Modelling and simulation infrastructure for smart energy and renewable technologies integration in urban districts

Candidate: Lorenzo Bottaccioli

Supervisor: Professor Enrico Macii

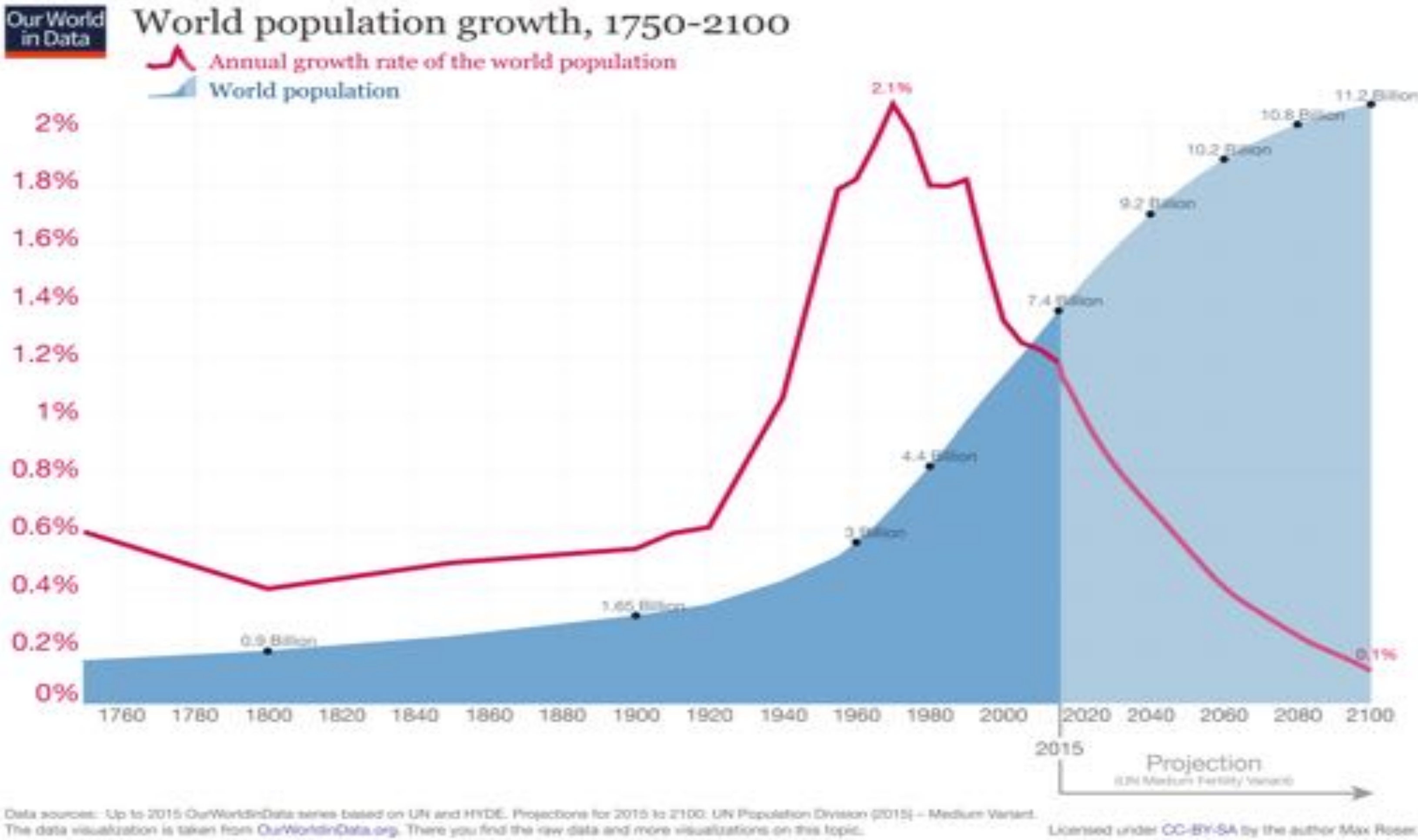
Turin 5 April 2018

Doctoral Dissertation Doctoral Program in Computer and Control Engineering (30th cycle)

Overview

- Introduction
- Challenges
- Motivation
- State of the Art
- Contribution
- Enabling technologies
- SMIRSE infrastructure
- Energy Simulations and Results
- Conclusions

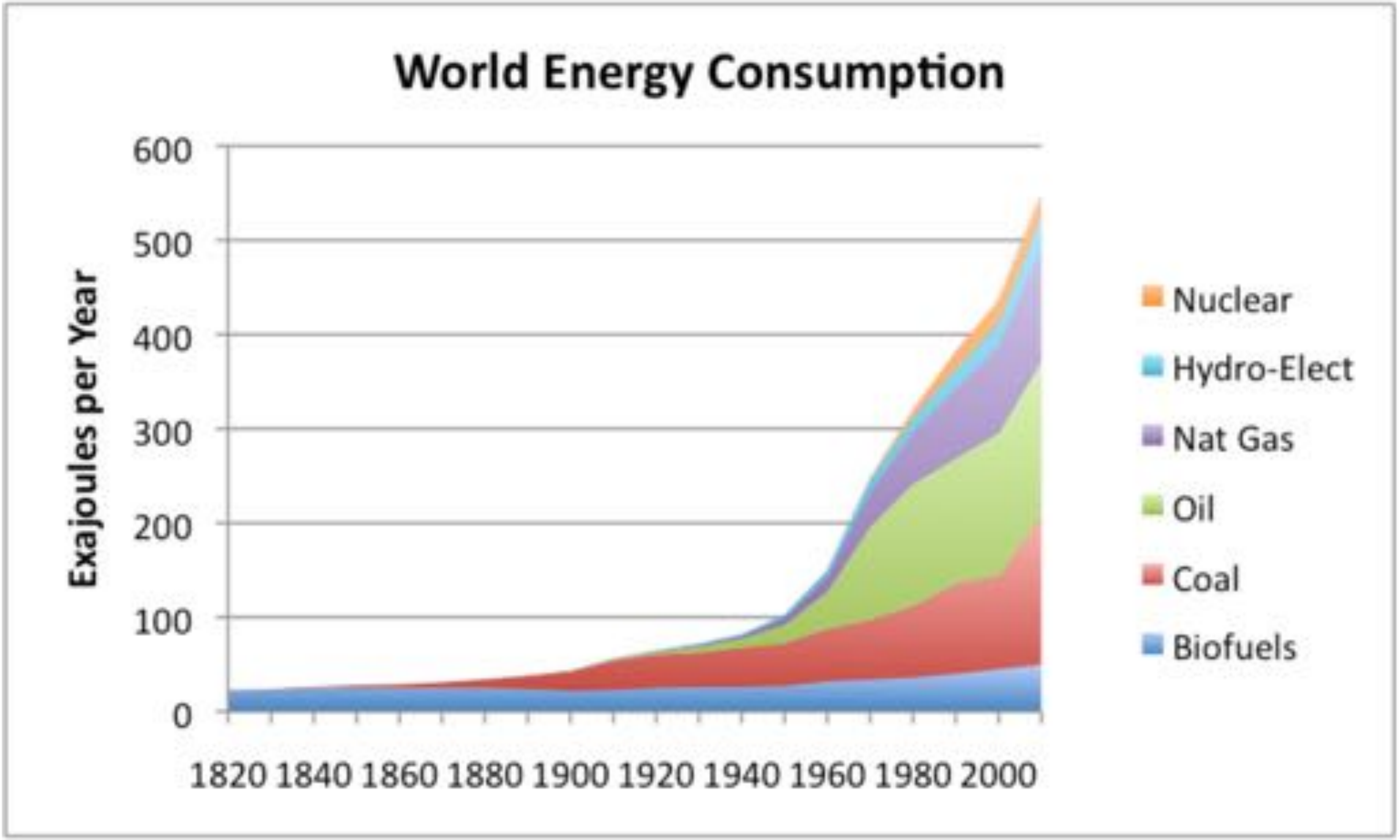
Introduction



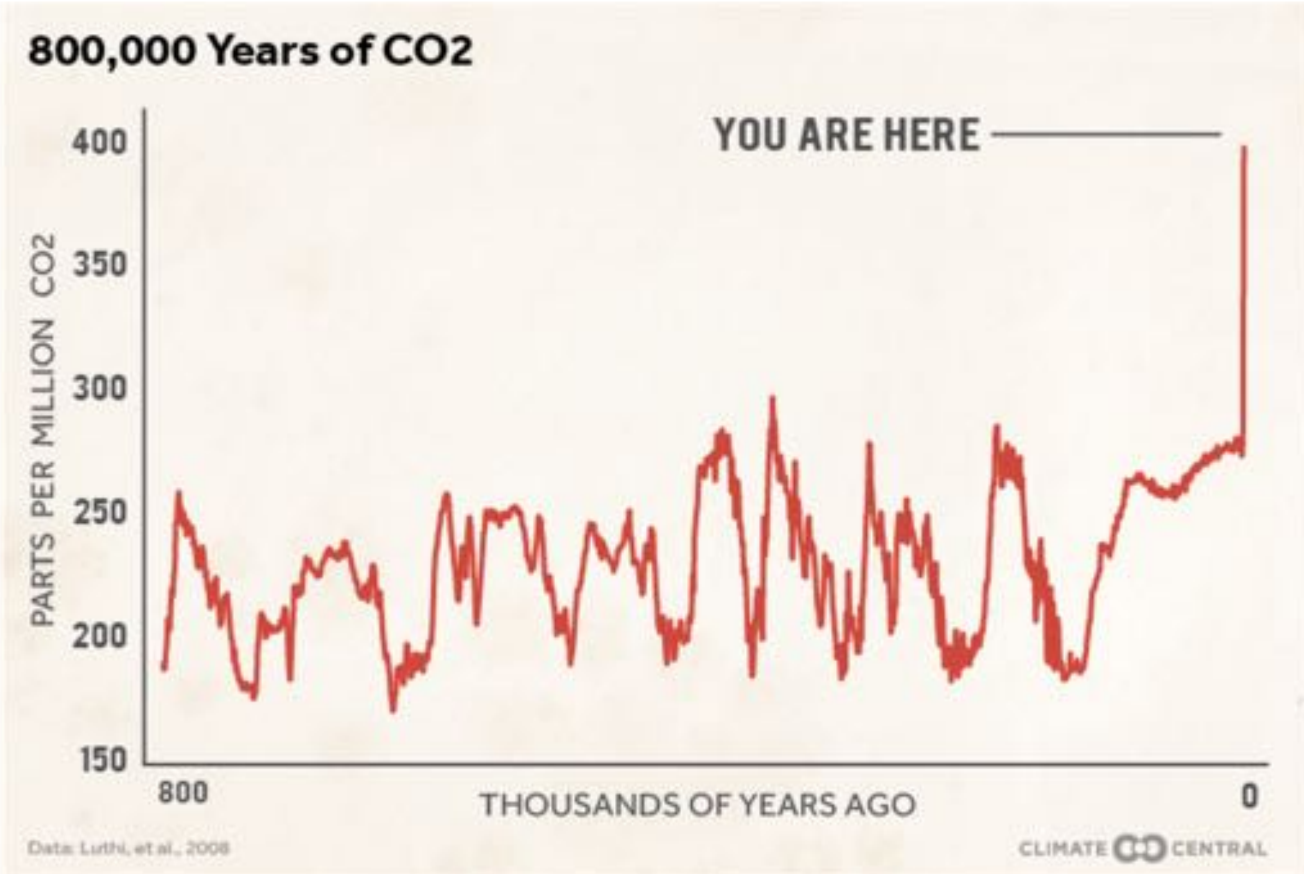
Introduction

Urbanizations consume about **75 %** of the **global primary energy** supply and are responsible for about **50-60 %** of the world's **total greenhouse gases**.

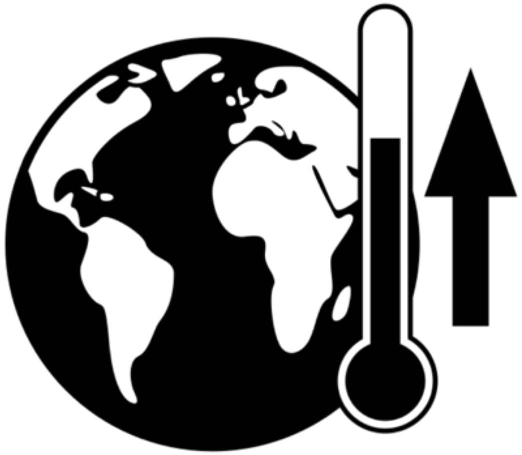
Introduction



Introduction

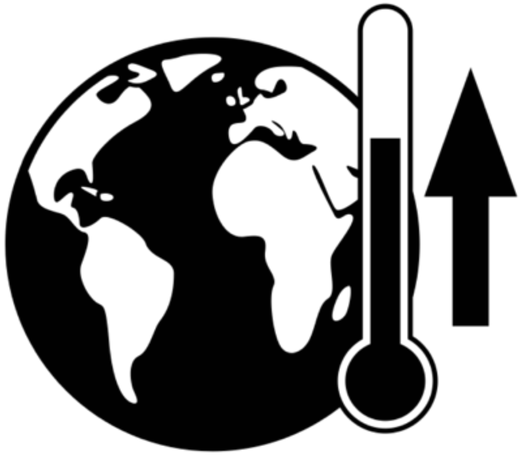


Introduction



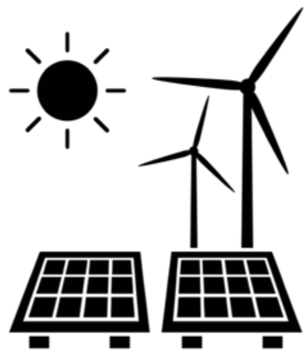
During the last conference on **Climate Change (COP21)** all **196** the participants states have signed an agreement for **reducing CO2 emission**, **energy consumption** and to move forward a **low-carbon and sustainable society**.

Introduction

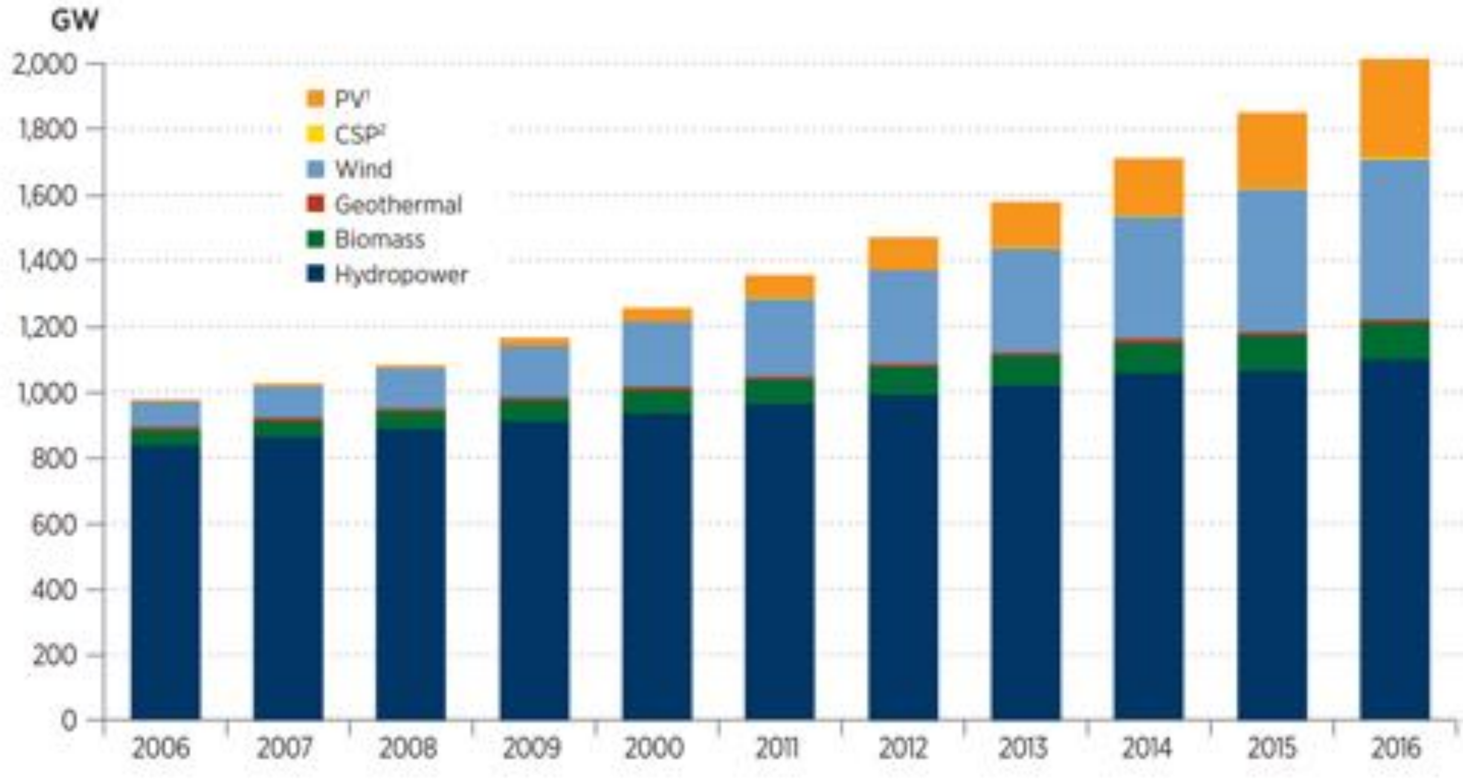


During the last conference on **Climate Change (COP21)** all **196** the participants states have signed an agreement for **reducing CO2 emission**, **energy consumption** and to move forward a **low-carbon and sustainable society**.

«The **reduction** of **CO2** emissions **depends** on about **70%** of a combination of **energy efficiency** and **renewable**» (International Energy Agency)



Introduction



Source: Renewable Energy Policy Network for the 21st Century (REN21)

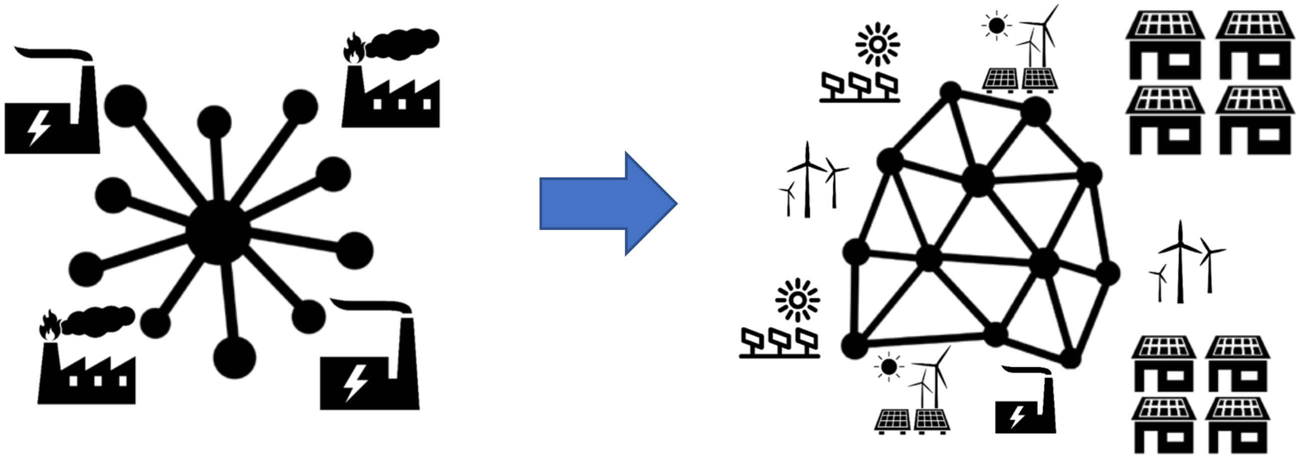
Introduction

Source: Company data, FERC, EPRI, Brattle Group, IEA, Morgan Stanley Research.
E = Morgan Stanley Research estimates

CAGR= Compounded Annual Growth Rate

Introduction

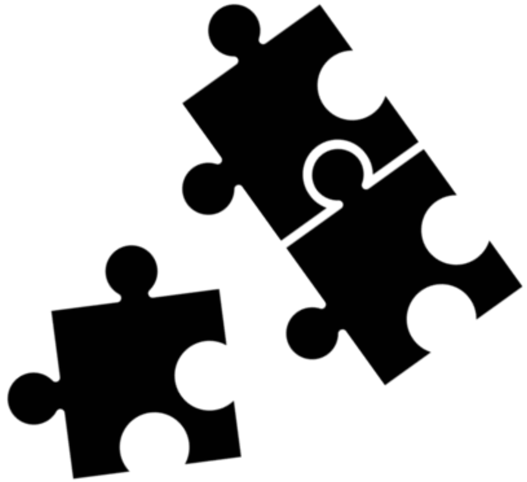
Transition from a **centralized** to a **distributed** system with increase of **RES** and **Smart energy policies**.



This transition needs to be planed with specific tools able to:

1. estimate **RES** production in **time**,
2. effects of **Smart energy policies**
3. to **assess** the capabilities and **requirements** of **distribution networks**.

Challenges



1. **Multi-Layer-System:** Smart urban districts are complex systems that can be represented with a Physical layer, a Cyber layer, a Social layer and an Environment layer.

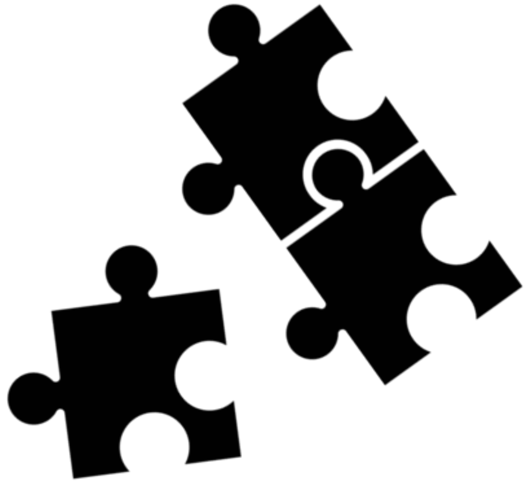
2. **Simulation of Renewable Energy Production:** The energy production of RES has to be simulated with a fine grained spatio-temporal resolution.

3. **Simulation of buildings dynamics**: Features for analysing both thermal and electrical dynamics in buildings.

4. **Simulation of novel energy management policies**: Novel control policies needs to be evaluated in a realistic environment before being applied in a real-world context.

5. **Simulation of distribution networks**: to analyse the effects of energy management policies.

Challenges



6. **Simulations with different spatio-temporal resolutions**: Simulate energy phenomena with different time and space resolutions.

7. **(Near-) real-time integration of real-world information**: Heterogeneous Internet connected devices are needed to develop more accurate event-based models for analysing the operational status of the grid.

8. **Modularity and extendibility in integrating data, models and simulators:** Able to integrate in a plug-and-play fashion heterogeneous data-sources, models and simulators.

9. **Scalability of the infrastructure**: Horizontal and vertical scalability of the infrastructure is another key requirement.

Motivation

This solution is intended to satisfy the needs of different end users such as:

i) **Single citizen**;

ii) **Energy aggregators** and **Energy Communities**;

iii) **Distribution system operators**;

iv) **Energy and City planners**;

v) **RES engineers**.

SMIRSE Positing in MES State of the Art

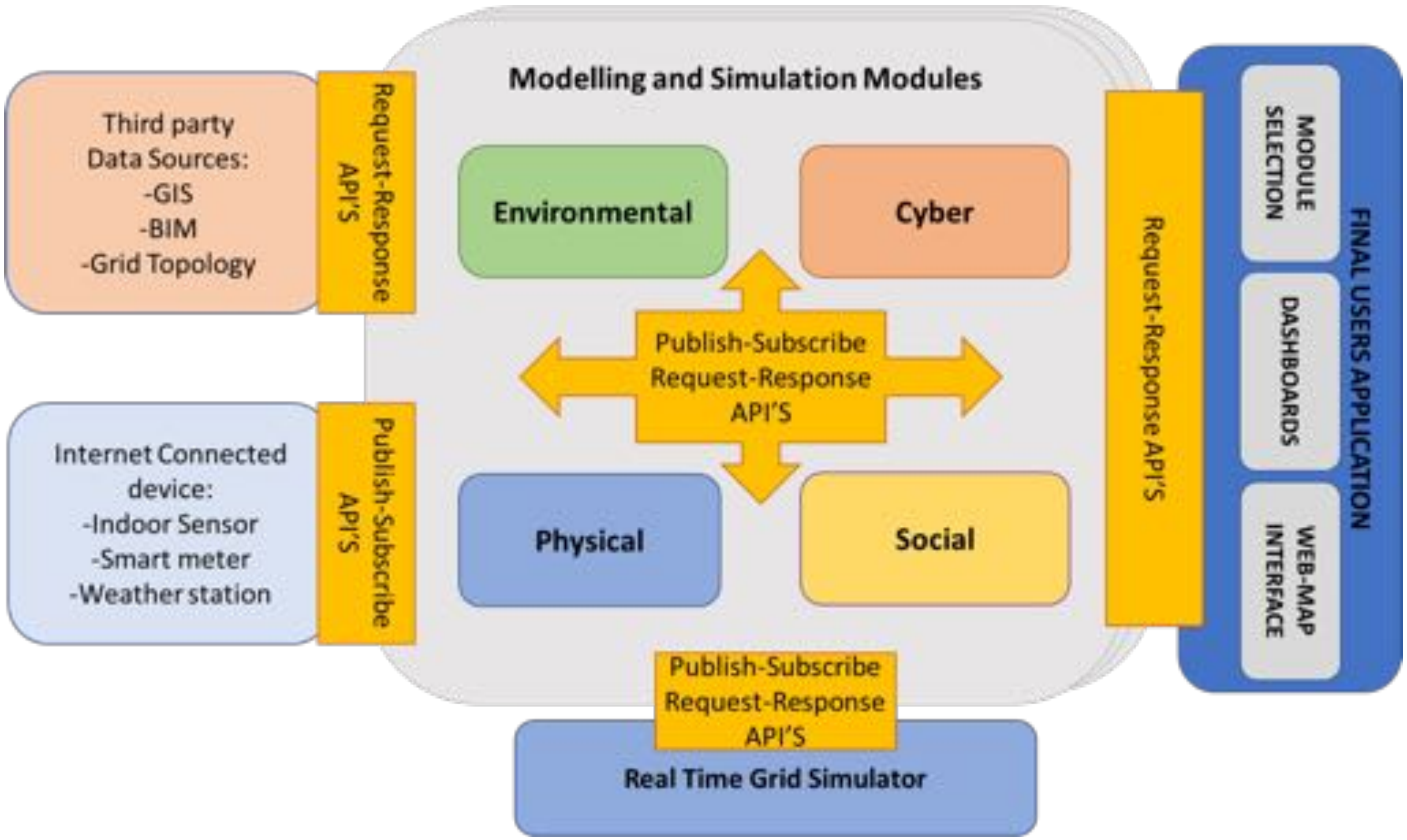
Solutions	Integrated layers	Co-Simulation	RTS	Use-case Scenario	HIL/SIL	IoT
DER-CAM [32]	Physical	Up to 5 minute resolution of physical energy-systems.	x	Multiple	x	x
HOMER [33]	Physical	Hourly simulation of micro grid energy-systems.	x	Multiple	x	x
EnergyPLAN [34]	Physical	Hourly simulation of MES energy-systems.	x	Multiple	x	x
GRIDspice [74]	Physical Cyber	Co-simulation of power- and communication-flows in smart-grids.	x	Multiple	SIL	x
SGsim [36]	Physical Cyber	Co-simulation of power- and communication-flows for smart-grids application such as CVR.	x	Multiple	SIL	x
DIMOSIM [37]	Physical	Co-simulation of MES no electrical power flows.	x	Multiple	x	x
MOSAIK [38–40]	Physical Cyber	Co-simulation of power flow and load generation.	x	Multiple	SIL	x
IDEAS [41]	Physical	Co-simulation of demand side management with thermal simualtion of buildings.	x	Single	x	x
MESCOS [15]	Physical	Co-simulation of demand side management with thermal simualtion of buildings.	x	Single	x	x

Solutions	Integrated layers	Co-Simulation	RTS	Use-case Scenario	HIL/SIL	IoT
HUES [42]	Repository	Repository of simulation models.	x	Multiple	x	x
INSPIRE [43]	Physical Cyber	Real-time co-simulation of Cyber-physical energy-systems.	x	Multiple	x	x
Yang et al. [45]	Physical Cyber	Real-time co-simulation between two simulation environments (MATLAB and Function Block).	x	Single	HIL SIL	x
Manbachi et al. [46]	Physical Cyber	Real-time co-simulation of grid status and volt variation controllers.	✓	Single	HIL SIL	x
Bottaccioli et al. [47, 48]	Physical Cyber Environmental	Real-time co-simulation of PV energy production and grid status.	✓	Single	HIL SIL	x
Hahn et al. [49]	Physical Cyber	Real-time co-simulation of power- and communication-flows to test control algorithms in micro-grids.	✓	Multiple	HIL SIL	x
ENEL [50]	Physical Cyber	Real-time simulation of protection and automation strategies.	✓	Multiple	HIL SIL	x
SMIRSE solution	Physical Cyber Environmental	Real-time co-simulation of smart grid control algorithms and building thermal loads.	✓	Multiple	HIL SIL	✓

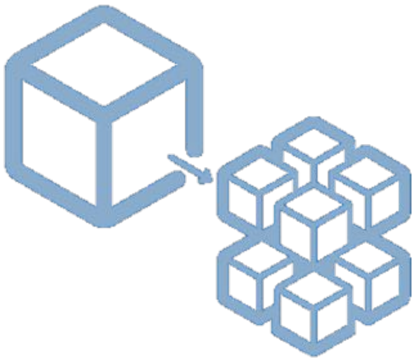
SMIRSE Positing in PV State of the Art

	Simulation Step			Sub-hourly Clear-sky simulation	Sub-hourly Real-sky simulation	Rooftop and/or ROI details	Weather Station data integration	Distributed and modular architecture	REST API
	Y	M	H						
SMIRSE	✓	✓	✓	✓	✓	✓	✓	✓	✓
PVWatts [65]	✓	✓	✓						
PVGIS [64]	✓	✓		✓					
i-GUESS [67]	✓								
Mapdwell [66]	✓					✓			
I-SCOPE [68]	✓	✓				✓			
Brumen [69]	✓	✓				✓			

Contribution



Enabling Technologies



MICRO-SERVICES
ARCHITECTURAL STYLE

IOT COMMUNICATION
PROTOCOLS

OGC®
Open Geospatial Consortium, Inc.

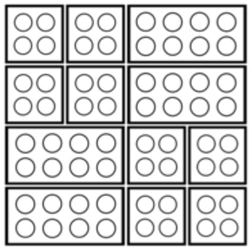
OPEN GEOSPATIAL CONSORTIUM
WEB SERVICES

Micro Services architectural style

Monolithic
Tightly Coupled

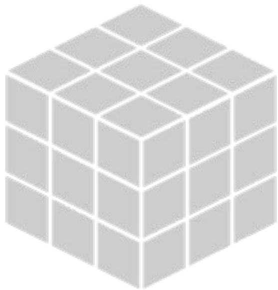
Micro Services architectural style

Monolithic
Tightly Coupled



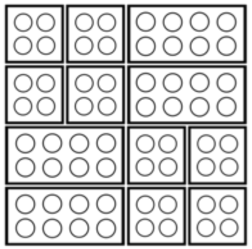
Microservice
Highly Decoupled

Micro Services architectural style



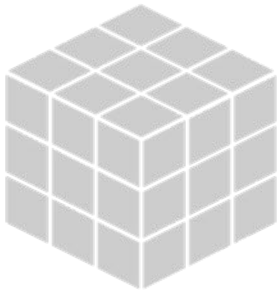
Monolithic
Tightly Coupled

Heterogeneity in
system technology



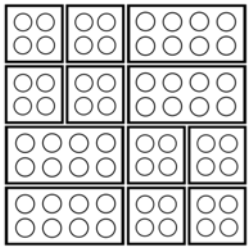
Microservice
Highly Decoupled

Micro Services architectural style



Monolithic
Tightly Coupled

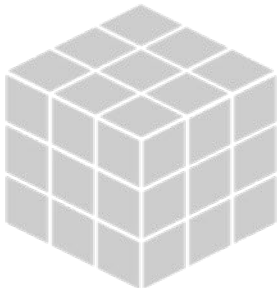
Heterogeneity in
system technology



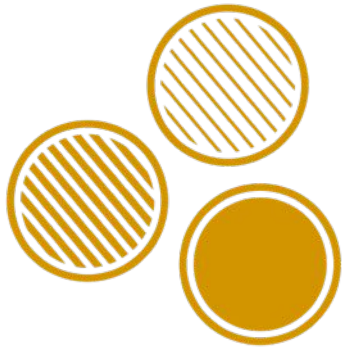
Microservice
Highly Decoupled

Resilience

Micro Services architectural style

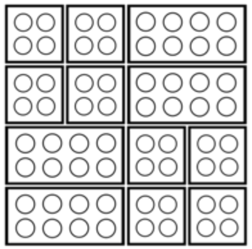


Monolithic
Tightly Coupled



Heterogeneity in
system technology

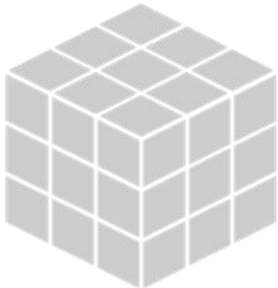
Composability



Microservice
Highly Decoupled

Resilience

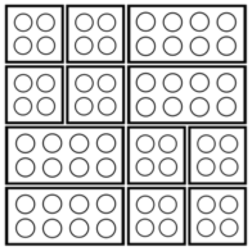
Micro Services architectural style



Monolithic
Tightly Coupled

Heterogeneity in
system technology

Composability



Microservice
Highly Decoupled

Resilience

Scalability

Representational State Transfer (REST)

Representational State Transfer (REST) *is a coordinated set of architectural constraints that attempts to minimize latency and network communication, while at the same time maximizing the independence and scalability of component implementations*.

Representational State Transfer (REST)

Representational State Transfer (REST) *is a coordinated set of architectural constraints that attempts to minimize latency and network communication, while at the same time maximizing the independence and scalability of component implementations.*

Client-Server

Representational State Transfer (REST)

Representational State Transfer (REST) *is a coordinated set of architectural constraints that attempts to minimize latency and network communication, while at the same time maximizing the independence and scalability of component implementations.*

Client-Server

Stateless

Representational State Transfer (REST)

Representational State Transfer (REST) *is a coordinated set of architectural constraints that attempts to minimize latency and network communication, while at the same time maximizing the independence and scalability of component implementations.*

Client-Server

Stateless

Layered System

Representational State Transfer (REST)

Representational State Transfer (REST) *is a coordinated set of architectural constraints that attempts to minimize latency and network communication, while at the same time maximizing the independence and scalability of component implementations.*

Client-Server

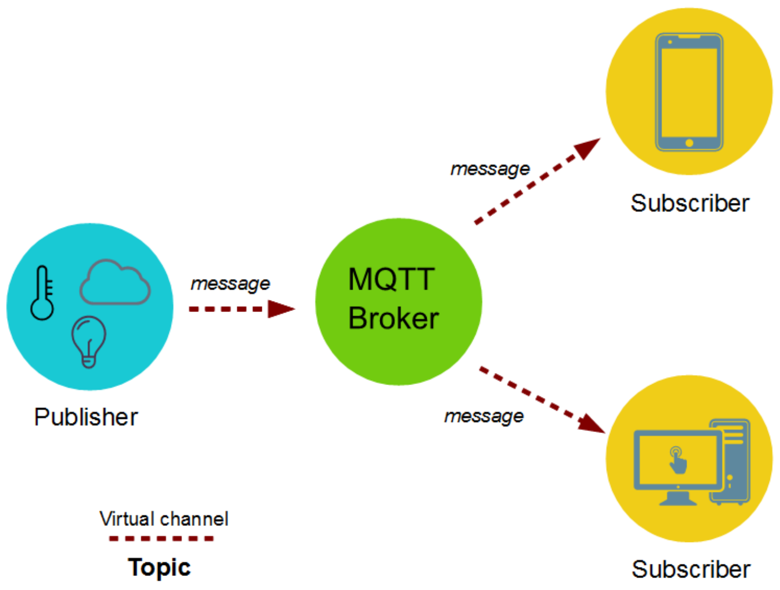
Stateless

Layered System

Uniform Interface

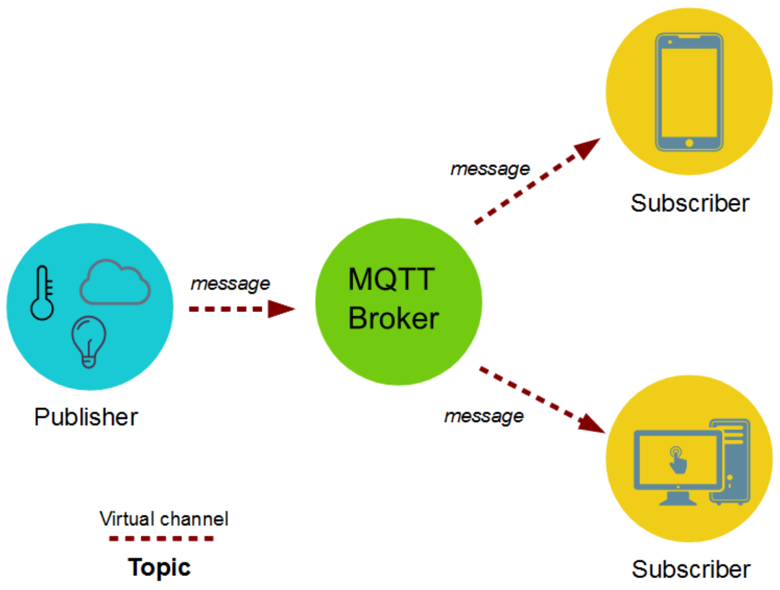
MQTT

*The **publish/subscribe** interaction paradigm provides subscribers with the ability to express their interest in an event or a pattern of events, in order to be notified subsequently of any event, generated by a publisher, that matches their registered interest.*



MQTT

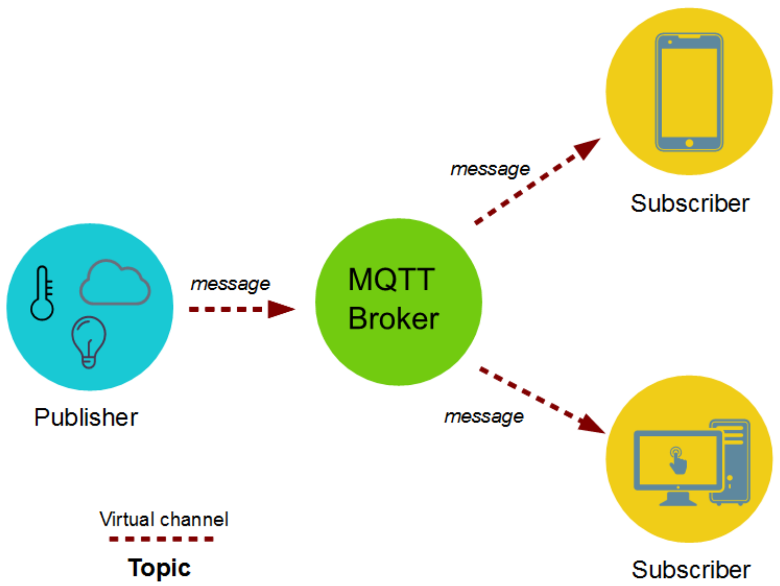
*The **publish/subscribe** interaction paradigm provides subscribers with the ability to express their interest in an event or a pattern of events, in order to be notified subsequently of any event, generated by a publisher, that matches their registered interest.*

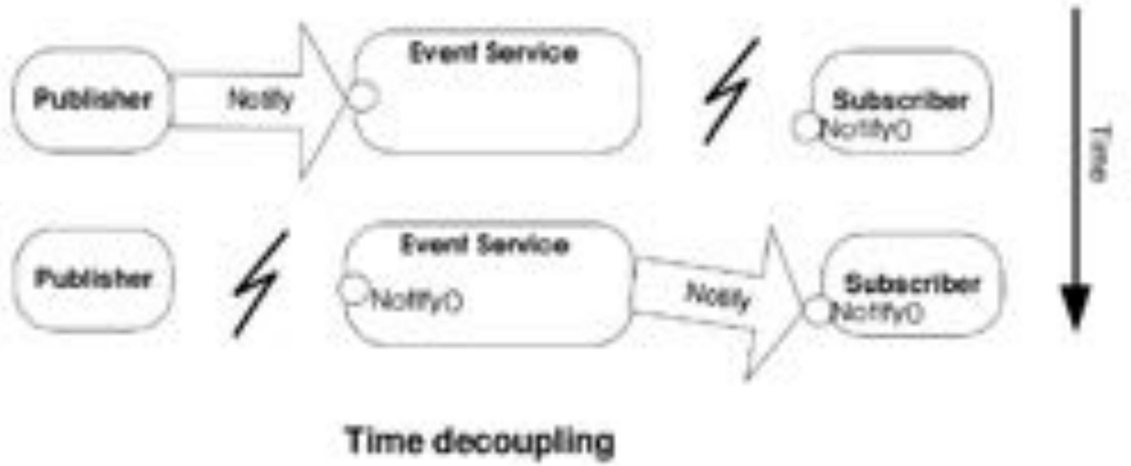


Space decoupling

MQTT

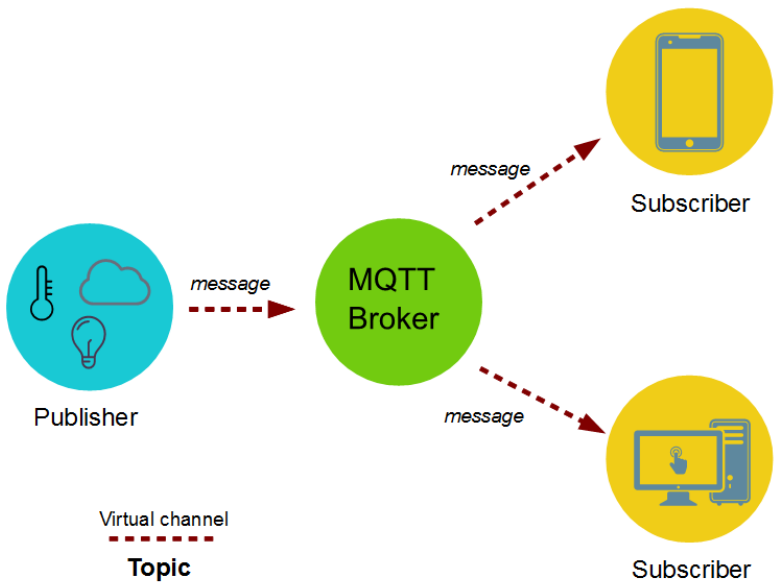
*The **publish/subscribe** interaction paradigm provides subscribers with the ability to express their interest in an event or a pattern of events, in order to be notified subsequently of any event, generated by a publisher, that matches their registered interest.*

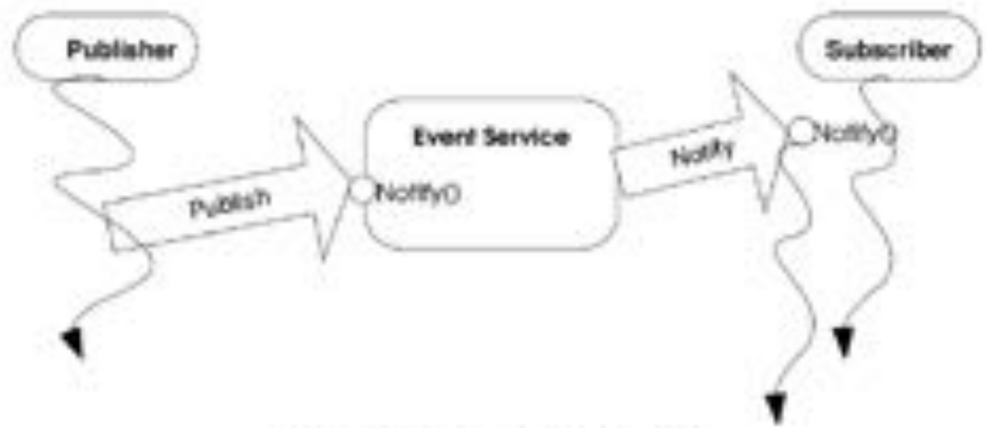




MQTT

*The **publish/subscribe** interaction paradigm provides subscribers with the ability to express their interest in an event or a pattern of events, in order to be notified subsequently of any event, generated by a publisher, that matches their registered interest.*





Synchronization decoupling

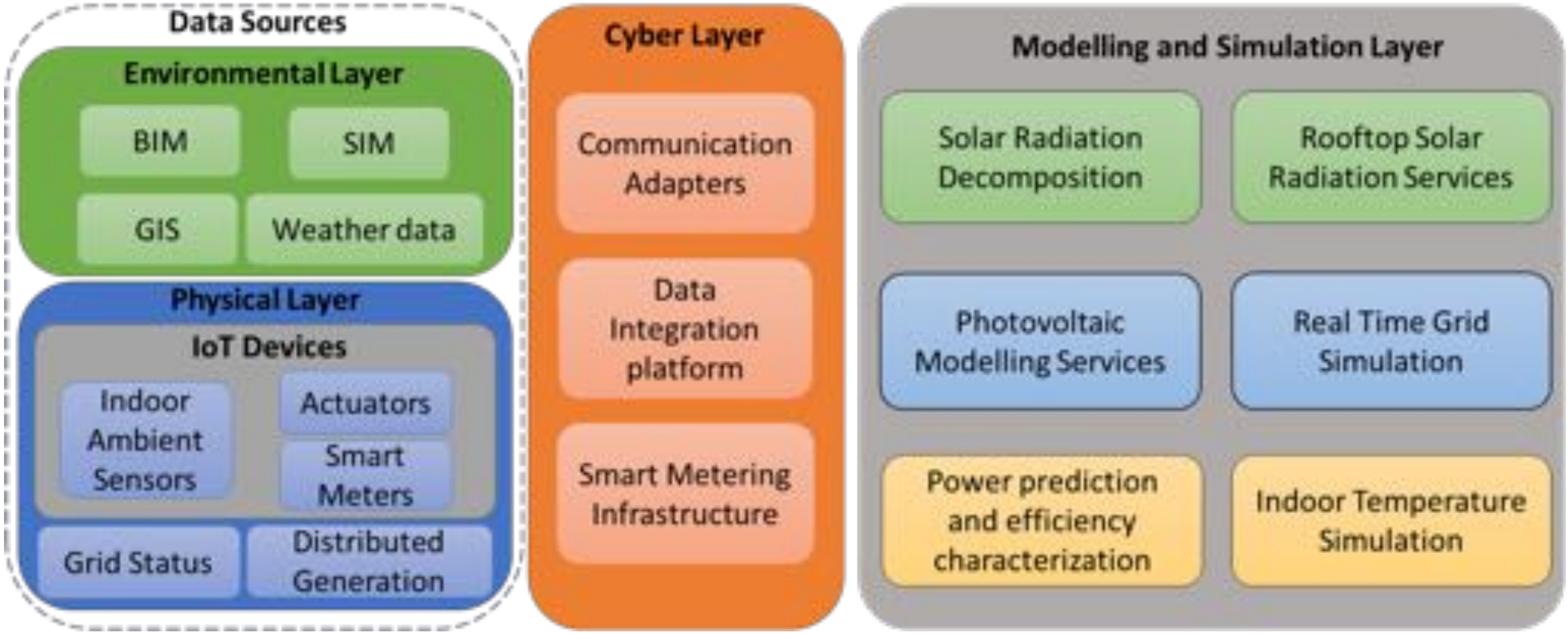
Open Geospatial Consortium Standards

- **Web Processing Service (WPS):** With this standard any geospatial process can be “wrapped” with a standard interface and integrated into existing workflows. WPS supports short and fast computational tasks and long and time consuming process exploiting asynchronous processing.

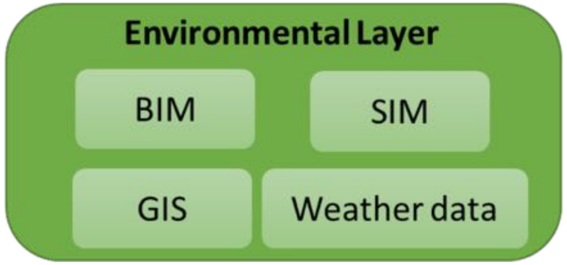
- **Web Feature Service (WFS):** specifies a standard for services that provides access and operations to GIS features abstracting from the underlying data store.

- **Web mapping Service (WMS):** standardizes a simple HTTP interface for retrieving GIS maps from one or more distributed geospatial

The SMIRSE Infrastructure

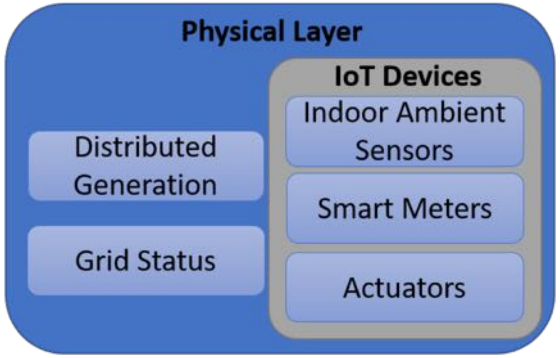


Enviromental Layer



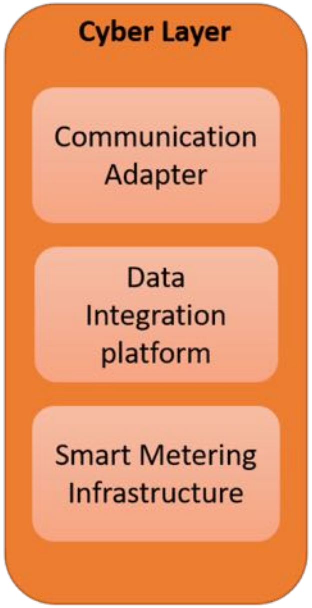
- **Geographical Information Systems** (GIS) integrate georeferenced information about the different entities (e.g. devices, buildings and pipelines) in cities. It also includes cartographies cadastral maps and Digital Elevation Models.
- **Building Information Models** (BIM) are parametric 3-Dimensional models, where each model describes a building, both structurally and semantically.
- **System Information Models** (SIM) describe size and structure of energy distribution networks. SIM is built by exploiting parametric and topological data.
- **Weather Data** are retrieved by third party services, such as (Weather Underground, 2017). This information is georeferenced and collected by personal weather stations deployed in cities.

Physical Layer



- **Distributed Generation** energy production measurements
- **Status of Distribution Grid** that are needed to simulate energy flows and evaluate the integration of RES. Thus, information sampled by devices monitoring the energy distribution network.
- **IoT devices**, such as **Ambient sensors**, multi-vector **Smart Meters** (i.e. electricity, gas, heating and water) and **Actuators**.

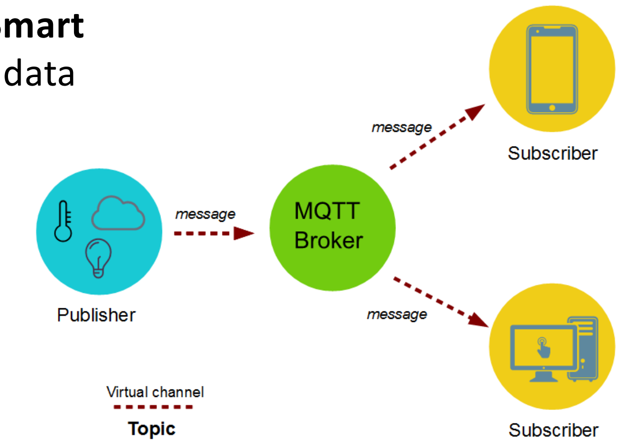
Cyber Layer



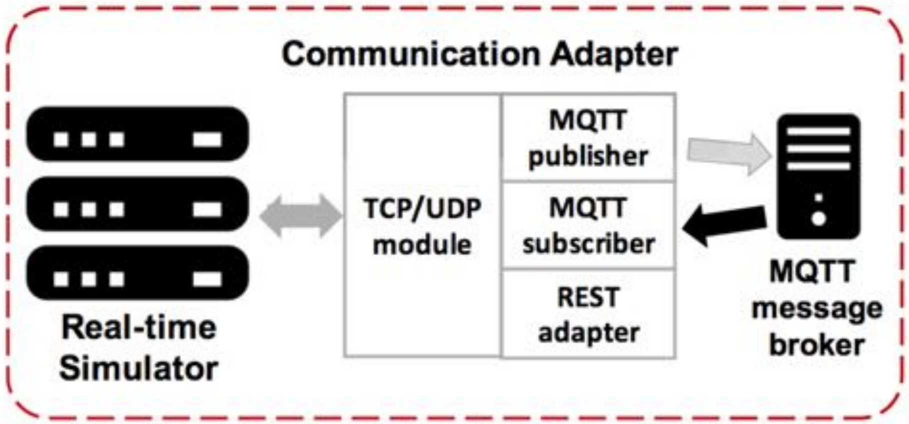
- The **Communication Adapter** enables the interoperability across the heterogeneous devices in the **Physical Layer** and among the **Simulation and Modelling modules**.

- The **Data Integration Platform** integrates third party data source and platforms in the **Environmental Layer**.

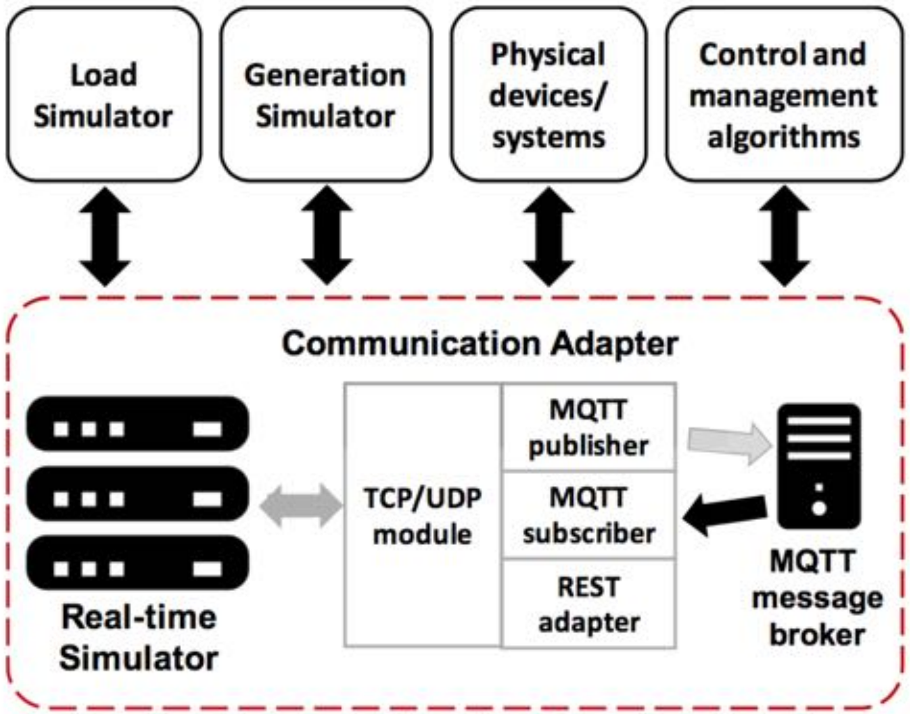
- SMIRSE provides features to integrate also third party **Smart Metering Infrastructure** that makes available historical data collected from real distribution networks and post-processed information output of its services.



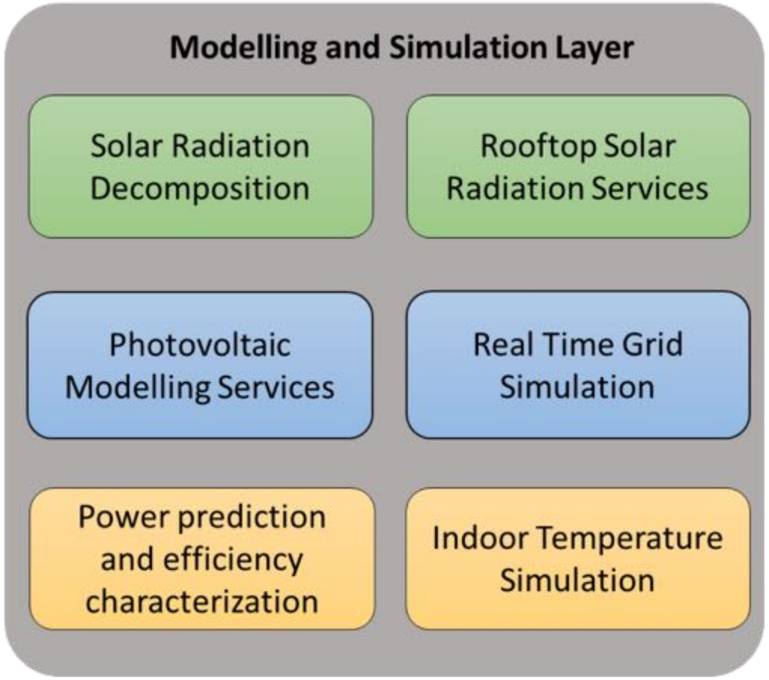
Example of a Communication Adapter



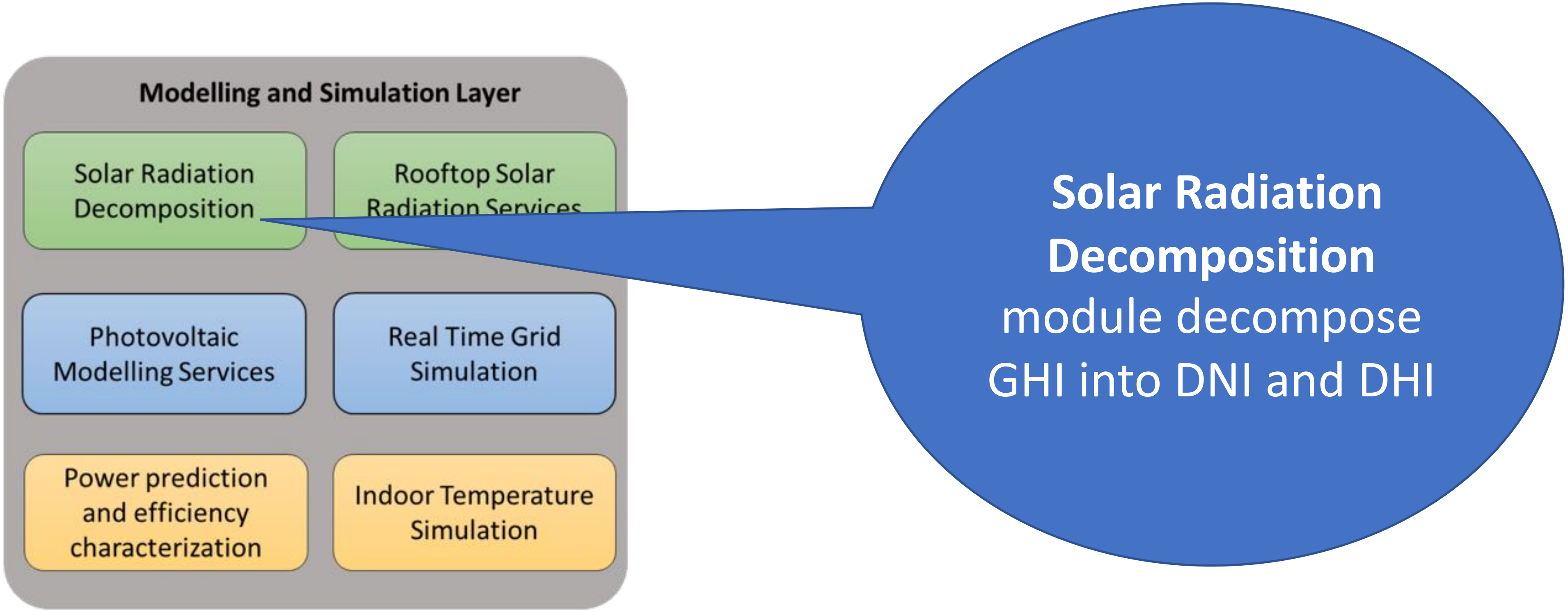
Example of a Communication Adapter



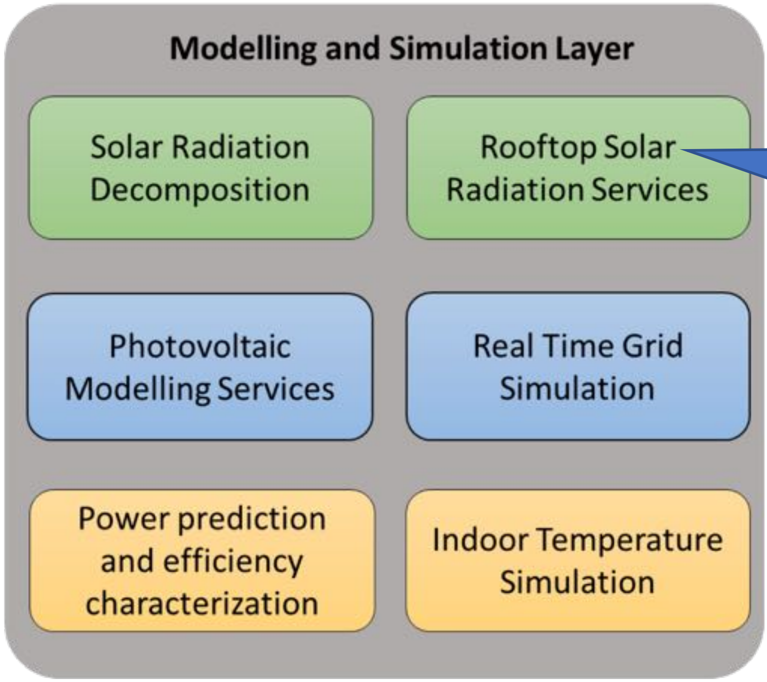
Modelling and Simulation Layer



Modelling and Simulation Layer

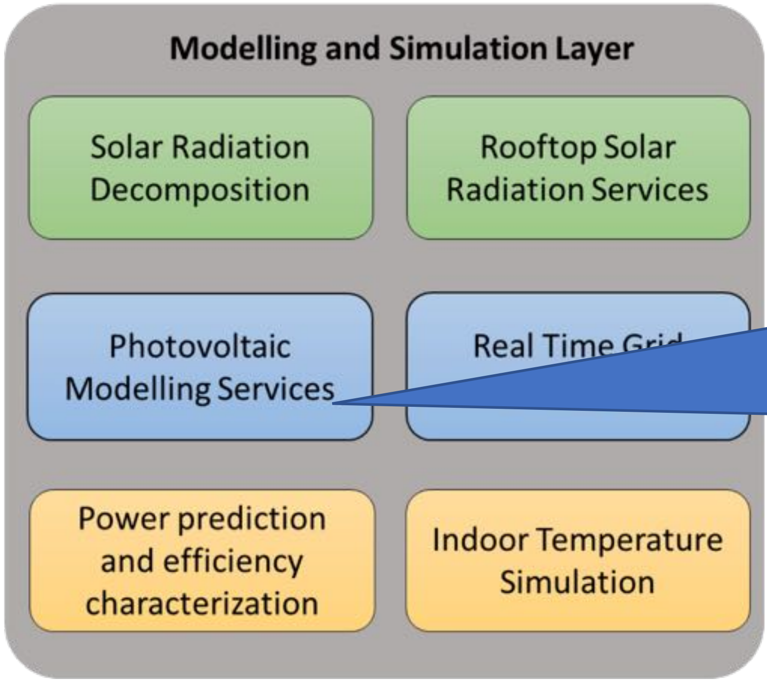


Modelling and Simulation Layer



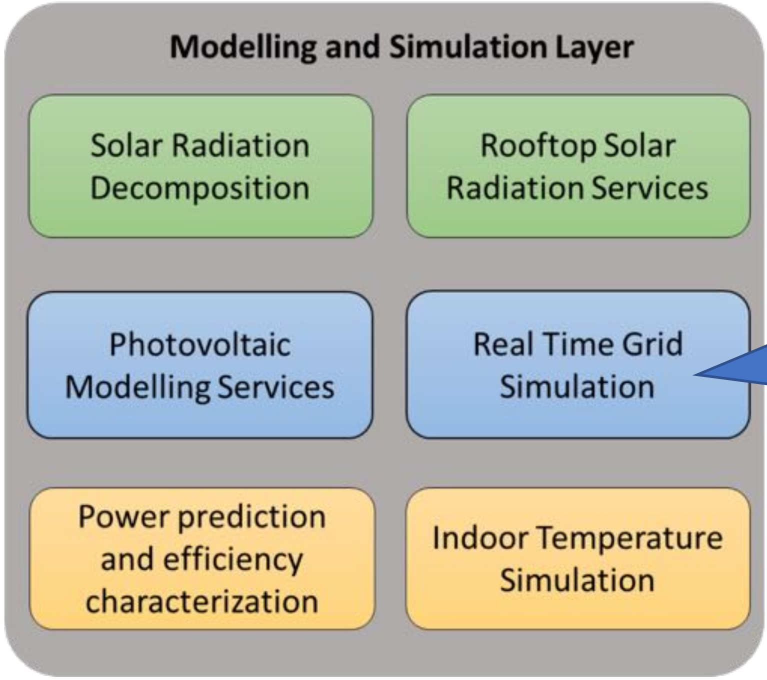
Rooftop Solar Radiation module simulates incident solar radiation on rooftops with a resolution of 15 minutes.

Modelling and Simulation Layer



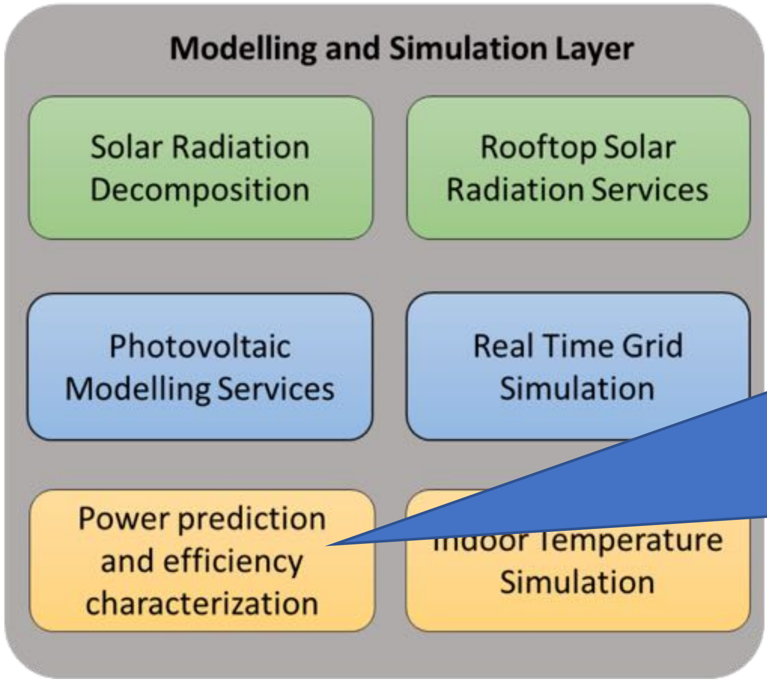
Photovoltaic Energy module exploits both **Rooftop Solar Radiation** and **Weather Data** modules to estimate PV system production.

Modelling and Simulation Layer



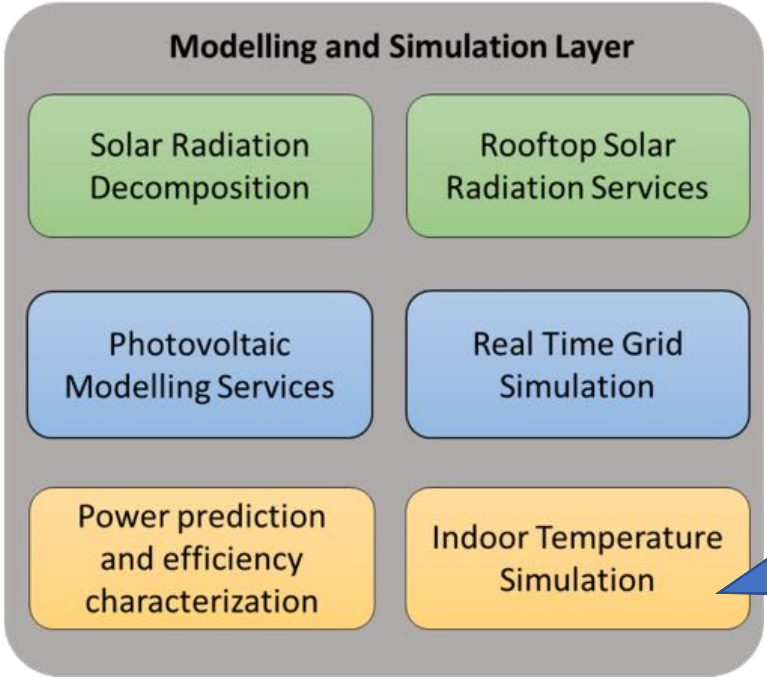
Real Time Grid Simulator module integrates a Real-Time Simulators to simulates power distribution networks with different time resolutions ranging from microseconds to hours.

Modelling and Simulation Layer



Power Prediction and thermal building characterization provides tools to analyze and predict the power demand of thermal systems in buildings connected to HDN. Provides KPIs for thermal characterization of the buildings

Modelling and Simulation Layer



Indoor Temperature Simulator provides tools to simulate and analyse the thermal behaviour of buildings. By combining **BIM, GIS, real Weather data** with environmental information coming from **IoT Devices.**

Energy Simulations with SMIRSE

- Photovoltaic energy simulation

Energy Simulations with SMIRSE

- Photovoltaic energy simulation

- Renewable energy and Smart policies grid integration

Real-time
Grid simulator

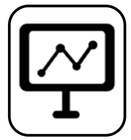
Energy Simulations with SMIRSE

- Photovoltaic energy simulation 
- Renewable energy and Smart policies grid integration 

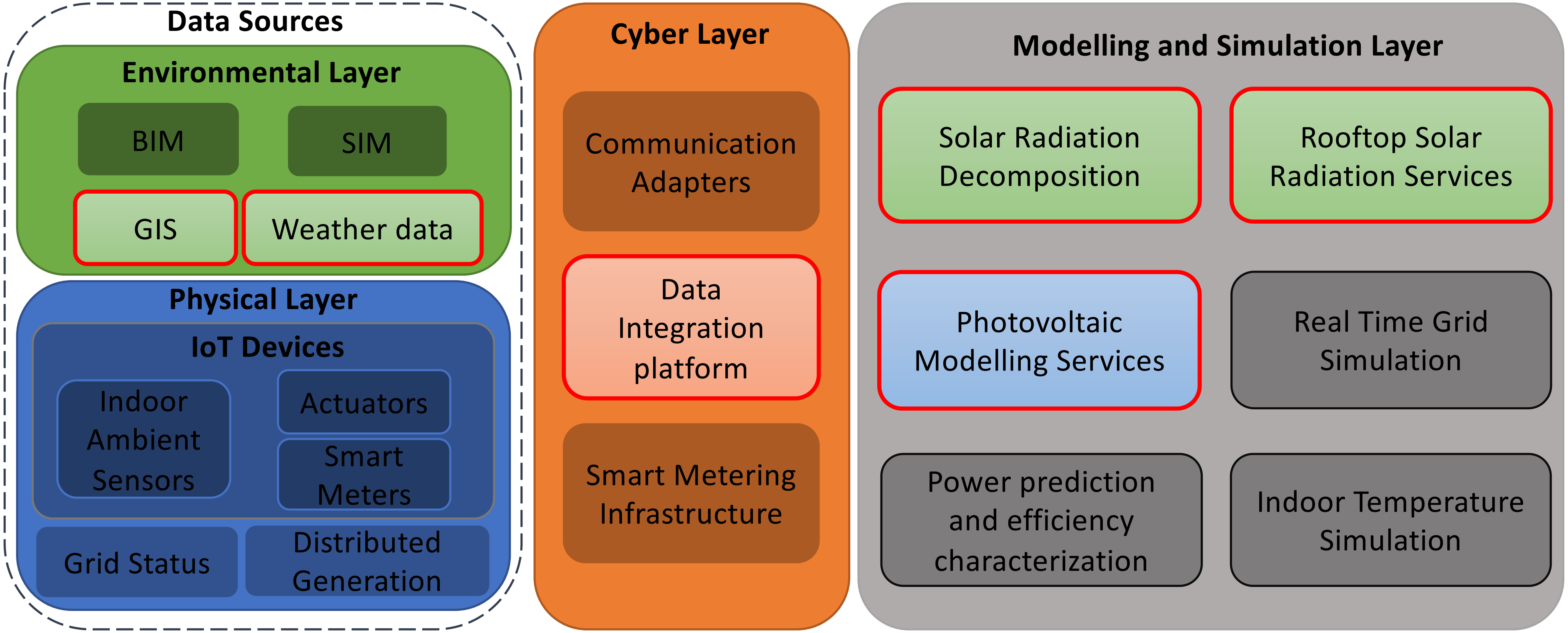
- Power Prediction and building efficiency characterization   

Energy Simulations with SMIRSE

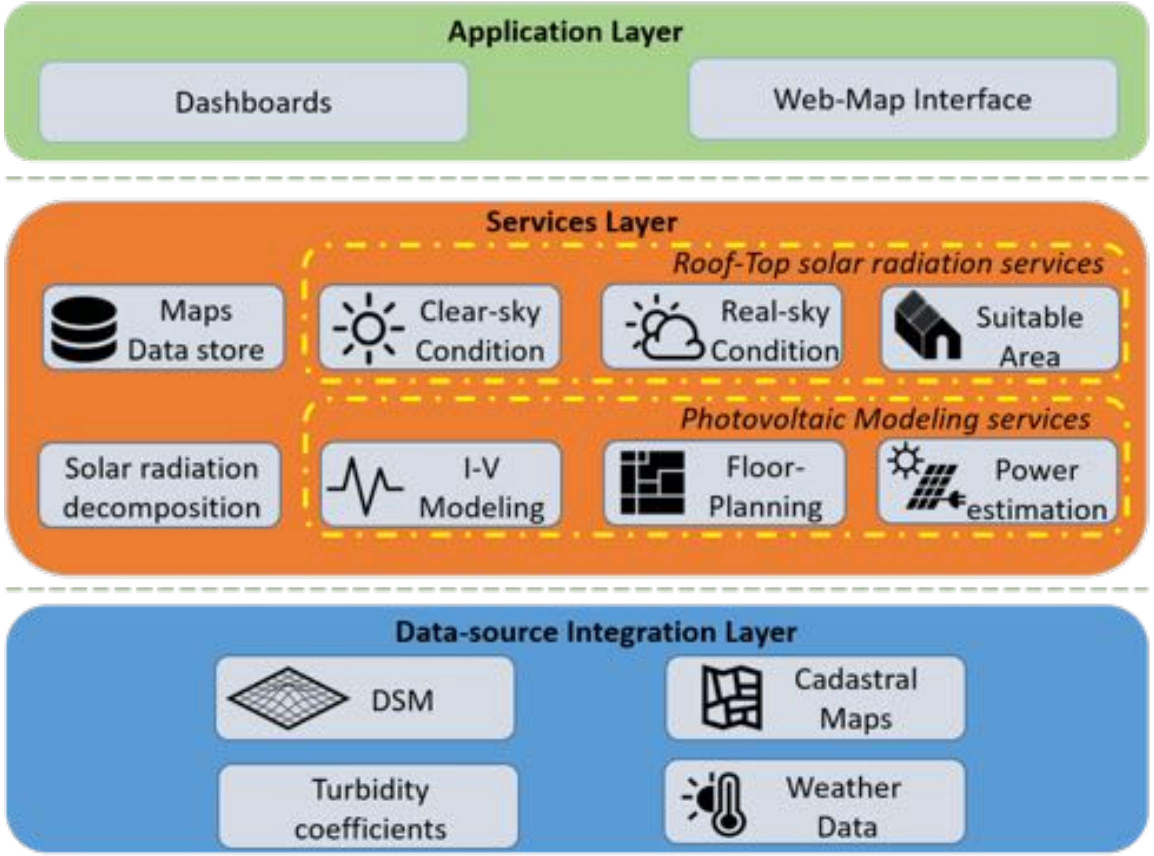
- Photovoltaic energy simulation 
- Renewable energy and Smart policies grid integration 

- Power Prediction and building efficiency characterization   
- Indoor Temperature simulation 

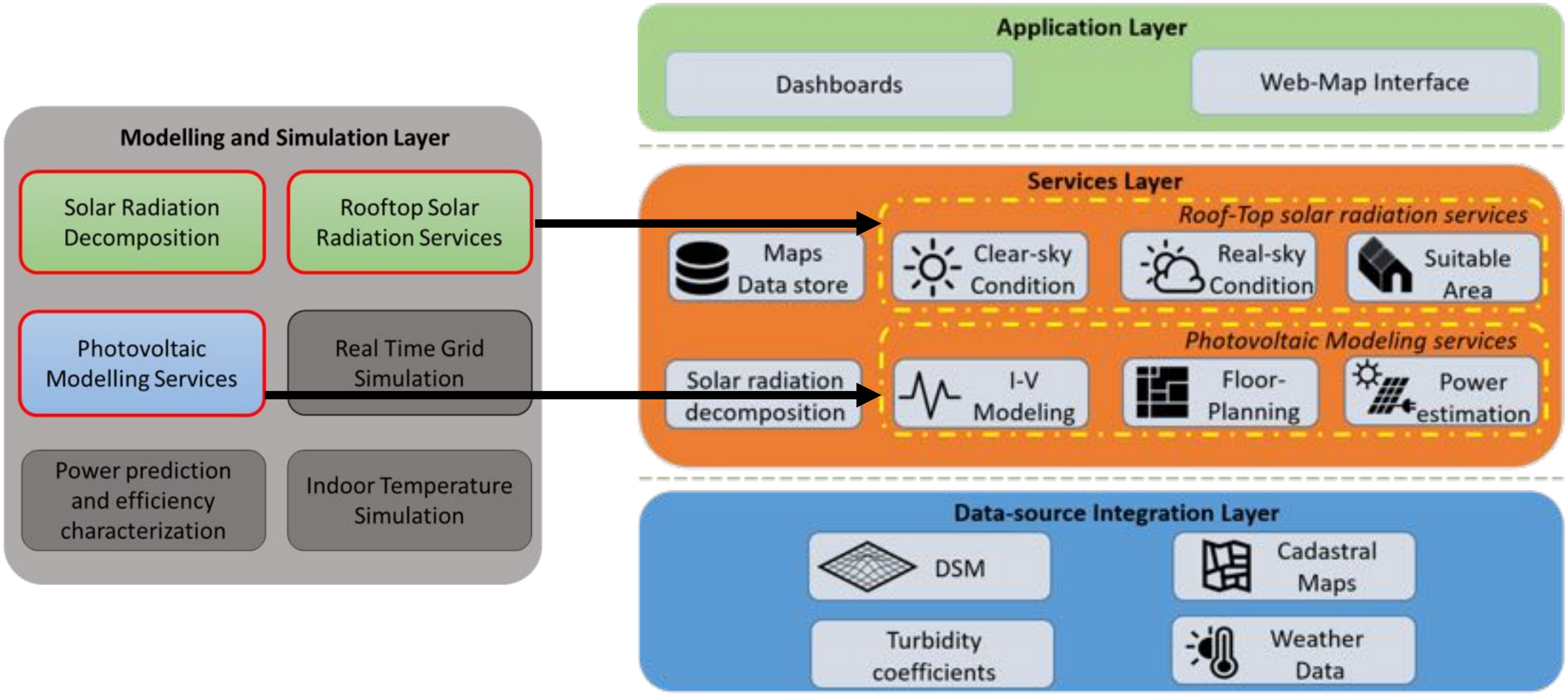
Photovoltaic Energy Simulation



Details of Photovoltaic Energy simulation

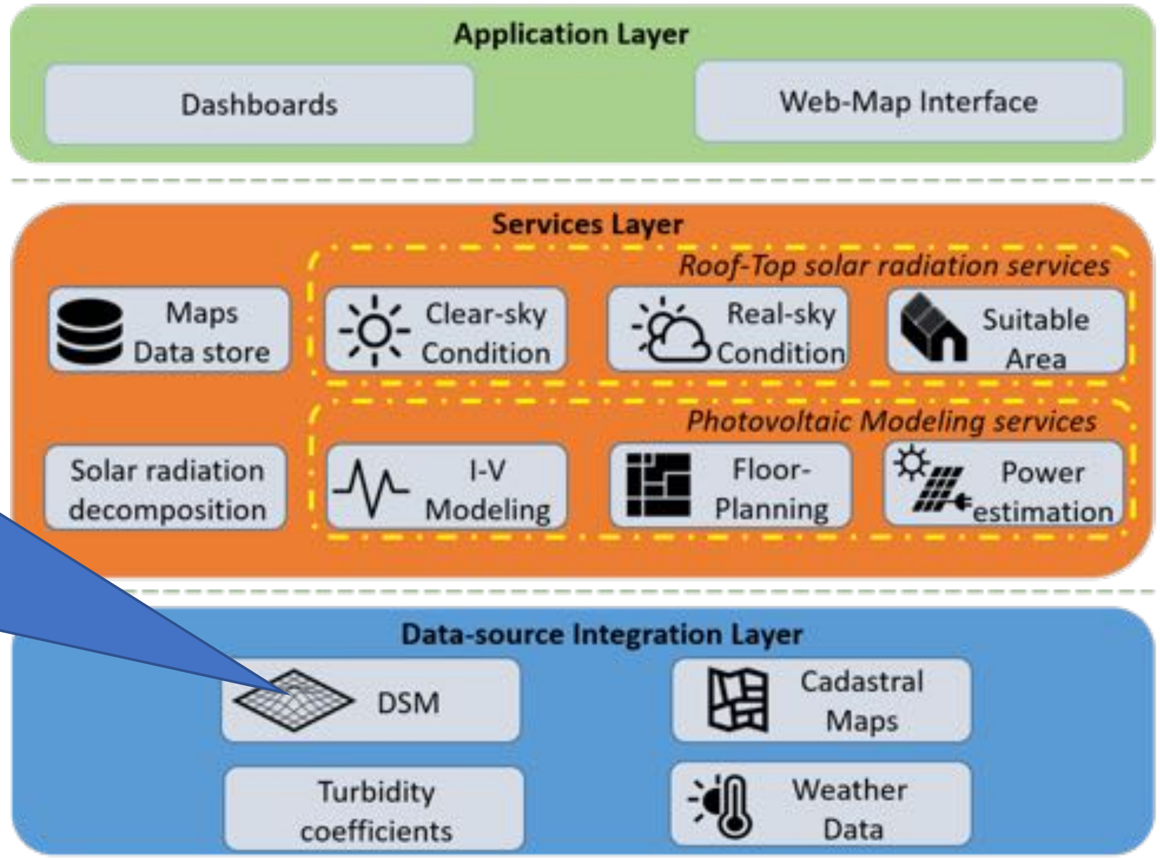


Details of Photovoltaic Energy simulation



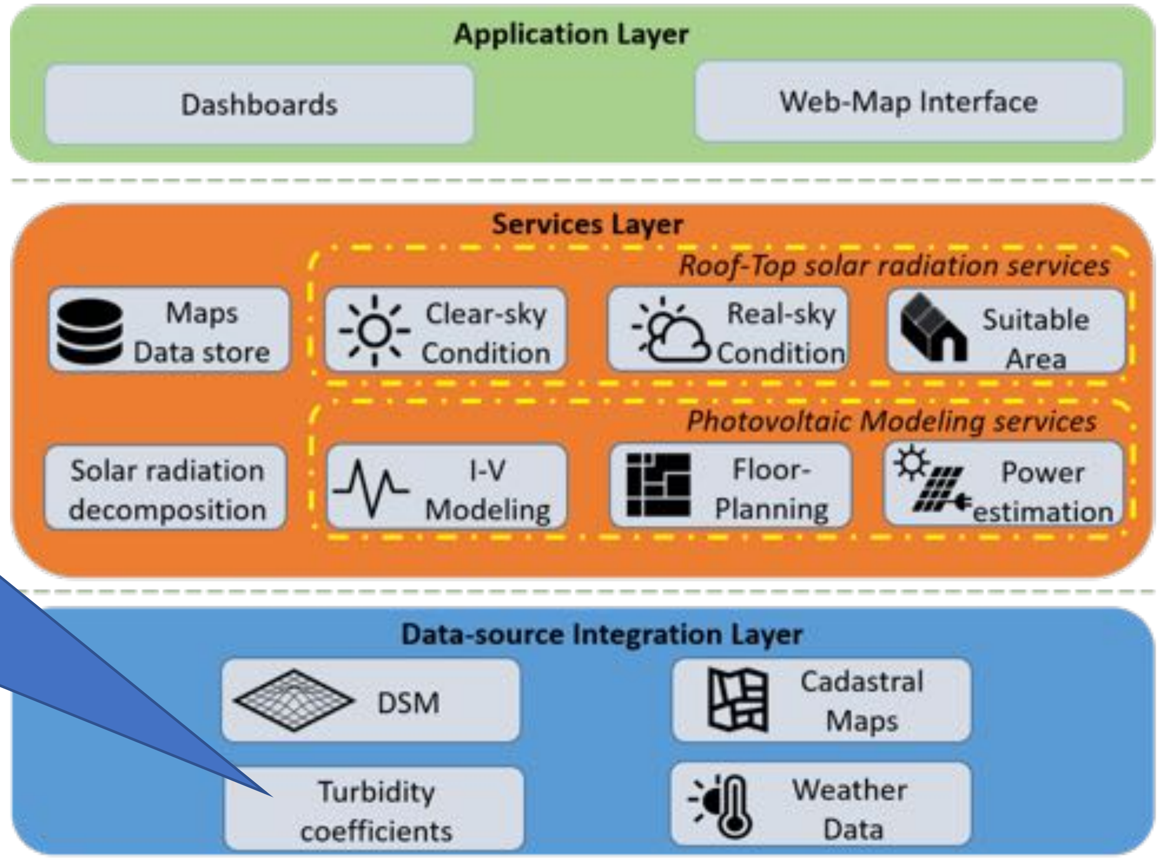
Details of Photovoltaic Energy simulation

Digital Surface Model(DSM), which is a raster image that represents terrain elevation in 2.5D considering the presence of manufactures.



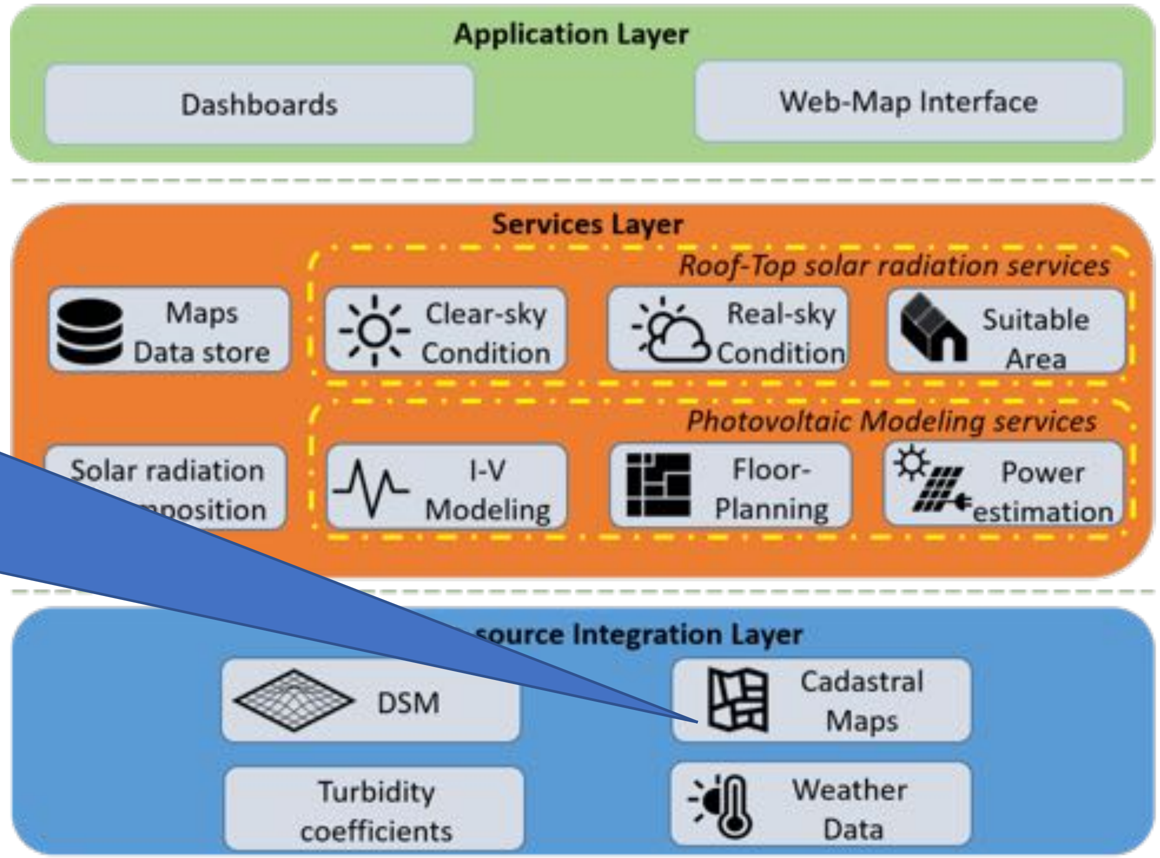
Details of Photovoltaic Energy simulation

Linke Turbidity coefficients express the attenuation of solar radiation related to air pollution.



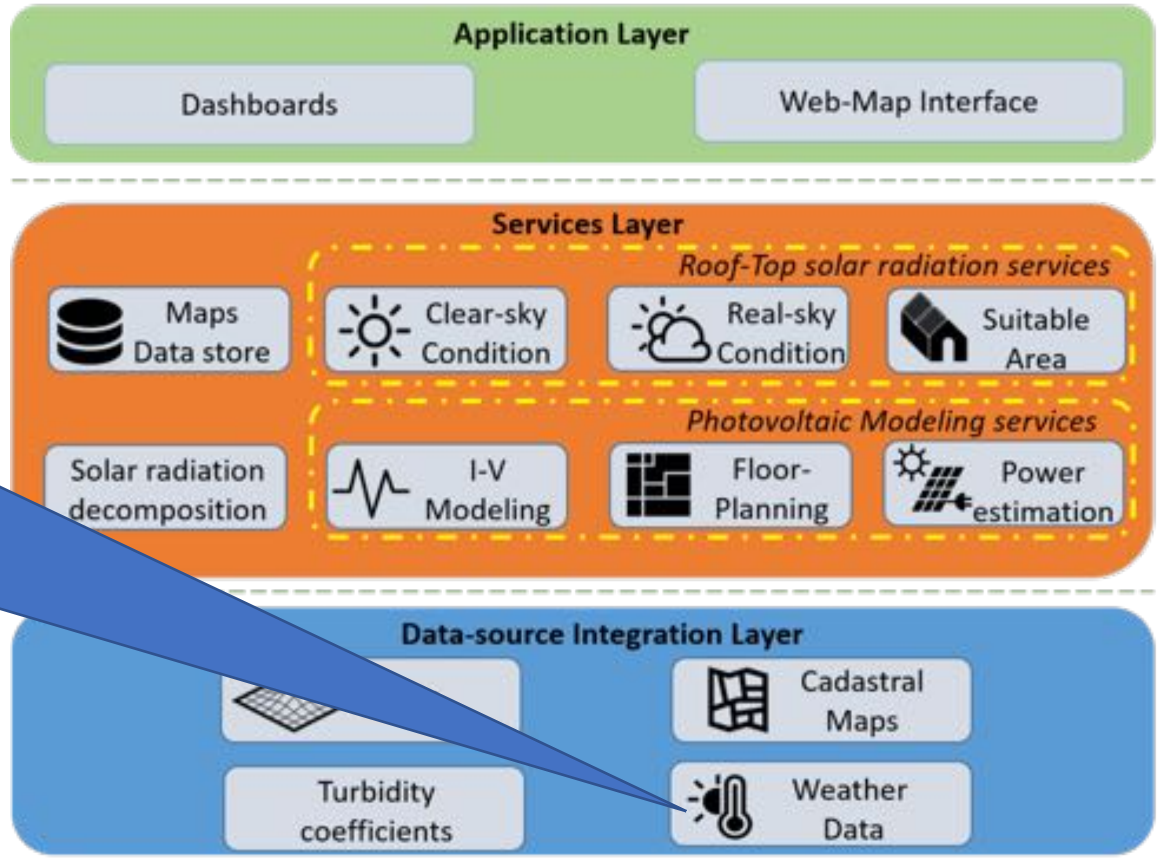
Details of Photovoltaic Energy simulation

Cadastral maps are 2-D vector images that represent the plants of buildings with buildings information (number of floors, ...)



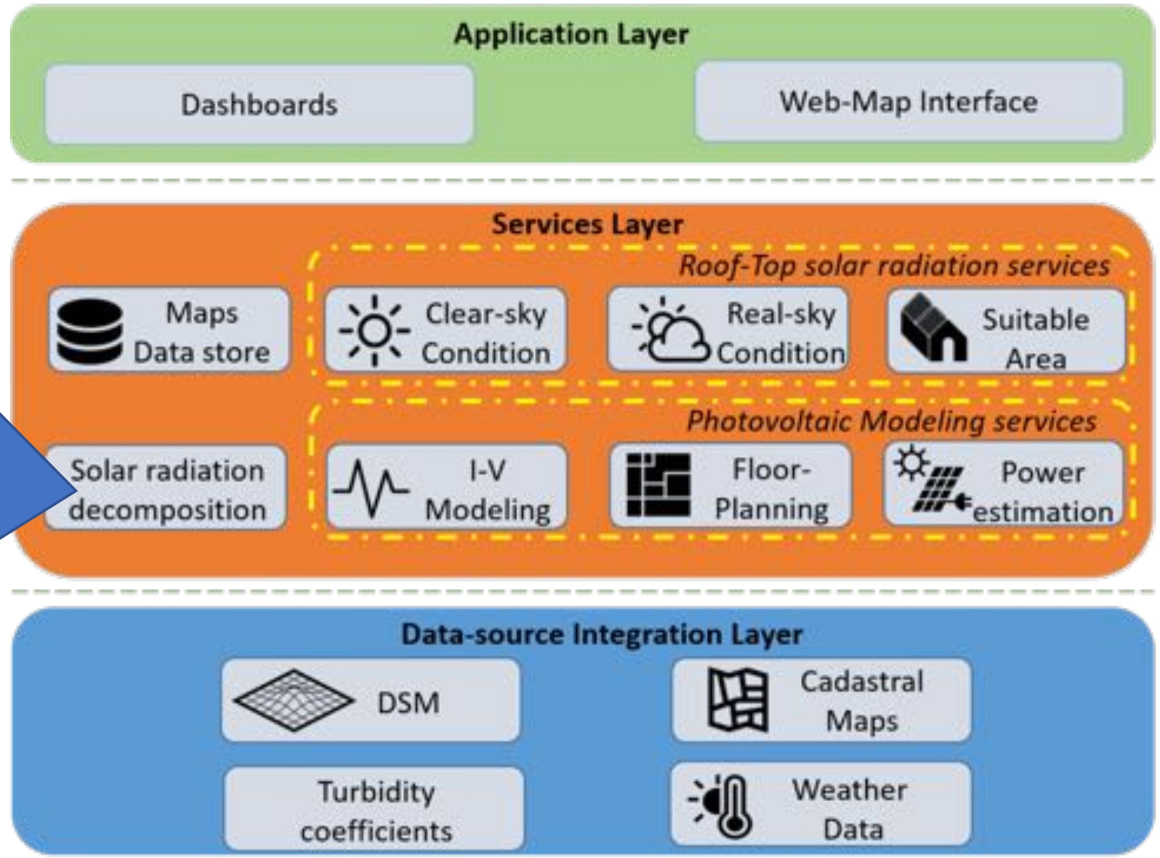
Details of Photovoltaic Energy simulation

Third party
Wheatear data
In particular solar radiation and ambient temperature



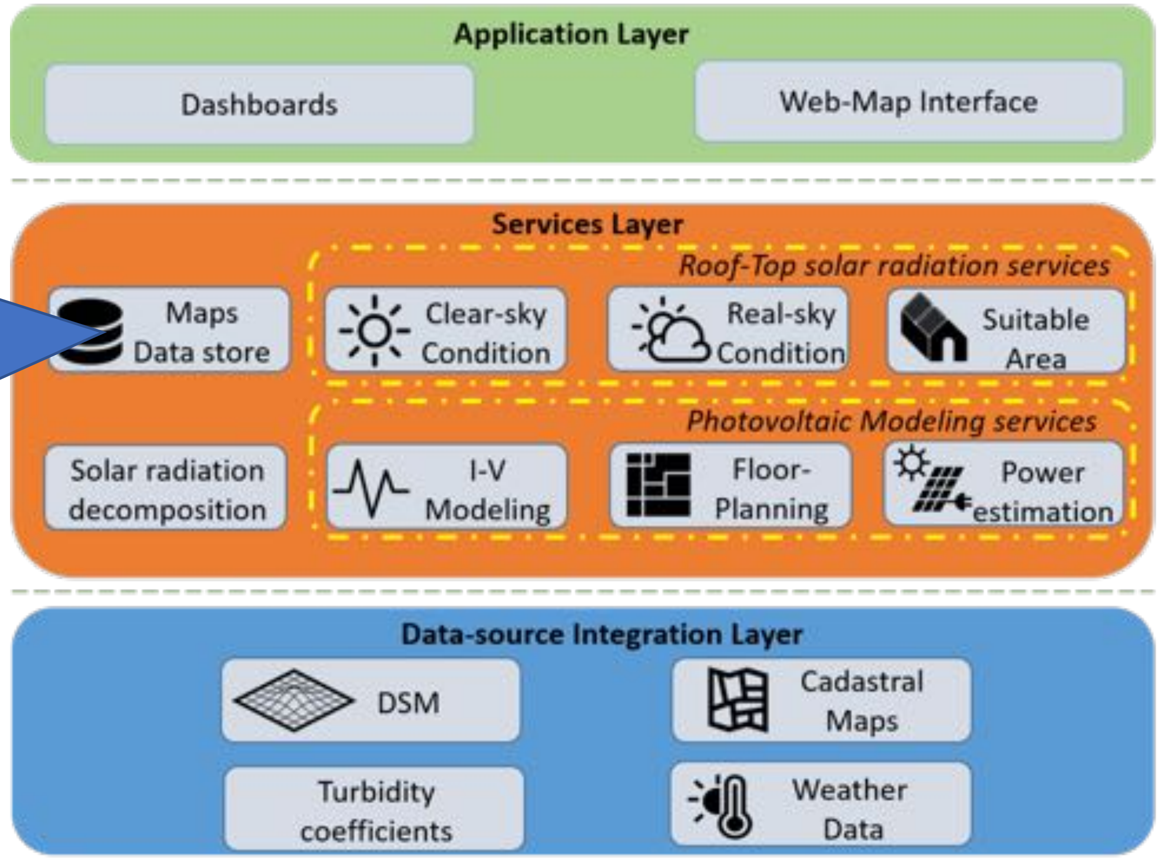
Details of Photovoltaic Energy simulation

Solar radiation decomposition service is in charge of proving **direct** and **diffuse** solar radiation components to the **Real-sky** service if third party weather services provide only **Global horizontal** radiation.



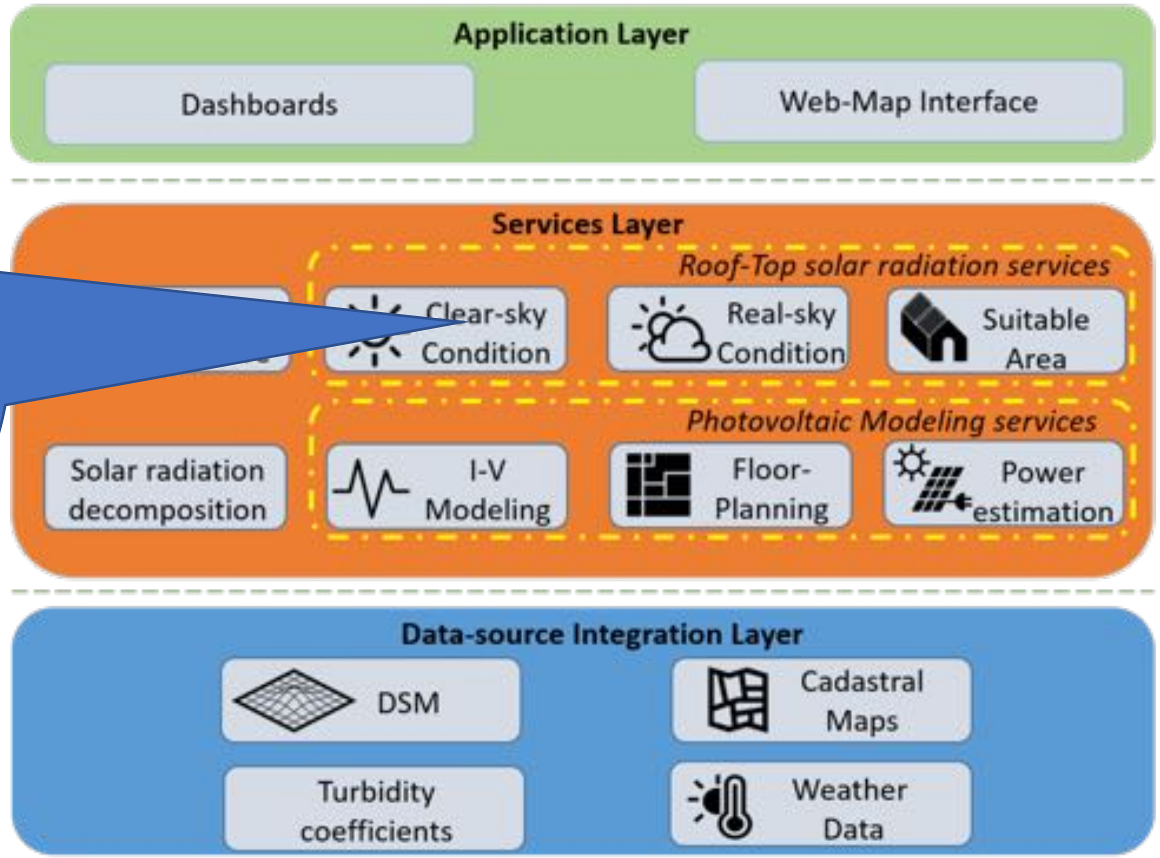
Details of Photovoltaic Energy simulation

Map Data Store service is in charge of storing produced (Clear sky maps and Suitable surface)



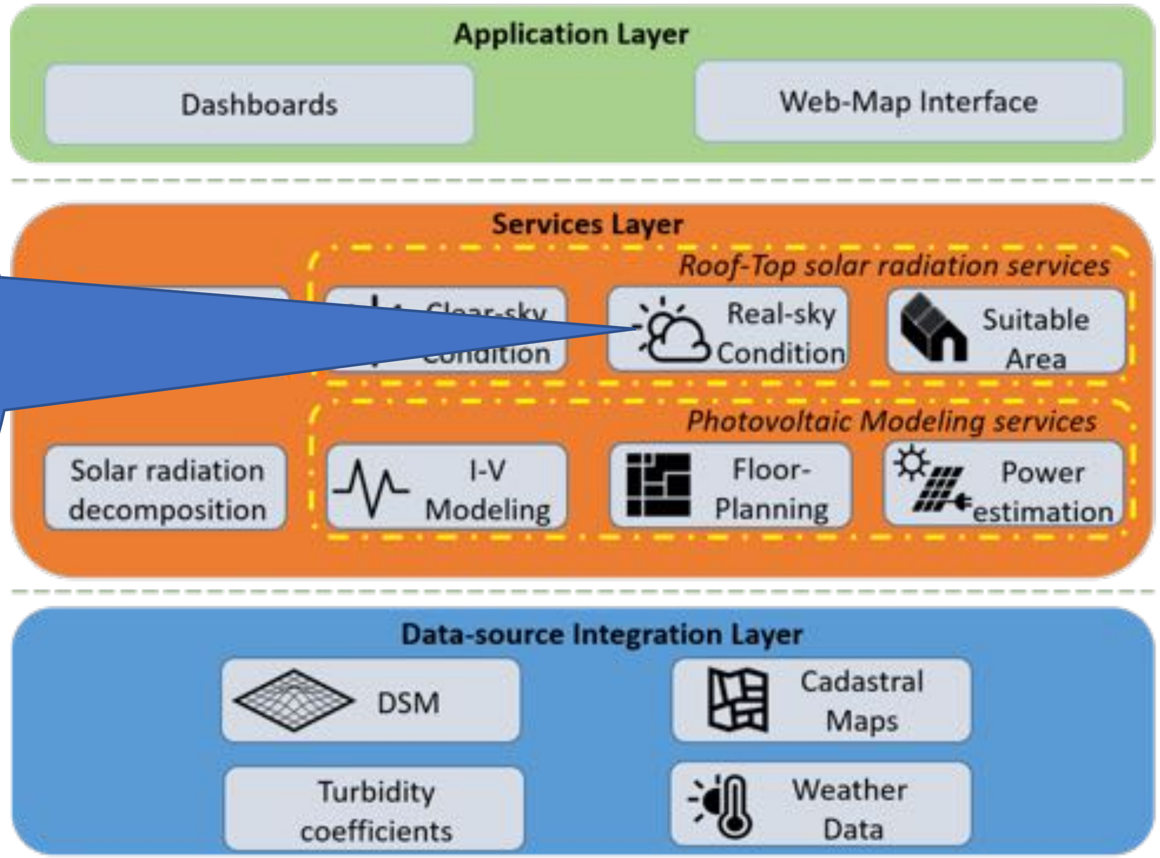
Details of Photovoltaic Energy simulation

Clear-sky condition service is in charge of producing clear-sky maps using as inputs the **DSM** and **Linke turbidity coefficients**.



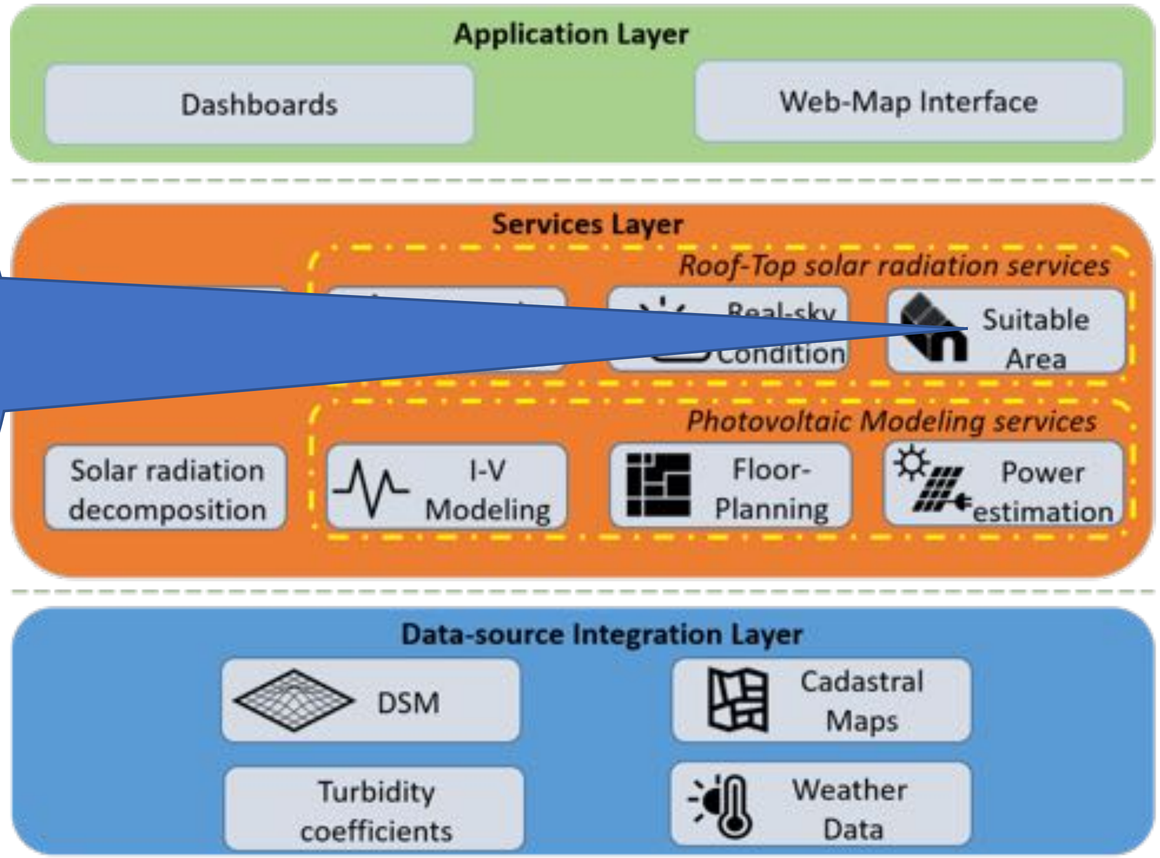
Details of Photovoltaic Energy simulation

Real-sky condition service is in charge of producing real-sky maps using as inputs **solar radiation data** provided by third party services.



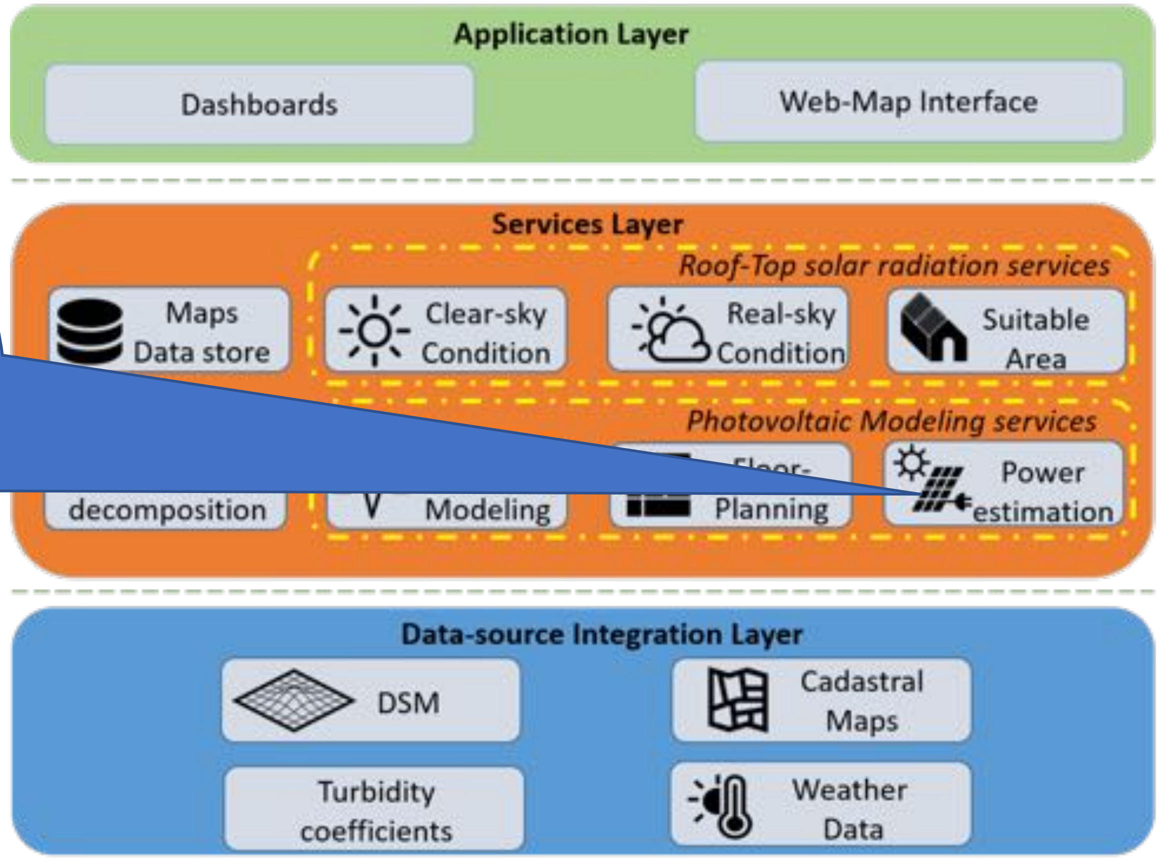
Details of Photovoltaic Energy simulation

Suitable area service identifies suitable surface for PV modules on rooftops, by analysing aspect and slope maps of the study area.



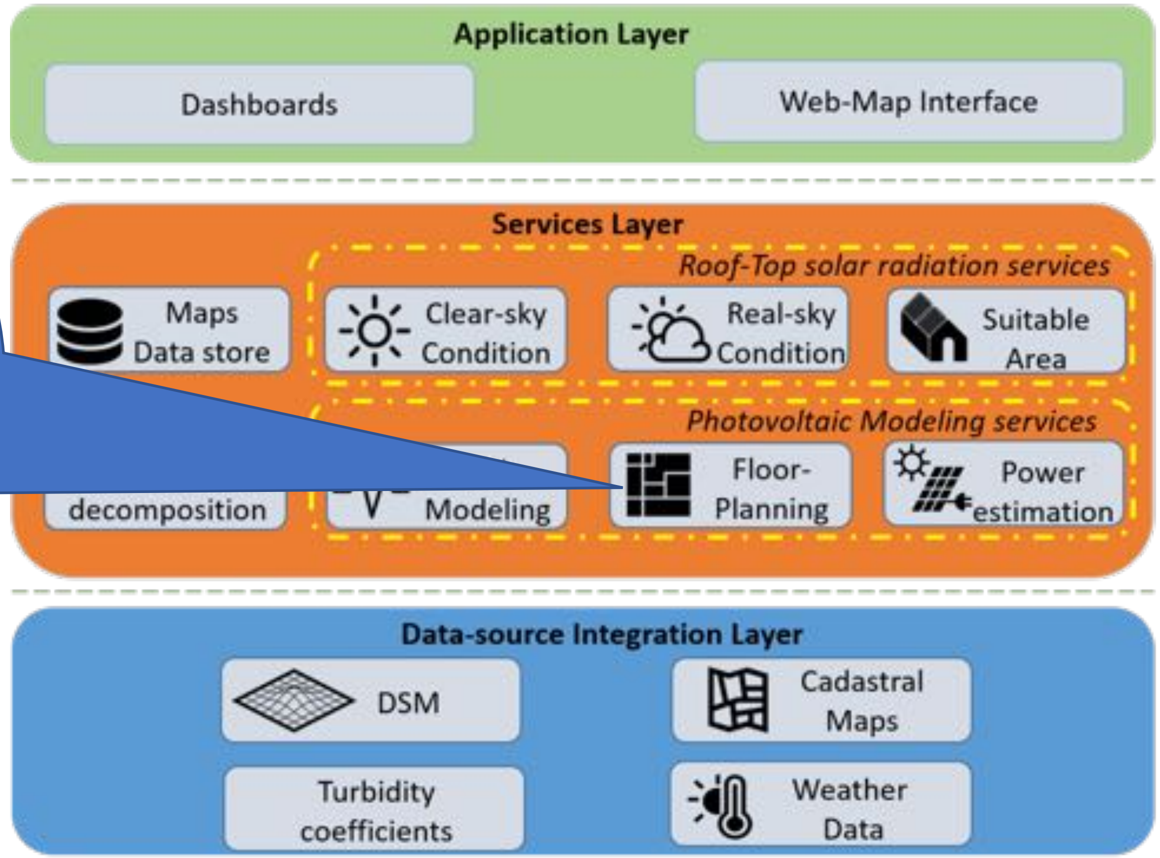
Details of Photovoltaic Energy simulation

PV Power estimation service provides NOCT models for evaluating the power production considering temperature effects.



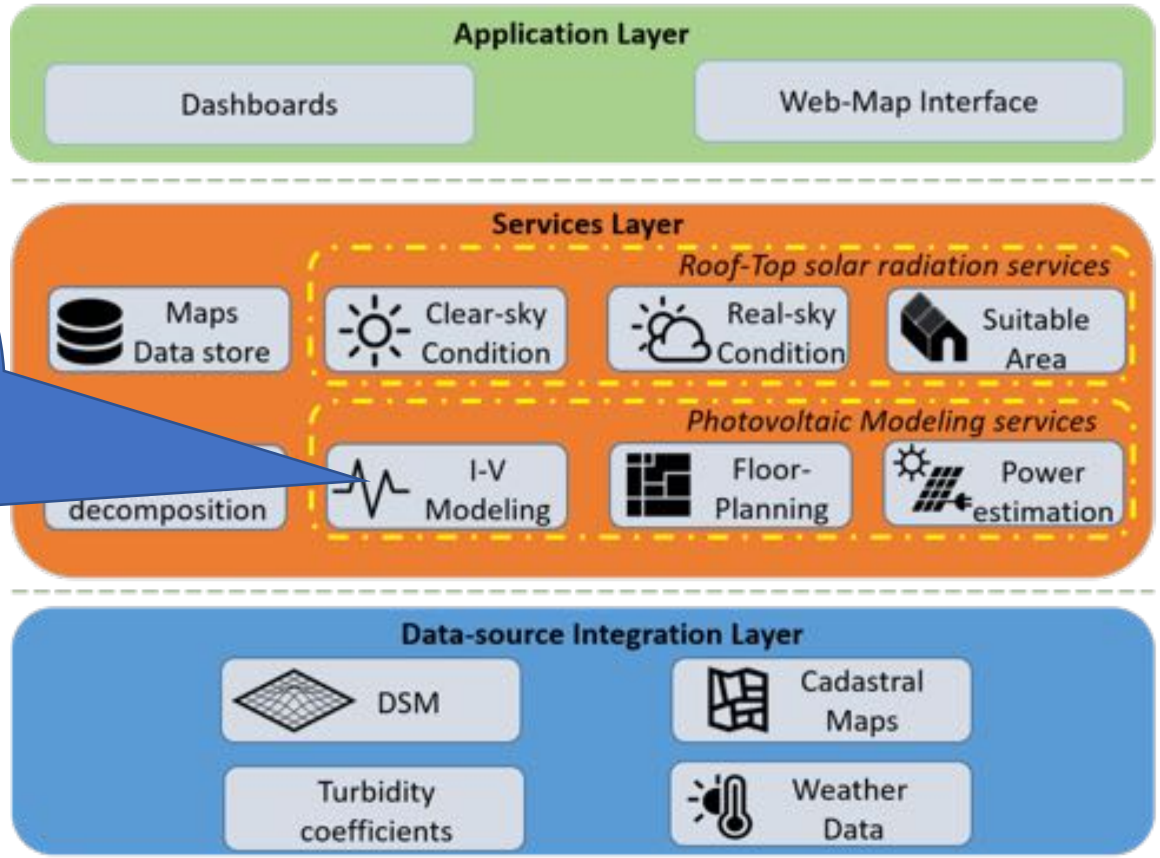
Details of Photovoltaic Energy simulation

Floor-Planning service provides a greedy algorithm for PV module placement with the objective of maximizing power production.

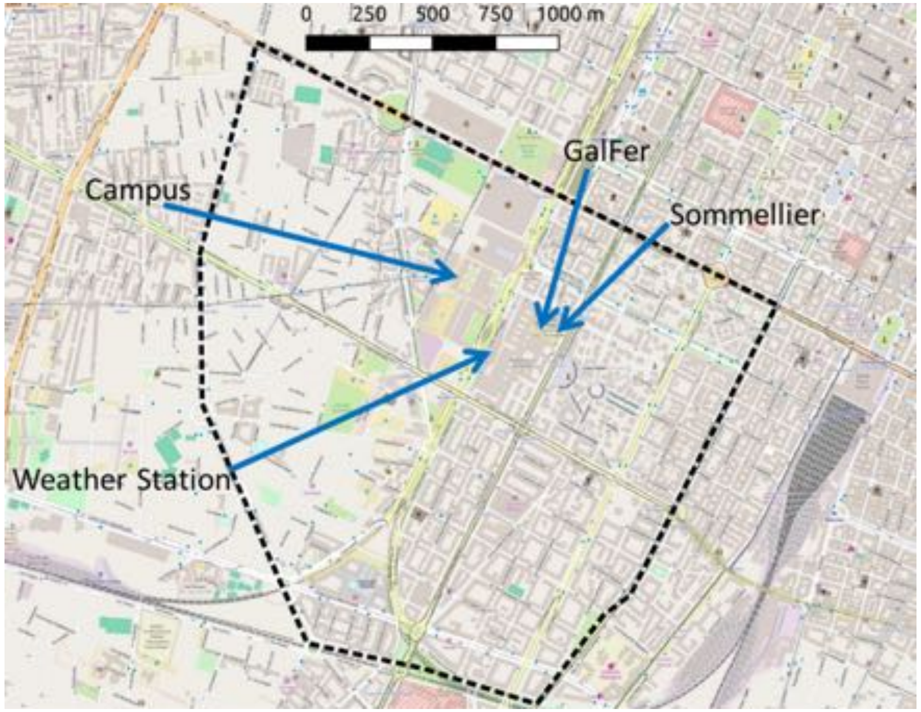


Details of Photovoltaic Energy simulation

I-V Modelling service provides simulation of tension and current simulation of a PV system by considering a hardware model of the module.



Case Study for PV simulation



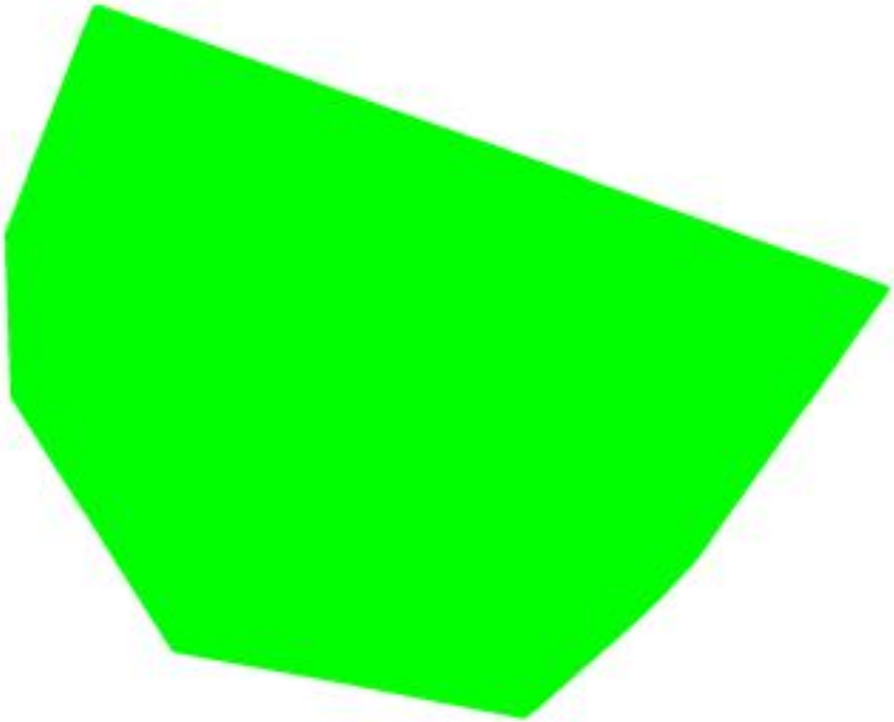
Sommelier and Galfer

Campus

	Campus	GalFer	Sommelier
Nominal Power [kW]	15.28	13.20	19.80
Module Power [W]	283	165	165
Number of PV modules	54	80	120
Module Efficiency [%]	20.2	13.1	13.1
Module Temp. Coef. [%/°C]	0.38	0.48	0.48
Slope [°]	26	35	20
Aspect [°] (South 270°)	23	240	240
Installation year	2008	2004	2004

Results for Real-sky irradiance simulation

Spatio-Temporal Simulation
in Real-Sky condition

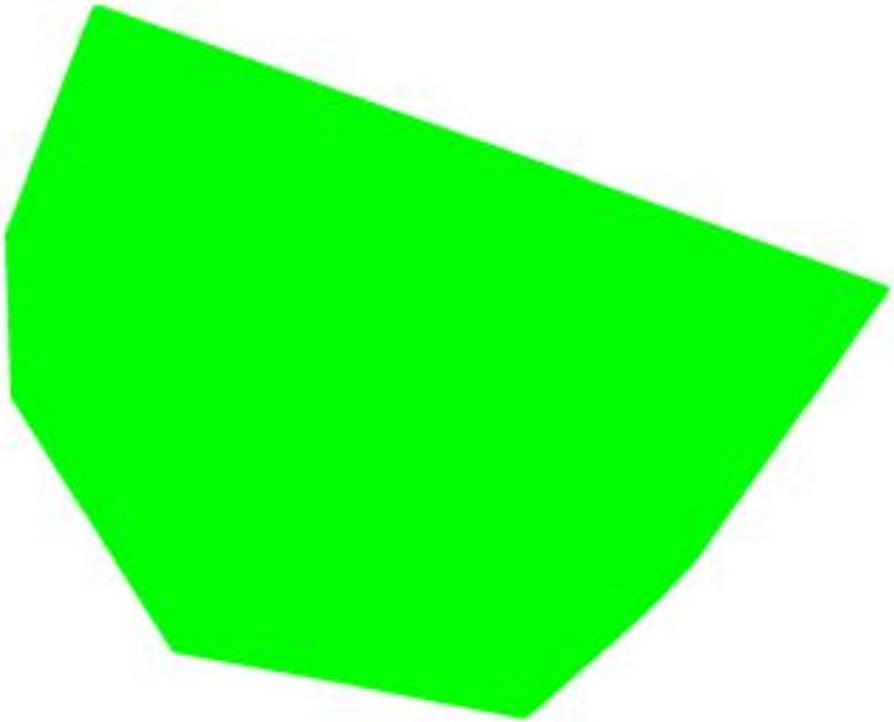


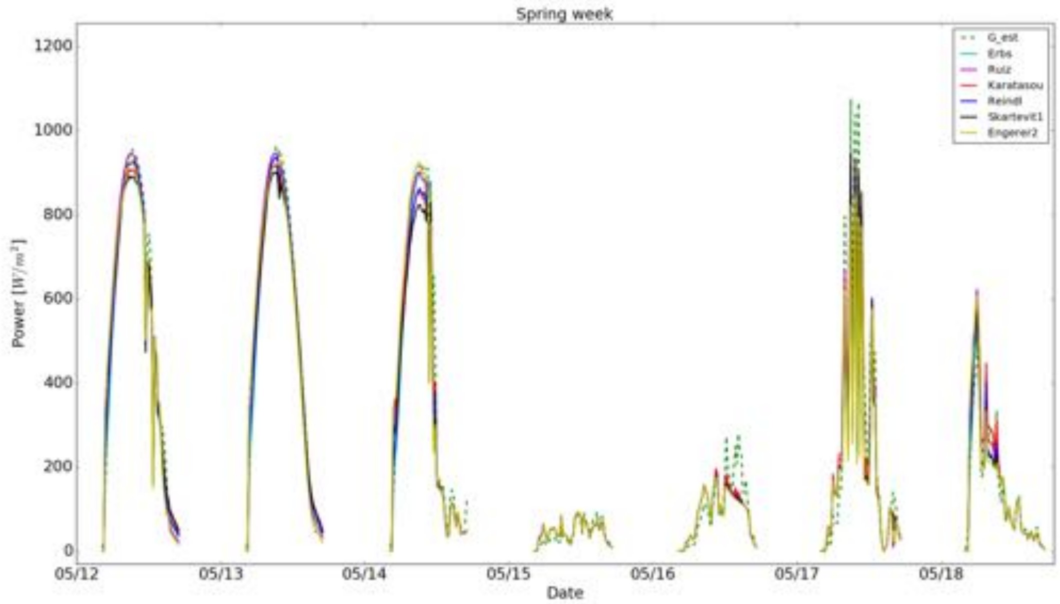
Solar radiation decomposition

Real-sky Condition

Results for Real-sky irradiance simulation

Spatio-Temporal Simulation
in Real-Sky condition



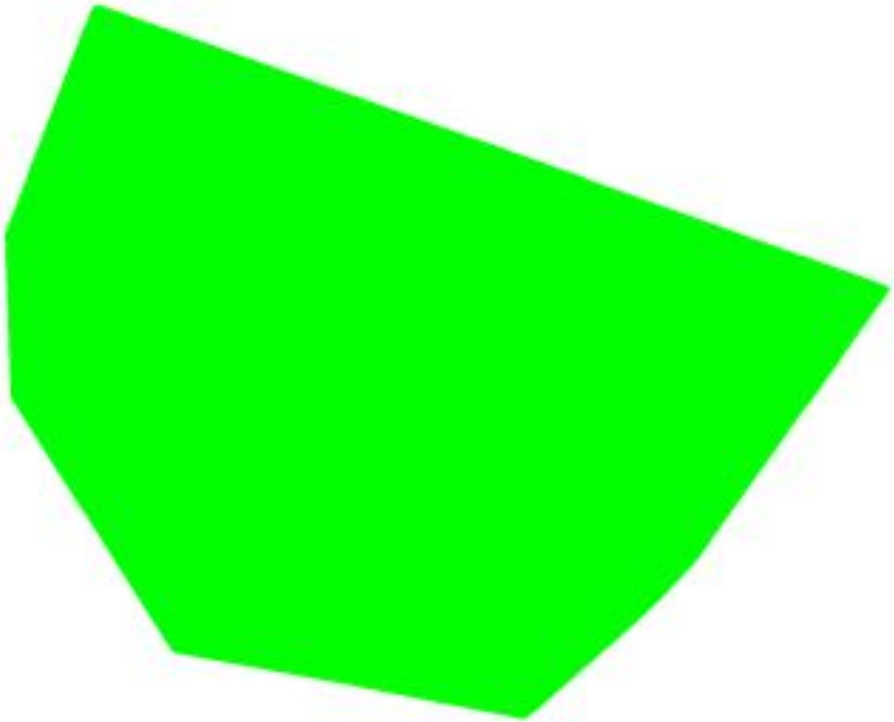


Solar radiation decomposition

Real-sky Condition

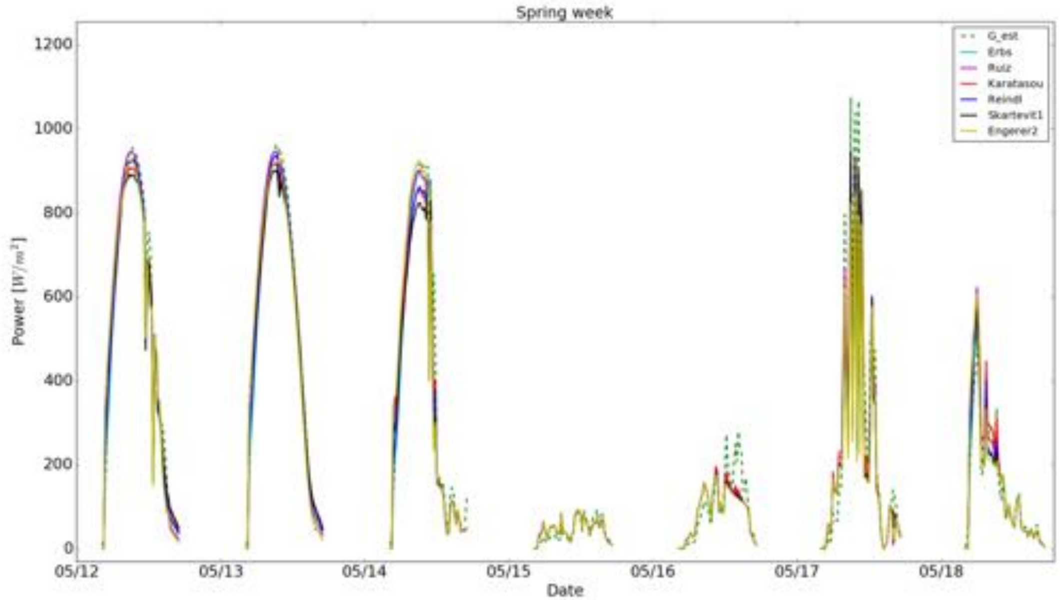
Results for Real-sky irradiance simulation

Spatio-Temporal Simulation
in Real-Sky condition



Solar radiation decomposition

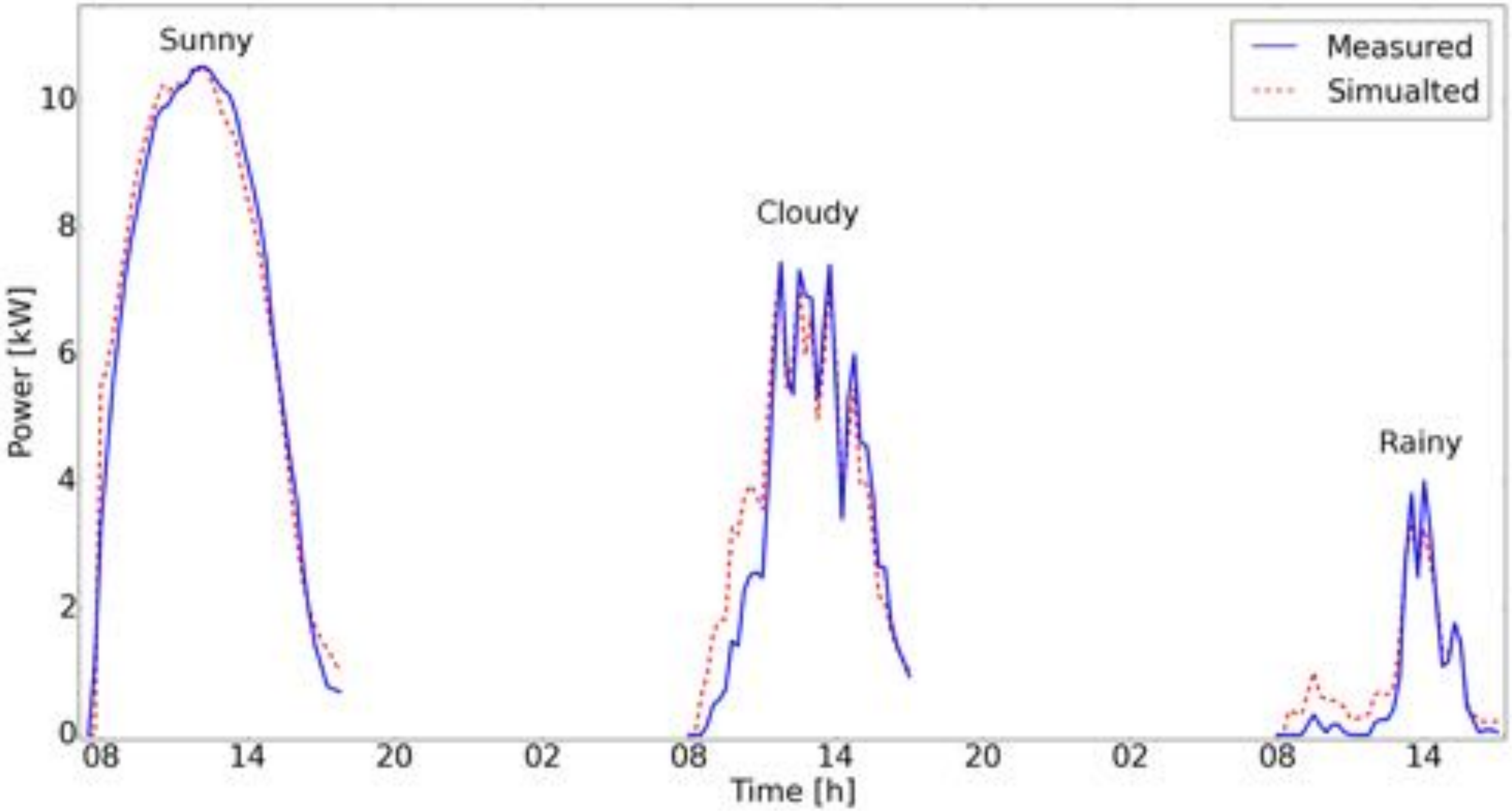
Real-sky Condition

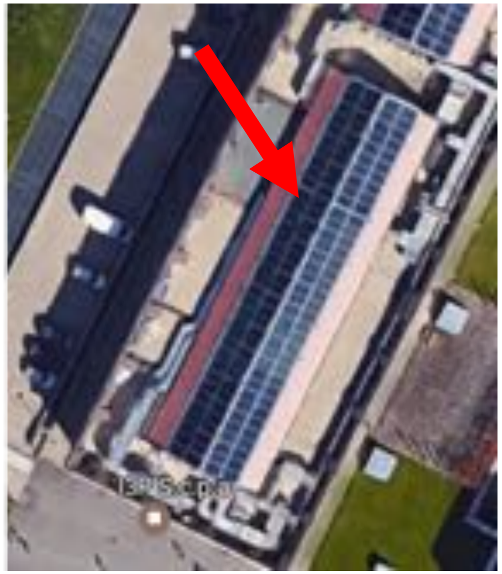


Model	Time resolution	*LCE*	*MAD* [%]	*MBD* [%]	r^2	*RMSD* [%]	*WIA*
Reindl [99]		0.80	15.38	-6.22	0.95	20.93	0.98
Engerer [97]		0.77	17.48	-5.96	0.93	24.16	0.98
Skartveit [100]		0.77	17.46	-8.62	0.93	24.10	0.98
Karatasou [11]	1 hour	0.80	15.44	-1.88	0.95	20.73	0.98
Ruiz-Arias [98]		0.80	15.31	-0.68	0.94	20.75	0.98
Erbs [96]		0.80	15.47	-6.54	0.94	21.42	0.98
Reindl [99]		0.78	16.21	-6.08	0.93	23.52	0.98
Engerer [97]		0.75	19.09	-5.82	0.90	27.83	0.97
Skartveit [100]		0.75	18.75	-8.55	0.91	26.84	0.97
Karatasou [11]	15 minutes	0.78	16.57	-1.40	0.93	23.42	0.98
Ruiz-Arias [98]		0.78	16.65	-0.5	093	23.62	0.98
Erbs [96]		0.78	16.95	-6.36	0.93	24.35	0.98

Results Campus PV Systems

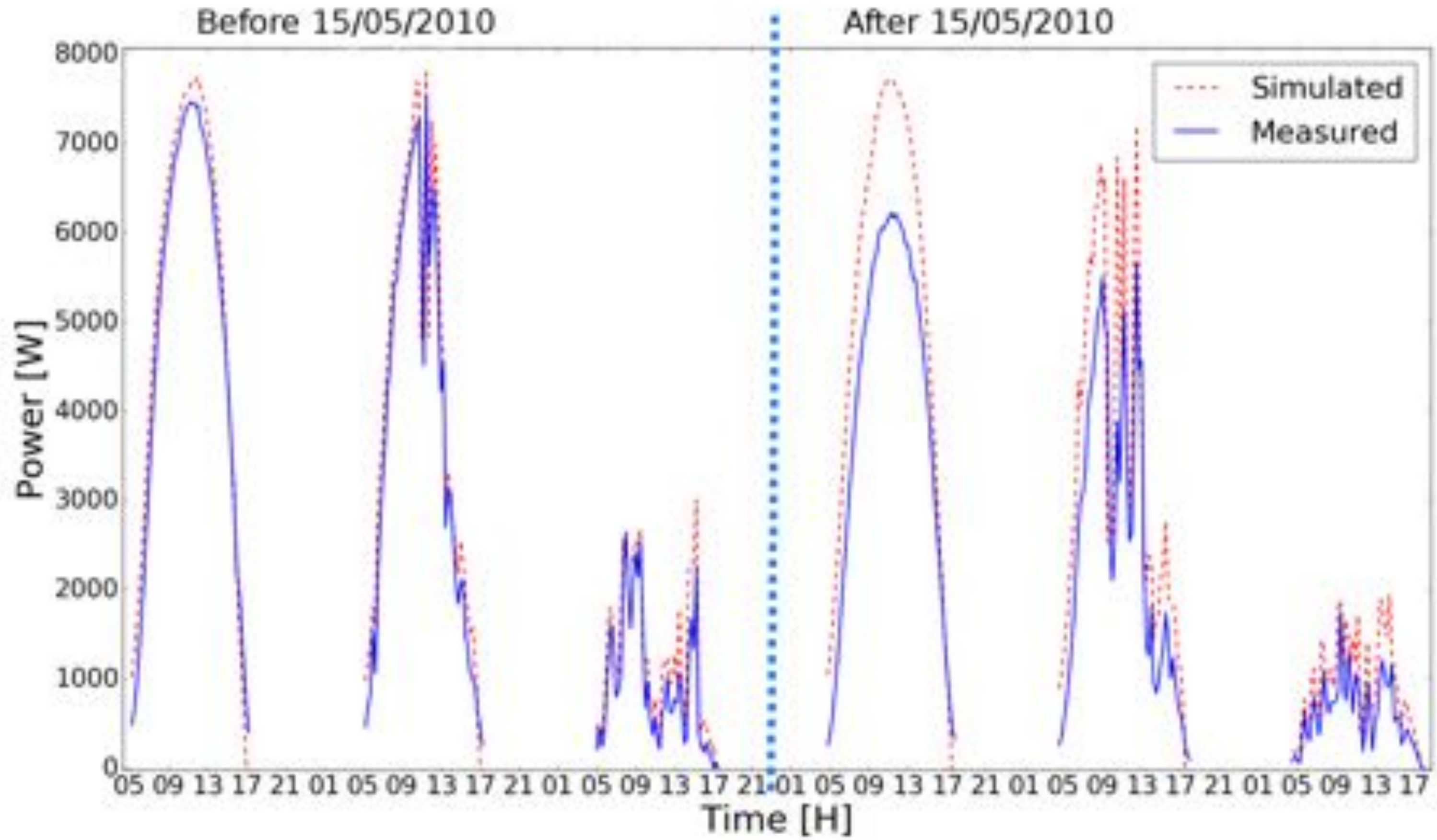
Power estimation

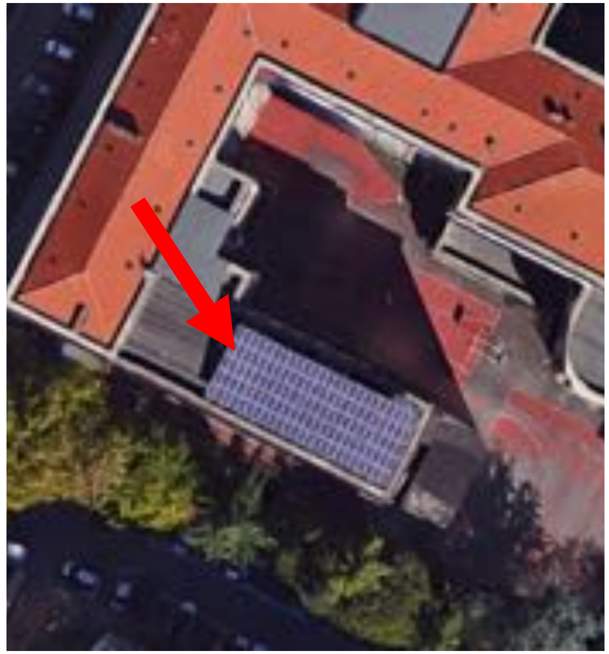




Results Sommelier PV System

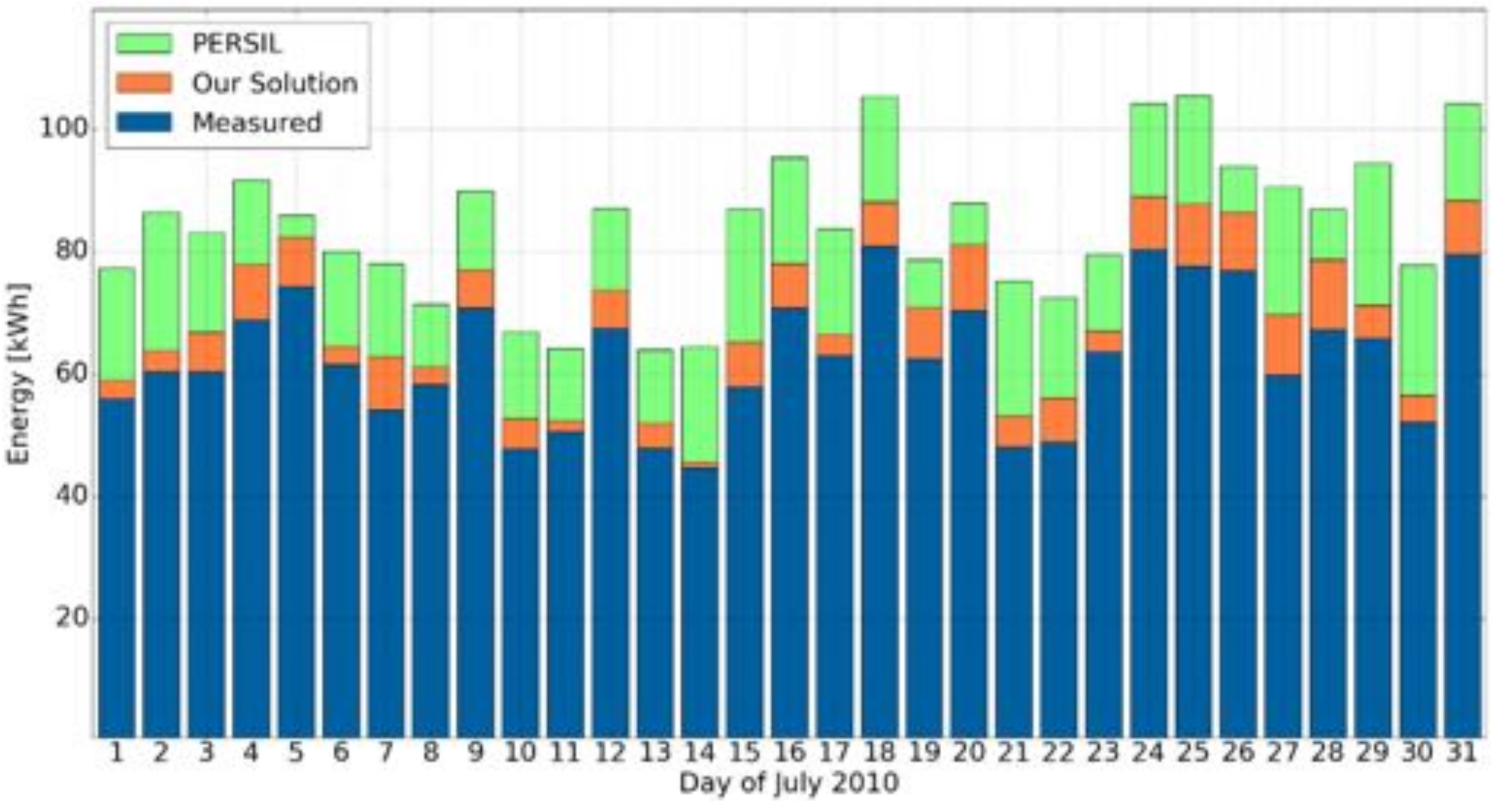
Power estimation





Comparison with PERSIL methodology

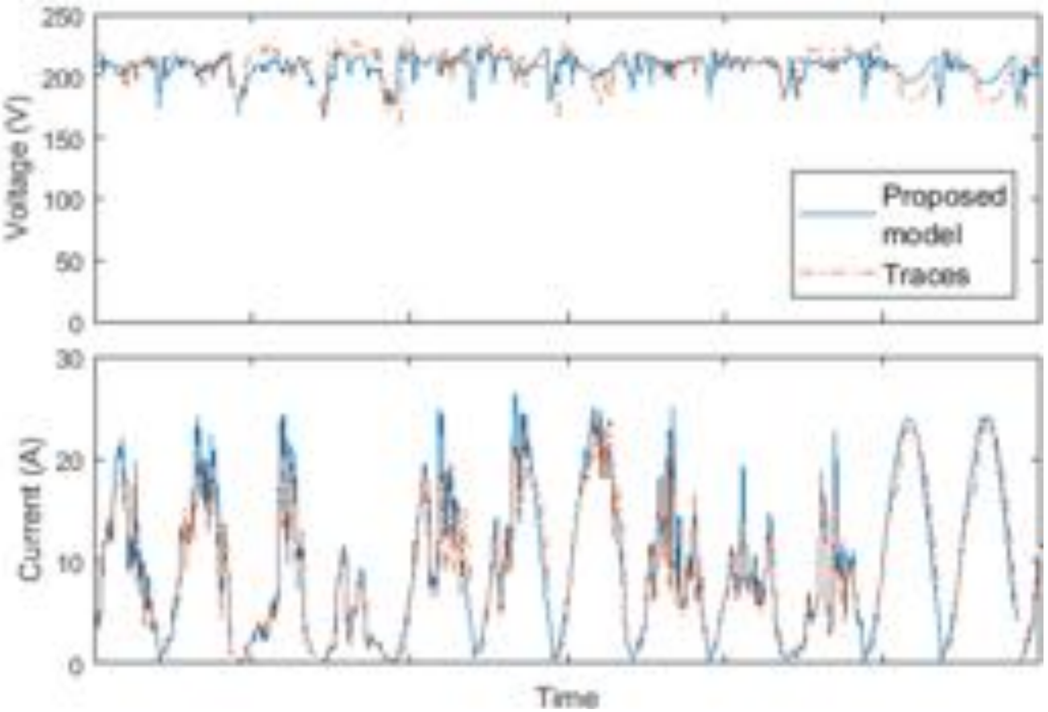
Power estimation

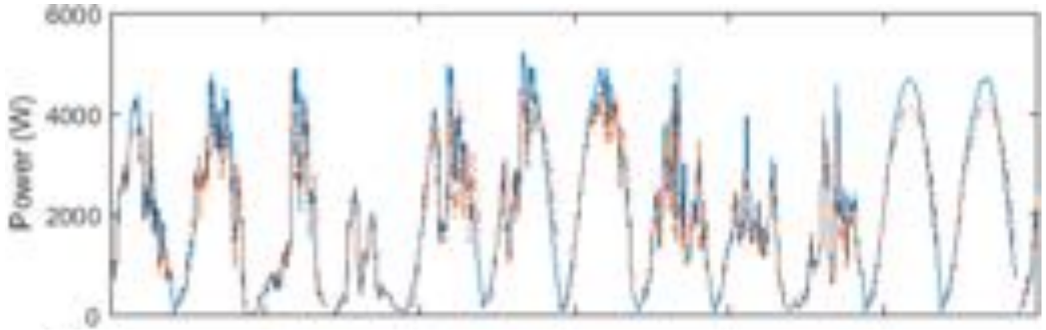


GalFer PV system

Results of I-V Modelling

I-V
Modeling

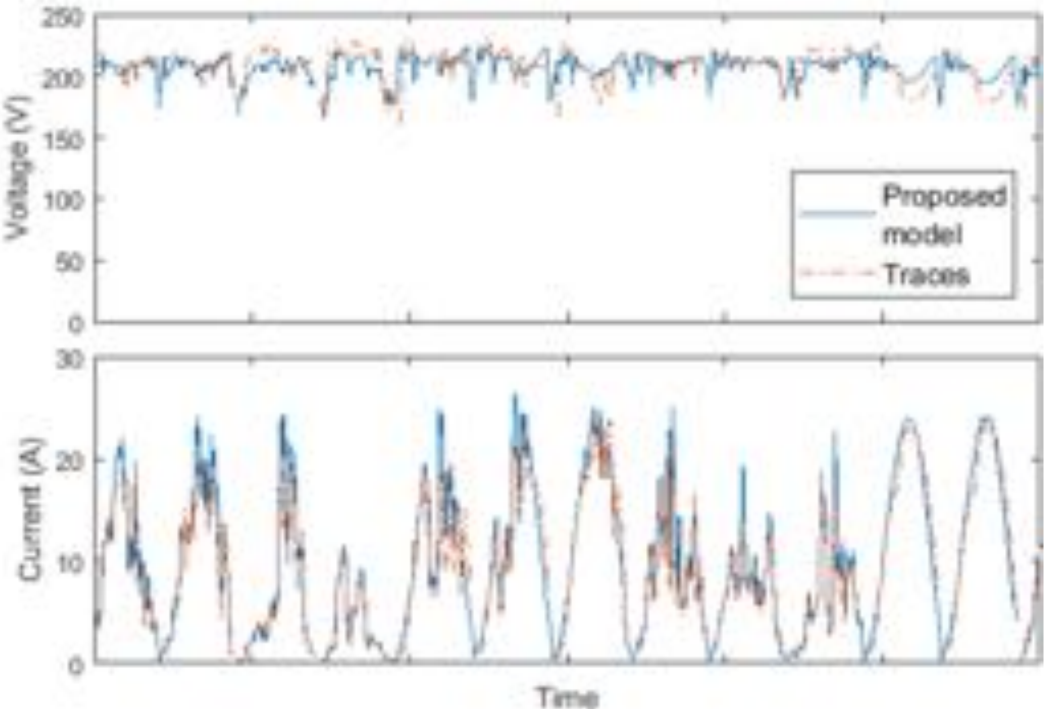


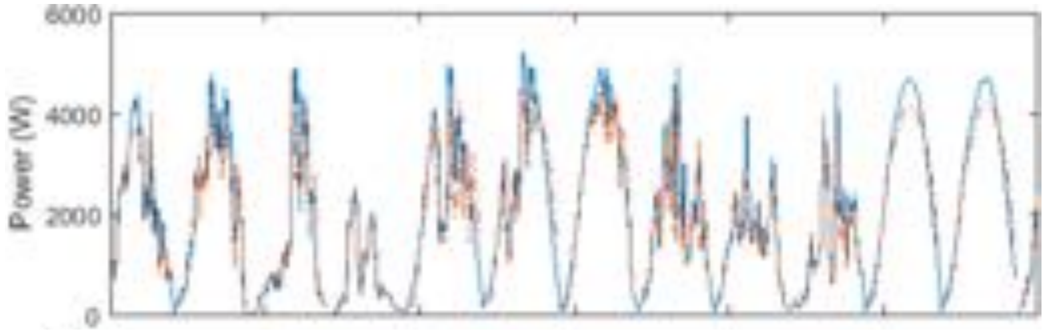


MODEL	RMSD	R^2	WIA	LCE
Proposed	22.20%	0.906	0.975	0.751
NOCT Formula	28.29%	0.870	0.970	0.700
PERSIL	45.60%	0.386	0.880	0.183

Results of I-V Modelling

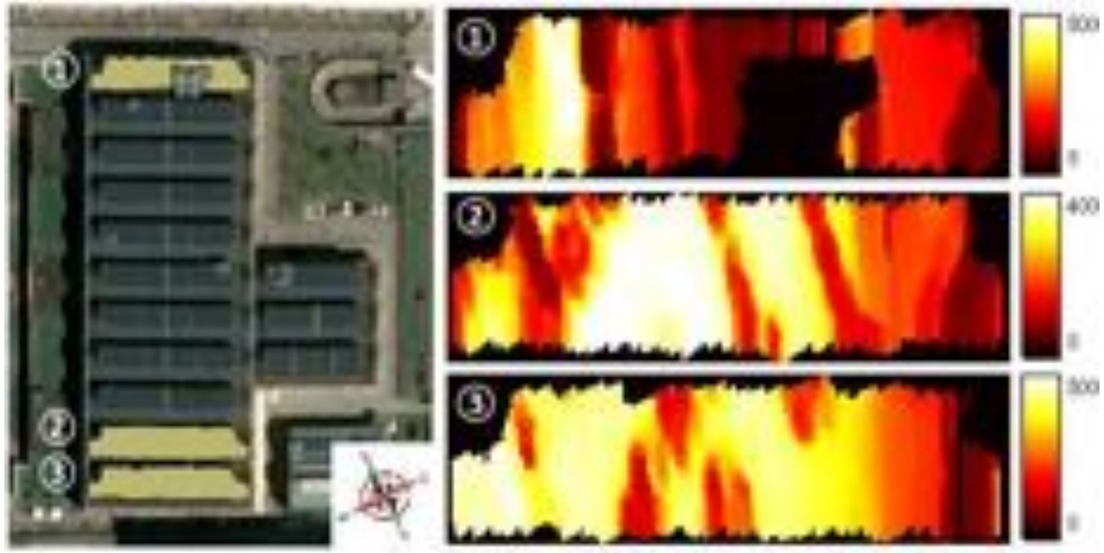
I-V Modeling





Model	RMSD	R^2	WIA	LCE
Proposed	22.20%	0.906	0.975	0.751
NOCT Formula	28.29%	0.870	0.970	0.700
PERSIL	45.60%	0.386	0.880	0.183

Results of Floor-planning



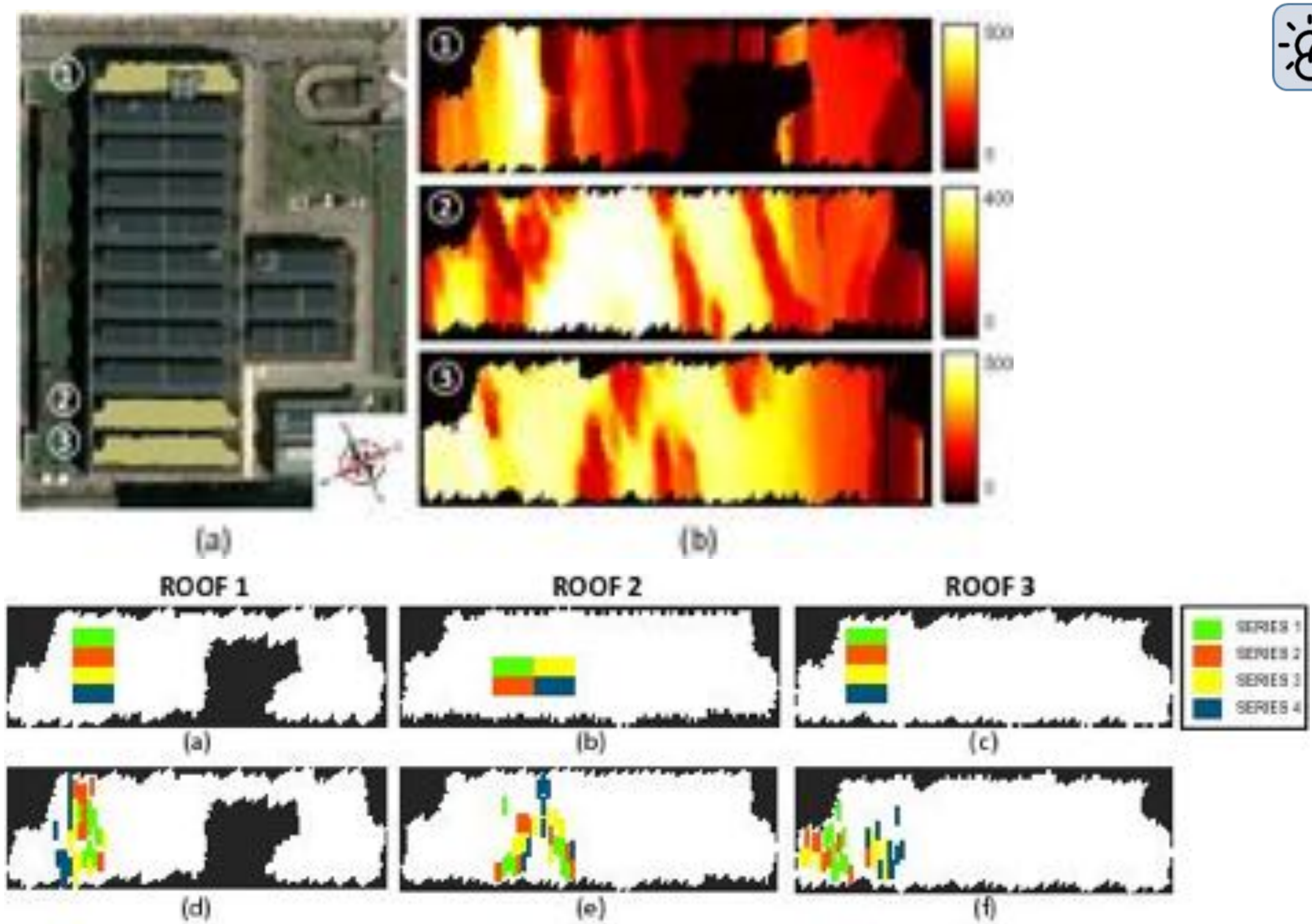
(a) (b)

Results of Floor-planning

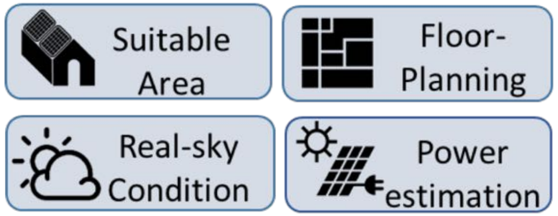
Suitable Area

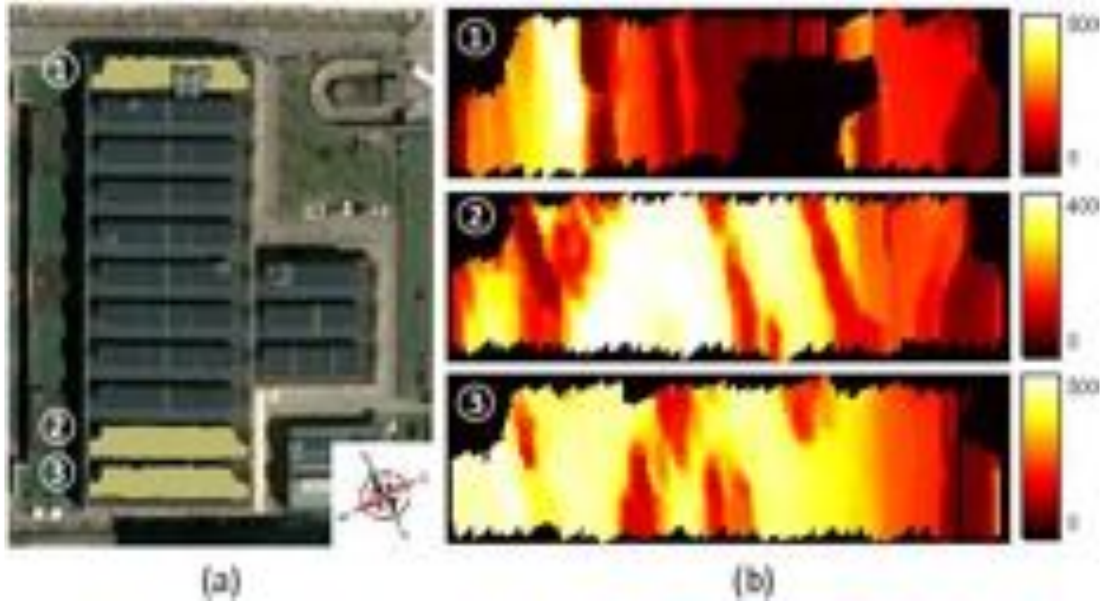
Floor-Planning

Real-sky Condition

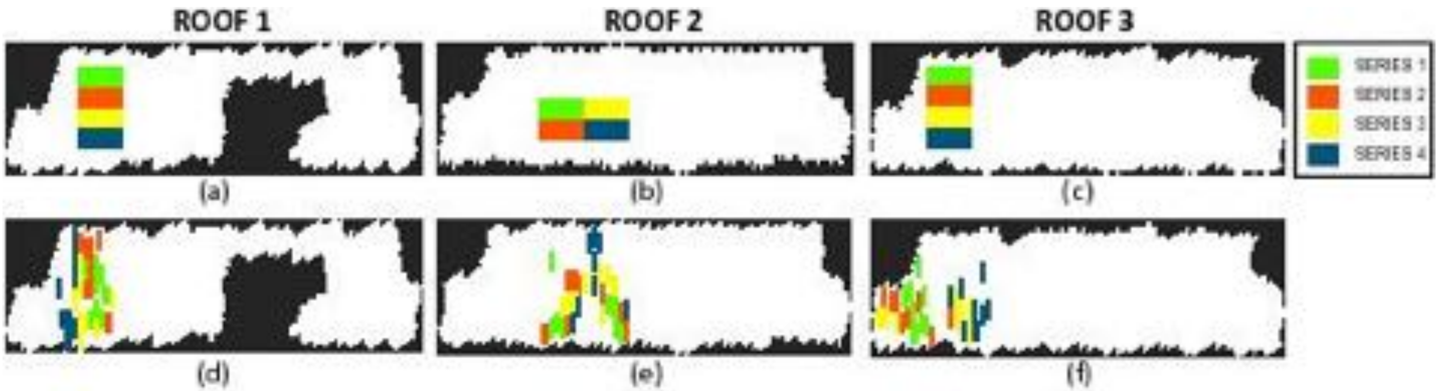


Results of Floor-planning

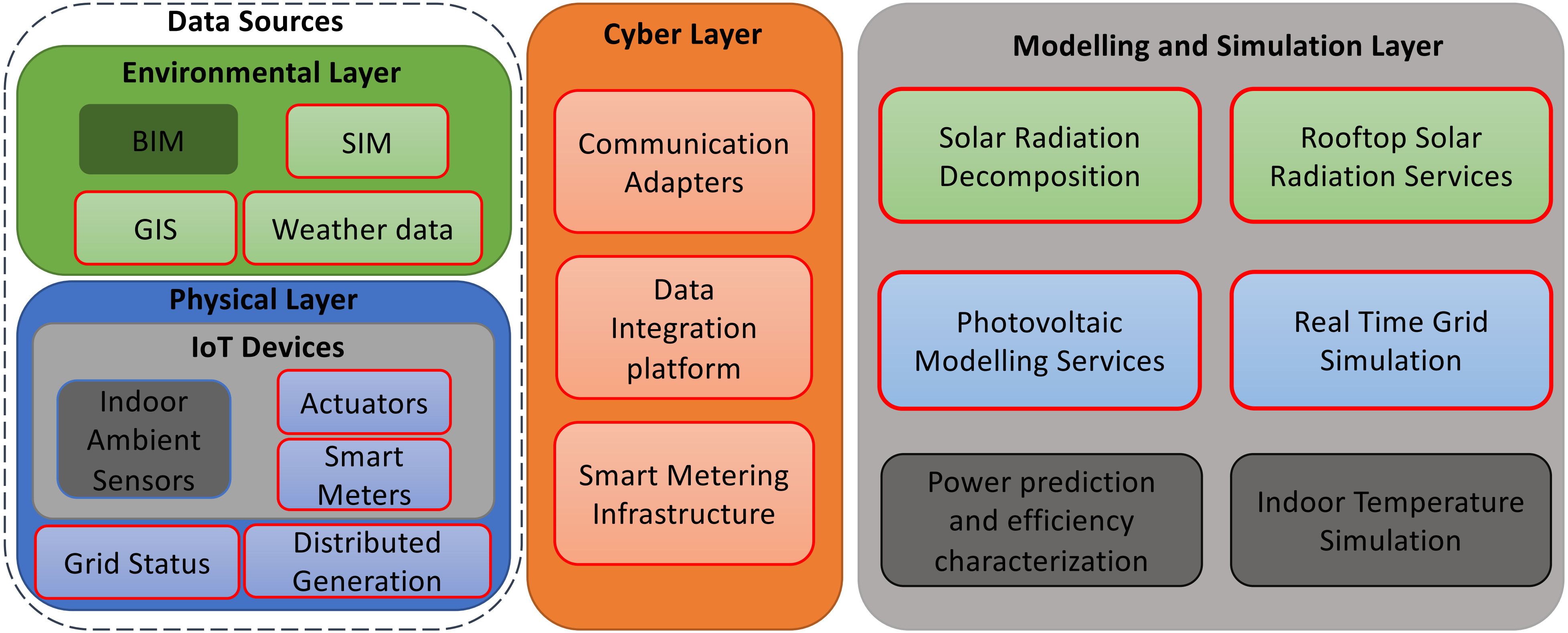




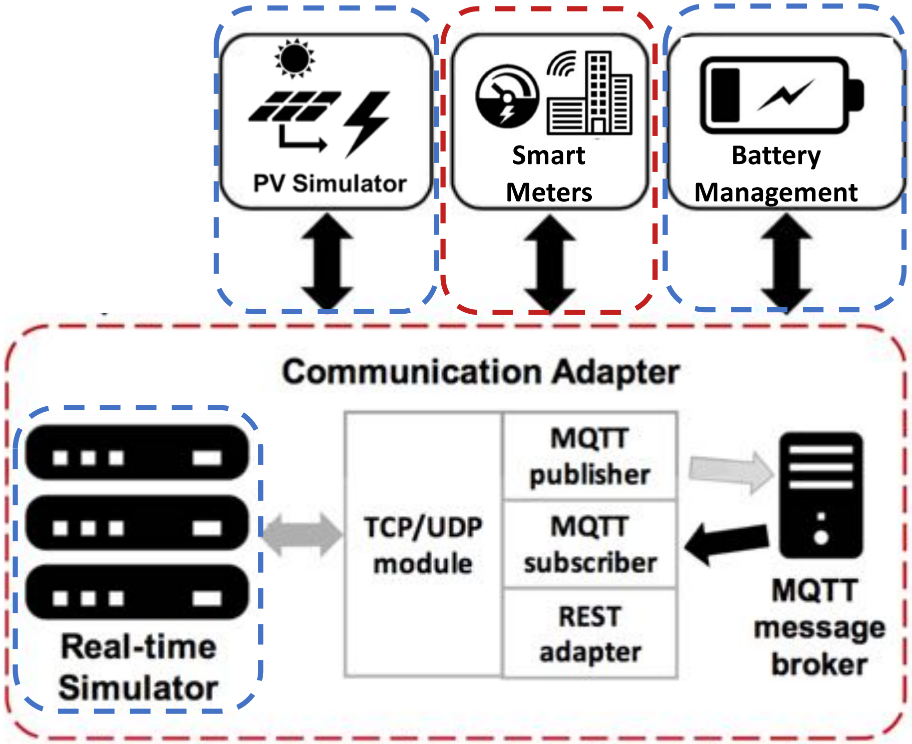
Roof	WxL	N_g	N	Traditional MWh	Proposed MWh	Proposed %
Roof 1	287x51	9,416	16	3.430	4.094	+19.37
			32	6.729	7.499	+11.44
Roof 2	298x51	11,892	16	2.971	3.619	+21.85
			32	5.941	7.404	+23.63
Roof 3	298x52	11,672	16	2.957	3.642	+23.16
			32	5.746	7.405	+28.86

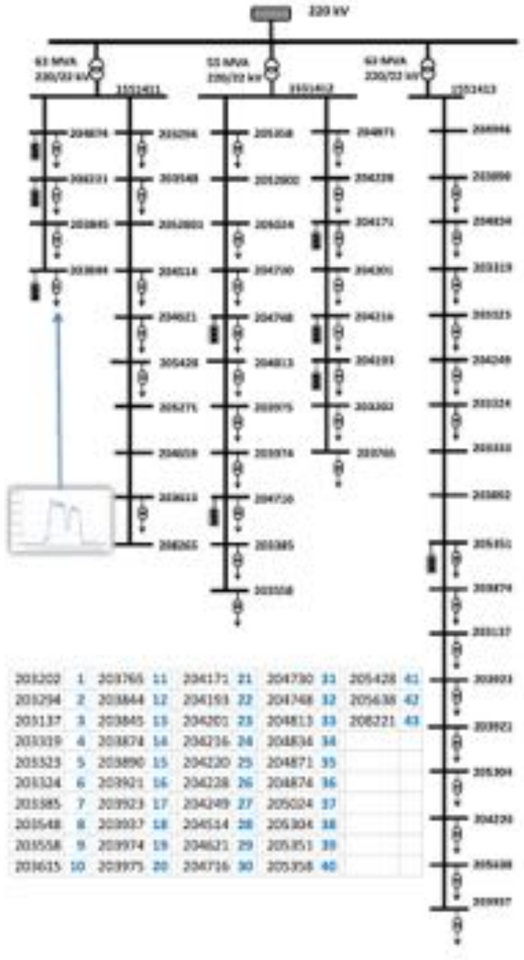


Renewable energy and Smart policies grid integration

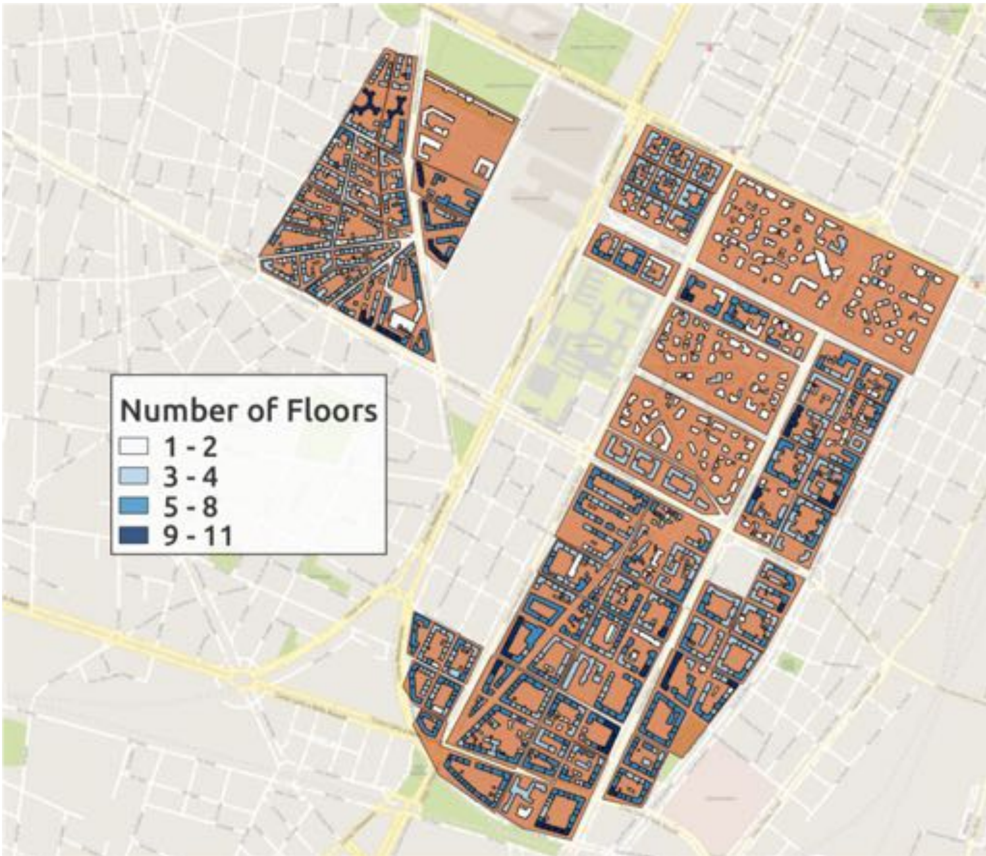


Case study of Realtime Grid Cosimulation

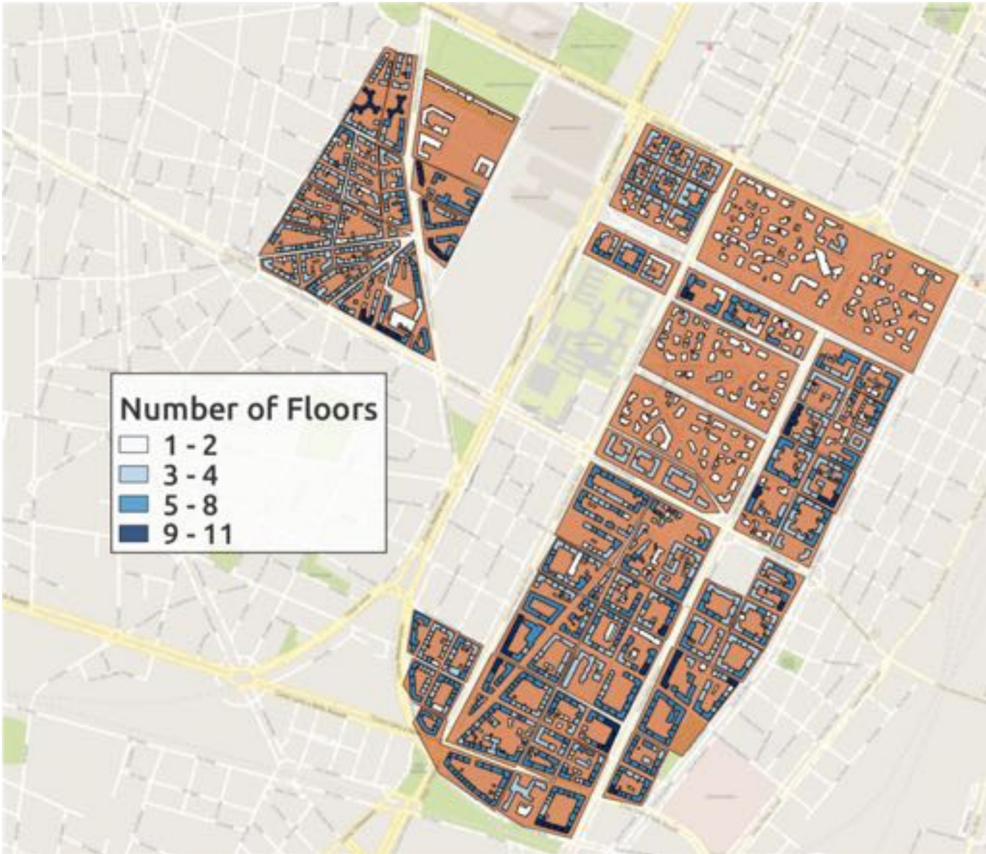


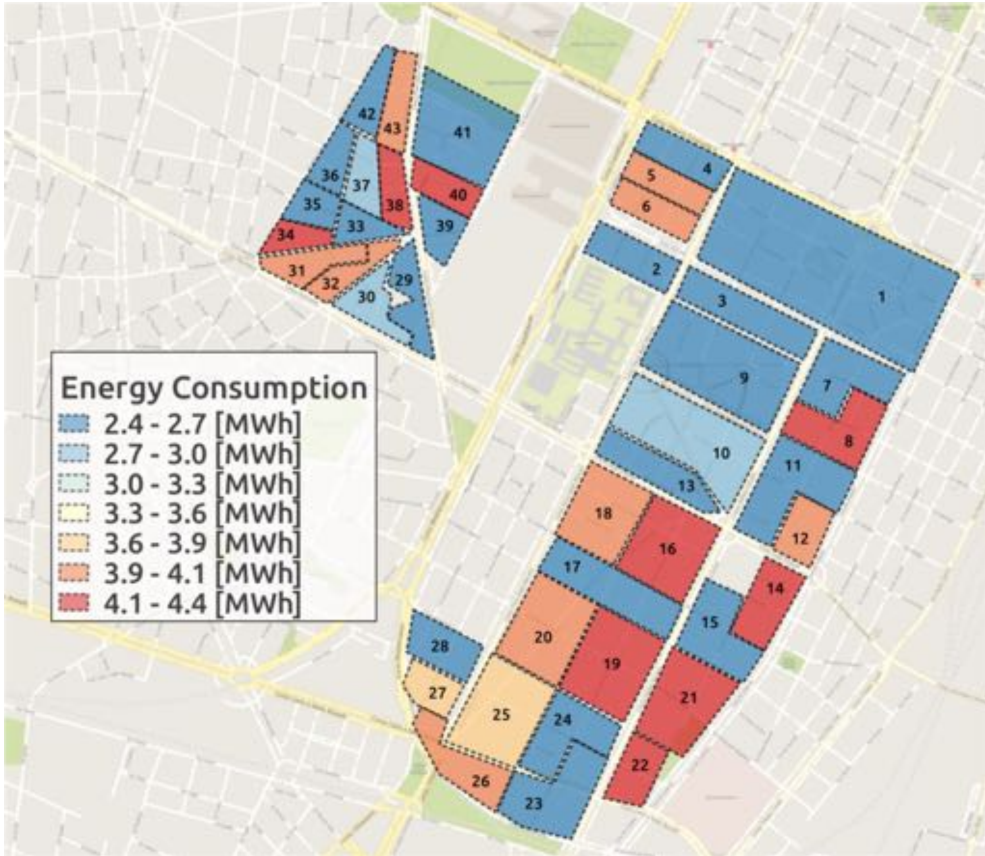


Case study of Realtime Grid Cosimulation

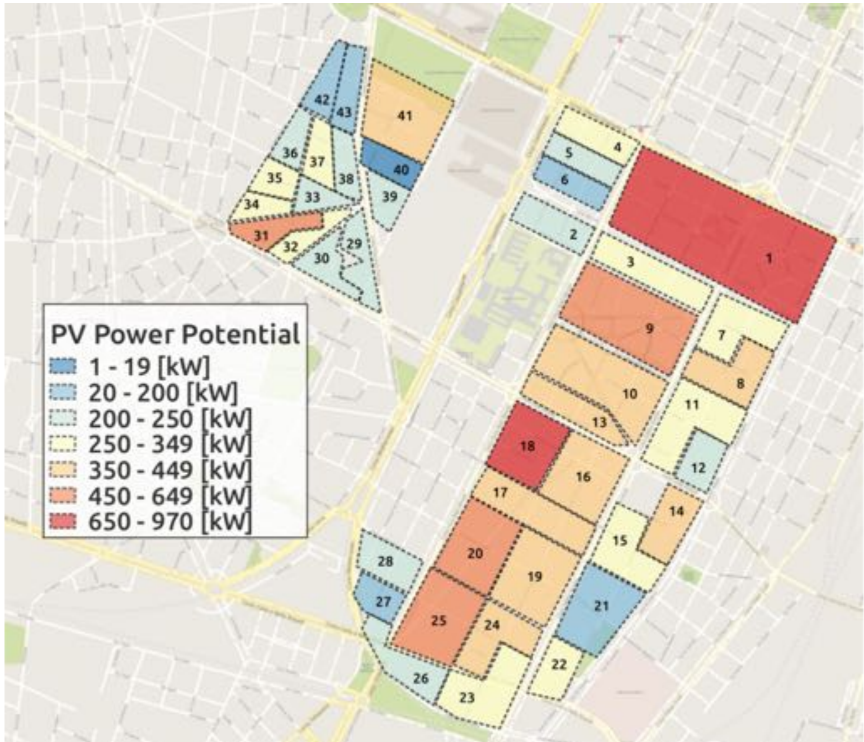


Case study of Realtime Grid Cosimulation



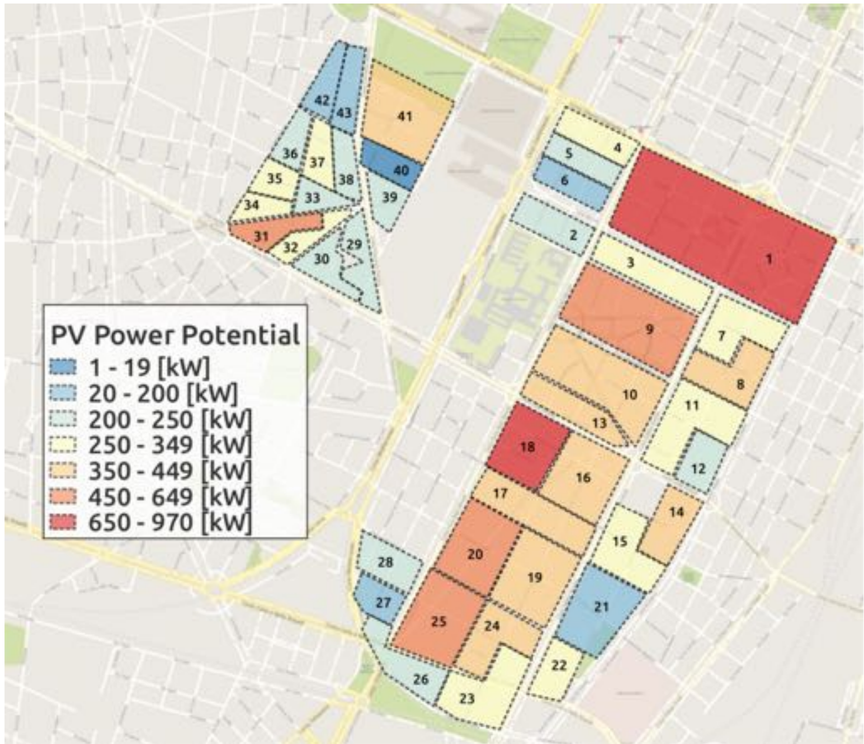


Photovoltaic Potential and Production

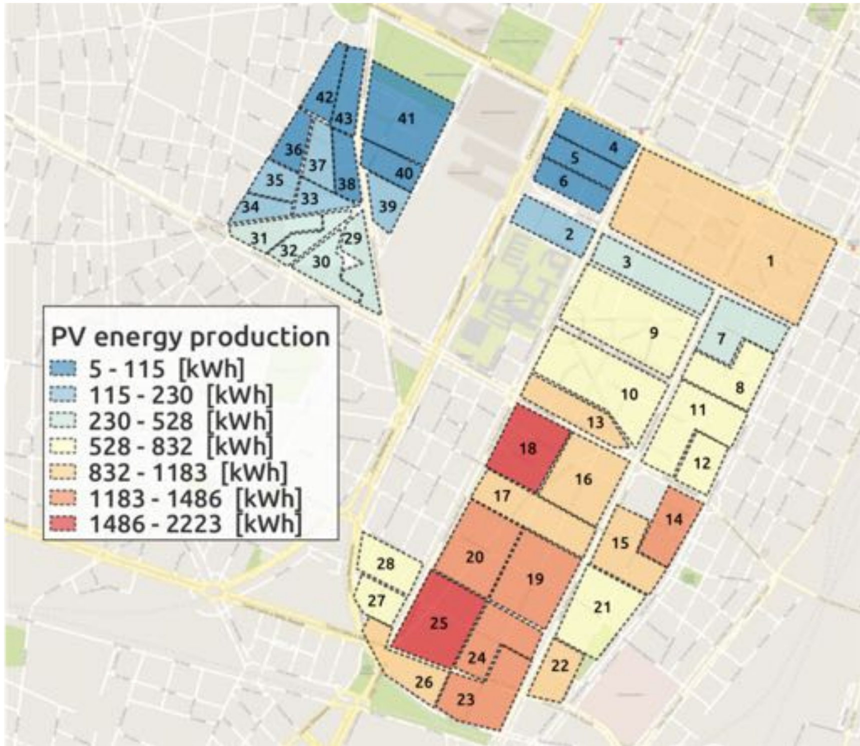


Potential PV power map

Photovoltaic Potential and Production

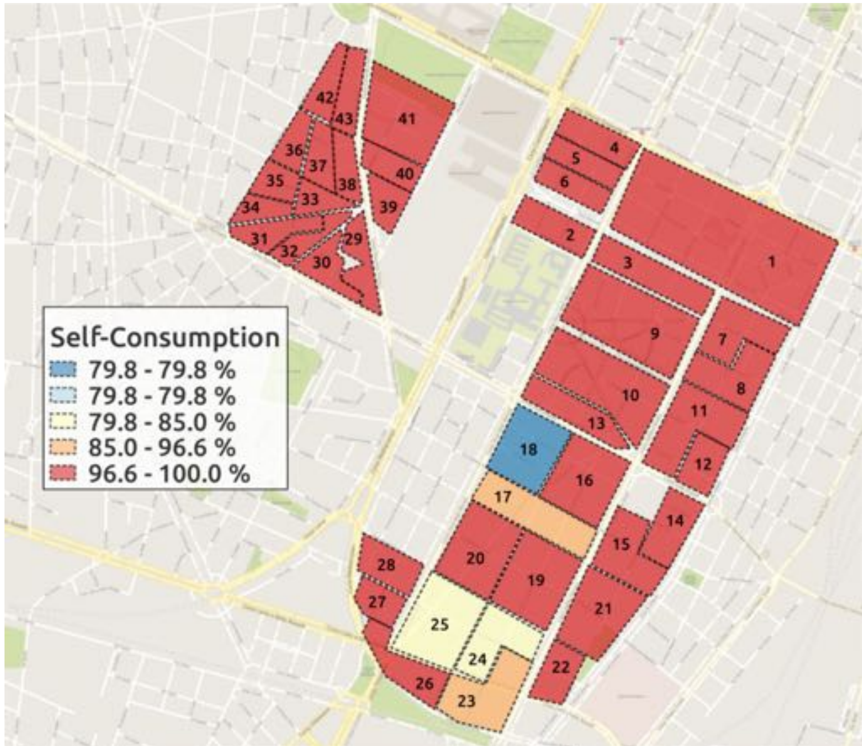


Potential PV power map



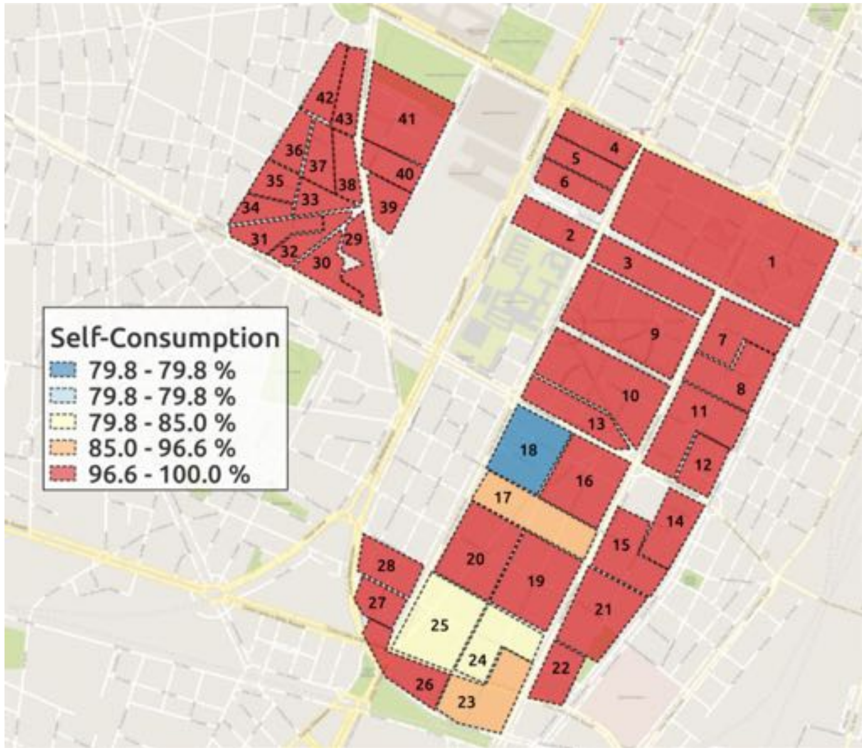
PV Energy Production map

Self-consumption and Self-sufficiency

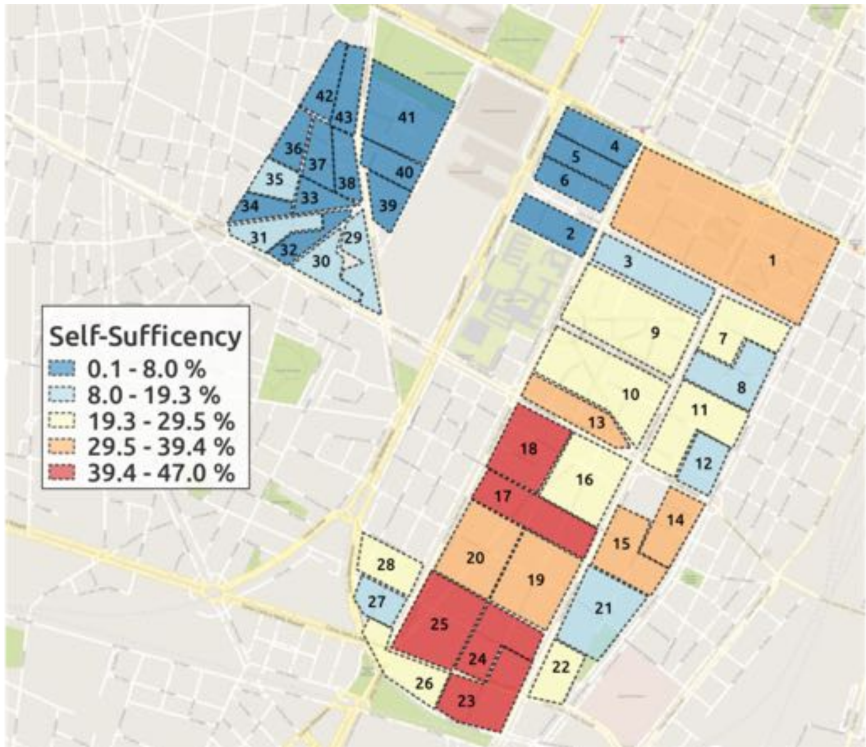


Self-Consumption map

Self-consumption and Self-sufficiency

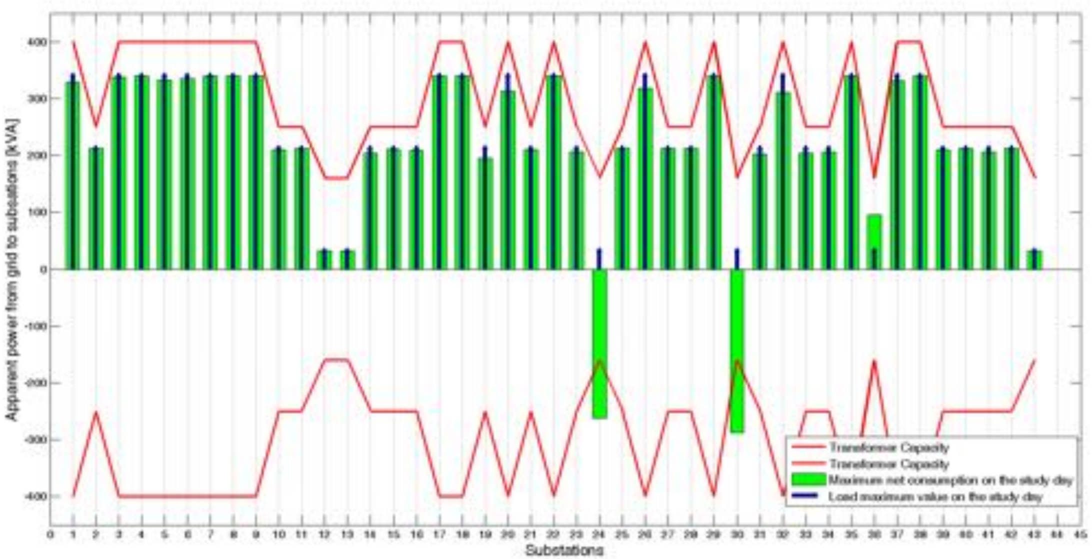


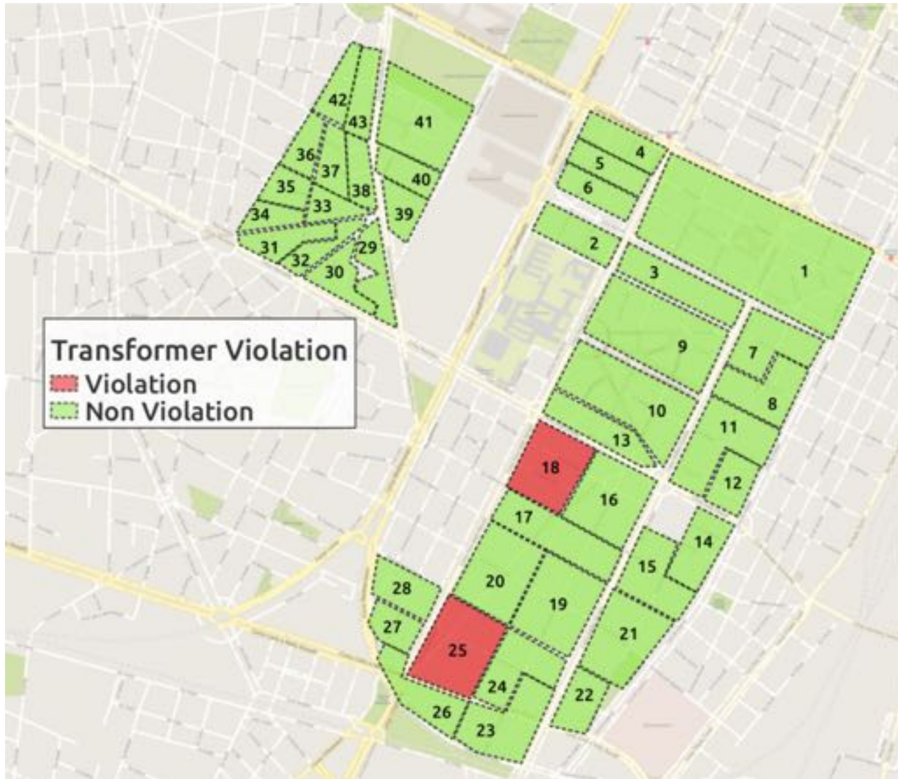
Self-Consumption map



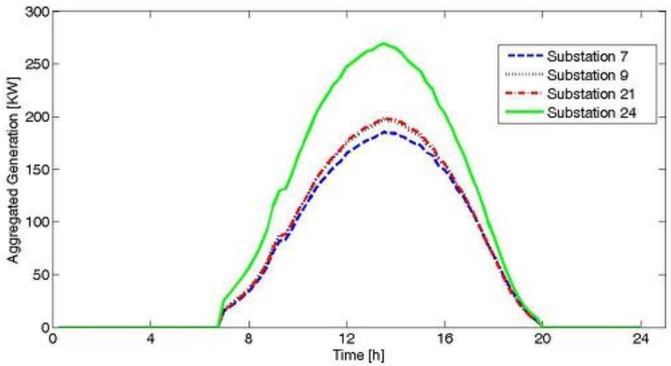
Self-sufficiency map

MV/LV Transformers capacity

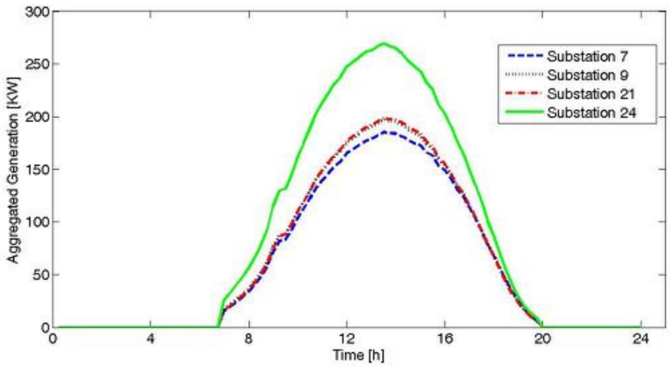


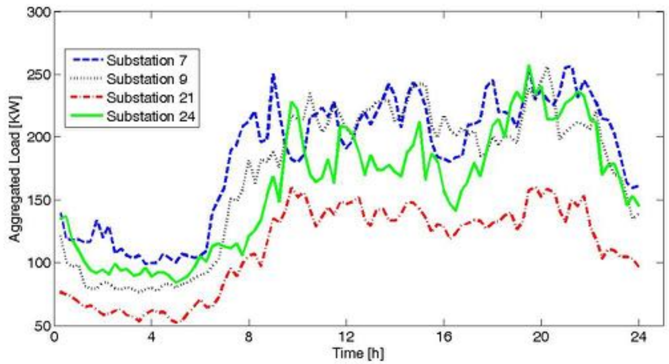


Power flow and Voltage Profile Monitoring

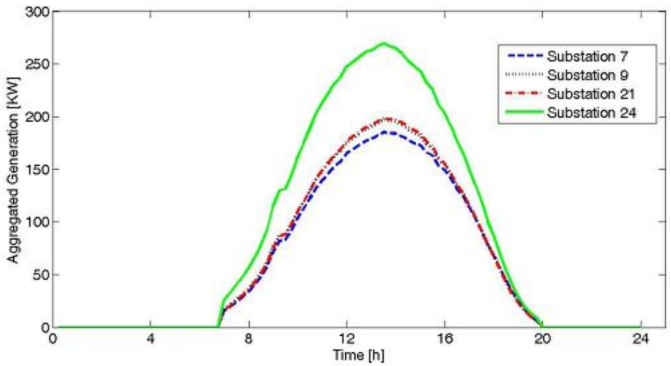


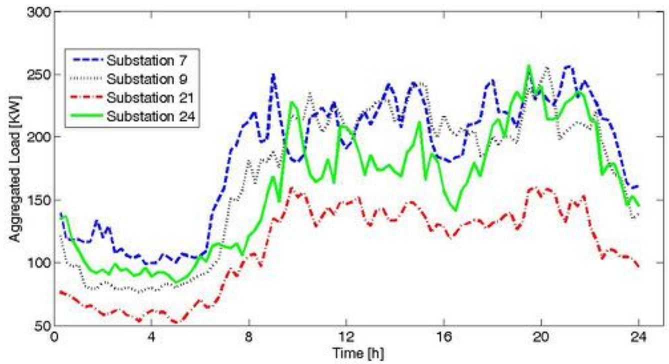
Power flow and Voltage Profile Monitoring

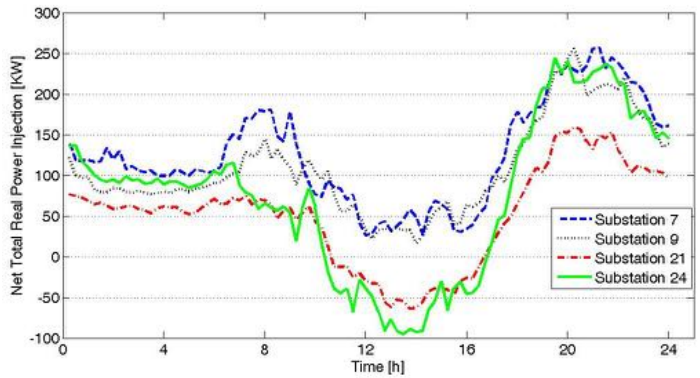




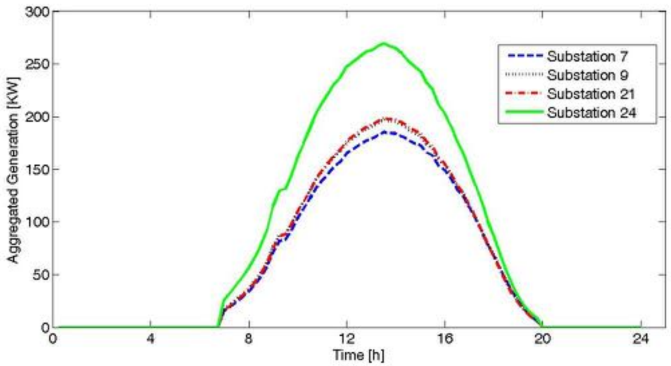
Power flow and Voltage Profile Monitoring

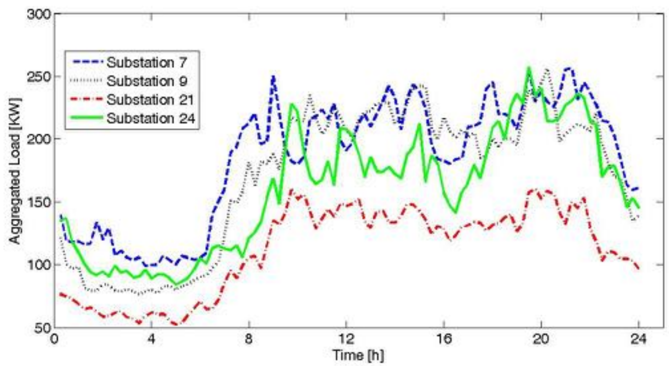


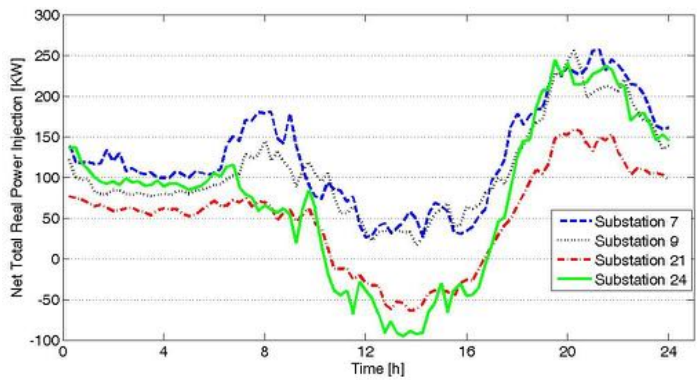


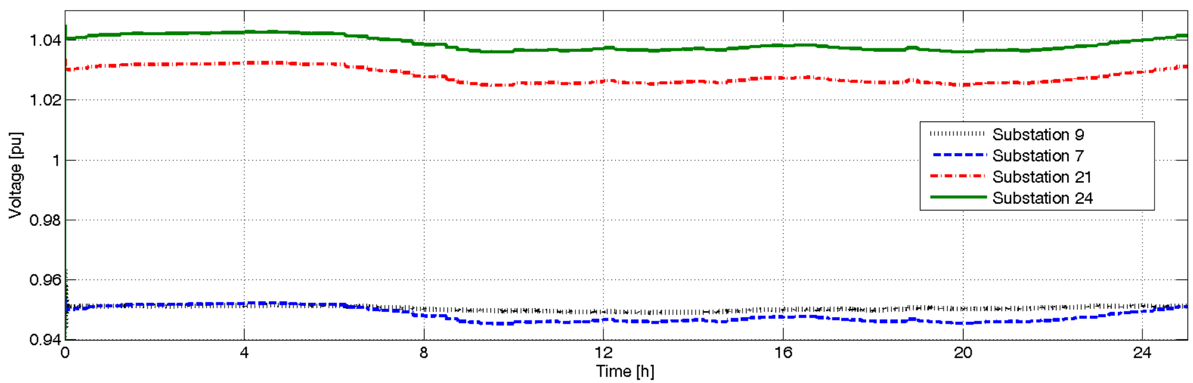


Power flow and Voltage Profile Monitoring

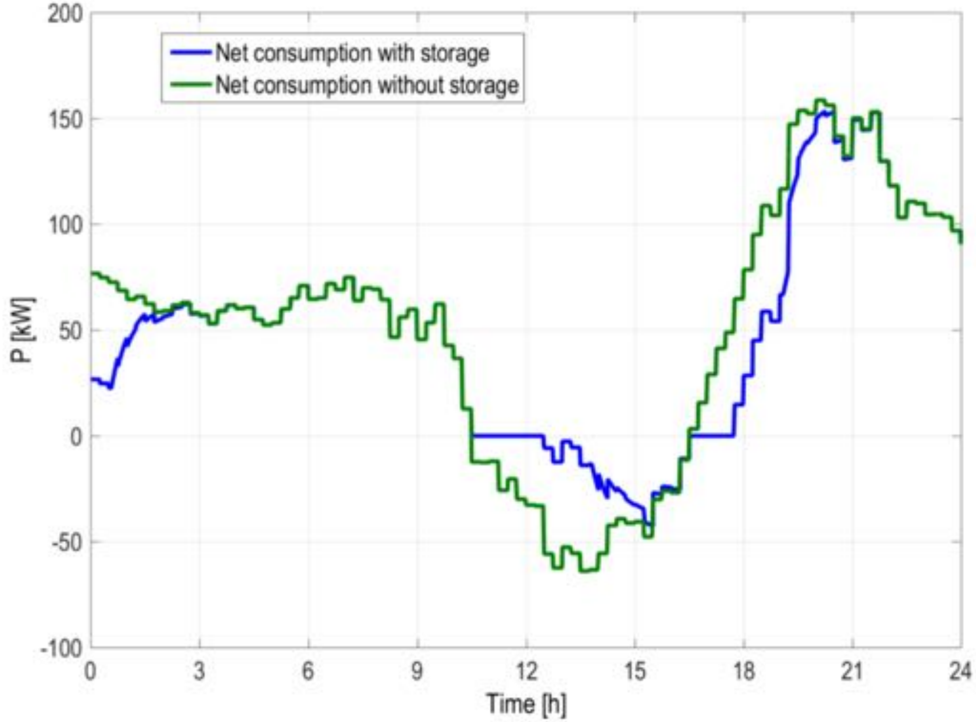




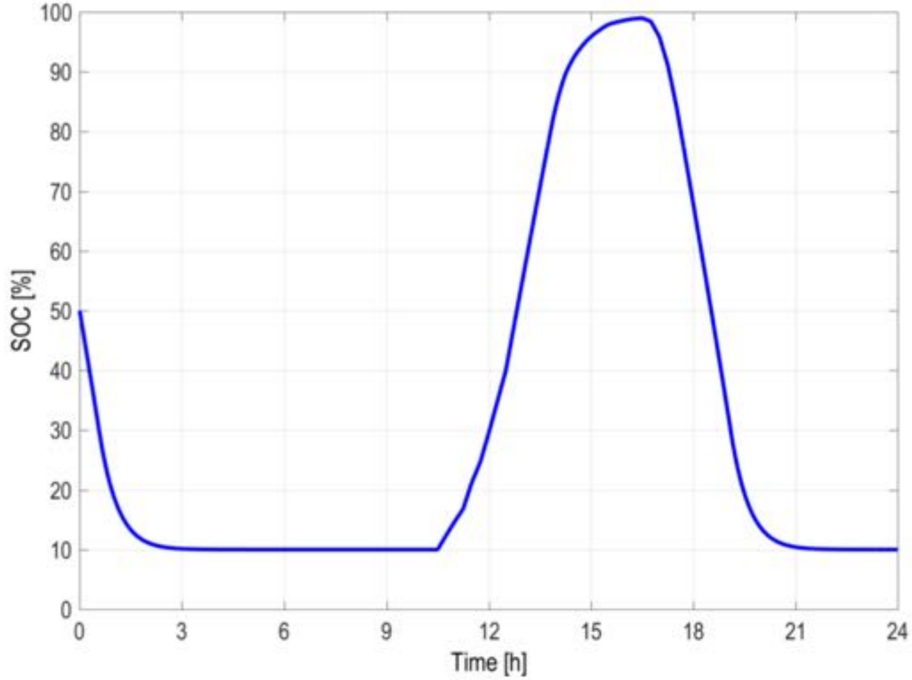




Distributed Battery Management

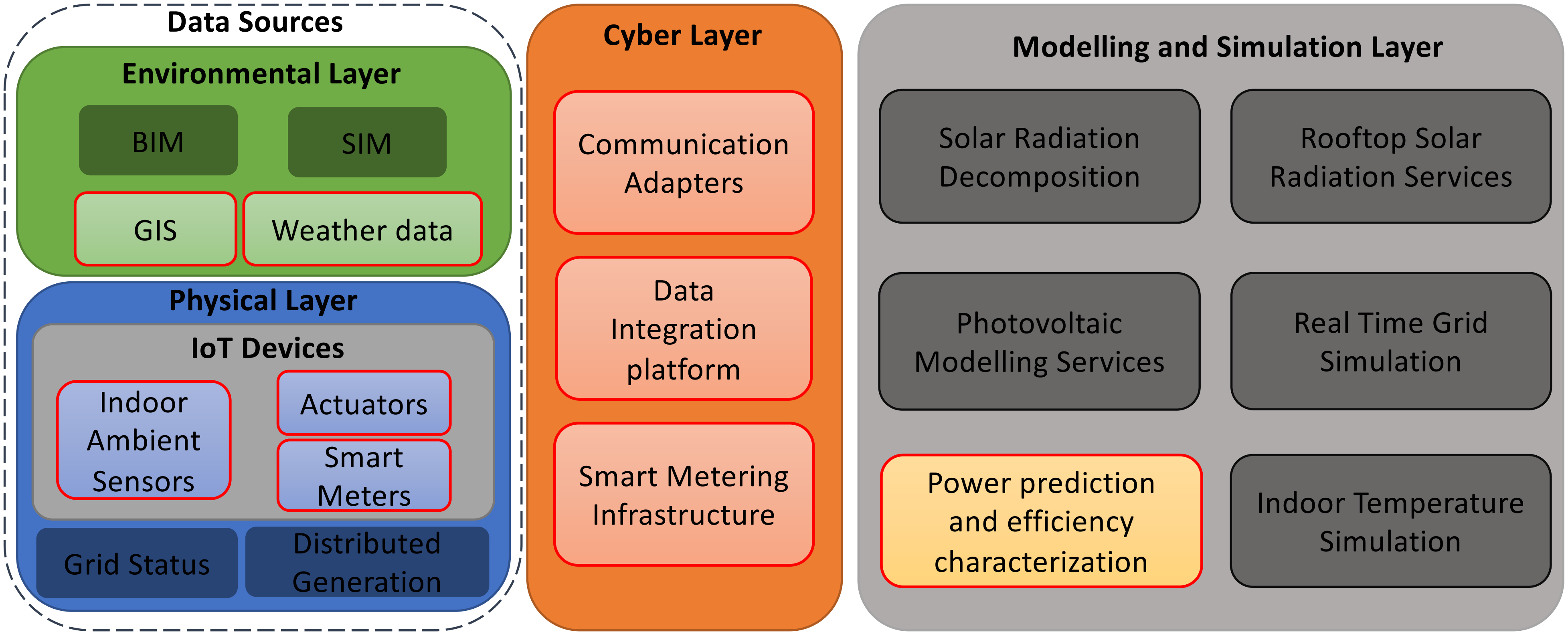


Electricity consumption of MV Substation with or without storage

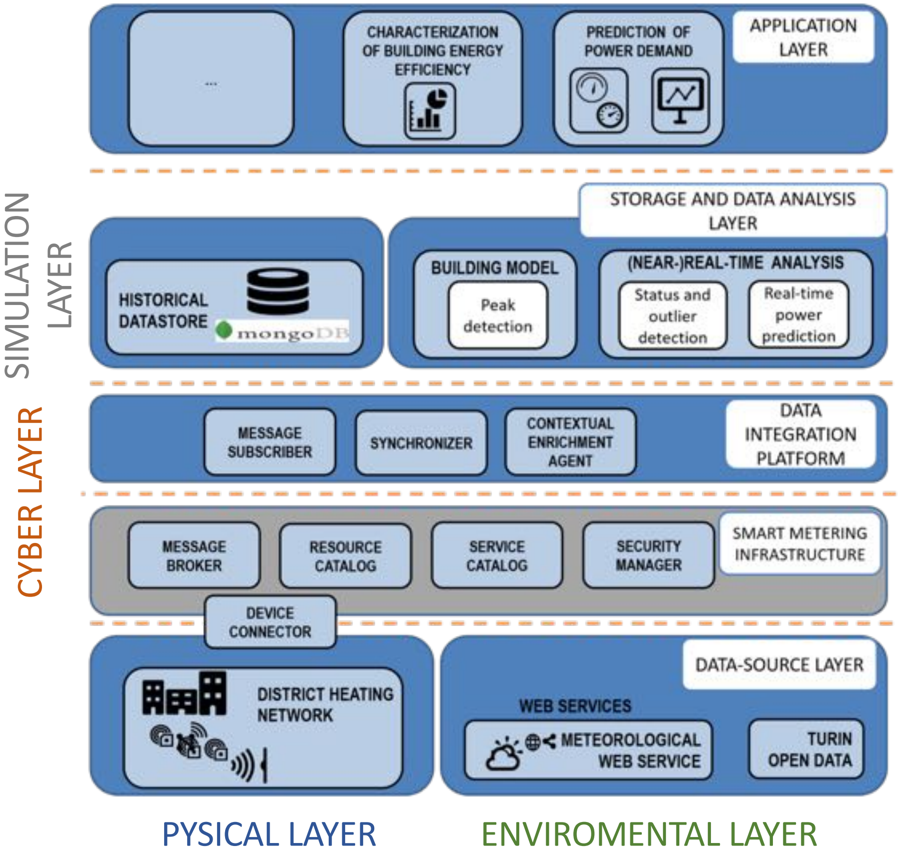


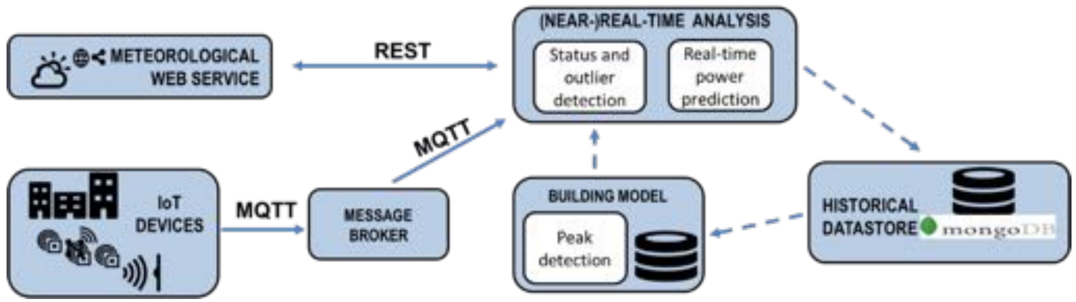
State of charge of the battery in the MV Substation

Power Prediction and building efficiency characterization

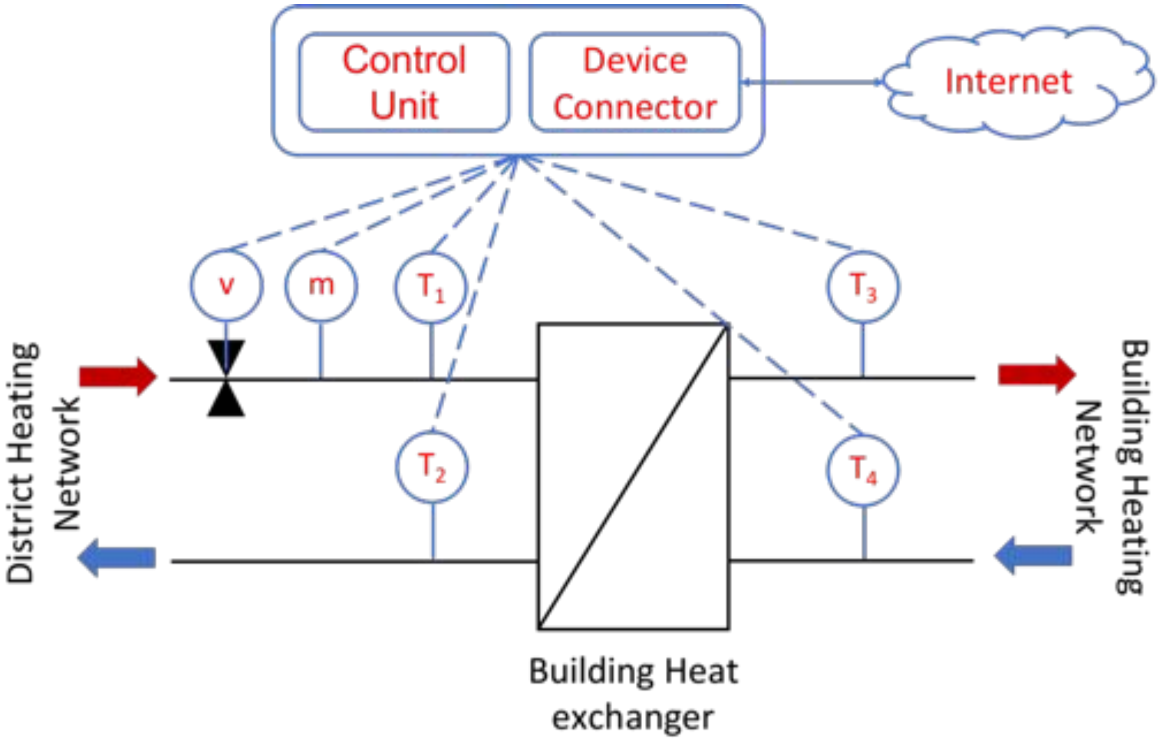


Details of Power Prediction and building efficiency characterization (PPBEC)





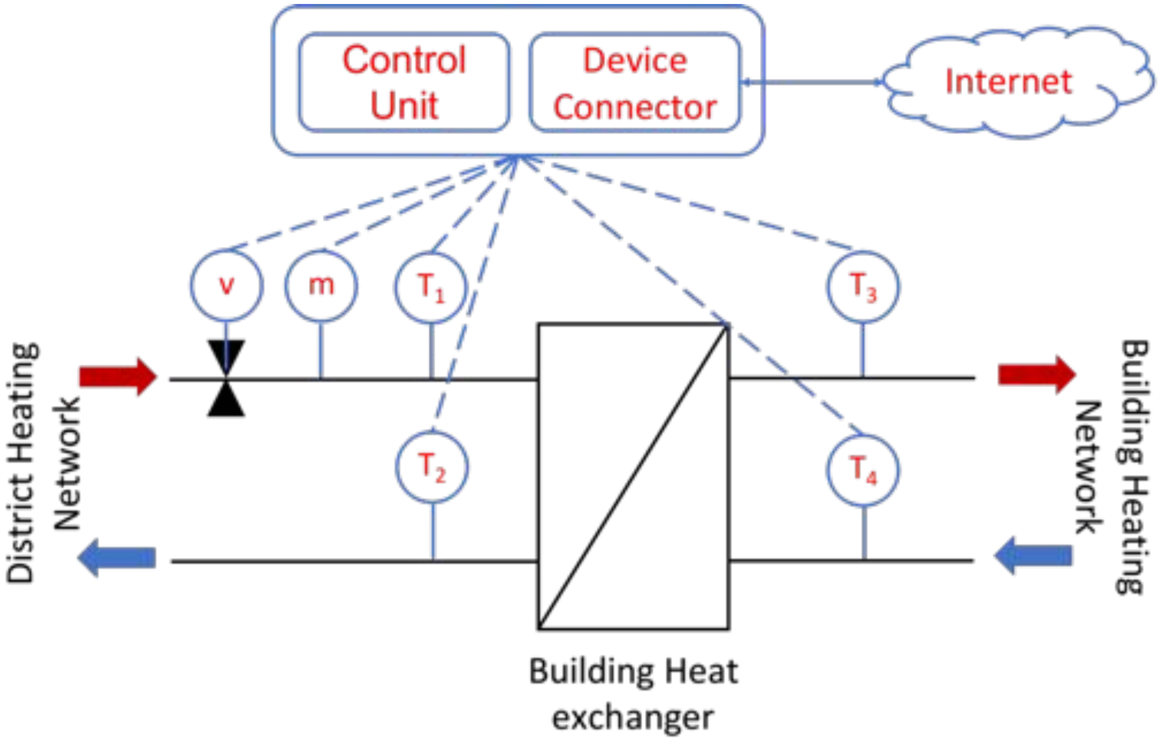
Case study



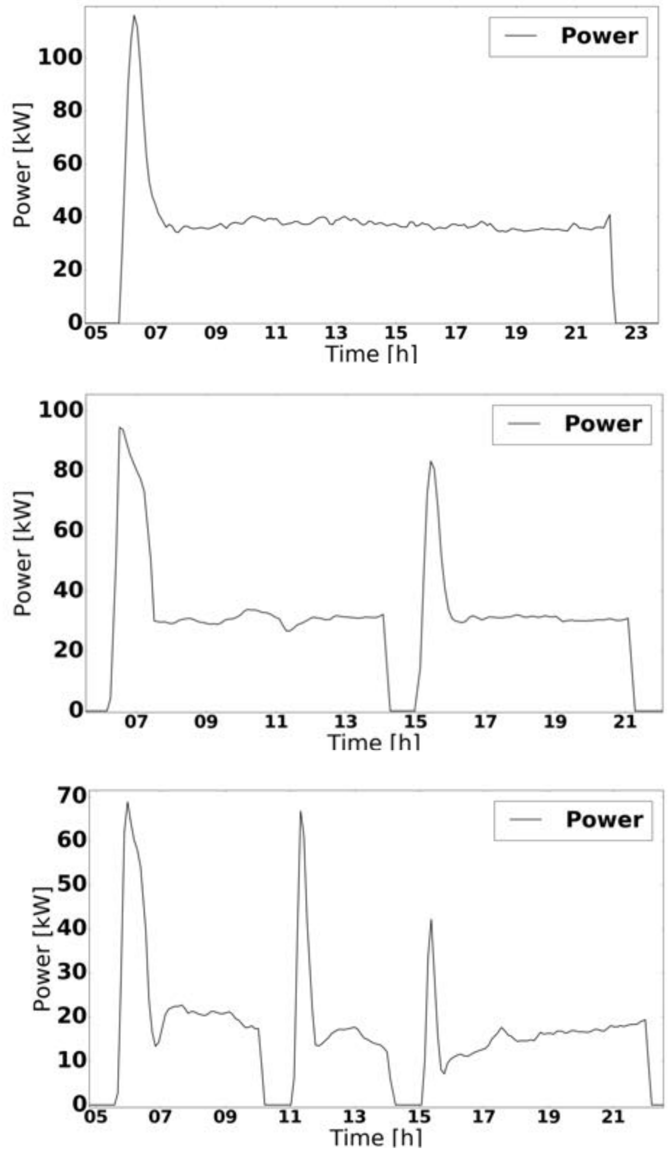
Turin District Heating:

300 Monitored Buildings

Case study

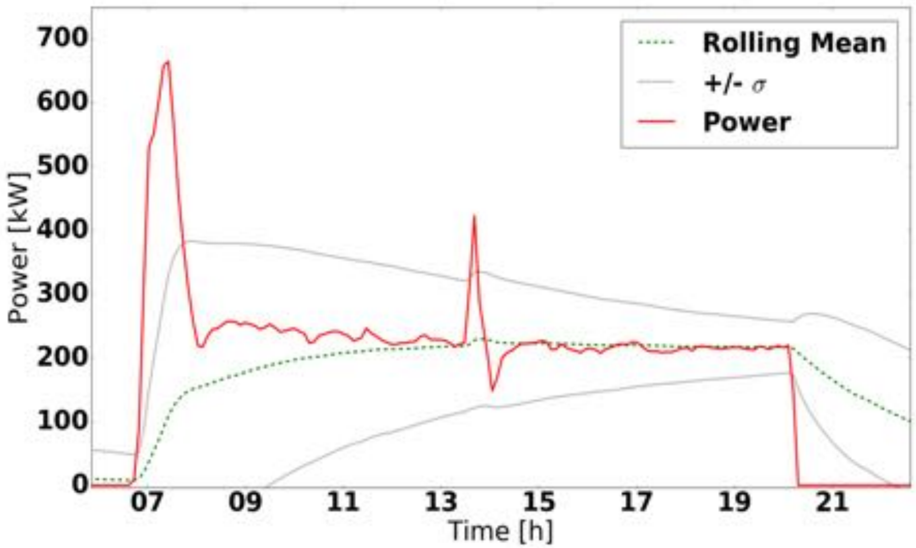


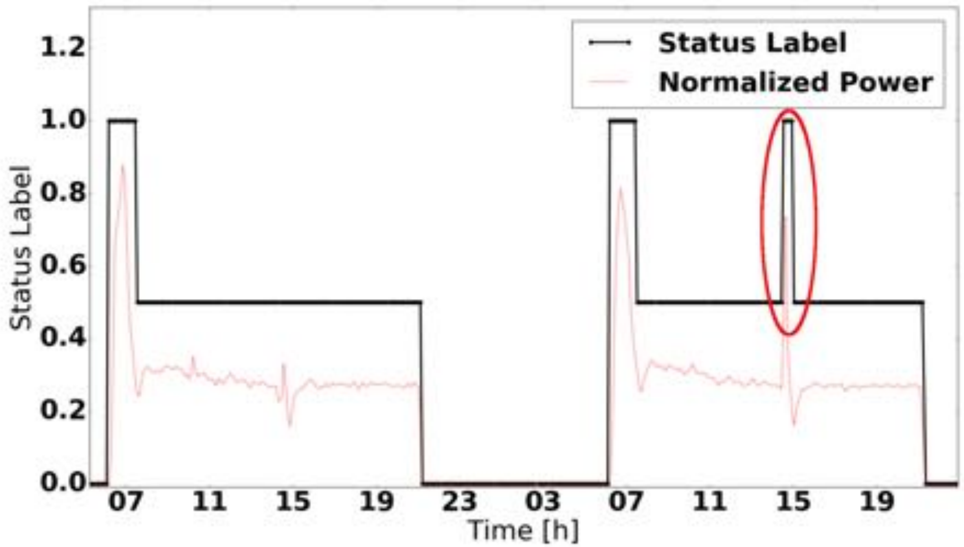
Control Unit
Device Connector
Internet
v
m
T_1
T_2
T_3
T_4
District Heating Network
Building Heating Network
Building Heat exchanger



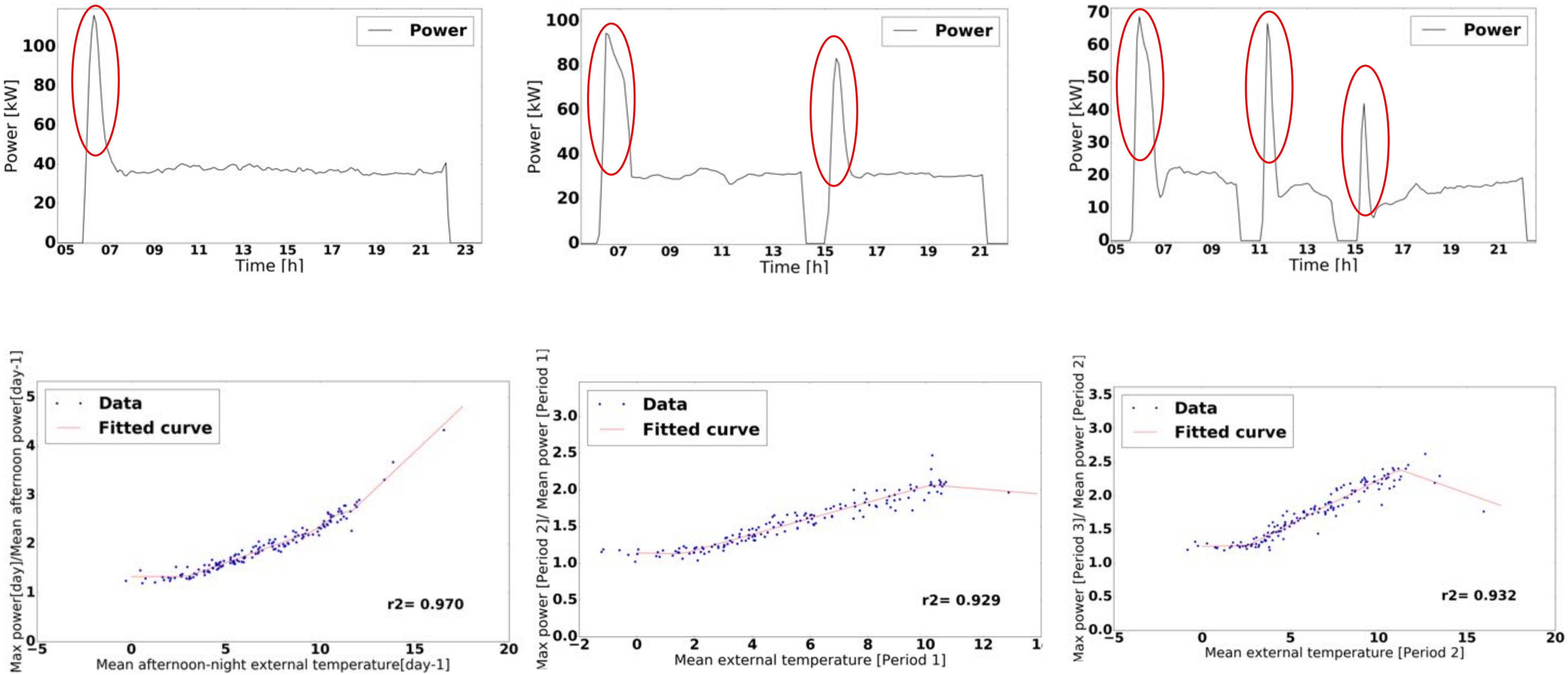
Power
Power [kW]
Time [h]

Status Identification and outlier algorithm (SOD)



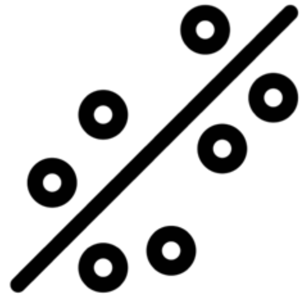


Peak Power identification algorithm (PD)



Power Prediction algorithm

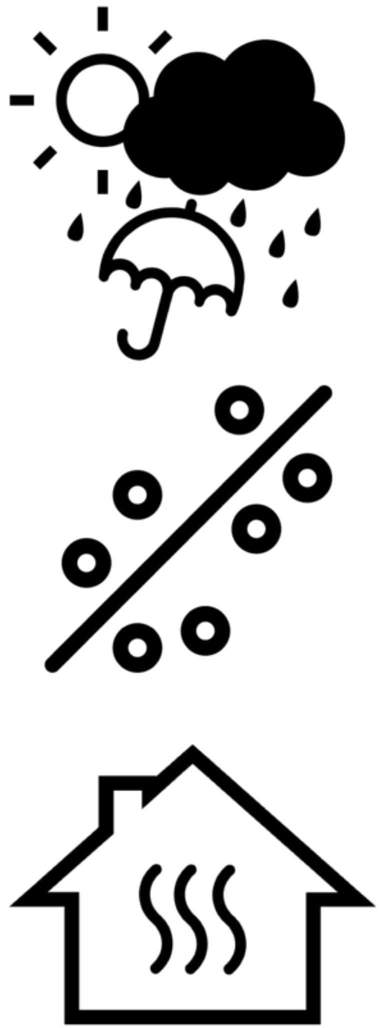
On the basis of the outcomes of the **SOD** and **PD** algorithms, the **Power Prediction** algorithm exploits the multiple version of the **Linear Regression with Stochastic Gradient Descent**



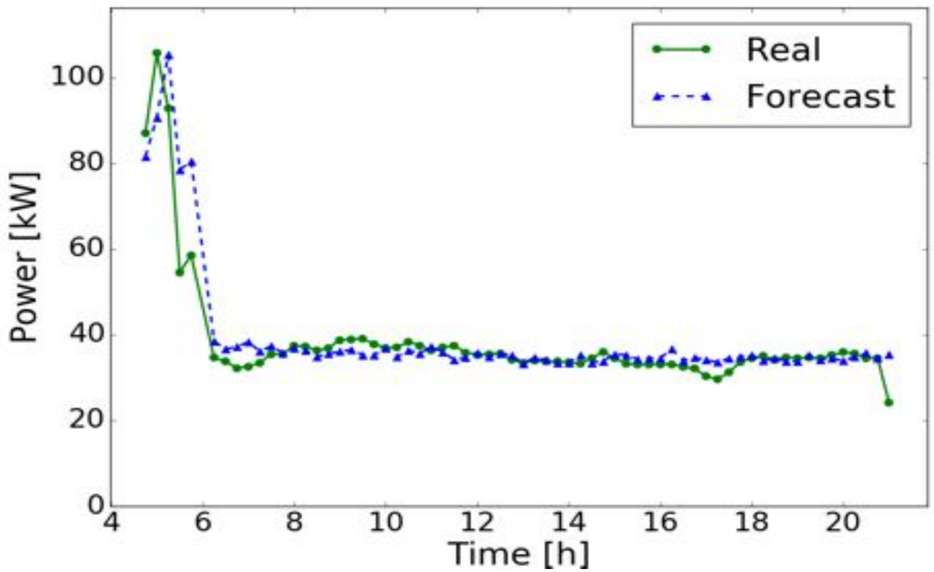
Power Prediction algorithm

On the basis of the outcomes of the **SOD** and **PD** algorithms, the **Power Prediction** algorithm exploits the multiple version of the **Linear Regression with Stochastic Gradient Descent**

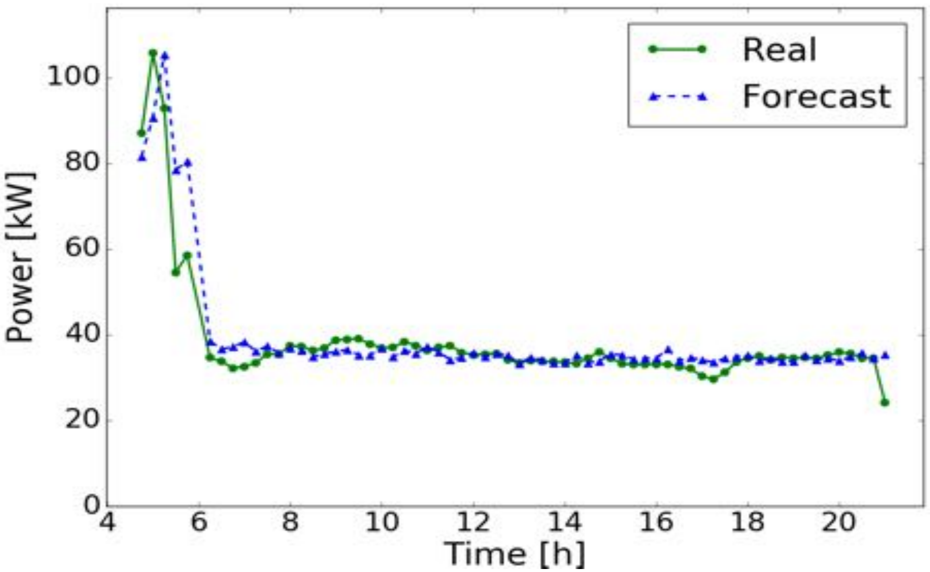
Power Prediction algorithm defines a building model based on **a linear dependency** between **weather data** and **power level**. PP relies on the **assumption** that the **average power exchange** for a building heating system at a given time instant is **likely to be correlated** with the **surrounding weather conditions**.



Results of Power Prediction

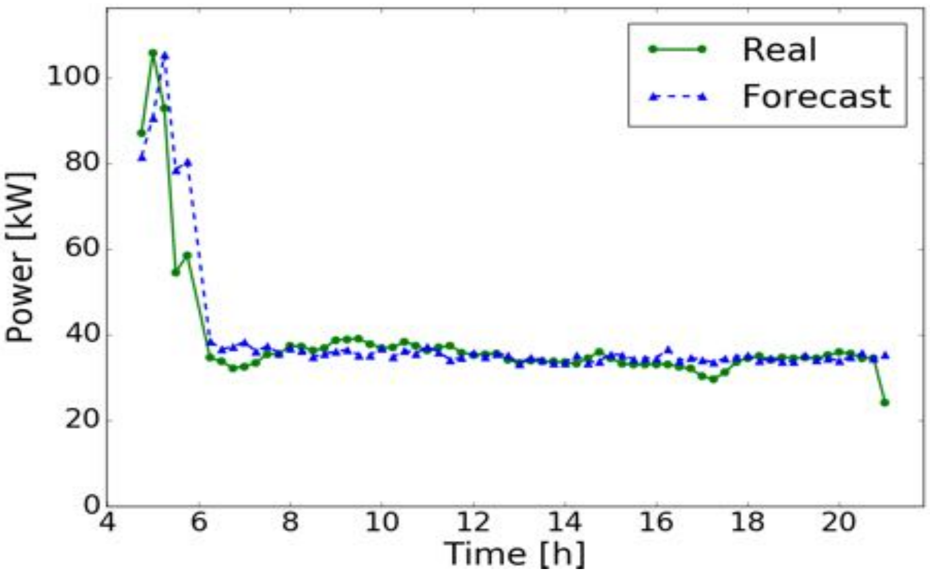


Results of Power Prediction



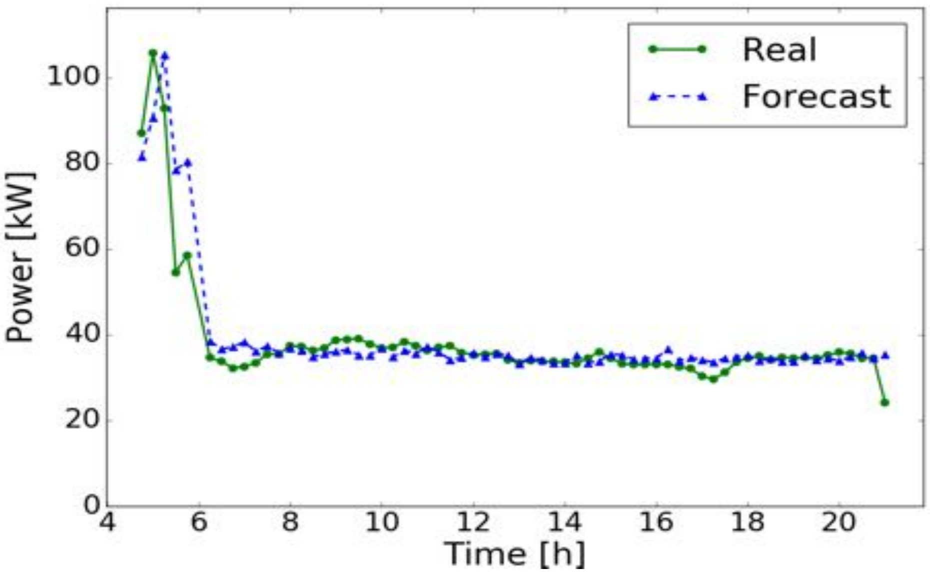
Heating cycles	Building ID	Overall MAPE	Overall SMAPE	First cycle MAPE	First cycle SMAPE	Second cycle MAPE	Second cycle SMAPE	Third cycle MAPE	Third cycle SMAPE
Single	1	15.56	6.78	15.56	6.78	-	-	-	-
	2	18.58	7.95	18.58	7.95	-	-	-	-
	3	20.48	8.35	20.48	8.35	-	-	-	-
	4	22.38	9.32	22.38	9.32	-	-	-	-
	5	20.42	8.46	20.42	8.46	-	-	-	-
Double	6	23.24	9.62	28.81	10.95	20.58	8.06	-	-
	7	22.02	9.56	36.98	13.35	15.52	7.10	-	-
Triple	8	23.11	9.72	35.35	13.90	17.38	7.67	18.33	7.63
	9	27.96	10.62	28.46	10.90	24.73	10.14	25.87	10.85
	10	33.75	11.64	39.70	14.40	38.44	14.49	26.53	10.21
	11	29.05	11.83	31.89	11.98	37.53	13.99	23.23	9.58
	12	27.26	11.56	32.62	13.26	28.39	11.42	23.01	9.27

Results of Power Prediction



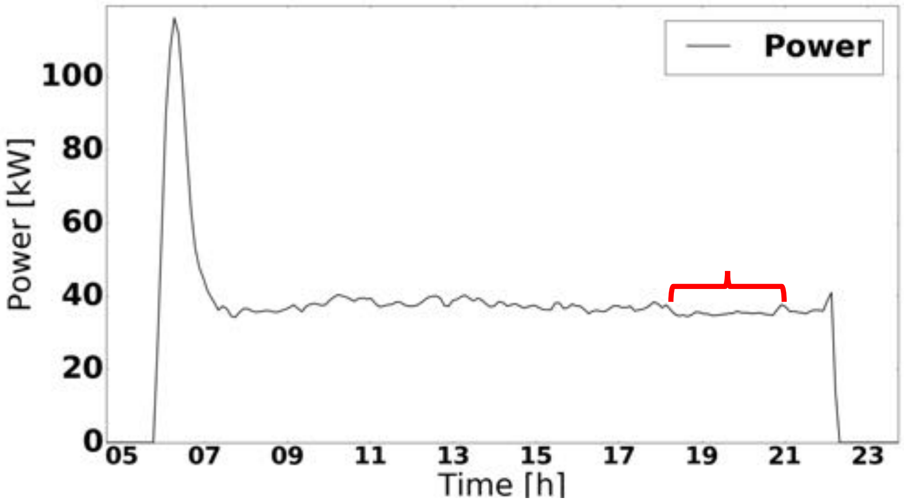
Heating cycles	Building ID	Overall		First cycle		Second cycle		Third cycle	
		MAPE	SMAPE	MAPE	SMAPE	MAPE	SMAPE	MAPE	SMAPE
Single	1	15.56	6.78	15.56	6.78	-	-	-	-
	2	18.58	7.95	18.58	7.95	-	-	-	-
	3	20.48	8.35	20.48	8.35	-	-	-	-
	4	22.38	9.32	22.38	9.32	-	-	-	-
	5	20.42	8.46	20.42	8.46	-	-	-	-
Double	6	23.24	9.62	28.81	10.95	20.58	8.06	-	-
	7	22.02	9.56	36.98	13.35	15.52	7.10	-	-
Triple	8	23.11	9.72	35.35	13.90	17.38	7.67	18.33	7.63
	9	27.96	10.62	28.46	10.90	24.73	10.14	25.87	10.85
	10	33.75	11.64	39.70	14.40	38.44	14.49	26.53	10.21
	11	29.05	11.83	31.89	11.98	37.53	13.99	23.23	9.58
	12	27.26	11.56	32.62	13.26	28.39	11.42	23.01	9.27

Results of Power Prediction

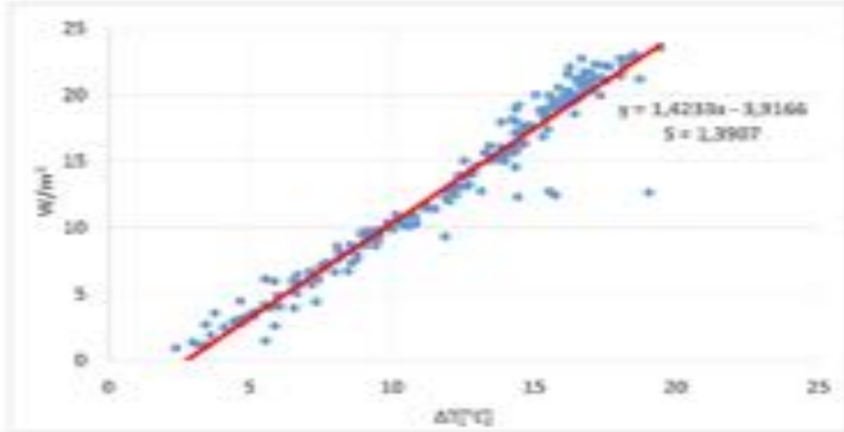


Heating cycles	Building ID	Overall MAPE	Overall SMAPE	First cycle MAPE	First cycle SMAPE	Second cycle MAPE	Second cycle SMAPE	Third cycle MAPE	Third cycle SMAPE
Single	1	15.56	6.78	15.56	6.78	-	-	-	-
	2	18.58	7.95	18.58	7.95	-	-	-	-
	3	20.48	8.35	20.48	8.35	-	-	-	-
	4	22.38	9.32	22.38	9.32	-	-	-	-
	5	20.42	8.46	20.42	8.46	-	-	-	-
Double	6	23.24	9.62	28.81	10.95	20.58	8.06	-	-
	7	22.02	9.56	36.98	13.35	15.52	7.10	-	-
Triple	8	23.11	9.72	35.35	13.90	17.38	7.67	18.33	7.63
	9	27.96	10.62	28.46	10.90	24.73	10.14	25.87	10.85
	10	33.75	11.64	39.70	14.40	38.44	14.49	26.53	10.21
	11	29.05	11.83	31.89	11.98	37.53	13.99	23.23	9.58
	12	27.26	11.56	32.62	13.26	28.39	11.42	23.01	9.27

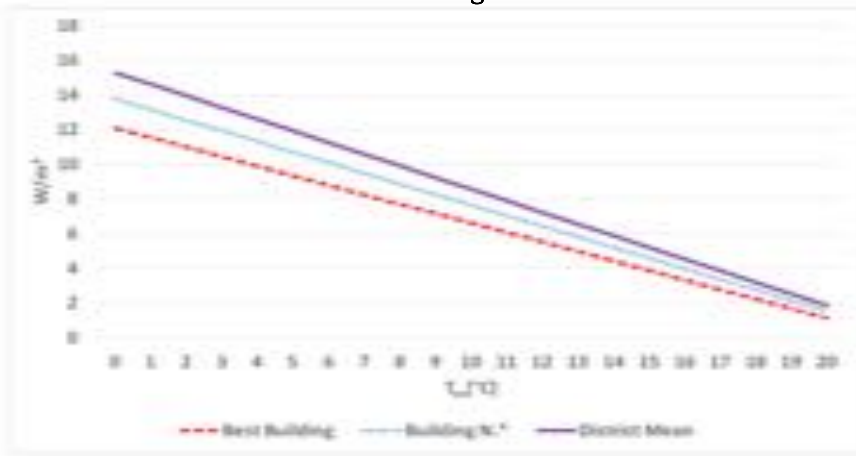
Characterization of Building thermal efficiency



Intra Building KPI

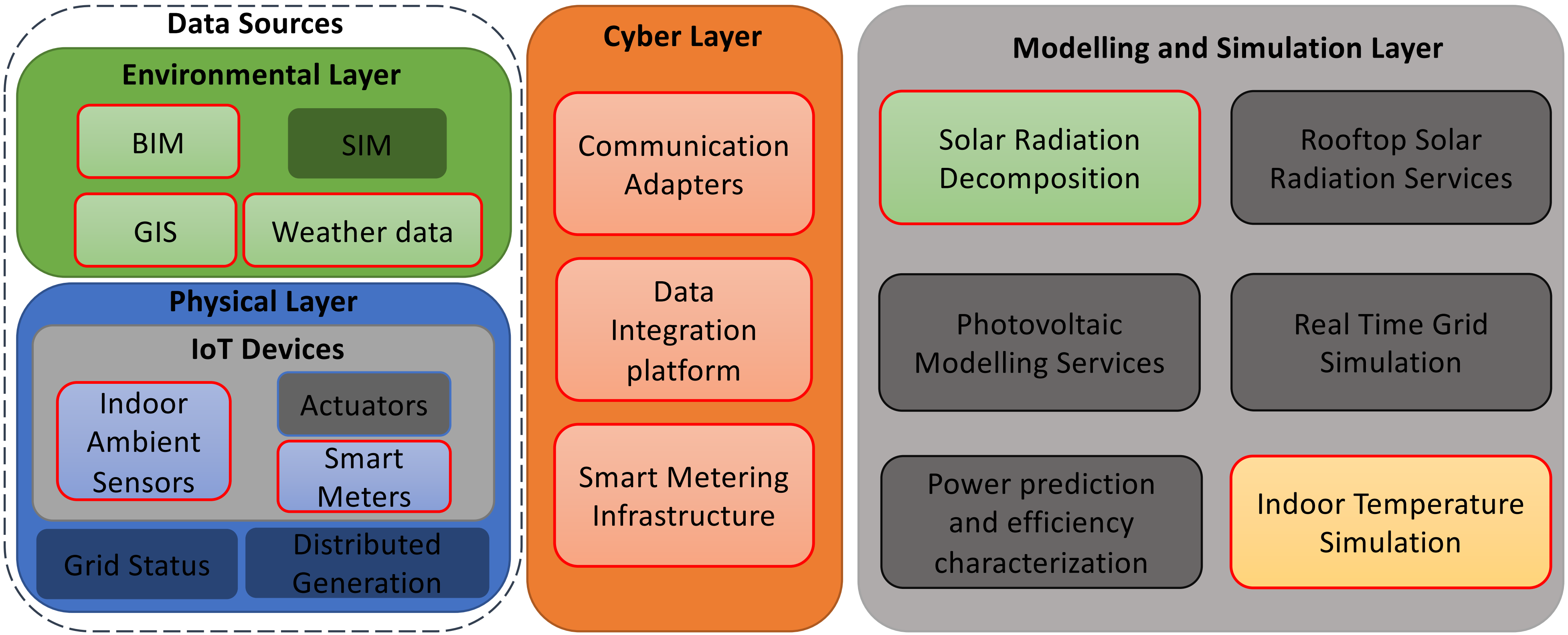


Inter Building KPI



$$Q_{tot} = K_{tot} * (T_{ex} - T_{in}) + \overset{\approx 0}{\cancel{C * \frac{dT}{dt}}} + \overset{\approx 0}{\cancel{Q_{sol}}} + \overset{\approx 0}{\cancel{Q_{end}}}$$

Indoor Temperature Simulation

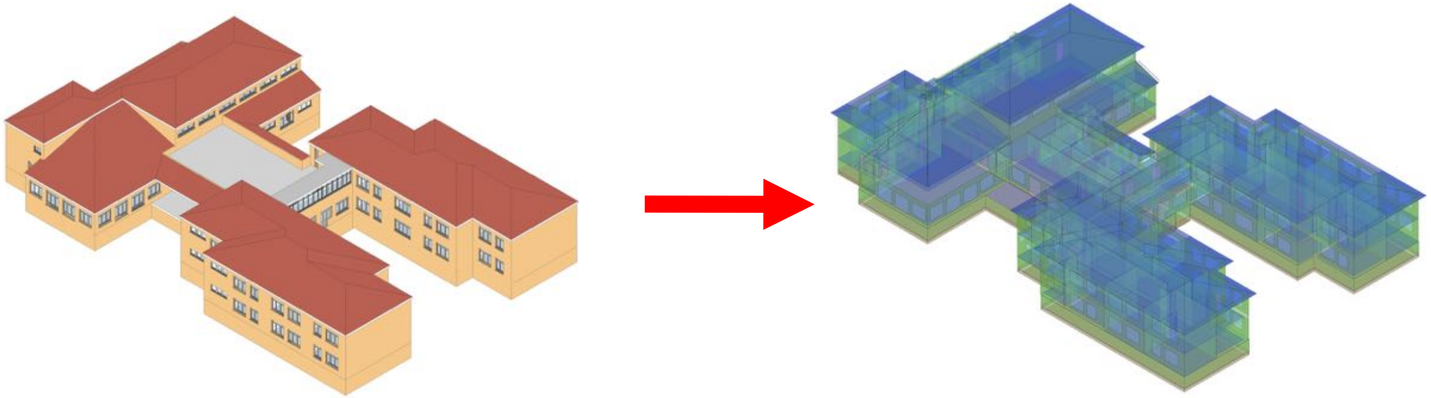


Methodology for Indoor Temperature Simulation

Simplified **BIM models** are the starting point for our energy simulations. They include:

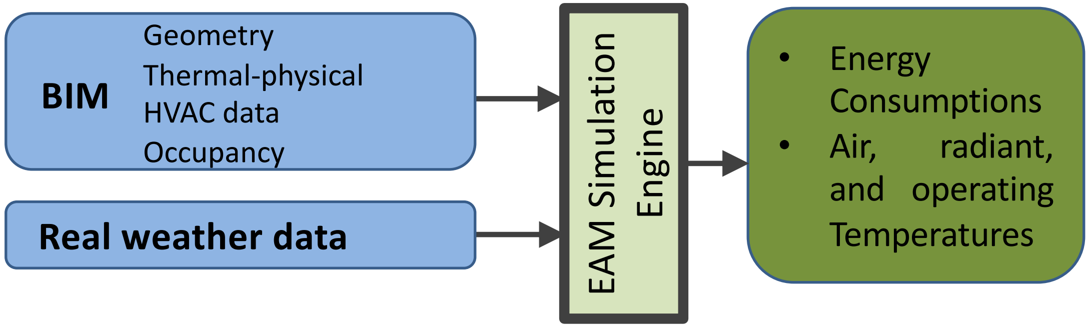
- accurate building envelope characterizations;
- facility management information (e.g. room type and occupants);
- materials nomenclature standards.

The **Energy Analysis Model** (EAM) consists of rooms and analytical surfaces generated from the BIM model.

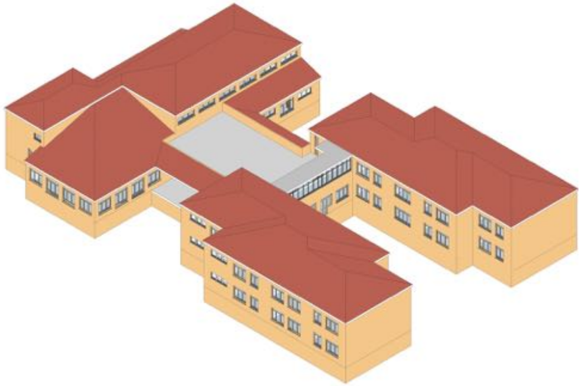


Methodology for Indoor Temperature Simulation

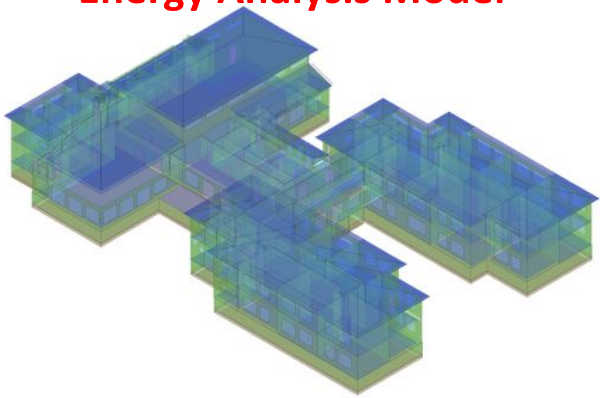
The **EAM Simulation Engine** evaluates energy performance of buildings



BIM

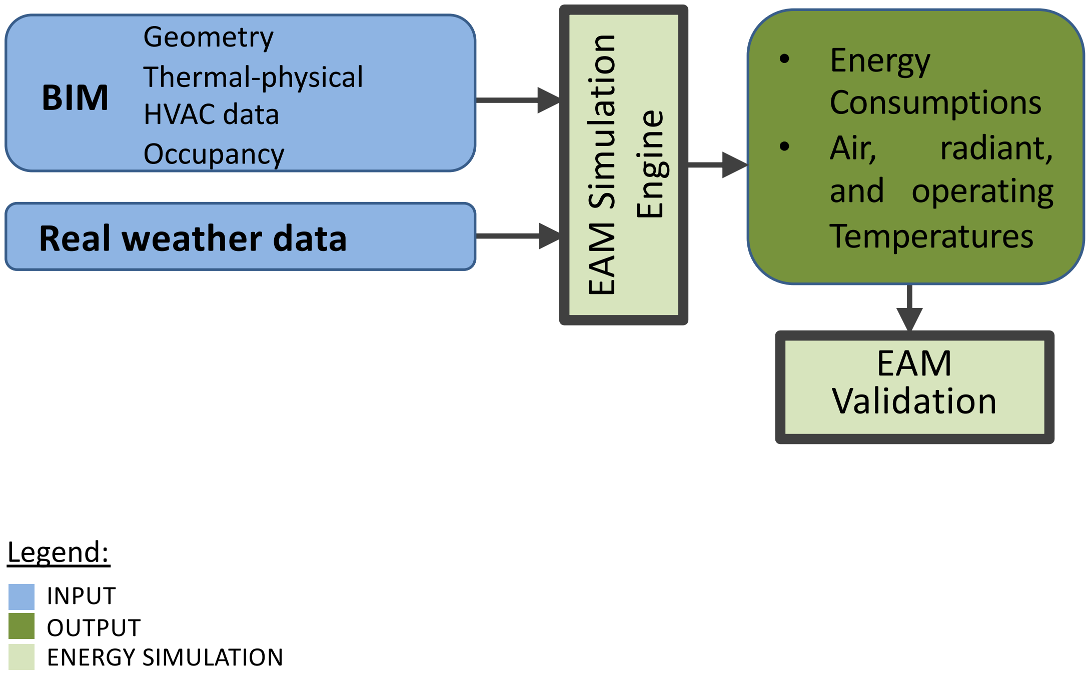


Energy Analysis Model



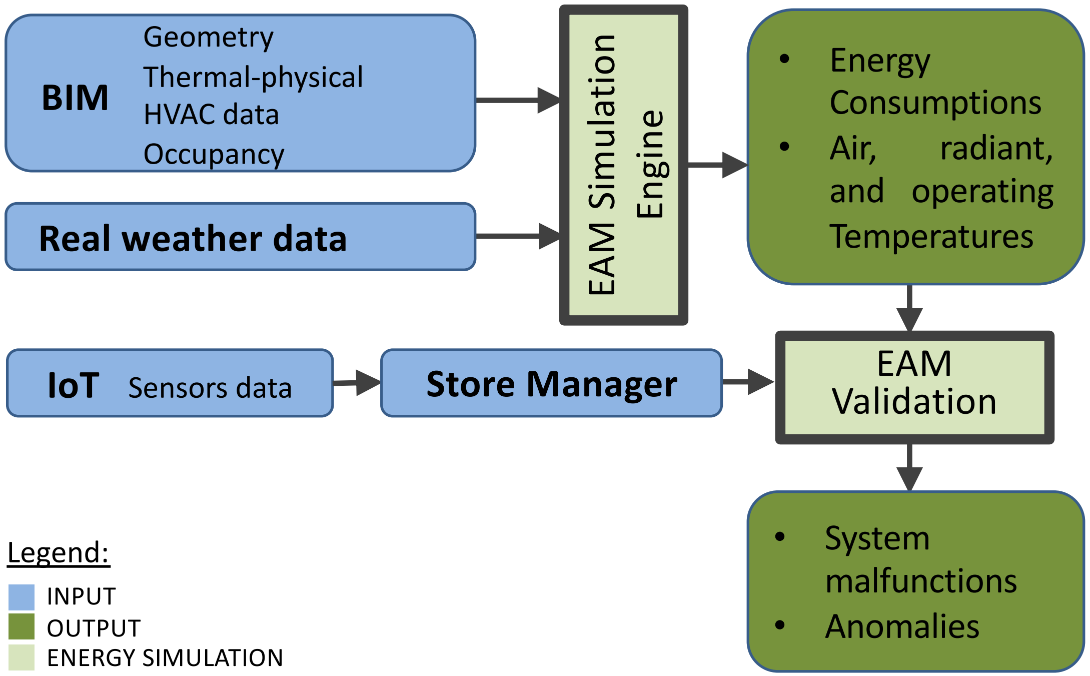
Methodology for Indoor Temperature Simulation

The **EAM Simulation Engine** evaluates energy performance of buildings



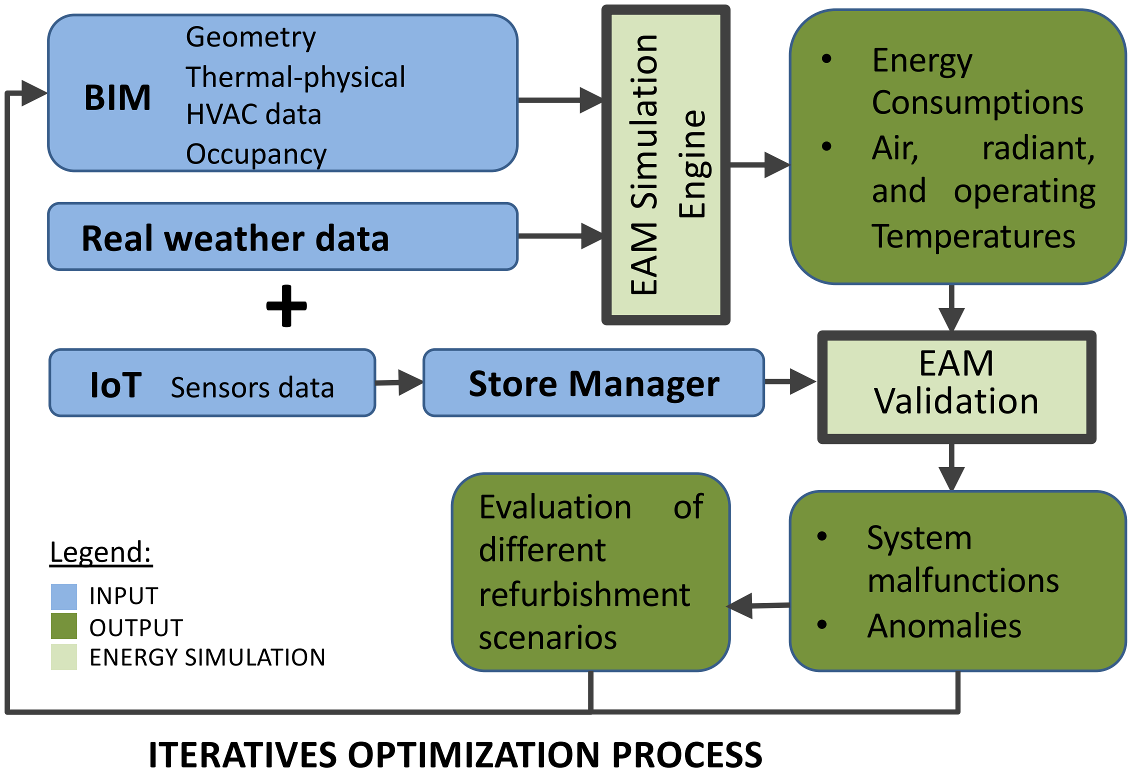
Methodology for Indoor Temperature Simulation

The **EAM Simulation Engine** evaluates energy performance of buildings



Methodology for Indoor Temperature Simulation

The **EAM Simulation Engine** evaluates energy performance of buildings



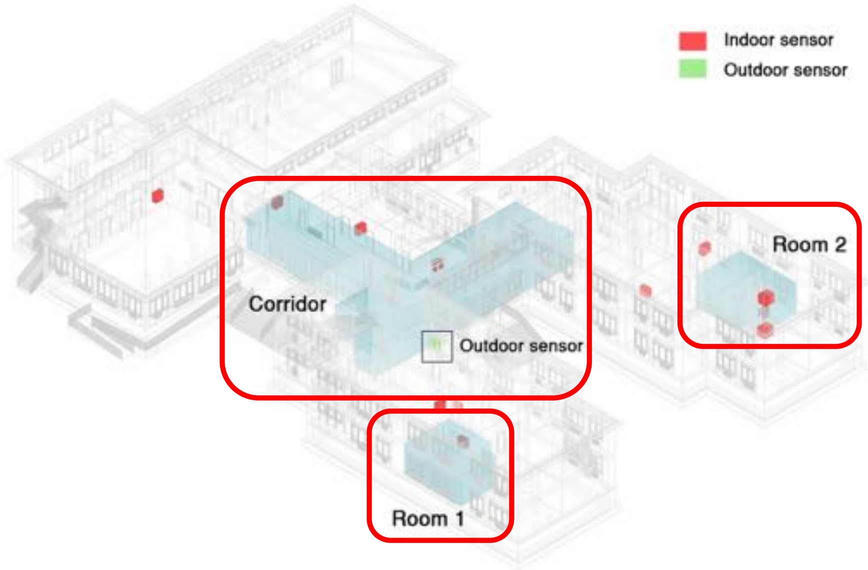
Case Study

Primary school of **14,500 m²** in two floors.

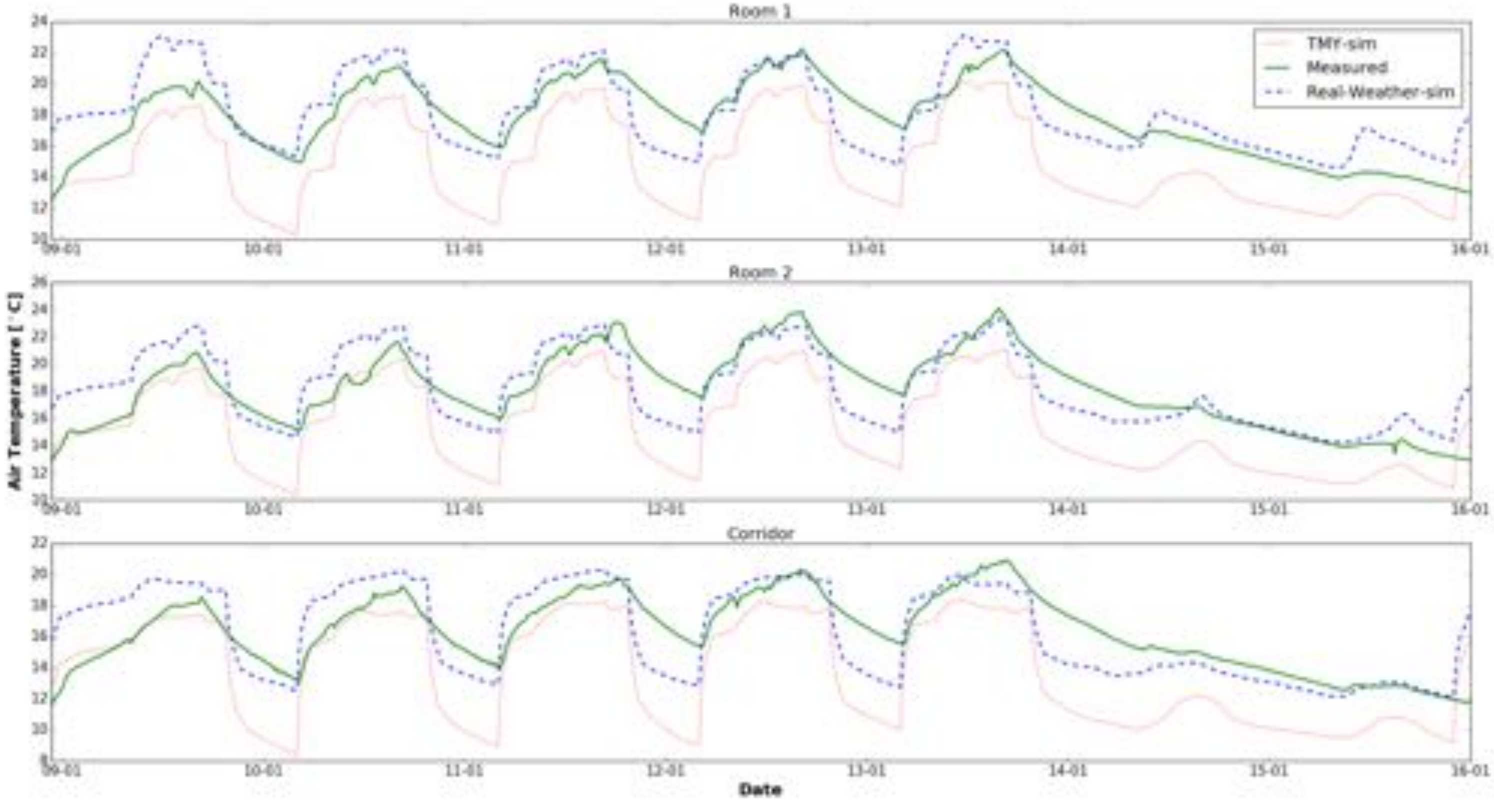
Heating system from **4:00 a.m.** to **7:30 p.m**.

16 **IoT devices** to collect air **temperature** and **relative humidity**:

- **15 indoor**
- **1 outdoor**



Experimental Results



Experimental Results

Rooms	Indicator [%]	Real-weather Sim vs Measured	TMY Sim vs Measured
Room 1	MAD	8.02	16.82
	MBD	2.18	-16.64
	RMSD	9.78	19.01
Room 2	MAD	9.07	18.55
	MBD	0.10	-18.34
	RMSD	10.83	20.74
Corridor	MAD	9.35	16.94
	MBD	-0.17	-16.06
	RMSD	11.52	20.85

Experimental Results

Rooms	Indicator [%]	Real-weather Sim vs Measured	TMY Sim vs Measured
Room 1	MAD	8.02	16.82
	MBD	2.18	-16.64
	RMSD	9.78	19.01
Room 2	MAD	9.07	18.55
	MBD	0.10	-18.34
	RMSD	10.83	20.74
Corridor	MAD	9.35	16.94
	MBD	-0.17	-16.06
	RMSD	11.52	20.85

Experimental Results

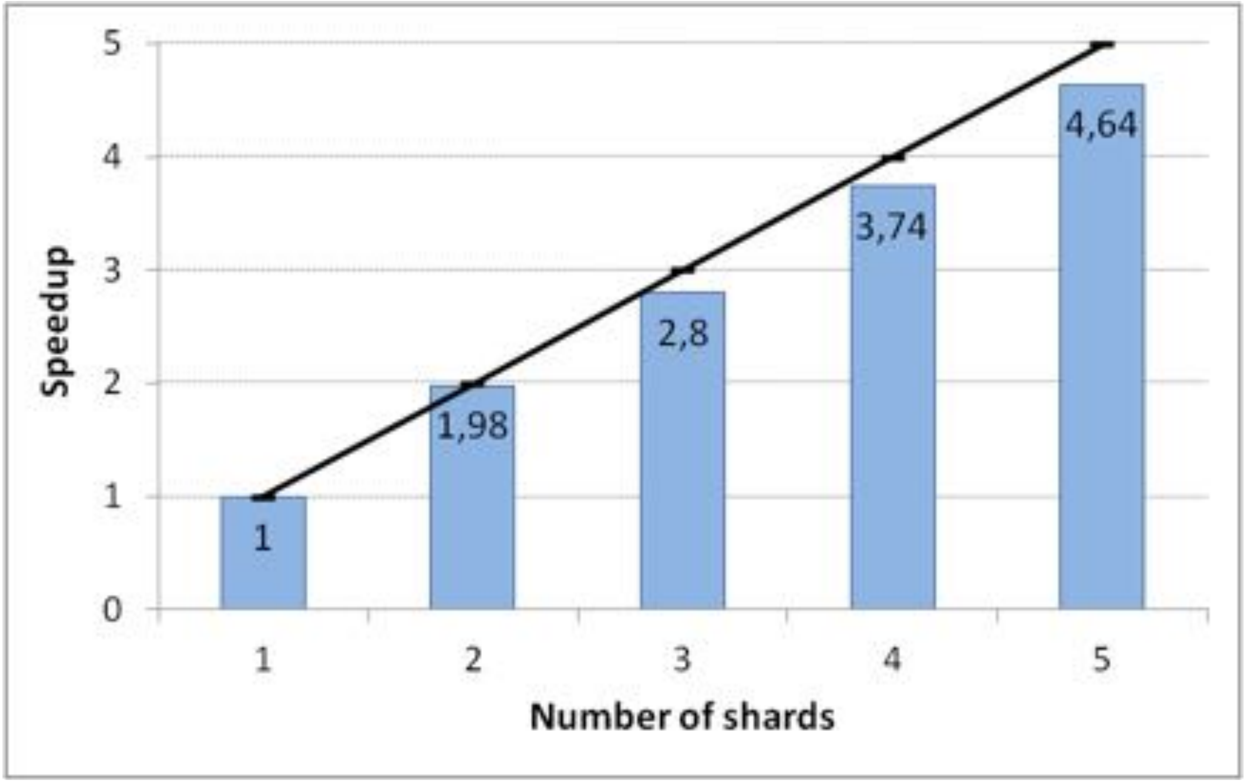
Rooms	Indicator [%]	Real-weather Sim vs Measured	TMY Sim vs Measured
Room 1	MAD	8.02	16.82
	MBD	2.18	-16.64
	RMSD	9.78	19.01
Room 2	MAD	9.07	18.55
	MBD	0.10	-18.34
	RMSD	10.83	20.74
Corridor	MAD	9.35	16.94
	MBD	-0.17	-16.06
	RMSD	11.52	20.85

Conclusions

- SMIRSE is a **flexible** and **modular** distributed infrastructure
- SMIRSE integrates **heterogeneous** information, also sent in **(near-) real-time**.
- SMIRSE evaluates the **impact** of **RES** and **Smart policies** in cities and distribution networks.
- SMIRSE **Photovoltaic** modelling and simulation **overcomes** the limitations of **SOA** by providing **real-sky** simulations integrating **weather stations**.
- SMIRSE **models** and simulate **thermal behaviour** of **buildings**.

Thanks for your attention

Scalability Issue



Scalability Issue