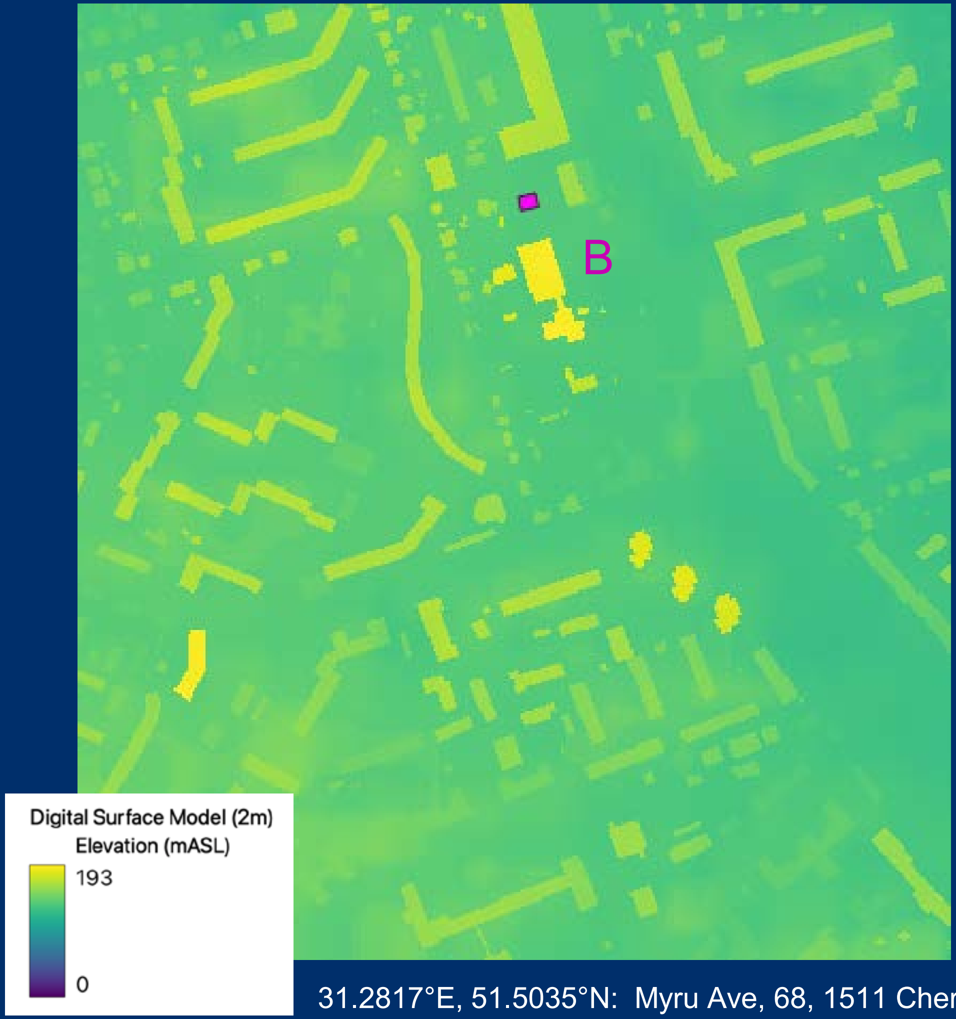


31.27479°E, 51.50646°N

Shading Method



High values in the horizon profile indicate large objects causing frequent shading. Prospective panel locations that are shaded 20% of daylight time steps or more are considered excessively shaded.

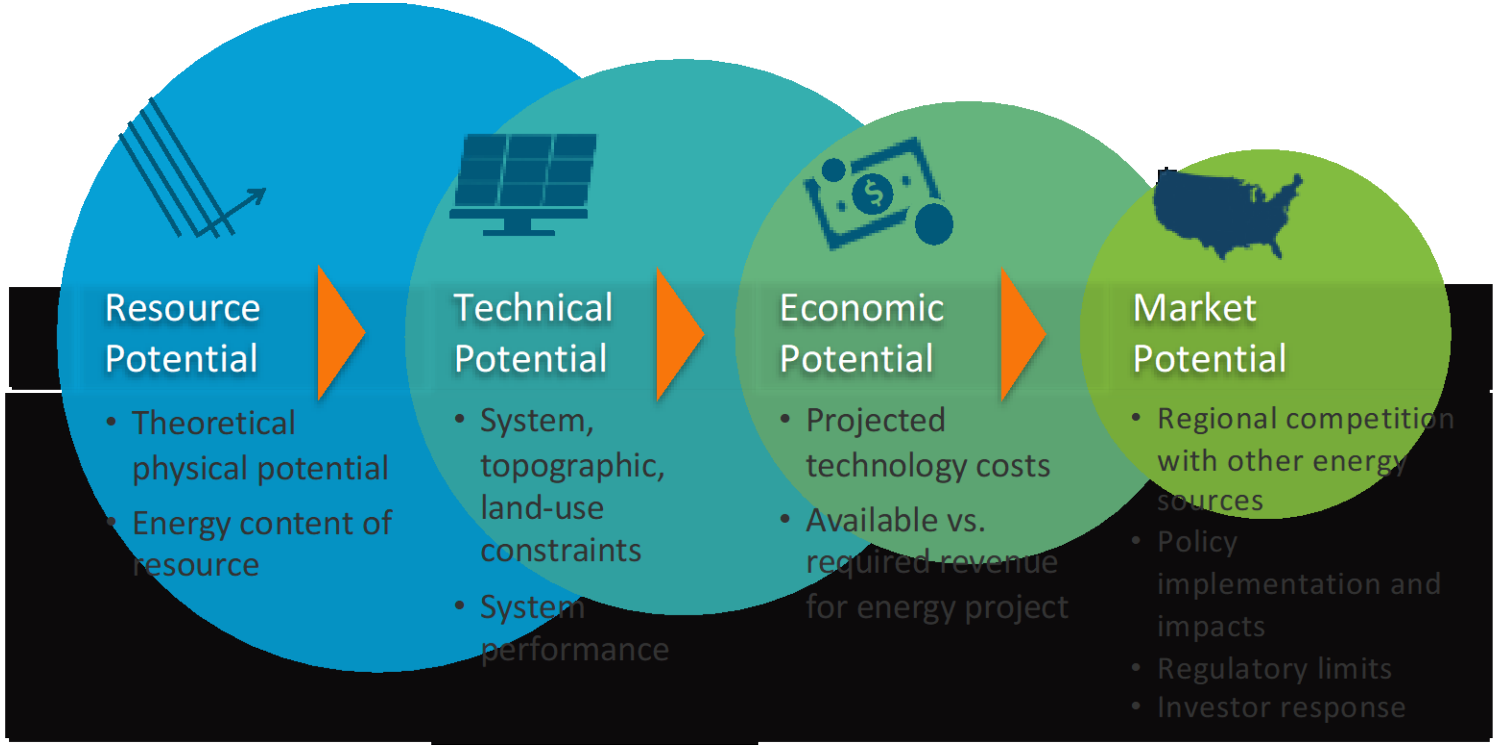


31.2817°E, 51.5035°N: Myru Ave, 68, 1511 Chernihiv
Google Street View: Ihorya Samostrova St, 7

RESULTS

- Lviv
- Chernihiv
- Simulated DSM

Renewable Energy Technical Potential



Technical potential establishes a theoretical maximum for renewable energy potential considering available resources and siting constraints, often including regulatory constraints and interconnection.

Technical potential does not consider project economics, market factors, or grid integration constraints.

Figure source: Brown, Austin, Philipp Beiter, Donna Heimiller, Carolyn Davidson, Paul Denholm, Jennifer Melius, Anthony Lopez, Dylan Hettinger, David Mulcahy, and Gian Porro. 2016. *Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results*. Golden, CO: National Renewable Energy Laboratory. NREL/TP 6A20-64503. https://www.nrel.gov/docs/fy15osti/64503.pdf

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PV System Info and Performance Overview

City	Mean Global Horizontal Irradiance (kWh/m²/day)	Annual Daylight Hours	Mean Capacity Factor (%)
Chernihiv	3.262	4,840 (55%)	15.58
Lviv	3.158	4,833 (55%)	15.09

Average solar resource, time in light, and mean annual PV performance for flat roof planes in Chernihiv and Ukraine calculated in reV using Meteosat SG (2005–2022).

PV System Configurations for System Advisor Model

System Type	Module Efficiency (%)	Array Type	Inverter Load Ratio	Inverter Efficiency (%)	Losses (%)	Panel Capacity (W)	Panel Dimensions (cm)	Tilt, Azimuth, Ground Coverage Ratio
Residential	90.5	1	1.21	96	14.1%	360	99.06 x 161	Variable
Commercial	91.1	1	1.23	98	14.1%	400	99.06 x 198	Variable

Where zoning data was absent, buildings greater than 464 m^2 were modeled using commercial system configuration, while buildings less than 464 m^2 were modeled using residential system configuration.

Lviv Siting Results: PV Rooftop

Size Class	Total Developable Area (m2)	Total Building Area (m2)	Total Count Developable Planes	Total Building Count	Total Capacity (MWdc)	Total Annual Energy Production (MWh)	Mean Capacity Density (W/m2)
Small (<200 sq m)	918,388	2,638,322	83,472	35,828	163.89	186,292	175
Small (<464 sq m)	689,872	2,233,018	48,011	7,781	125.21	142,424	180
Medium (<929 sq m)	558,364	1,770,133	25,575	2,688	90.80	103,540	166
Medium (<1,393 sq m)	567,369	1,804,523	18,836	1,580	91.37	104,373	165
Medium (<1,858 sq m)	390,943	1,359,739	12,784	850	63.12	72,107	165
Medium (<2,232 sq m)	305,152	1,118,698	9,512	539	49.31	56,328	166
Large (<2,787 sq m)	253,996	918,718	7,301	361	40.92	46,765	166
Large (<3,251 sq m)	177,391	709,129	5,400	236	28.65	32,730	166
Large (<3,716 sq m)	123,496	558,873	4,094	161	20.04	22,883	167
Large (<4,180 sq m)	144,464	538,934	4,484	137	23.31	26,630	167
Large (>4,180 sq m)	1,087,076	6,234,851	29,440	648	176.37	201,458	166
Total	5,216,512	19,884,938	248,909	50,809	873.00	995,530	168

- 15.5% of buildings do not have suitable areas for rooftop PV (*n*=7,764).
- Lviv, despite having fewer buildings modeled, has more technical potential for rooftop PV than Chernihiv.
  - Significantly higher capacity densities and sloped roofs mean Lviv can pack more panels into smaller spaces and still yield more energy with slightly poorer solar resource than Chernihiv.

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Lviv Siting Results: Commercial

Size Class	Total Developable Area (m2)	Total Building Area (m2)	Total Count Developable Planes	Total Building Count	Total Capacity (MWdc)	Total Annual Energy Production (MWh)	Mean Capacity Density (W/m2)
Small (<200 sq m)	8,924	24,797	829	364	1.56	1,773	171
Small (<464 sq m)	7,522	22,993	499	80	1.33	1,517	175
Medium (<929 sq m)	5,803	18,392	258	27	0.94	1,073	164
Medium (<1,393 sq m)	4,966	16,139	211	14	0.79	907	162
Medium (<1,858 sq m)	5,237	15,898	172	10	0.83	951	162
Medium (<2,232 sq m)	4,405	12,158	82	6	0.70	801	165
Large (<2,787 sq m)	717	2,398	32	1	0.11	129	156
Large (<3,251 sq m)	3,803	6,199	29	2	0.60	689	167
Large (<3,716 sq m)	-	-	-	-	-	-	-
Large (<4,180 sq m)	3,115	11,866	115	3	0.51	577	168
Large (>4,180 sq m)	10,597	30,490	274	6	1.70	1,944	164
Total	55,089	161,330	2,501	513	9.08	10,361	165

- Only 20% of sampled Lviv buildings have an associated zoning classification.
- This subset includes 513 buildings that are classified as zoned commercial and constitutes 1.0% of the total Lviv building sample.
- While identified commercial buildings are few, they serve as a representative sample for commercial building technical potential in Lviv.

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Lviv Siting Results: Industrial

Size Class	Total Developable Area (m2)	Total Building Area (m2)	Total Count Developable Planes	Total Building Count	Total Capacity (MWdc)	Total Annual Energy Production (MWh)	Mean Capacity Density (W/m2)
Small (<200 sq m)	8,063	22,297	716	311	1.44	1,634	175
Small (<464 sq m)	4,449	14,706	297	50	0.81	925	181
Medium (<929 sq m)	4,722	13,065	200	20	0.76	872	164
Medium (<1,393 sq m)	4,551	12,721	144	11	0.73	832	165
Medium (<1,858 sq m)	1,554	6,470	56	4	0.25	282	164
Medium (<2,232 sq m)	1,926	10,283	92	5	0.32	361	170
Large (<2,787 sq m)	-	4,688	-	2	-	-	-
Large (<3,251 sq m)	1,561	2,833	8	1	0.25	290	172
Large (<3,716 sq m)	1,631	6,826	27	2	0.26	299	170
Large (<4,180 sq m)	1,095	4,001	68	1	0.18	206	169
Large (>4,180 sq m)	15,507	85,017	823	10	2.60	2,954	169
Total	45,059	182,907	2,431	417	7.60	8,655	170

- Only 20% of sampled Lviv buildings have an associated zoning classification.
- This subset includes 417 buildings that are classified as zoned industrial and constitutes 0.8% of the total Lviv building sample.
- While identified industrial buildings are few, they serve as a representative sample for industrial building technical potential in Lviv.

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Lviv Siting Results: Residential

Size Class	Total Developable Area (m2)	Total Building Area (m2)	Total Count Developable Planes	Total Building Count	Total Capacity (MWdc)	Total Annual Energy Production (MWh)	Mean Capacity Density (W/m2)
Small (<200 sq m)	159,318	464,380	14,958	6,311	28.68	32,591	177
Small (<464 sq m)	133,090	448,757	9,518	1,539	24.26	27,587	181
Medium (<929 sq m)	110,643	374,282	5,166	565	18.00	20,523	166
Medium (<1,393 sq m)	103,527	358,707	3,720	317	16.72	19,095	166
Medium (<1,858 sq m)	74,310	274,040	2,557	171	12.04	13,744	166
Medium (<2,232 sq m)	56,582	223,922	2,018	107	9.19	10,487	166
Large (<2,787 sq m)	44,459	202,272	1,347	80	7.16	8,176	166
Large (<3,251 sq m)	33,564	147,512	899	49	5.41	6,187	166
Large (<3,716 sq m)	25,916	128,201	964	37	4.24	4,832	167
Large (<4,180 sq m)	31,158	121,840	1,033	31	5.04	5,761	167
Large (>4,180 sq m)	198,442	1,325,042	8,064	152	32.54	37,084	167
Total	971,009	4,068,955	50,244	9,359	163.28	186,066	168

- Only 20% of sampled Lviv buildings have an associated zoning classification.
- This subset includes 9,359 buildings that are classified as zoned residential and constitutes 18.4% of the total Lviv building sample.
- Residential buildings at every size in Lviv rely on many smaller arrays to maximize capacity. This likely will require more complex PV panel stringing, potentially increasing losses.

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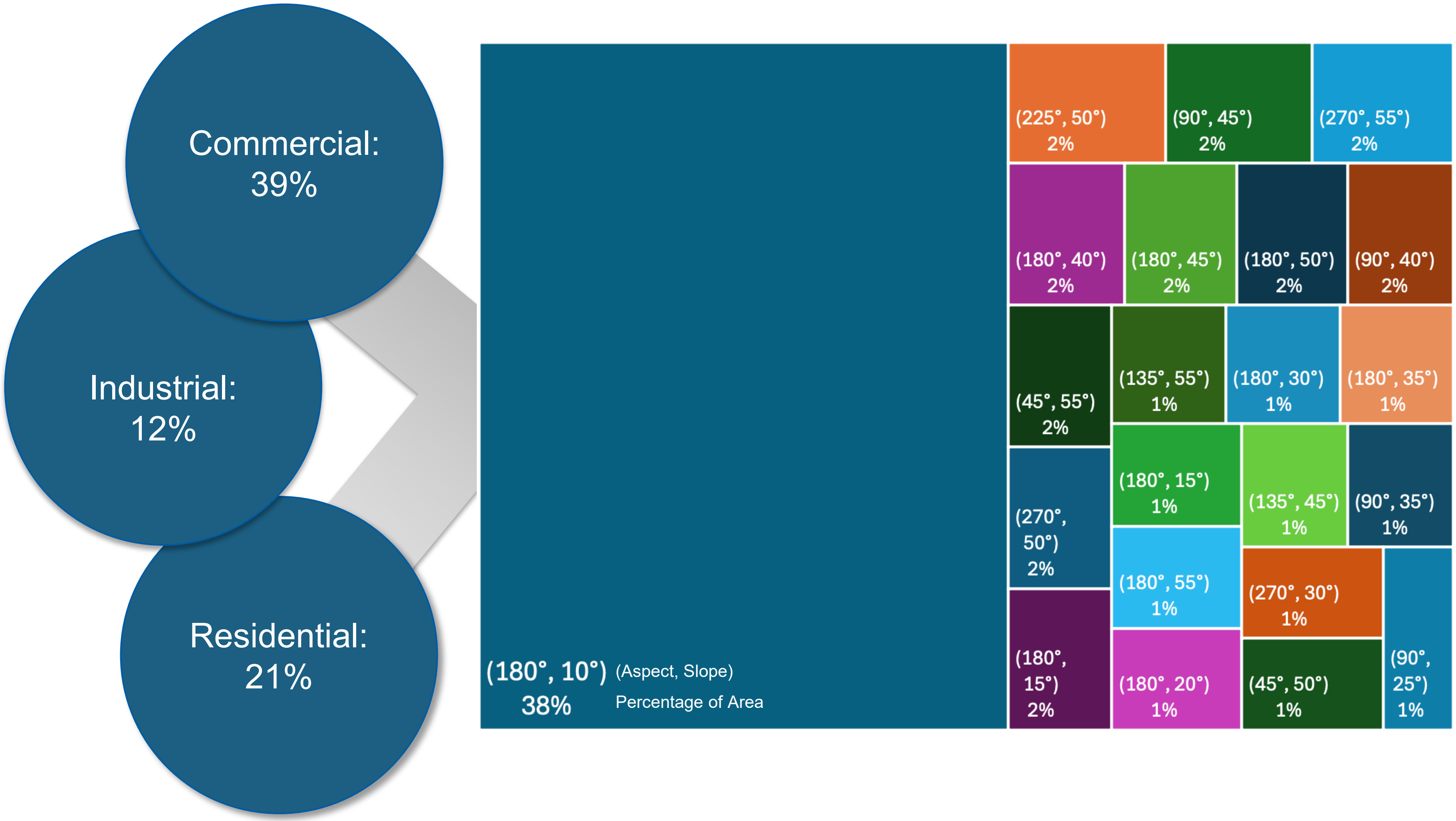
Percentage of Developable Planes Area by Orientation



In Lviv, PV-suitable roof areas are more often found on sloped roof planes. Sloped planes, comprising planes with slopes greater than 12°, assume that PV arrays are tilted flush to the roof plane.

The proportion of developable flat roof planes is atypical and unusually low to architecture previously modeled in PVRDB. This distribution illustrates the importance of utilizing very-high-resolution data; Gothic, Renaissance, Baroque architecture strongly influence these results.

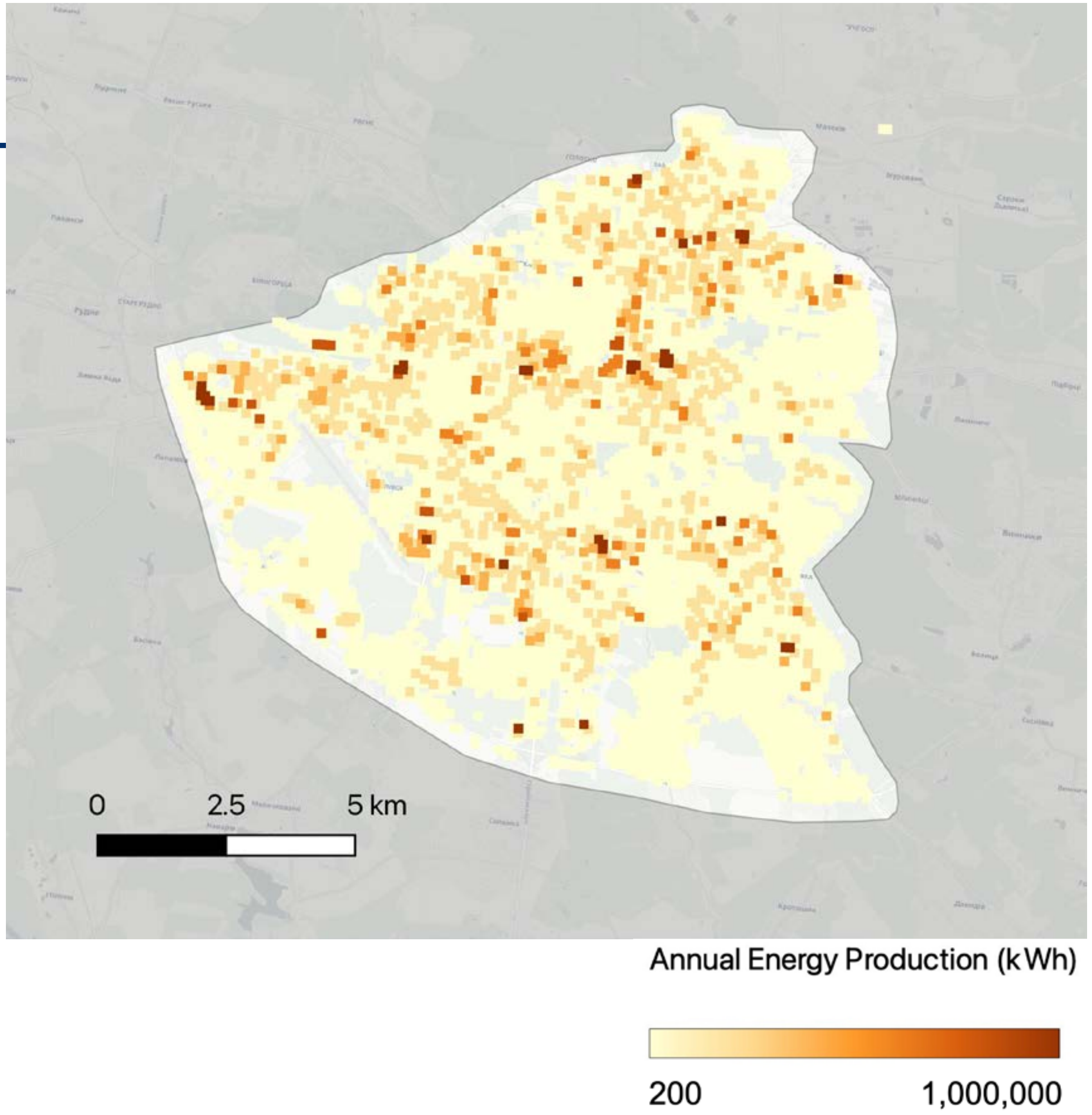
Lviv Siting Results

Small buildings hold high percentage of developable area per building, high capacity density, and low shading percentage.

Medium and large buildings may offer comparable system sizes and performance. Clustering of large buildings increases module shading.

The skew toward sloped developable planes increases mean capacity density vis-à-vis reducing interrow spacing.

Size Class	Mean Developable Area (m2)	Mean Building Size (m2)	Mean Developable Area Percentage	Mean Capacity Density (W/m2)	Mean Shading Percentage
Small (<200 sq m)	30	74	43%	175	3.5%
Small (<464 sq m)	100	287	31%	180	2.6%
Medium (<929 sq m)	241	659	34%	166	2.8%
Medium (<1,393 sq m)	434	1,142	36%	165	2.7%
Medium (<1,858 sq m)	597	1,600	35%	165	3.3%
Medium (<2,232 sq m)	755	2,076	35%	166	4.0%
Large (<2,787 sq m)	930	2,545	35%	166	4.9%
Large (<3,251 sq m)	1,062	3,005	33%	166	5.2%
Large (<3,716 sq m)	1,187	3,471	32%	167	5.8%
Large (<4,180 sq m)	1,350	3,934	32%	167	6.2%
Large (>4,180 sq m)	2,678	9,622	31%	166	4.8%



Chernihiv Siting Results: PV Rooftop

Size Class	Total Developable Area (m2)	Total Building Area (m2)	Total Count Developable Planes	Total Building Count	Total Capacity (MWdc)	Total Annual Energy Production (MWh)	Mean Capacity Density (W/m2)
Small (<200 sq m)	1,216,019	3,879,240	139,689	57,530	158.36	178,729	145
Small (<464 sq m)	459,798	1,411,178	30,375	5,056	50.55	57,234	148
Medium (<929 sq m)	473,504	1,109,492	13,615	1,681	37.84	43,048	134
Medium (<1,393 sq m)	400,856	835,115	7,243	746	29.24	33,346	133
Medium (<1,858 sq m)	224,019	456,770	3,114	288	15.87	18,108	133
Medium (<2,232 sq m)	147,280	306,583	1,694	148	9.79	11,190	127
Large (<2,787 sq m)	81,534	201,684	1,081	79	5.51	6,290	133
Large (<3,251 sq m)	80,849	170,550	699	57	5.20	5,953	130
Large (<3,716 sq m)	62,176	151,721	689	44	4.03	4,613	127
Large (<4,180 sq m)	39,128	89,920	342	23	2.46	2,814	123
Large (>4,180 sq m)	209,301	589,015	1,143	82	12.99	14,873	124
Total	3,394,466	9,201,268	199,684	65,734	331.84	376,197	132

- 11.1% of buildings do not have suitable areas for rooftop PV (*n*=8,209).
- Chernihiv has unusually high proportion of small buildings (87%) with approximately one-quarter of the quantity of large buildings in Lviv. The combination of the very high proportion of small buildings and dominance of flat roof planes leads to lower density of PV arrays and thus lower capacity per unit of roof area.

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Chernihiv Siting Results: Commercial

Size Class	Total Developable Area (m2)	Total Building Area (m2)	Total Count Developable Planes	Total Building Count	Total Capacity (MWdc)	Total Annual Energy Production (MWh)	Mean Capacity Density (W/m2)
Small (<200 sq m)	4,640	15,310	514	240	595.44	672	145
Small (<464 sq m)	1,891	6,133	152	23	214.92	243	148
Medium (<929 sq m)	888	3,221	23	5	72.4	82	133
Medium (<1,393 sq m)	304	1,038	10	1	57.2	64	172
Medium (<1,858 sq m)	827	3,089	48	2	70.8	80	146
Medium (<2,232 sq m)	339	2,261	26	1	30	34	135
Large (<2,787 sq m)	1,379	2,499	11	1	82	94	95
Large (<3,251 sq m)	1,629	2,900	16	1	104.4	120	144
Large (<3,716 sq m)	0	0	0	0	0	0	0
Large (<4,180 sq m)	0	0	0	0	0	0	0
Large (>4,180 sq m)	0	0	0	0	0	0	0
Total	11,897	36,451	800	274	1.23	1,389	140

- Only 24% of sampled Chernihiv buildings have an associated zoning classification.
- This subset includes 274 buildings that are classified as zoned commercial and constitutes 0.4% of the total Chernihiv building sample.
- While identified commercial buildings are few, they serve as a representative sample for commercial building technical potential in Chernihiv.

Chernihiv Siting Results: Industrial

Size Class	Total Developable Area (m2)	Total Building Area (m2)	Total Count Developable Planes	Total Building Count	Total Capacity (MWdc)	Total Annual Energy Production (MWh)	Mean Capacity Density (W/m2)
Small (<200 sq m)	3,806	11,790	416	176	0.49	555	141
Small (<464 sq m)	1,274	4,209	109	16	0.15	170	149
Medium (<929 sq m)	2,232	4,623	48	7	0.16	180	135
Medium (<1,393 sq m)	1,065	2,156	15	2	0.08	87	104
Medium (<1,858 sq m)	0	0	0	0	0	0	0
Medium (<2,232 sq m)	0	0	0	0	0	0	0
Large (<2,787 sq m)	748	2,752	10	1	0.05	52	102
Large (<3,251 sq m)	0	0	0	0	0	0	0
Large (<3,716 sq m)	0	0	0	0	0	0	0
Large (<4,180 sq m)	0	0	0	0	0	0	0
Large (>4,180 sq m)	0	0	0	0	0	0	0
Total	9,126	25,531	598	202	0.92	1,044	127

- Only 24% of sampled Chernihiv buildings have an associated zoning classification.
- This subset includes 202 buildings that are classified as zoned industrial and constitutes 0.3% of the total Chernihiv building sample.
- While identified industrial buildings are few, they serve as a representative sample for commercial building technical potential in Chernihiv.

Chernihiv Siting Results: Residential

Size Class	Total Developable Area (m2)	Total Building Area (m2)	Total Count Developable Planes	Total Building Count	Total Capacity (MWdc)	Total Annual Energy Production (MWh)	Mean Capacity Density (W/m2)
Small (<200 sq m)	275,474	914,624	31,654	14758	35.85	40,459	145
Small (<464 sq m)	109,897	351,261	7,190	1251	12.09	13,688	148
Medium (<929 sq m)	114,748	287,284	3,289	428	9.06	10,303	134
Medium (<1,393 sq m)	93,428	244,151	1,950	218	6.88	7,843	135
Medium (<1,858 sq m)	38,002	99,543	552	63	2.75	3,134	136
Medium (<2,232 sq m)	31,807	87,872	326	43	2.02	2,314	124
Large (<2,787 sq m)	22,724	70,707	284	28	1.51	1,722	130
Large (<3,251 sq m)	25,711	68,526	156	23	1.58	1,815	126
Large (<3,716 sq m)	20,734	55,472	221	16	1.34	1,532	130
Large (<4,180 sq m)	9,587	19,262	69	5	0.60	685	121
Large (>4,180 sq m)	30,845	134,288	206	19	1.91	2,191	145
Total	772,958	2,332,990	45,897	16,852	75.59	85,686	134

- Only 24% of sampled Chernihiv buildings have an associated zoning classification.
- This subset includes 16,582 buildings that are classified as zoned industrial and constitutes 25.6% of the total Chernihiv building sample.
- Residential buildings in Chernihiv are predominantly small, which may indicate a bias in the zoning identification that omits large multifamily buildings.
- Large residential buildings are more competitive than small residential buildings regarding developable area and capacity density.

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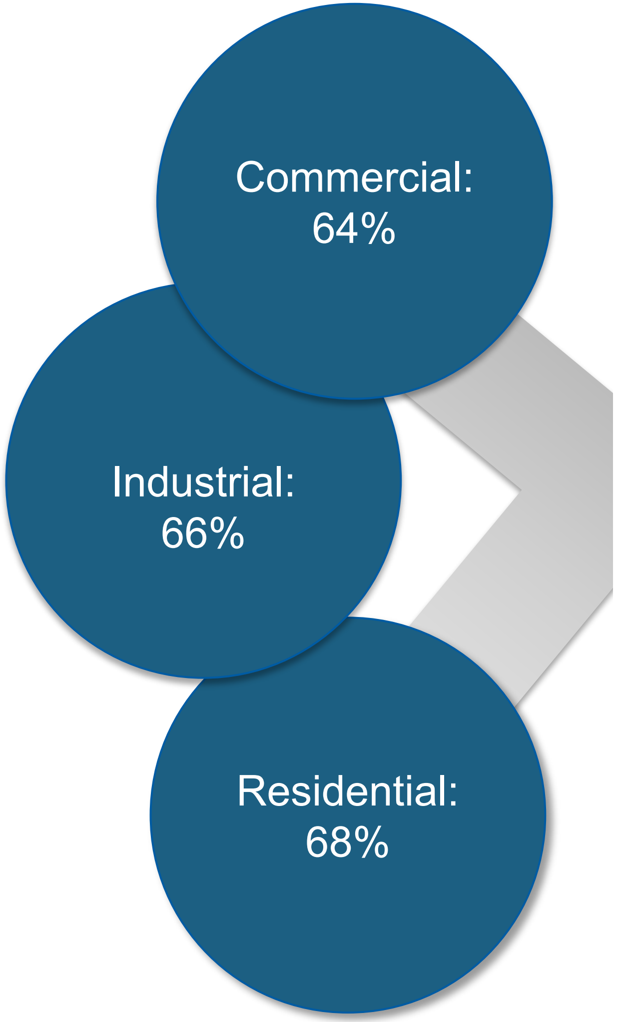
Percentage of Developable Planes Area by Orientation



In Chernihiv, PV-suitable roof areas are more often found on flat roof planes. Flat planes require panels face south and are tilted equal to latitude with dynamically calculated row spacing, averaging a 1.4-meter row spacing*.

Sloped suitable roof areas are assumed to be flush-mounted with 20-cm panel spacing.

The distribution of suitable roof planes' orientation is important for determining capacity density and system performance in time.

* Based on absolute winter solstice solar positions needed for 80% generation yield.

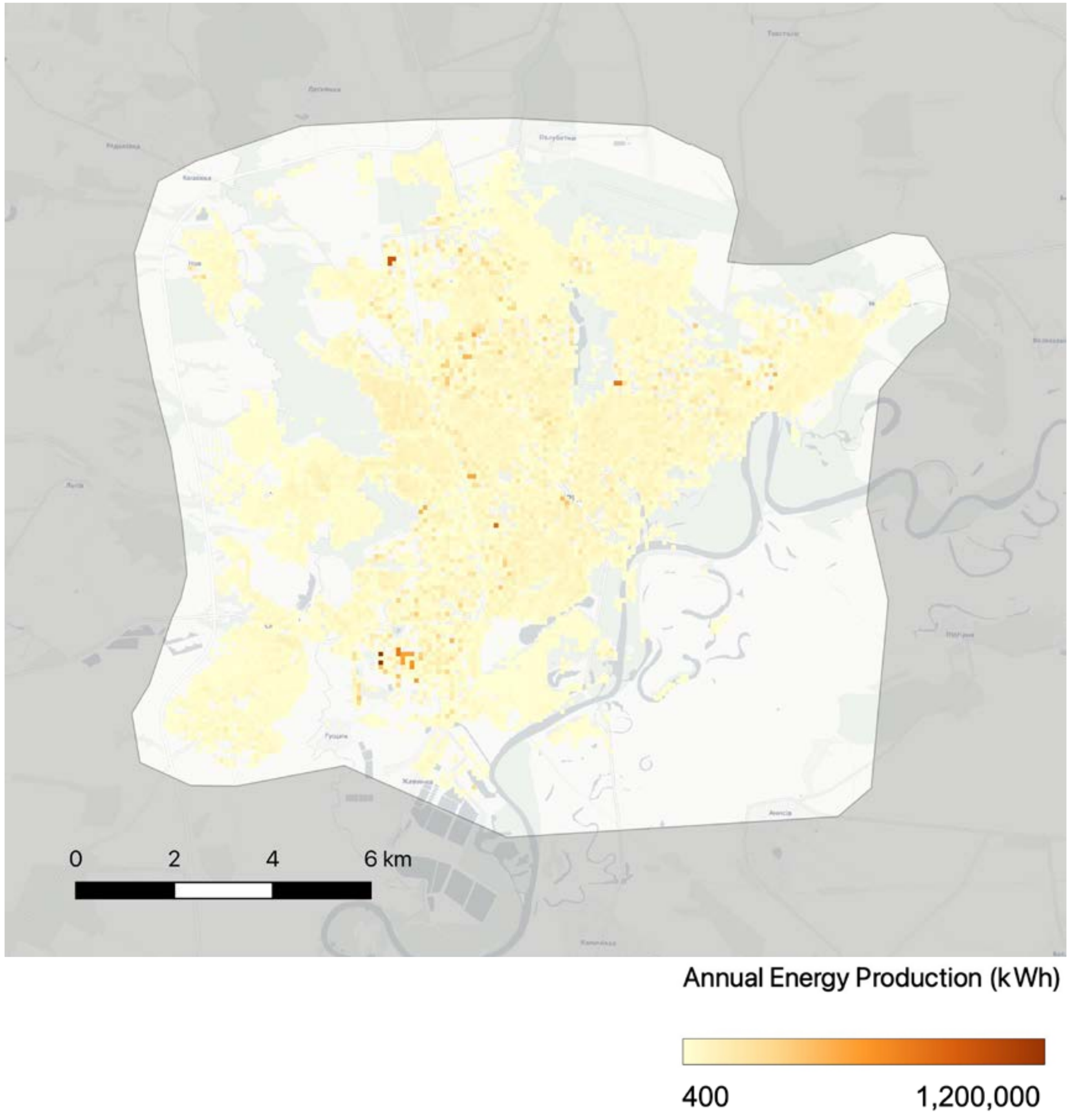
Chernihiv Siting Results

Small building siting statistics are consistent with other mid-latitude locations (e.g., moderate percentage developable area and capacity density).

Medium buildings hold high percentage of developable area per building, high capacity density, and low shading percentage.

Large buildings offer larger system sizes despite lower developable area percentage and lower capacity density.

Size Class	Mean Developable Area (m2)	Mean Building Size (m2)	Mean Developable Area Percentage	Mean Capacity Density (W/m2)	Mean Shading Percentage
Small (<200 sq m)	21	63	34	145	4.2
Small (<464 sq m)	91	280	32	148	3.6
Medium (<929 sq m)	282	662	43	134	2.9
Medium (<1,393 sq m)	537	1,125	48	133	2.2
Medium (<1,858 sq m)	778	1,587	49	133	3.1
Medium (<2,232 sq m)	995	2,069	48	127	3.1
Large (<2,787 sq m)	1,032	2,558	40	133	4.7
Large (<3,251 sq m)	1,418	2,986	47	130	4.3
Large (<3,716 sq m)	1,413	3,465	41	127	4.9
Large (<4,180 sq m)	1,701	3,903	44	123	3.1
Large (>4,180 sq m)	2,552	7,208	35	124	3.6



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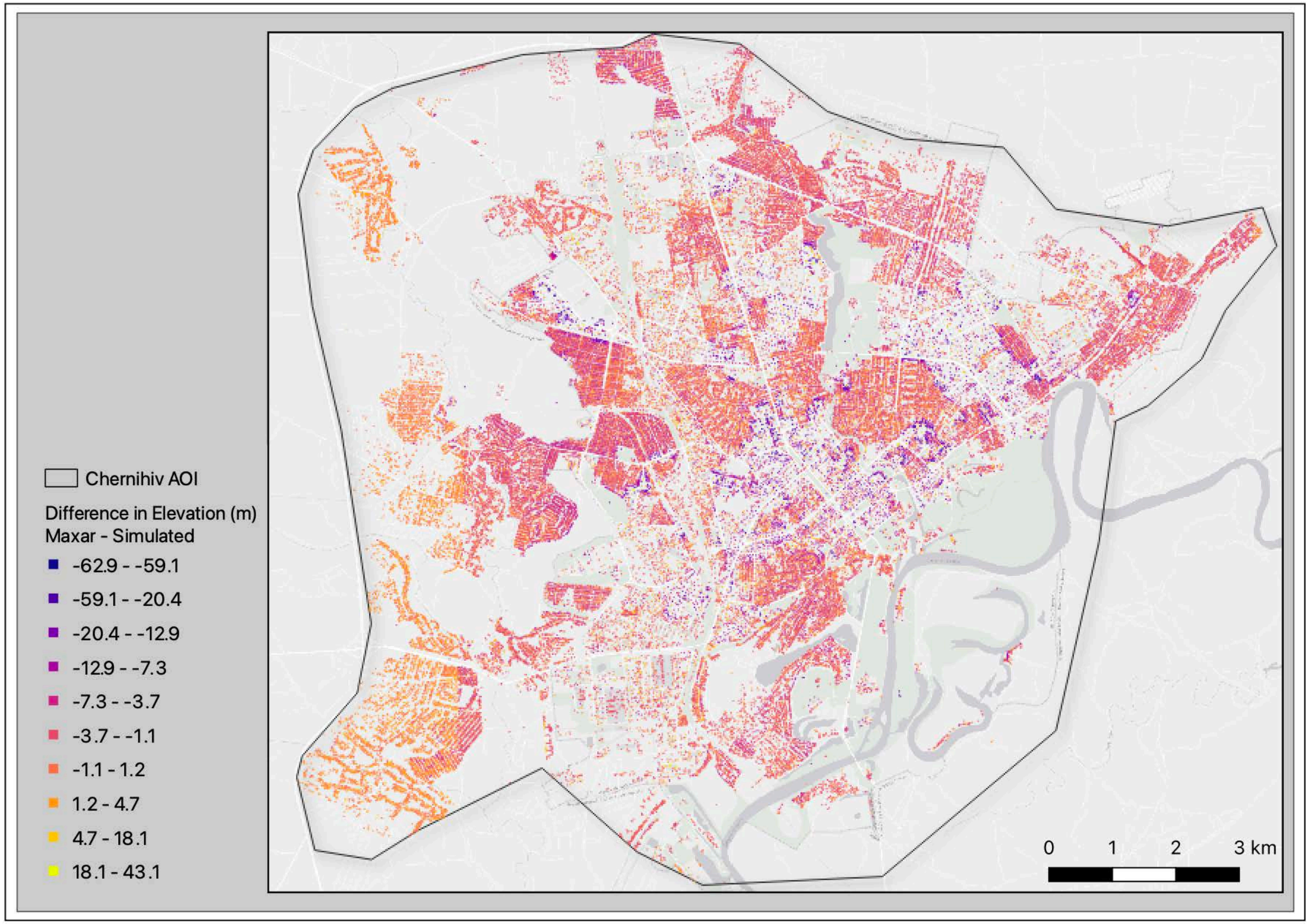
Building Height Comparison: Simulated DSM and Precision 3D DSM



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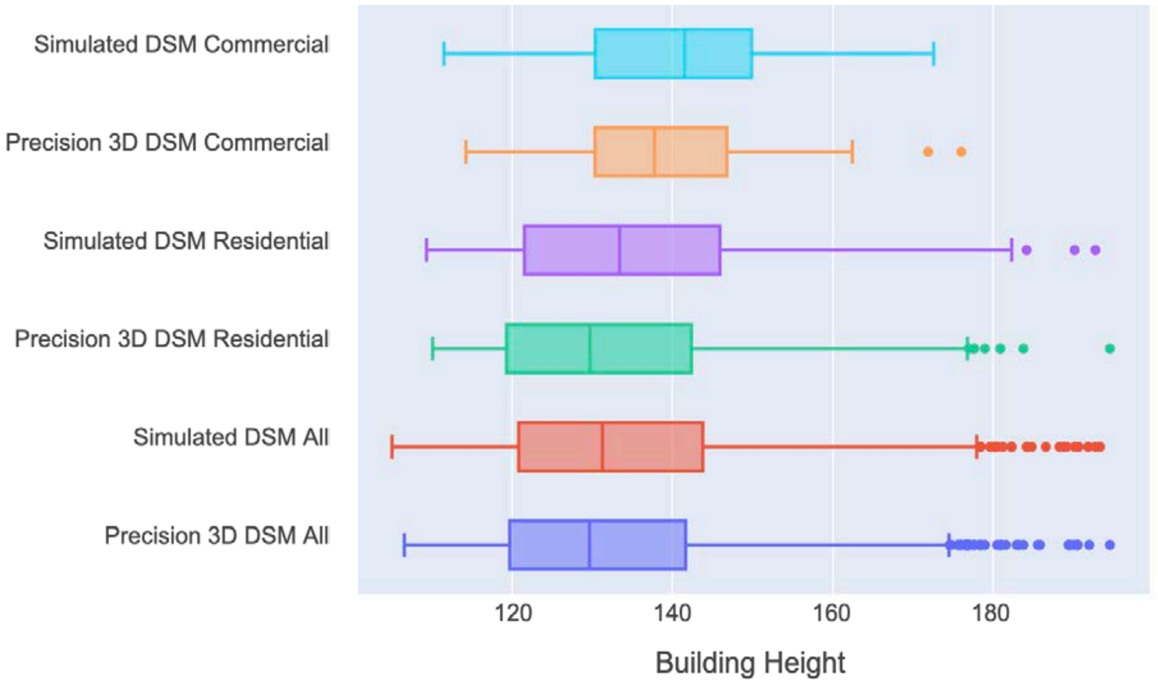
The simulated DSM systematically overestimates building height compared to the elevations identified by Precision 3D. In the case of the simulated DSM, Precision 3D data is considered a standard to match.

Representing building height higher than reality can increase the influence of shading on modeled PV systems as well as increase open sky exposure.

Additional work needs to be done on non-building objects, such as trees, as well as in Lviv to evaluate biases and assumptions used to create the simulated DSM.



Building Height Means (m)

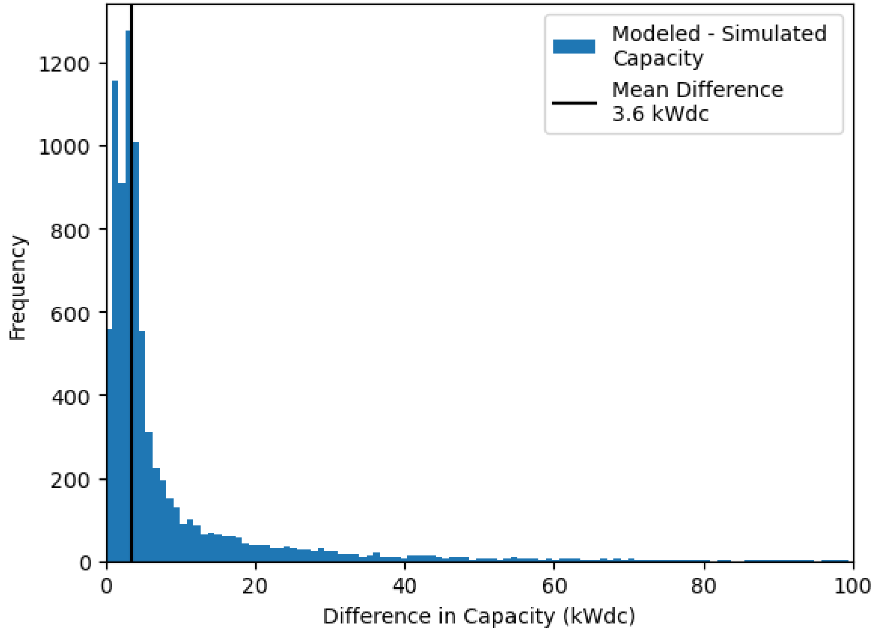
	Commercial *Maxar*	**Commercial** *Simulated*	**Residential** *Maxar*	**Residential** *Simulated*	**All** *Maxar*	**All** *Simulated*
Count	274	274	17,257	17,257	74,477	74,477
Mean	137.96	141.17	130.90	133.88	130.52	132.32
Standard Deviation	10.31	11.78	12.78	13.56	12.29	12.91
Minimum	114.27	111.53	110.13	109.36	106.60	105.06
25%	130.37	130.39	119.34	121.56	119.73	120.85
50%	137.77	141.53	129.74	133.42	129.67	131.29
75%	146.79	149.84	142.38	145.93	141.66	143.79
Maximum	176.02	172.58	194.54	192.73	194.54	193.21

Comparison of Simulated DSM and Precision 3D DSM Results

The technical potential results from the simulated DSM yields 45 MWdc more capacity and 51,977 MWh more annual energy production (87.3M UAH, 2.6M USD)[3].

Individual building and aggregate calculated capacity estimates are systemically higher using the simulated DSM. The mean difference in capacity per building is 3.6 kWdc, which can range from 25–30 square meters of developable area.

DSM	Developable Area (m2)	Buildings With Developable Area	Capacity (MWdc)	Annual Energy Production (MWh)	Mean Shading Percentage
Precision 3D Maxar	3,659,990	65,734	331.84	376,197	4.42
Simulated	3,307,615	64,164	376.89	428,174	6.11



[3] International Energy Agency. "Ukraine energy profile – Analysis." IEA, 2019. Available at: https://www.iea.org/reports/ukraine-energy-profile.

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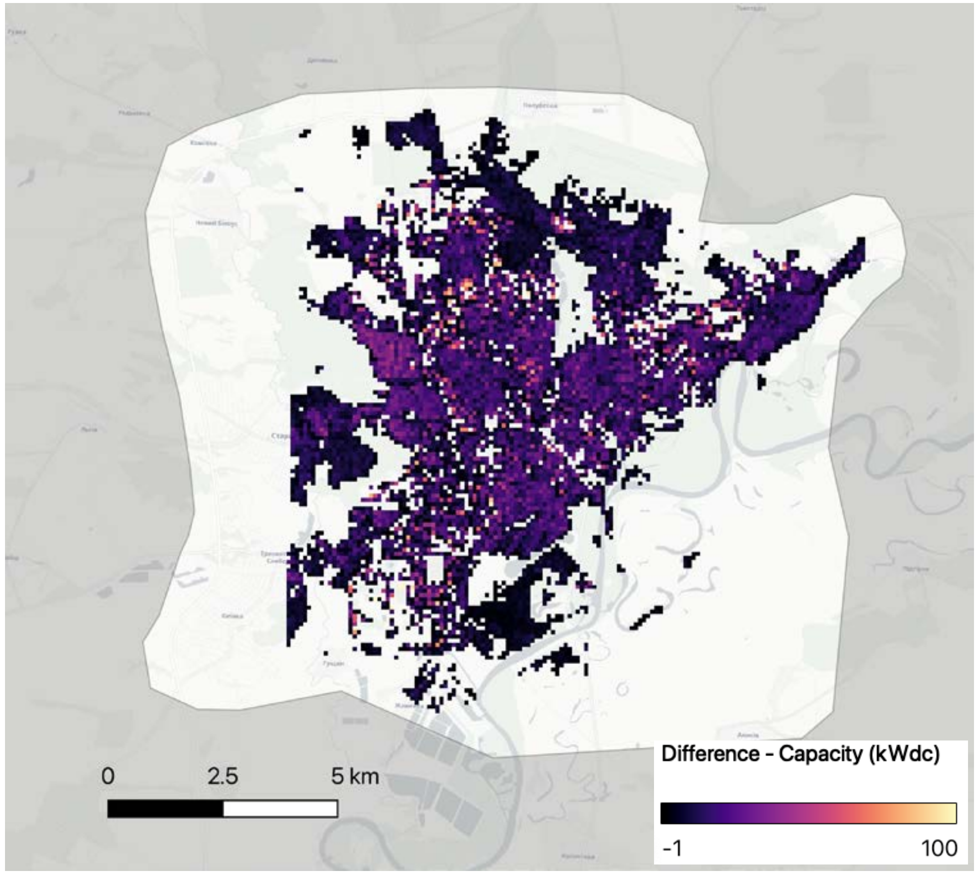
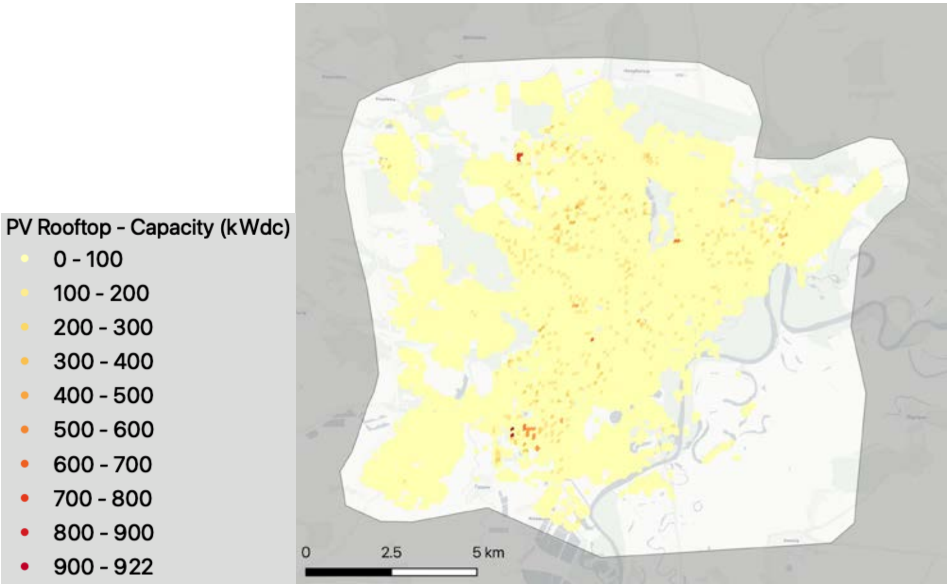
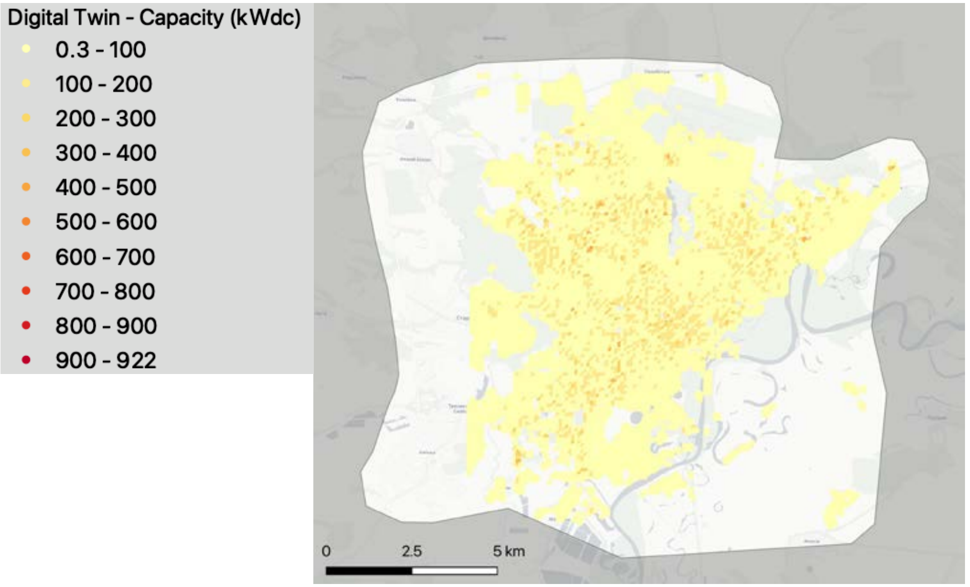
Comparison of Simulated DSM and Precision 3D DSM: Capacity

Difference in capacity outliers are clustered in two types of locations:

- Dense subdivisions with only small buildings
- Areas with very low density of buildings.







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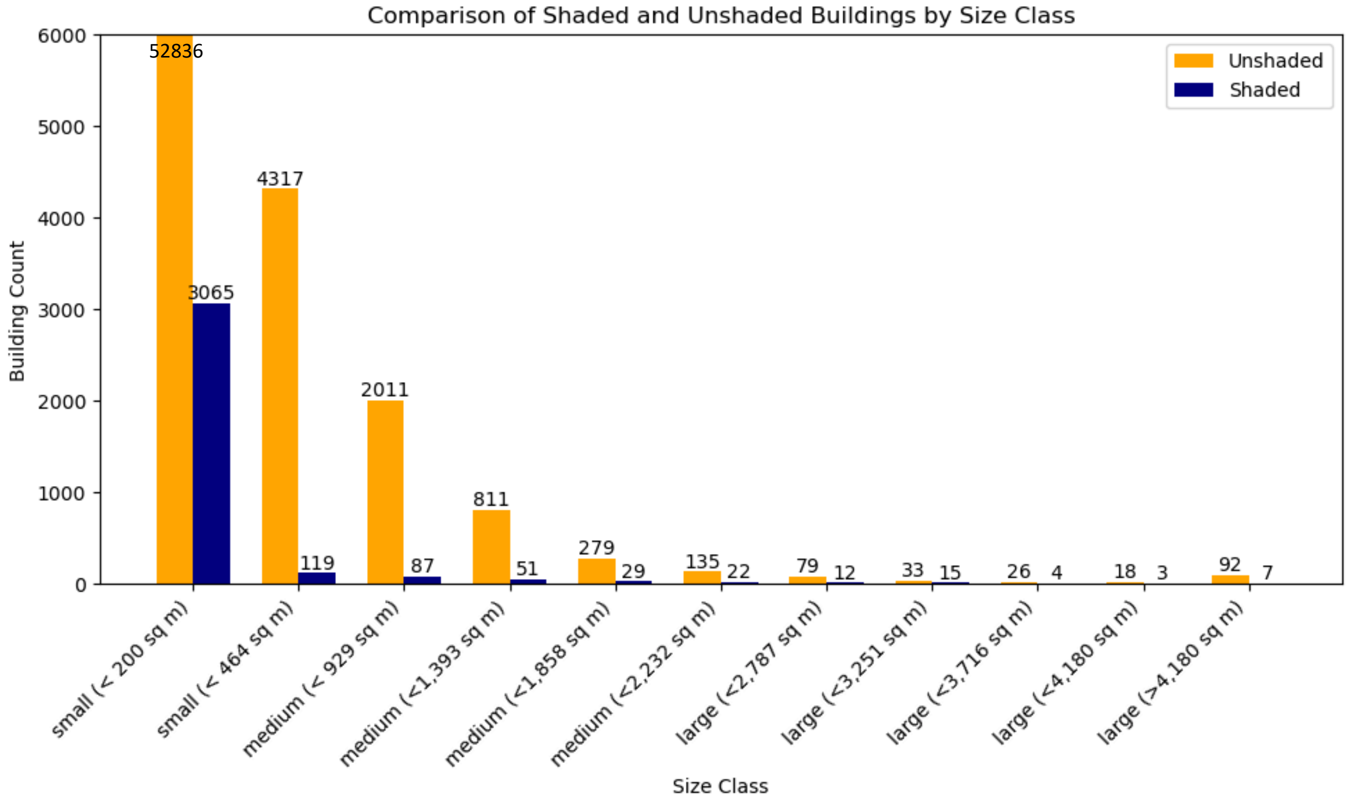

Roof plane tilt and orientation are not detectable via the simulated DSM.

The difference (5.8%) between the distribution of developable planes via Maxar's Precision 3D and the simulated DSM likely results from commission assuming suitable tilts, azimuths, and plane sizes.

Comparing Shading Results

Using the simulated DSM, 5.3% of buildings in Chernihiv were identified as excessively shaded and not suitable sites for rooftop PV. This is less than the 11.1% of buildings in Chernihiv that were identified as not having any suitable rooftop PV-hosting spaces.

Future Work

- Building on the high-resolution 3D elevation models used to assess rooftop solar opportunities in Chernihiv and Lviv, we will scale our analysis in future work to evaluate the national technical potential for rooftop solar across Ukraine. This expansion includes refining the methods used to create the simulated DSMs, or digital twins, and inputting these models to assess rooftop siting opportunities nationwide.

- We will compile additional training data on architectural styles across Ukraine and develop a machine learning model to identify likely architectural types for each building. This approach aims to reduce the inclusion of buildings that lack suitable rooftop areas for solar PV installation.

- Additionally, we will expand our PV system performance simulations across Ukraine, calculating exceedance probabilities for all tilt and aspect combinations, ensuring optimized performance modeling for diverse building characteristics.

Thank you!

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- This analysis relies on elevation data provided to NREL that have not been independently validated by NREL.
- The analysis results are not intended to be the sole basis of investment, policy, or regulatory decisions.
- This analysis was conducted using the NREL PV Rooftop and Renewable Energy Potential (https://github.com/NREL/reV) models. PV Rooftop is a rooftop PV siting suitability model while the Renewable Energy Potential (reV) model is an open-source geospatial techno-economic tool that estimates renewable energy technical potential (capacity and generation), system cost, and supply curves for solar photovoltaics (PV), concentrating solar power (CSP), geothermal, and wind energy.
- The data, results, conclusions, and interpretations presented in this document have not been reviewed by technical experts outside NREL.