D5.1: Description of sustainability experimentation framework

Revision: v.1.0

Work package	WP 5
Task	Tasks 5.1, 5.3
Due date	30/06/2024
Submission date	26/06/2024
Deliverable lead	UOULU
Version	1.0
Authors	Hamid Malik (UOULU) Juho Markkula (UOULU), Mikko Hongisto (VTT), Seppo J. Rantala (VTT), Olli Apilo (VTT), Mikko Uitto (VTT), Jaakko Sirviö (Nokia)
Reviewers	Ibrahim Hemadeh (InterDigital), Javier Fernandez Hidalgo (i2CAT)
Abstract	This report details a sustainability experimentation framework built within the north node. This framework will support upcoming trials designed to investigate energy performance and savings in an E2E system. The system will include all central elements, such as application servers, RAN, and UE devices. In addition, KPIs like indirect cumulative CO2-emissions and costs can be followed up. By means of real-time electricity monitoring system and interlinked data-streams from external services, optimal and distributed control actions can be developed to improve systemic energy efficiency as well as increase the share of locally produced electricity.
Keywords	Energy measurement framework, Energy Weather forecast, Dynamic Energy Storage System, Radio Access Network, Open Air Interface, Next Generation Node B

WWW.6G-XR.EU

Grant Agreement No.: 101096838
Call: HORIZON-JU-SNS-2022

Topic: HORIZON-JU-SNS-2022-STREAM-C-01-01
Type of action: HORIZON-JU-RIA

Document Revision History

Version	Date	Description of change	List of contributor(s)
V0.1	08/09/2023	1st version of the template	Hamid (UOULU)
V0.2	25/09/2023	2nd version with revised ToC	Hamid (UOULU), Mikko (VTT)
V0.3	31/12/2023	Initial contriutions	Hamid (UOULU), Mikko (VTT)
V0.4	24/01/2024	Chapters and subchapters	Hamid (UOULU), Mikko (VTT)
V0.5	26/03/2024	Ist internal review updates	Hamid (UOULU). Mikko (VTT)
V0.6	12/05/2024	Updates from VTT	Mikko (VTT)
V0.7	21/05/2024	Document reviewed (External)	Ibrahim Hemadeh (InterDigital), Javier Fernandez Hidalgo (i2CAT)
V0.8	31/05/2024	Document updated after external review comments addressed	Hamid (UOULU), Mikko (VTT), Olli (VTT), Juho (UOULU)
V0.9	10/06/2024	Technical Review	Muhmmad Al-Rawi (IT)
V1.0	20/06/2024	Final version	All

DISCLAIMER

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

The 6G-XR (*6G eXperimental Research infrastructure to enable next-generation XR services*) project has received funding from the **Smart Networks and Services Joint Undertaking (SNS JU)** under the European Union's **Horizon Europe research and innovation programme** under Grant Agreement No 101096838. This work has received funding from the **Swiss State Secretariat for Education, Research, and Innovation (SERI)**

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

COPYRIGHT NOTICE

Project co-funded by the European Commission in the Horizon Europe Programme		
Nature of the deliverable:	**R**	
Dissemination Level		
PU	*Public, fully open, e.g. web (Deliverables flagged as public will be automatically published in CORDIS project's page)*	☒
SEN	*Sensitive, limited under the conditions of the Grant Agreement*	
Classified R-UE/ EU-R	*EU RESTRICTED under the Commission Decision No2015/ 444*	
Classified C-UE/ EU-C	*EU CONFIDENTIAL under the Commission Decision No2015/ 444*	
Classified S-UE/ EU-S	*EU SECRET under the Commission Decision No2015/ 444*	

* R: Document, report (excluding the periodic and final reports)

DEM: Demonstrator, pilot, prototype, plan designs

DEC: Websites, patents filing, press & media actions, videos, etc.

DATA: Data sets, microdata, etc.

DMP: Data management plan

ETHICS: Deliverables related to ethics issues.

SECURITY: Deliverables related to security issues

OTHER: Software, technical diagram, algorithms, models, etc.

EXECUTIVE SUMMARY

This report describes and specifies the central elements of the constructed sustainability experimentation framework. It will be utilised in upcoming trials to investigate run-time electrical energy consumption of a communication system covering E2E components such as application servers and client machines, end-user devices, radio access network (baseband and radio units, core server) and potential enlargements. In addition to a real-time electricity monitoring system of consumers, the experimentation framework consists of numerous real-time data streams from electricity supply side devices (a PV-hybrid with battery energy storage), integrated auxiliary systems (weather stations' sensors) and external data services. Systems and devices were mainly integrated by reading their datapoints from Modbus-TCP registries to time series database (InfluxDB) enabling real-time visualizations. Open source Grafana multi-platform web application was used to create interactive monitoring panels and visualize aggregated and comparative data streams from various sources. In addition to experimental design, Grafana platform will be used in upcoming trials. Interlinking of external services was needed to create forecasts to estimate prospective energy consumption and solar energy yield, which are essential to create control actions aimed at maintaining energy balance in an optimized way for longer periods of time. Impacts of control actions are stored to numerous operative data streams to enable follow up of system's performance from various perspectives. This can be done by means of specified KPIs combining real-time data from the monitoring system devices with the data streams from external data services. This way KPIs like cumulated indirect CO_2 emissions and operative costs related to auxiliary grid intake or feed-in can be constructed. Distribution of local electricity supply to E2E system's devices is partly realized by means of solar systems (a PV-hybrid installation with batteries and a grid-tie grid-parallel unit). Installations enable research and development work on both production and consumption side related to forecasting, optimization and development of control patterns and energy saving features. Additionally, the extensive energy measurement framework enables testing of new functionalities aiming to reduce overall energy consumption, improve controllability and energy efficiency, as well as increase the share of self-sufficiency towards fully energy-autonomous usage. In the longer run, all of these objectives together may contribute to decreased and direct CO_2-emissions, more sustainable and resilient operation of the E2E-system.

Note that within the 6G-XR project there are two experimentation sites, North Node and South Node. The sustainability experimentation solution is deployed only at the North Node site. The North Node consist of two research facilities, UOULU and VTT. The energy measurement framework is deployed for both sites covering the E2E 5G Test Network infrastructure. The approach for this experimentation solution will be to consider the commercial gNB sites as well as open source 5G environment. This descriptive document mainly consists of the experiments which are and will be conducted using the energy measurement framework. The control and transformative strategies are discussed to engage power saving measures at the gNB site using forecasting APIs such as energy weather forecasts for the next 66 hours and electricity market pricing APIs. With these APIs directions, the goal is to achieve energy efficiency and reduction in linked CO2 emissions as our KPIs, in powering up the next generation of mobile communication and their energy consumption behaviours.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

3GPP	The 3rd Generation Partnership Project
5G	The 5th Generation of Mobile Networks
5GTN	5G Test Network
6G	The 6th Generation of Mobile Networks
AI	Artifical Intelligence
AI/ML	Artificial Intelligence/ Machine Learning
ATS	Automatic Transfer Switch
BMS	Battery Management System
CPU	Central Processing Unit
DESS	Dynamic Energy Storage System
DL	Deep Learning
DSO	Electricity Distribution System Operator
DTX	Discontinuous Transmission
ELSPOT	Elspot Area Price means the settlement price for the power traded in a specific Bidding Area through the Elspot Market (more information: Nordpoolgroup.com)
E2E	End-to-End
ESS	Energy Storage System
FMI	Finnish Meteorological Institute
GPU	Graphics Processing Unit
gNB	Next Generation Node B
Grafana	Multi-platform open source analytics and interactive visualization web application
InfluxDB	Open-Source Time Series Database
IoT	Internet of Things
IP	Internet Protocol
JSON	JavaScript Object Notation
KPI	Key Performance Indicators

Co-funded by the European Union

KVI	Key Value Indicators
kWh	Kilo Watt Hour
MEC	Multiaccess Edge Computing
MID	Measuring Instruments Directive
MIMO	Multiple-Input Multiple-Output
Modbus	Client/server Data Communications Protocol (in the application layer)
MQTT	Message Queuing Telemetry Transport
OAI	Open Air Interface
PMD	Power Metering and Monitoring Device
PSU	Power Supply Unit
PV-hybrid	Photovoltaic system with battery energy storage system
PV-system	Photovoltaic or solar power system
QoS	Quality of Service
QoE	Quality of Experience
RAN	Radio Access Network
RES	Renewable Energy Source
RRH	Remote Radio Head
SA	Stand Alone
SoC	State of Charge
SoH	State of Health
TCP	Transmission Control Protocol
TSO	Electricity Transmission System Operator
UC	Use Case
UE	User Equipment
UPS	Uninterruptible Power Supply
USRP	Universal Software Radio Peripheral
VTT	VTT Technical Research Centre of Finland Ltd

1 INTRODUCTION

1.1 OBJECTIVE OF THE DELIVERBALE

The objective of this deliverable is to provide a description of the energy measurement framework for autonomous, optimized, and sustainable communication solutions for the 6G-XR use case UC5: Energy Measurement Framework for Energy Sustainability [1]. It provides the specification of the energy measurement framework for off grid powering systems with hybrid and islanding solutions of the experimentation facilities at the North Node used in this project. This deliverable also details the gaps that the current facilities have to develop energy measurement solutions for energy forecasting, production, storing and consumption in order to predict network and energy resources for achieving E2E energy efficiency and self-sustainability in next-generation mobile networks.

The document contains 6G-XR project progress for two tasks from Work Package 5, including T5.1 Energy measurement framework and T5.3: AI tools for 48 h Energy Weather. These tasks are mostly focusing on developing energy monitoring, forecasting, and storing capabilities for energy consumption per network elements and the E2E data path of 6G-XR UC5 architecture components [1]. Furthermore, potential modifications may be necessary for the energy measurement framework and sustainability experimentation solution during the development phase. Hence, D5.1 captures most of the work accomplished up to the document's production, while the comprehensive solution will be detailed in deliverable 5.2.

1.2 STRUCTURE OF THE DELIVERABLE

This report contains descriptions of the constructed energy measurement framework in its current extent. The report contains 5 chapters: 1st introduction, 2nd energy measurement framework, 3rd energy system dimensioning and forecasting framework. 4rth chapter is a bridge towards performance evaluation methodology and specifies follow-up systems and potential energy saving measures, tests, and trials to be executed in further phases in WP5 tasks (related to T5.2, T5.4 and T5.5). In the 5th chapter, there are some preliminary conclusions.

The monitoring system itself is operational “up and running”, but only a few first trials “to visualize triggered changes on electricity consumption” have been made. It may also be necessary to “select subsets and tailor-made configurations” for the data-streams in various trials. Thus, continuous development of the framework is still needed. The higher-level automated control system, which will be operating above the monitoring system and aiming to integrate both long-term energy management and energy related controls of the whole E2E system is currently in its infancy. However, for the time being, next day “planning” is already enabled by means of applicable prognoses.

The focus of the chapter 2 “energy measurement framework” is on system architecture, selected technical solutions, and their achieved capabilities targeted to achieve the given multidimensional objectives presented in the chapters 3.4.3 and 4.2.3 [1]. The created monitoring framework also contains descriptions related to applied technical power supply solutions and internal distribution of electricity, as well as references to used measurement devices, systems, and software. We selected certain data-streams and -sources to support retrospective follow up on key performance indicators (KPIs) defined in the WP1. Some of them are critical i.e., are already used to control electricity system on a real-time basis, and some streams are used to optimize operations to overcome prospective challenges. All applied systems are “modular”, and some datasets could be easily re-used to support scale-up efforts. To make the design of new (partly stochastic) systems easier, both experimental and partly simulated datasets can be utilized (and can be combined in visualizations – this was applied to investigate the role of virtual wind power production in power supply by means of datasets derived from the nearby weather station). The framework was designed to support inclusion of distributed systems so that it could be enlarged on a flexible way also in multi-site and multi-organizational levels.

Chapter 3 focuses on dimensioning principles of the main power supply system's components (aggregated power of solar modules and inverter, energy storage system) needed to match consumption requirements and set self-sufficiency targets over time. In addition, analysis of energy production and yield forecasting is included. Based on experimental data or simulation tools (like PV-GIS 111 [2]), systems can be designed and implemented to operate for desired periods of time according to set self-sufficiency criteria. Other criteria for dimensioning (and for operative controls) could be minimization of primary energy usage, energy related costs or indirect CO_2-emissions. Fully energy autonomous usage (e.g., 100% off-grid without any auxiliary fuels or power generator) year-round, 24/7, is an expensive and non-feasible alternative in 6G-XR North Node's seasonal conditions. However, for a major proportion of the year, and if a local grid-interface is available, battery investment and the operational costs of charging/discharging can be reduced significantly by means of "smarter" grid-parallel operation of a PV-hybrid containing a bi-directional inverter and controllable battery energy storage system (ESS). ESS typically includes several battery blocks and an embedded battery management system which communicate with the inverter/charger -units and amongst other things, takes care of safety issues in various operational situations. Forecasting of the coming "energy weather" and resulting energy yield together with the consumption prognoses are an inevitable prerequisite for proactive energy budgeting and scheduling of dynamic control and optimized usage of the electricity storage. If coming energy deficit or surplus periods are foreseeable beforehand, it may enable optimization, prioritization, and scheduling of energy related control actions (initiate flexibility measures) in consuming devices or systems.

Chapter 4 describes the monitoring system's performance evaluation methodologies (a subset of energy, costs, and CO_2 emissions related KPI's) supporting learning and fine tuning of operative control patterns. It also paves the way forward to link the constructed framework to potential E2E -energy saving measures, test principles and trials, which will be executed in later phases of WP5 tasks, and which will be reported in deliverable 5.2.

1.3 PURPOSE AND SCOPE OF THE EXPERIMENTATION FRAMEWORK

The purpose of the experimental framework is to enable energy related studies in the laboratory environment, where a lot of measurements and data-infrastructure is already in place, and also to interlink data from the operating context by means of available external data-streams. This enables R&D work related to the sub-systems containing multiple, partly interdependent electrical loads (network components) supplied via a resilient microgrid and containing alternating primary energy production. The electricity supply system may integrate various local and renewable energy sources like solar and wind power units together with controllable dynamic energy storage system (DESS). It can also operate flexible and grid-parallel way with the sub-system boundary's bi-directional monitoring device.

New technology enables multi-functional, flexible, and safe operation with the grid-interface on several millisecond level, even in case of power outages in the public grid. Automatic transfer switch (ATS) required relays and features of inverter enable fast transfer to island-mode, where all connected loads in the microgrid are supplied from the battery energy storage and parallel PV-yield. In this mode inverter takes care about 50 Hz frequency, voltage-level, and power balance in the sub-system. This "microgrid -island" is then able to survive as a self-sufficient electrical cell as long as its energy management system is able to maintain real-time power and longer-term energy balances, or power quality of the grid enable reconnecting.

On the system level, consumption and production depend on partly behavioural and stochastic phenomena making perfect forecasting and matching impossible. In practice, there is always some amount of forecasting error in the energy balance. This is why all operators in the electricity markets need some adaptive systems or flexibility measures to match their production and consumption. To reach this in an E2E system, a battery energy storage is needed (to maintain a millisecond level power balance with an inverter/charger). To keep the hourly energy balance "on track", it is also necessary to prepare "a set of slower flexibility measures" (to be activated if needed). However, those may also have multidimensional adverse impacts e.g., on the quality level of service. Thus, diverse data-streams need to be linked to the framework to make complex issues visible. Combining numerous real-time data-streams enables the development of smarter monitoring and control systems to maintain energy balance taking various historical, real-time, and prospective aspects into account at the same time. By means of developed framework multidimensional impacts of adaptive measures (e.g., triggered energy saving actions) can be made visible in their time context not only in device level but also on the aggregated and cumulative system level reflecting progress towards objectives.

The scope of the investigated system contains both energy production and consumption. Production is investigated primarily by means of a small PV-hybrid installation capable to operate in UPS-mode (as an uninterruptible power supply system for multiple devices in the microgrid). This PV-hybrid installation contains its own microcontroller, monitoring devices, PV-modules, solar-chargers, multifunctional inverter/charger, $LiFePO_4$ battery energy storage with battery management system (BMS) and electricity distribution cabinets including required protection systems supporting flexible islanding together with connected loads. The consumption side contains configured communication system's "end to end" components including application servers and client machines, end-user devices, and radio access network (baseband and radio units, core server). The scope of the system can be enlarged according to developing test setups. Main electricity monitoring system components (transducers, meters) are installed into fixed distribution cabinets to measure feeder cables. Data is read by means of field-bus converters to servers in a local IP-network.

1.4 TARGET AUDIENCE OF THE DELIVERBALE

This deliverable is mainly addressed to the target partners in the consortium for obtaining a better understanding of the energy measurement framework for 6G-XR UC5 [1]. It shows how the North Node of the consortium will conduct trials and validation for the energy measurement framework in deploying off-grid powering systems for the next generation of mobile networks defined within the project. 6G-XR's envisioned outcomes aim to bring about substantial societal changes. To achieve these effects, the project has carefully recognized various stakeholders, dividing them into specific target groups. These groups will be the main beneficiaries of the innovation and technology enablers provided by the project.

- Community groups
- Manufactures
- Society
- Business
- End users

In the Climate and Environmental Strategy for the ICT Sector in Finland, one area of recommendations was related directly to the development of the measurement frameworks [3]. Especially energy consumption on data centres and communication networks was mentioned as an important area where knowledge base should be improved. Other recommendations considered measures to create a climate- and environment-friendly ICT infrastructure and data economy, sustainable material flows and a circular economy, enhancing consumer awareness and expertise, and utilising emerging technologies and responding to challenges. In the larger working group's background report [4] the role of future network technologies and a summary of measures and tools to manage energy consumption, climate and environmental impacts were presented. The energy measurement framework specified in this D5.1 is desired to help researchers in their efforts to improve knowledge base on energy consumption of network devices in various trial set-ups.

2 ENERGY MEASUREMENT FRAMEWORK

This chapter describes the state-of-the-art energy measurement framework and the requirements to deploy the sustainability experimentation solution for the 6G-XR use case 5 (UC5) [1]. The implementation of the sustainability experimentation solution will be deployed at 5G Test Network (5GTN) research facilities including University of Oulu and VTT Technical Research Centre of Finland Ltd. The experimentation solution is provided for 6G-XR architecture components within the North Node 5GTN including features such as real time energy monitoring and forecasting based control of E2E datapath. First, an energy measurements solution overview and architecture are described along with the scope and structure of the monitoring system. Finally, the main components and the data sets used in this project are provided.

2.1 ENERGY MEASUREMENT OVERVIEW

Development of energy efficiency of transmitted mobile data (kWh/gigabyte) in Finland during 2010–2017 was estimated in the reference [5] but the continuity of found positive trend was uncertain. More measurement activities and a development of comparative framework capable to monitor energy consumption of the different network components were assessed to be important steps forward.

Real-time energy monitoring and load control systems together with increasing self-production, based on local renewables and new technologies, are introduced as a one important area of research and development activities aiming to improve energy efficiency, flexibility, and resilience of various service. Smarter cities, buildings and sub-systems require robust monitoring to be able to adapt to sharpened price volatility in the electricity markets and climate policies. Telecommunication operators, device and system manufacturers are part of this evolution, and they are seeking effective measures to improve energy efficiency and resilience.

To tackle these and other challenges VTT and University of Oulu have invested to experimental research infrastructure and knowledge enabling studies targeted at systemic energy efficiency improvements at the entire E2E-network level. The North Node consist of these two research sites as shown in Figure 1.

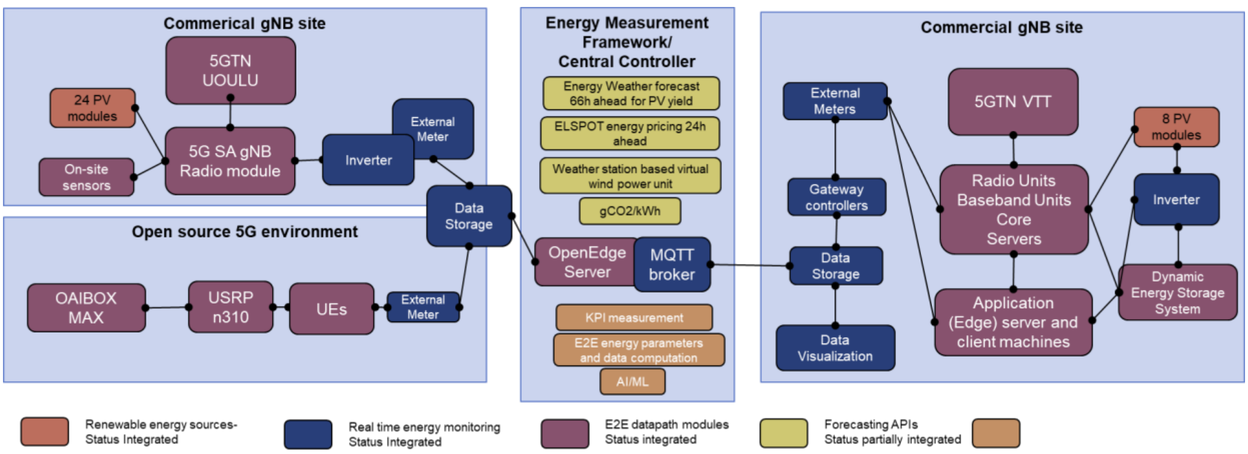

Figure 1: Block diagram for North Node architecture

In this 6G XR-project, network infrastructure and measurement frameworks have been developed in both institutions by means of varying technical choices and steps. Preliminary tests related to the specified Message Queuing Telemetry Transport (MQTT)-based data exchange architecture have been conducted between UOULU and VTT using the central controller as shown in Figure 1. This kind of technical solution and architecture enable effective usage of real-time data streams from both internal and external sources on both sides as well as stepwise development of combined control system. Figure 1 also indicates the integration status of the different components of 6G-XR reference architecture for UC5.

2.1.1 VTT Energy measurement framework architecture

In Figure 2, VTT's energy measurement framework related to the electricity production and consumption side is illustrated (bi-directional and multifunctional PV-hybrid system supplying electricity to radio access network i.e., RAN-system devices). The framework under measurement can be differentiated into energy production, energy consumption and system controller parts. Additionally, some essential functionalities such as data storing and connections to external systems are present. The measurement framework architecture regarding the energy consumption part covers all E2E connections starting from wired-connected application servers to wirelessly connected end user terminals.

Starting from top-left in Figure 2, measuring of energy consumed in RAN is performed on the component-level: baseband unit, radio parts and core network server. Regarding the solar energy system (PV-hybrid) in the middle of top row, the system has internal (embedded) meters marked as blue dots and from those via field bus, the Venus GX system controller is collecting data. The solar energy system has also some external meters connected to enable independent monitoring of energy balances, also read by the Venus GX controller. The application (EDGE) servers and end user terminals energy consumption are measured with different type of meters depending on how the measurement can be performed: for instance, from electrical circuitry where a server AC outlet is connected to, or from a probe point of circuit board holding the 5G modem chip.

The measurement data pipe consists of energy meter, field-bus cabling, bus-converter and datalogger unit, IP-network and an application running on a server which reads the data from datalogger unit and passes it as MQTT message to a connected broker. The datalogger and the application can be also integrated. Several MQTT listening capable instances, including one with database access, can receive the measurement data. Also, an interface broker towards other entities in 5GTN North Node, listens certain MQTT topics of measurement data. A MQTT client inside the other 5GTN North Node entity, which is connected to the interface broker, can receive the VTT energy measurement framework data.

In addition to the monitoring capabilities of the VTT energy measurement framework, there is a system controller which takes care of controlling the energy production system and energy-consuming parts of the framework based on pre-defined rules of energy management (production and usage). The pre-defined rules can be changed at run-time. In Figure 2, VTT's energy measurement framework related to the electricity production side is illustrated (bi-directional PV-hybrid system supplying electricity to RAN-system).

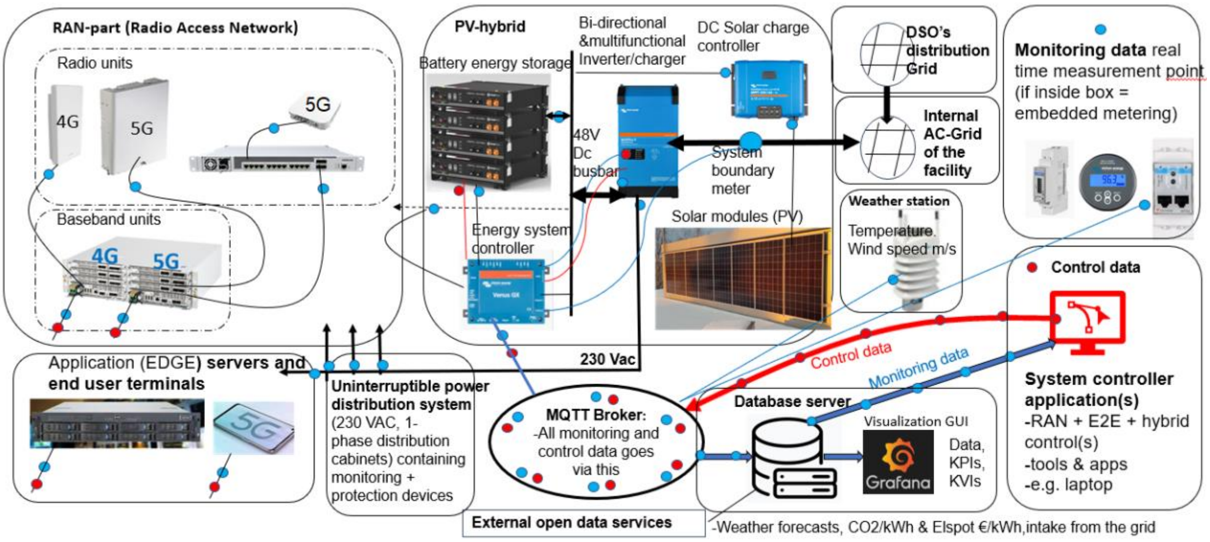

Figure 2: A schematic illustration about the existing power supply, monitoring and control systems and key elements in the energy measurement framework constructed to VTT's Kaitoväylä 1 premises. MQTT Broker is also used to exchange almost real-time data with the University of Oulu.

The illustration in Figure 2 no longer reflects the current (and continuously evolving) network configuration at a detailed level.

For the time-being only a subset of RAN-devices are directly connected to the PV-hybrids' uninterruptible power supply circuits (UPS-branches) capable to operate in island -mode as far as the state of charge (SoC) of the battery allows operation. SoC % typically refers to the amount of remaining energy in the battery system. If SoC % and corresponding voltage level of the battery reach its minimum acceptable level, BMS of the system must initiate shut-down process to prevent damages to the battery. A restricting factor is currently the space for PV-modules (and their aggregated nominal power) installed on the south wall and supplying alternating DC-energy to the solar charger and then to the controllable ESS and consumption. This part of the system is modular and will be enlarged. The obtained experimental data was used to design cost-efficient enlargement options for the electricity supply side.

2.1.2 Architecture and specification description of energy measurement framework within 5GTN (UOULU side of the north node)

The current state of the energy measurement framework at UOULU is illustrated in Figure 3, describing an energy management system with four distinct sections: the energy production side, the energy consumption side, the energy storage, and the orchestration/management side. If ESS-unit would be interfaced to AC-distribution as a separate bi-directional add-on unit "in front of micro-grid switch" (not after) it does not support islanding, but it is still able to provide flexibility services to the investigated sub-system "envelope" in normal usage.

In the upper section of Figure 3, PV modules are used to generate renewable solar energy, which powers the various components of the commercial Next Generation Node B (gNB) site. The middle section holds the gNB components, including the RAN, Baseband Unit, Remote Radio Head, and Network Core. The lower section of Figure 3 integrates an open-source 5G environment into the test network with Open Air Interface (OAI) RAN, Open 5GS core and two sets of Universal Software Radio Peripheral (USRP) Software defined radios (SDR) and OAIBOX MAX devices [6]. Within the 5GTN at the North Node, we have deployed a server infrastructure that servers a as a backbone for our energy measurement framework and energy efficiency enhancement efforts identified as the central controller. Inside the energy measurement framework, the central controller will host two APIs: an energy weather forecasting and ELSPOT electricity spot pricing API. They are deployed to orchestrate, manage, and assist in deciding the activate/deactivate power saving measures for the gNB sites at the North Node. Based on the expected traffic profile and network load, number of User equipment (UEs) connected, future energy availability, price of the electricity and grid related CO_2 emissions, these rules can be adopted by Machine Learning/Deep Learning ML/DL techniques for facilitating the deployment of power-saving measures. On the left-hand side of Figure 3, the control/orchestration section (the central controller) is responsible for managing energy storage capabilities, such as the Venus GX, Raspberry Pi, and Openedge blade a powerful server within 5GTN. These modules facilitate the exchange of bidirectional (UOULU-VTT) information and control between the energy storage, energy forecasting, on-site sensors (direct irradiance, module temperature), energy pricing, grid CO_2, network power consumption, and energy production components. These data pipelines converge into the central section, where AI algorithms will be applied as described in [1][7] and a central database is used for advanced data analytics. Grafana is used for the visualization of all collected data and real time monitoring of all the related parameters.

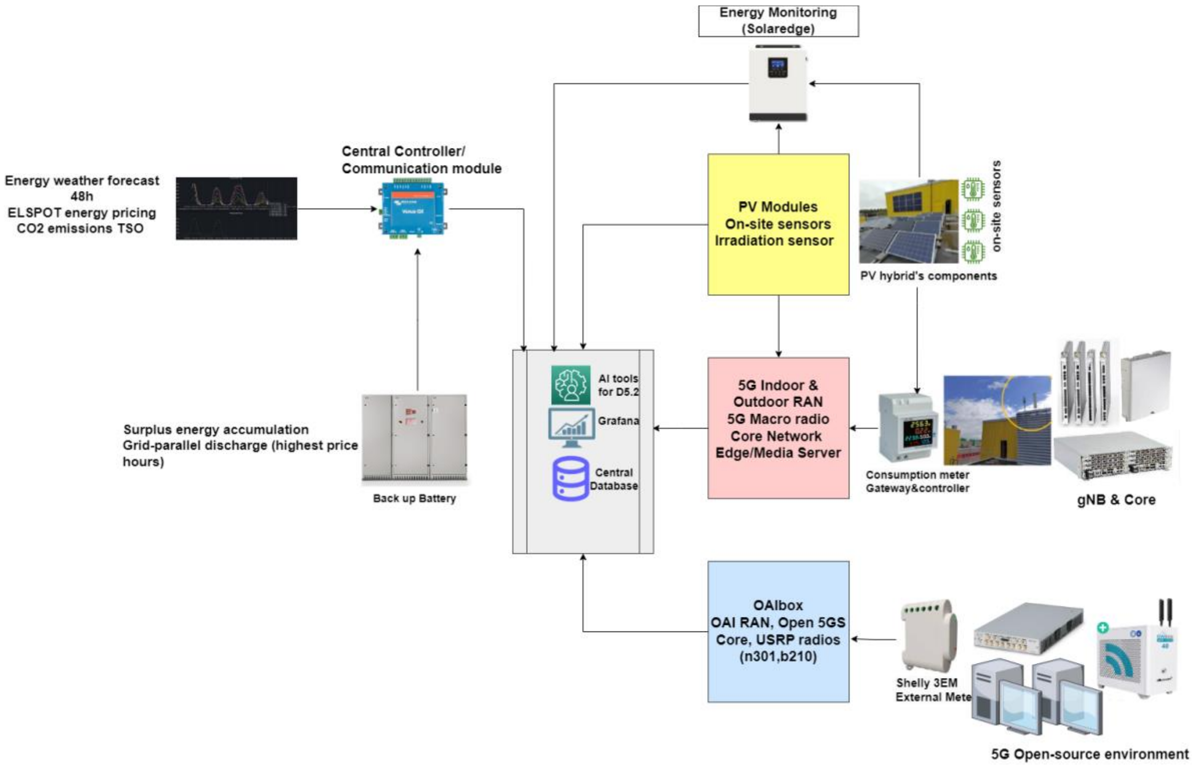

Figure 3: Specification functional diagram for off-Grid powering system North Node

The complete framework presented in Figure 3 is designed to optimize energy usage, enhance efficiency, and provide a holistic view of the energy ecosystem within the context of the 5G network infrastructure and future wireless networks. Specially, during adverse weather conditions or Nordic environment, activation of energy conservation measures becomes useful when the state of charge of the battery falls below the predetermined planned "survival" pathway. In the context of a PV hybrid system, the battery operates in accordance with the planned daily round-cycle ("SoC-coping" strategy applied e.g. also in Victron Energy's DESS-system [8]). The utilization of energy weather forecasts and spot electricity pricing APIs shown in Figure 3, allows for proactive planning and utilizing AI tools for prediction. However, the operational planning of Power Supply Units (PSU) functionalities is treated as a traditional optimization problem, considering the dynamic interplay between forecasted and realized data. In scenarios where the battery state of charge falls below the predefined "optimized" baseline or pathway, the activation of energy conservation measures becomes a strategic move. This is particularly crucial for the effective management of loads, leveraging the flexibility provided not only by RAN components but also by other site elements like Heating, Ventilation and Air Conditioning (HVAC) systems and connected media/edge servers.

The energy management framework, especially the so-called Dynamic ESS-system (DESS), is shown on the left-hand side of Figure 3. In recent VENUS-operating system -publication (version 3.30 or later) DESS can be integrated to PV-hybrid's control system based on previous consumption data. However, to control loads and correct potential forecasting errors, opportunities to access controllable devices and more specifically send control commands to set operating points impacting energy consumption of base station's devices are investigated. It is worth to consider how this methodology can be implemented or integrated into the base station controls. DESS may serve a sub-system as a critical -software component in ensuring energy efficiency of internal energy transfers (in set time slots) and reducing costs of procured auxiliary electricity, maximising earnings related to the feed-in schedule and even decrease cumulative indirect CO_2 emissions [9].

2.1.3 Scope setting and capabilities

North Node represents 5G test network developed and deployed in Oulu, Finland, together with different partners that are closely involved in the development and specification of the 5G technology. The test network targets to serve various application developers by providing extensive test facilities in a carrier-grade state-of-the-art network. 5GTN includes the University of Oulu campus, VTT and the technology village together with several distant locations around Oulu, for example, Oulu University Hospital Test Lab and Nokia factory [10].

UOULU resources and assets for real-time energy tracking include a setup of PV modules and a grid-tie inverter unit operating grid-parallel way, on-site sensors, energy measurement devices, and access to seven Finnish Meteorological Institute (FMI) site-specific energy-weather forecasts for next 48 hours and next 18 hours of single power output prediction. Additionally, a comprehensive monitoring system is in place for measuring overall and individual component level power consumption of the commercial and open source 5G network elements with the average interval of one second.

VTT designed and constructed its small-scale PV-hybrid -pilot installation at Oulu's premises during 2018 to distribute and supply energy to telecommunication devices in the 5G-laboratory [11]. First devices (one indoor pico-unit + 2 system and radio modules) were connected to this "Zencom-hybrid system" at the end in June 2019 [12]. This system, containing bi-directional, multifunctional, and controllable inverter/charger has been investigated further. Additionally, long-term datasets have been collected and various control patterns have been developed and tested during all seasons of the year. This system and extended real-time measurement network applications enable more profound energy focused impact analyses and new test-setups in multi component environment. During the years 2021-2023, the system and especially energy measurement framework was enlarged step by step to cover new telecommunication system components so that impacts can be analysed covering the whole E2E network. The scope of the research is still evolving, and additions and new applications will be made. Practical longer-term indicators (as KPIs) can be built based on experimental data to support e.g., system scale-up efforts and modifications to improve its competitiveness as a sustainability investment. A new milestone was reached during April 2024 when VENUS-OS and all system components' firmware were upgraded to enable introduction and testing of dynamic-ESS functionality together with E2E-components in operative usage (i.e. introduction of automated and adaptive control system based on yield and consumption forecasts, levelled (or experimental) battery costs, set "power channel" boundaries and day-ahead hourly electricity prices).

At the current state of understanding it seems to be possible that prospective hourly energy transfer results of DESS indicates how and when load-control commands impacting other E2E-devices consumption level could be generated and sent. This may be one alternative for the development of combined E2E-energy management towards higher levels of self-sufficiency (30-100%). Possibilities to implement combined control system will be investigated further in the later phases of this 6G XR WP5-project.

2.2 STRUCTURE OF THE MONITORING SYSTEM

The sustainability experimentation framework is only deployed at the North Node of the 6G-XR project for UC5 [1]. The overall network sites consist of roof top or wall instalments along with PV modules (horizontal and vertical mounts), inverter/chargers, on-site sensors, backup battery, energy-weather forecast, external meters, and a central controller. This document includes the following components for deployment of E2E energy measurement framework.

2.2.1 5GTN Capabilities

The 5GTN North Node energy measurement framework is a comprehensive solution for measuring, analyzing, and optimizing energy consumption in 5G networks. The framework is based on the E2E energy management capability of the 5GTN North Node and uses internal and external power meters for overall monitoring and controlling of each component of the North Node architecture. The current state of the network sites and the target state of the commercial network sites (target state 1) and the open-source network (target state 2) is described below.

Current state:

- North node resources and assets for real-time energy tracking include a setup of PV modules, on-site sensors, inverters, and external power meters/energy measurement devices. Additionally, an API monitoring system is in place to measure aggregated power and consumption of 5G Stand Alone (SA) gNB site.
- The 5GTN site features on-site sensors that measure solar irradiation, module temperature, and ambient temperature with the sampling interval of every 5 minutes. The sensor data has been consistently recorded and stored in a local database over the past two and a half years.
- The 5GTN site has access to seven FMI site-specific energy-weather forecasts for next 66 hours. The provided energy weather forecast converts solar radiation such as global and system specific radiation into kilowatt hours for each site-specific coordinate over the next 66 hours (about 3 days).
- 5GTN has the capability to share energy production and consumption data, along with other energy parameters like system production, self-consumption, and power consumption, updated at 15-minute intervals (two years of dataset already exists). Additionally, hourly weather forecasting related information such as cloud coverage, solar panel, and air temperature, diffuse and direct radiation is also available using FMI APIs.
- The 5GTN (6G-XR North Node) currently does not have an open-source 5G environment for experimenting and validating UC5.

Target state 1 (Macro Commercial gNBs and Core network):

- The energy measurement framework is based on the E2E energy management capability of the 5GTN North Node using external power meters for monitoring and controlling each component of the 5GTN individually such as Baseband units, Radio Units, Core, Application EDGE servers and end user terminals.

- Energy measurement framework contains various energy parameters such as active energy (kWh), reactive energy (kVARh), apparent energy (kVAh), power factor (pf), current (A), Weather forecasts 66h ahead, grid intake related carbon emissions (gCO2/kWh) and day-ahead published hourly areal electricity spot-market (ELSPOT) prices €/kWh.
- Site specific 5G network-based energy weather forecast, historical data, and on-site sensors data will be used for training ML/DL models such as Long Short Term Memory (LSTM).
- The framework's architecture will involve deploying multiple communication modules. These communication modules will act as the central hub for all data exchange between the sites. It will be responsible for collecting data from various sources/modules with defined sampling intervals, such as PV modules, Network elements power consumption, E2E power aggregator, and remote radio heads (RRHs), APIs related to energy-weather forecast, energy pricing and power intake (consumption) related gCO2/kWh. These communication modules will be implemented using a variety of hardware platforms, such as Victron Energy's central controller (VENUS-OS in VENUS-GX hardware device (Beaglebone micro-controller), Raspberry Pi and 5GTN EDGE server.
- To improve energy measurement and perform trials on energy forecasting, production, storage, and consumption at the 5GTN site, power-saving measures will be studied and the use of ML/DL algorithms to predict network and energy resources for better E2E energy efficiency.
- The North Node 5GTN will also investigate how the integration of ML/DL methods can enable energy efficiency techniques for developing energy efficient solutions for different components of the gNB site, OpenRAN, Open 5GS Core and other key components of the network.
- Introduction of measurement solution will also be able to identify energy-consumption per network element and perform energy budgeting trials and validation of KPIs mentioned in D1.1 and D2.1 [1][7].

Target state 2 (Open-source OAI environment):

- Open source 5G solutions as an enabler for 6G-XR UC5 Energy Measurement Framework for Energy Sustainability [7].
- The OAIBOX serves the purpose of facilitating the North Node 5GTN deployment for implementing non-dynamic adjustments to RAN configurations and energy aware service orchestration.
- Experimental Evaluation of OAI RAN, 5GS Core and USRP radios using energy measurement framework and control methods for energy efficiency and to explore energy saving potential.

Table 1 presents gap summary analysis at the 5GTN gNB site. It details current states, target goals, and the gaps that need addressing across various critical areas: E2E energy metering, the application of AI/ML algorithms, integration of energy-weather forecasts, and the integration and research of an open-source environment for network operations and sustainability experimentation.

Table 1: Gap Analysis

Requirement	Current state	Target state	Gap
E2E energy metering	Overall power consumption of the 5GTN gNB site.	Using external and internal power meters for monitoring and controlling each component of the network individually.	Deploy an energy measurement framework within the 5GTN North Node and utilize energy measurement devices with per-second sampling rates (e.g., Carlo Gavazzi energy meters, Shelly 3EM, Netio Powerbox). These devices will be capable of measuring energy consumption with average sampling rate of every second and subscribing/publishing MQTT data/commands using 5GTN EDGE server
AI/ML algorithms using historic data sets	Dataset for the last two years stored in a local database using APIs, including energy production, consumption, and on-site sensors	Develop and deploy AI/ML algorithms for energy forecasting and conservation	Use the central controller to implement AI/ML algorithms to enable energy efficiency
Integrating energy-weather forecast 66h, CO2/kWh & ELSPOT €/kWh, grid intake	API based site-specific energy-weather forecasts for next 66 hours	Integrate energy weather forecast, energy pricing and grid CO2 emissions, to assist in achieving E2E energy efficiency such as when the state of charge of the battery falls below the predetermined "survival" level.	Create a communication link between energy production side, inverters, and back up batteries to deploy desired APIs and to establish control commands
Open source OAI environment	No connection with energy measurement framework	Implement energy measurement framework for OAI RAN, 5GS Core, USRP radios and OAIBOX.	Adjust the base station parameters using ML/DL algorithms and offering an open-source testing environment
Documentation	Not documented yet	Comprehensive documentation in D5.1	Create comprehensive documentation with more than 50 data pipes of energy/network related parameters of different components of the North Node 5GTN

Table 2 shows the 5G network elements and components/devices which will be used from UOULU side.

Table 2: North Node 5GTN components

Component	Function	Role/Status
5G SA	N78 (3.5 GHz, 60MHz)	Outdoor Macro RAN
Local SA/Open 5GS	Core	Commercial Network Core and Open-source Core
USRP	Increases the capacity of a 5G base station	Radios n310, b210
OAIBOX	Open-source RAN+Core	Open-source test bed
User devices	UE connected to 5GTN	5G UE Quectel RM500Q, 2pc Mobile device(s)

Table 3 captures the server capabilities and specifications where the energy measurement framework is deployed. This is used as central controllers for all the interfaces and data exchange at the North node sites.

Table 3: North Node resources Nokia OpenEdge Server

Processor	Memory	Storage	Network Interface
Intel(R) Xeon(R) Gold 6338N CPU @ 2.20GHz Ice Lake D0- 32 cores	**N256 GiB DDR ECC RAM78 (3.5 GHz, 60MHz)**	**2x 447 GB NVMe SSD 2x 1788 GB NVMe SSD**	**2x 100 Gigabit Ethernet (GE) Intel X710 interfaces**

2.2.2 Main components and devices of VTT's energy measurement framework

System construction started with simple current meters measuring and recording power supply to a few radio units. Those "early phase devices" were used to estimate power levels and profiles in practice and introduce data transfer routes to further analysis. Currently this "screening phase" of a power supply to investigated system can be executed e.g., by means of smart current clamp -meters, which include programmable data reading and logging options and Bluetooth connectivity to smart phones to enable seamless data-file transfer to analysis software in the desired format. These calibrated devices (such as Fluke Connect compatible current, voltage and apparent power meters) can also be used to validate some embedded meter readings of the RAN's and PV-hybrid's own control systems. The main metering system contains fixed transducer installations directly to the distribution cabinets. We selected Carlo-Gavazzi's devices (transducers, bus-converters, -generators and relays, see [13])due to their small size and suitability to distributed 1-phase installations as well as compatibility with the selected PV-hybrid's controller (Victron Energy's Venus-GX). However, this does not mean that these would have been somehow better than the other major component manufacturer's devices (like Siemens, ABB, Schneider Electric etc. who also produce similar solutions).

2.2.3 Components, tools, and specifications for both sites

As a consequence of collaborative selection process by researchers, we decided to procure, install and utilize these below mentioned VTT's and UOULU devices to build flexible energy measurement system enabling real-time monitoring and control as well as data transfer to the storages for retrospective analysis. Table 4 shows the list of items, specifications and the sampling speed of the integrated components used within the energy measurement framework.

Table 4: Components of the system and specifications.

Items & usage	Specification	Sampling speed
Carlo-Gavazzi, energy analyzer EM111, 1-phase load monitoring	Single-Phase Energy analyzer, RS485 Modbus RTU -version	Internally 4096samples/s @50Hz, data refresh time 1/s
Carlo-Gavazzi, energy analyzer **EM511, 1-phase load monitoring and fast bi-directional monitoring (M) and control (C)**	New fast single-phase energy analyzer, RS485 Modbus RTU -version (not yet available but considered as an alternative to EM111 in new installations)	1600 samples/s @50 Hz also from distorted waveforms, Modbus RTU RS485 communication (data refresh 1/0,1 s), THD U and I %. Suitable to applications which require fast control actions based on power.
Otii Ace Pro, power profiler and energy analyzer	DC energy analyzer. Can be also used as source voltage up to 25V and current up to 5A.	High sampling rate: 50000 samples/s. Currently 1000 samples/s used for 5G modem measurements which is enough for our tests.
Carlo-Gavazzi, energy transducer, ET112, 1-phase load monitoring and bi-directional system boundary M & C	Single phase energy transducer RS485 Modbus RTU -version	Data refresh time 1 sec. Sampling rate 4096 samples/s @ 50Hz, compatible with Victron energy's VENUS-GX control loop.
Carlo-Gavazzi, energy transducer, ET340, 3-phase load monitoring and bi-directional control, transboundary metering	3-phase M & C. (Also so that unbalance between phases can be taken into account in power control modes)	Sampling rate 4096 samples/s @ 50Hz. Data refresh time 1sec
Carlo-Gavazzi ,EM24, load M & C, 3 phase systems	Energy analyzer for three-phase systems, in addition to M-bus and Modbus RTU, also Modbus TCP/IP versions are available as well as	1600 samples/s @50 Hz also from distorted waveforms, Refresh time < 750 ms. RS-485 fieldbus and needed TCP/IP bus-converter do not slow down data transfer in TCP/IP version

	a wireless M-bus version.	
Carlo-Gavazzi UWP 3.0 Universal web platform, gateway and automation controller for energy management and building automation.	Numerous RS-485, modbus RTU meters can be configured to be read by one UWP 3.0. Also bus generators and e.g. remotely controllable relays can be added	UWP 3.0 is used as a bridge to read data from Modbus RTU meters to TCP/IP network. 1/s sampling speed was reached together with EM111s.
Carlo-Gavazzi VMU-C, field bus-converter + web server	Several RS-485, modbus RTU meters can be configured to one VMU-C unit. Web-server store data from meters on 1/min basis (min, avg max values, all datapoints).	If VMU-C is used as a bridge to read data from Modbus RTU meters to TCP/IP network 1/s sampling speed was reached.
Victron Energy's Venus GX PV-hybrid's system controller.	Victron Energy's central controller containing VENUS-OS (open-source system) which monitor and process R-T data-points from lower level components, like inverter(s), solar chargers, battery energy storage, system boundary meter and sensors etc.	By means of remote console or MQTT solution numerous datapoints can be read from Venus GX's Modbus TCP register on 1/s basis (or when the value changes). Register contain also readable for system control.
Grafana	A programmable SW environment capable to visualize connected real-time data streams e.g., in monitoring panels	Typical refresh rate 5 s, but data can be read to connected InfluxDB on required 1/s basis. Capacity to integrate data from various devices and distributed sources
InfluxDB	All "data-pipes" from numerous sources are connected to InfluxDB and data is available for researchers there for visualizations or exporting e.g. 2 weeks or some datapoints also longer time.	Data can be analysed afterwards by means of Grafana interface and tools.

MQTT-broker (Mosquitto)	By means Mosquito Brokers MQTT data exchange between system components and e.g research organizations can be enabled.	In addition to distributed monitoring MQTT solution enable sending control commands to system controllers. For example, VENUS-GX can be controlled by means of MQTT -commands.
Energy weather forecast	Areal data from FMI's open data service to be applied to generate production/PV- yield forecasts	Updated every 3 hours
ELSPOT hourly day-ahead electricity market prices in Finland	Available (a bit later) from power retailers services or Nordpool and other market exchange platforms. Needed to calculate cost/savings related KPI's.	Available during the previous day at 14:00 to next day's hours
Fingrid's estimate for gCO2 for consumed kWh	To be used to generate cumulative emission counter for power intake (from the grid) as an avoided CO2 KPI.	Original data 1/3 min, to be processed to match ET112 system boundary meter readings (in Grafana)
Shelly 3Em	Smart energy monitoring system	1sample/s @1Hz
SolarEgde	Grid-tie PV inverter and associated web-service	Updated every 15 mins
Netio PowerBOX 4KF	Smart power socket (smart power strip) with four 230V/16A sockets and with consumption metering for each socket	2 samples per second
5GTN EDGE server	MQTT broker deployed for data exchange	64GB Storage

Server's add-on measurements devices and related data pipes are under construction. Technical work is progressing according to the framework specifications.

2.2.4 External Meters

External energy meters are used to measure active energy consumption of each block of the architecture, as shown in Figure 2 and Figure 3. Most of the selected AC measurements units are compliant with the international accuracy standard IEC/EN62053-21, Class-1 (Standard EN 50470-3:2022 or older versions, Class B). These devices are also able to measure and deliver other datapoints by means of serial communication. Available datapoints are typically: current, voltage, active power, reactive power, frequency, power factor and active and reactive energies (to both directions). Requirements for power metering and monitoring devices (PMDs) and measurement functions such as voltage magnitude, current magnitude, power, frequency, etc., are covered in EN IEC 61557-12:2022 standard.

Furthermore, other types of metering units are used. The installation of external current sensors of metering units requires splitting conductors of cables, enabling the setup of open-core current sensors or the option to install meters between wires and devices. If disconnecting is possible, solid core current sensors are also applicable. This process may involve cutting off the DC-supply cables. Meters are built and tested according to metering standards (EN/IEC). Meters in the laboratories are not used to fiscal purposes and that is why EU's MID compliant. models were not selected. MI-marking refers to EU's Measuring Instruments Directive (2014/32/EU). In some cases (e.g., entire base station site measurements), MID-models should be selected. Manufacturers offer interfaces and information on how metering systems can be read remotely from external systems.

2.2.5 Software tools

Measurement device manufacturers offer specific SW-tools to read their devices on real-time basis. This can be done with the configuration software via specific adapters (e.g., directly from the RS485, modbus-rtu field-bus to USB of user terminals or from bus-converter units RS-485 to TCP/IP). These field bus converter units may also contain embedded WEB-servers for data monitoring and energy management purposes.

2.2.6 Schematic relations

Metering system is described in the next picture. In practice, various type on meters (also embedded devices) could be added to field bus-cabling behind bus converter or datalogger units or micro-controllers.

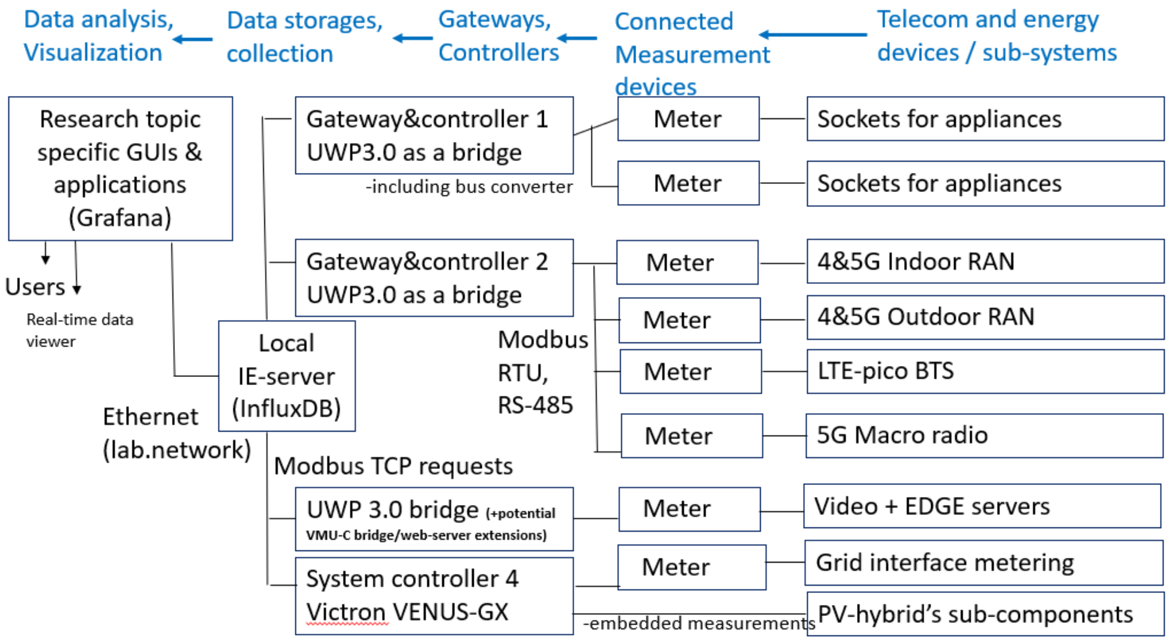

Figure 4: Illustration of the schematic relations in constructed energy metering framework (VTT's side).

The illustration in Figure 4 explains how data flows from decentralized metering systems to a real-time database (InfluxDB) via bus converters. Then desired panels above Grafana platform were built. It is also possible to read data-streams from distributed databases and processing data on the visualization phase.

2.2.7 Selected applied solutions for data collection and transfer

On the energy consumption measurement's side, cloud services were not used. They typically operate less than 1/min logging interval which was considered to be too slow. Instead of that, bus-converter units (RS-485 -> TCP/IP) were used as a bridge to read metering units on 1/s basis, which was considered to be sufficient in most trials. Modbus-TCP devices with open TCP-registries and available guidance information were preferred. In some cases, SW-solutions (Python code) were created to read devices data to server's RT-database. Mosquito MQTT brokers (for pub/sub) were utilised and preliminarily tested with few data-streams to exchange data streams between organizations.

It was also possible to formulate MQTT messages from PV-hybrid's controller's TCP-registry information to enable both versatile monitoring (read datapoints) and generate various control commands (write commands to registry).

When available, a higher level setpoint based control was preferred instead of direct control of inverter/charger's internal factors. System level setpoints (like sub-system boundary power setting) was found to be stable safe and useful parameter in energy management. However, cyber security issues must be considered in this kind of control system development.

Metering units were configured in the implementation phase and there is seldom a need to change configurations or update firmware.

2.2.8 Data storages, analysis and visualization

Data from the PV-hybrid's all datapoints (energy production system -part) is logged from central controllers memory on 1/min bases to Victron Energy's remote monitoring service (VRM-cloud) where it can be analysed. Data is downloaded on monthly basis to user's device (and stored) covering selected time periods 1/min xls or csv files. Energy transfer tables revealing Hybrid's internal operation with the battery system are processed and stored on 1/15 min basis. This data is also used to follow up system performance according to the desired criteria (or KPIs defined in source [1])

VRM-service is able to combine several other external data-sources (e.g., electricity market's price information from ENTSO-E transparency platform and irradiation data from Solcast's service to generate dynamic-ESS service option, which was made available to VRM-platform users). VRM-service store and makes available (max. last 6 months) all necessary datapoints needed for monitoring system components operation and configuration parameters for controlling the PV-hybrid on a desired way. Configuration of the system can be made locally (only critical choices) or via remote console (on LAN) or by means of cloud service.

Data from consumption metering units is stored to InfluxDB in VTT's server on 1/s bases. Researchers are able to download it and make selected rollups to transfer data to other analysis programs if necessary (often Excel). Practical work can be done also by means of tailor-made visualizations above Grafana platform.

2.2.9 Used data sets by North Node

The datasets used in the 6G-XR UC5 experimentation and validation are obtained from various sources, such as the real-time power consumption at commercial and open source 5G SA base station gNB, radio head, network core and solar PV production from a system installed on the rooftop of the University of Oulu. The solar array consists of twenty-four panels with an inverter capacity of 6 kWh, situated at coordinates 65.0593° N, 25.4663° E. The Grafana snapshots in Figure 5 and Figure 6, display solar PV yield data from September 2020 to May 2024 (ongoing). The data includes Solar PV yield power recorded every 15 minutes, and energy production recorded hourly, daily, and monthly. Real-time power consumption data for the 5G Test Network (5GTN) site, which comprises a baseband unit, switch, and radio modules, is also being collected and logged as shown in Figure 5 and Figure 6. These datasets are visualized using Grafana for real time monitoring, using APIs from SolarEdge inverters/FMI/ELPSOT and Python scripts used to request these APIs and store them in local database.

Figure 5 captures a snapshot from the large dataset of hourly energy production, self-consumption, import from the grid, export from the grid and consumption of the gNB site. Figure 6 presents a monthly overview of energy production and consumption at the gNB site (with energy production in green and consumption in red) from the collected dataset for identifying the energy positive months compared to the load, and Figure 7 shows the snapshot of dataset collected from gNB on-site sensors monitoring solar irradiation, module temperature, and ambient temperature, updated every 5 minutes (on-going). These visual representations help in understanding the dynamics between energy consumption by 5G infrastructure and renewable energy production over the three-year period.

Figure 8 shows three different datasets related to energy and forecasted data for the period of one year (2023). The top part is the energy weather forecast provided by FMI compared with the real solar production at the bottom. The middle section shows the accuracy of these forecasts with "Percentage of Error" with various colours representing different error rates. Together, these visuals provide a comprehensive view of energy weather forecasting and its real-time application.

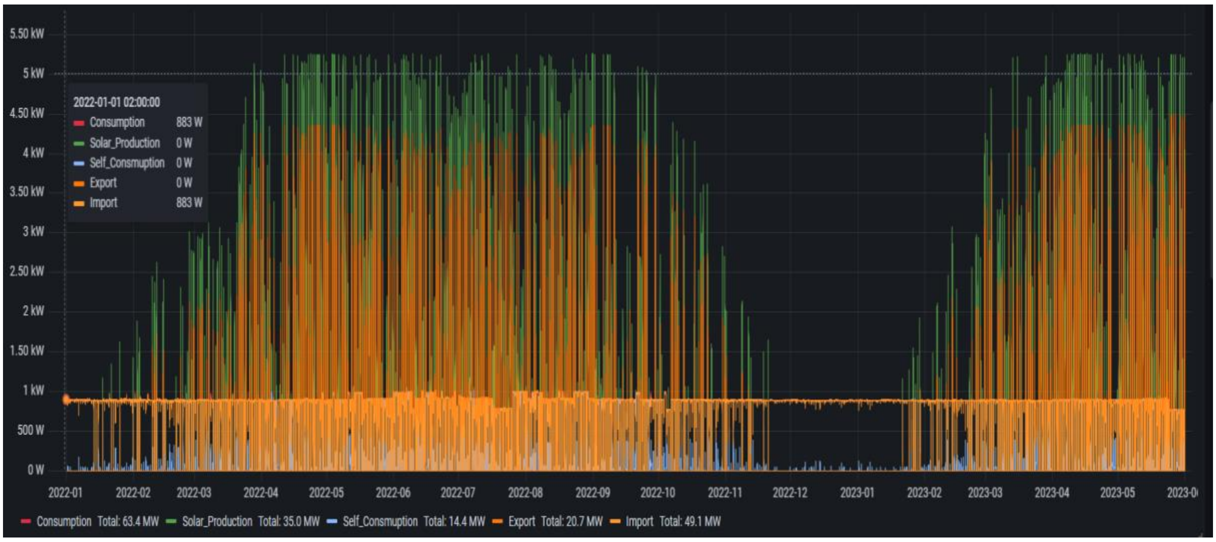

Figure 5: Power consumption vs Solar production vs Self-consumption vs Export vs Import (updated every 15 min)

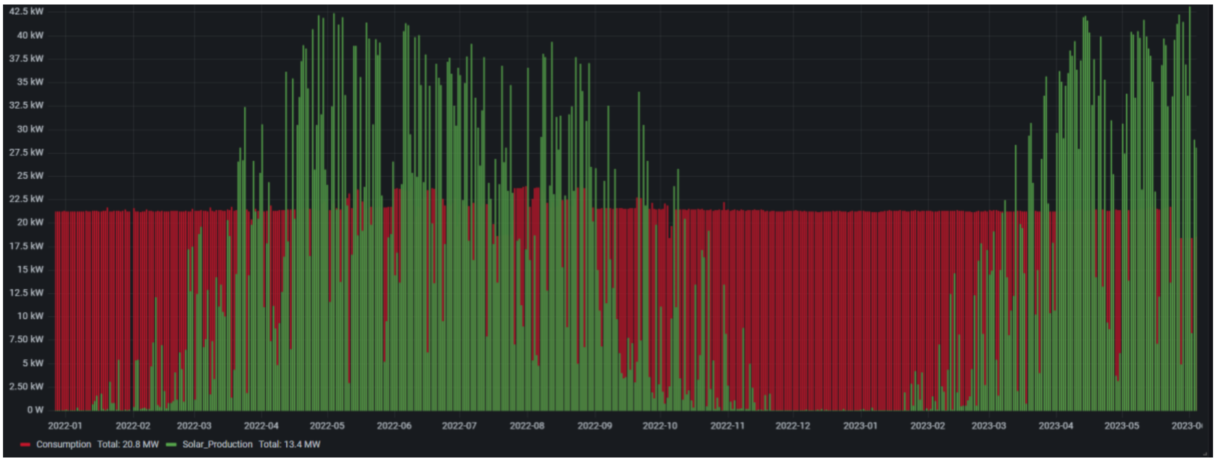

Figure 6: Monthly energy production (green) vs consumption data at gNB site (red).

Figure 7: On-site sensor data collected over two last years (solar irradiance at top and temperature at bottom)

Figure 8: FMI data vs real-time collected data over the last years

2.2.10 Used datasets by VTT

VTT's data sources cover PV-hybrids internal datasets partly read from VENUS-GX's modbus-TCP registry (1/s data from few selected datapoints) but also data from associated VRM-global cloud service. On monthly basis data has been stored containing 1/min logged data from all connected system components and pre-processed data from the cloud service. Also 1/15 min data related to system operation (energy transfer between hybrid's components) is stored to enable retrospective performance calculations together with linked data from external data services.

In addition to production side data, also all consumption side measurement devices in front of RAN-devices have been linked to data system. E.g. data from the meter before system module's PSU is read to influxDB. The aim is to include all system components in the E2E chain to the measurement framework and then create a real time summary meter as a sum of all active power and energy counter readings. Also, data from embedded sensors from RAN-components will be analyzed and used if it is relevant for individual test setups. The fourth type of data (which is utilized to create KPIs) is collected from external machine-readable APIs of open data services. Fifth data-group cover additional external devices e.g. wind speed and outdoor temperature data from weather station (manufactured by Vaisala). Also, operational real-time data exchange between organizations is under development by means of MQTT-brokers and architecture.

Appendix A pv-hybrid’s time series data contains a list of datapoints from a VTT’s Zencom -PV-hybrid installation and illustrates the complexity and multidimensionality of the applied monitoring and control system. Only a subset of data-streams will be used for the control approach.

3 ENERGY MONITORING, FORECASTING, STORING AND OFF-GRID CAPABILITIES

This section highlights the necessary aspects of dimensioning principles essential for hybrid PV power supply systems to align with consumption needs and self-sufficiency objectives for experimentation trails of UC5 and the 6G-XR reference components of the North Node site [1]. The dimensioning criteria covers the UC5 architecture details, background, integration of open-source environment for experimentation and validation, energy saving methods using OAIBOX and the integration of on-site sensors and energy weather forecasting into the deployed energy measurement framework. It also covers the dynamic energy storage system required to deal with the distinct seasonal variations (especially Nordic conditions), adopting intelligent grid-parallel operations using PV-hybrid system.

3.1 BACKGROUND

The North Node 5GTN Energy Measurement Framework is set to be established within the 5GTN network for experimentation of UC5 [1]. The architecture of this framework is structured around a central communication module that acts as the central controller. This controller is crucial for mediating data interactions among several important components, which include solar PV modules, system power supply units, the base station system module, and remote radio heads.

By means of energy measurement framework, understanding on device and system level consumption patterns can be improved step by step. Within this setup, energy measurement devices like Carlo Gavazzi meters will be connected to power outlets to enable flexible changes of devices to be investigated. Impacts of triggered changes on power levels of devices can be monitored via Grafana panels. When the baseline on consumption and impacts of various control measures are known then controlling of the system in the frame of forecasted “energy availability budget” becomes possible. The aim is to match consumption with the availability of energy. Some additional datapoints are also needed to check correct operation of lower level devices or sub- systems or to follow up KPIs. The monitoring system should be wide enough to serve multiple needs.

In addition to match consumption to production opportunities, a prospective view is needed to manage energy related costs when the volatility of hourly electricity prices increases. A prospective view or some level of energy consumption planning is also needed if the operator is willing to participate in reserve market segments. It is necessary to understand when there is probable energy surplus or deficit in relation to desired quality level of services. This depends on the dimensioning of components (battery, power capabilities of the bi-directional system). The first dynamic energy storage system applications have been recently published (2024) but there are plenty of development opportunities left to decrease forecasting errors.

Nighttime prices of electricity may often be higher than battery degradation costs for discharged energy. In such circumstances, 100% self-sufficiency (or off-grid usage, when grid is present) is not an optimal target for daily operation. In addition, power saving measures capable of decreasing nighttime consumption decrease the required battery capacity and improve energy economics of the system. In addition to controllable energy storage function during the normal operation, back-up power needs and time can also be considered when battery size is determined in practice. According to preliminary setups, dimensioning to 4-8 hours of operation time in the case of blackout situation is enough to support zero energy intake (or other controlled operation) during the daily working hours. During those hours prices of electricity in the Nordic markets have been typically higher than at nighttime. Overcoming evening price peaks also may require additional battery capacity or auxiliary charging during late afternoon hours resulting in 1,5 – 2 charging cycles per day instead of typically one full cycle. This consideration becomes possible when batteries are selected to endure cyclic usage and their round cycle losses are small enough. Batteries can also be charged fully proactively based on storm prognoses to maximize operating time during conceivable power cuts. At least these compromises are worth consideration when aiming to find optimal investment decisions related to batteries.

Wide enough monitoring is necessary, but only a subset of the energy-related data-streams or processed higher level parameters are needed in the operative control system. However, in addition to energy issues numerous other datapoints are also needed and must be considered before making smarter control decisions and in the end generate control commands. Typically, energy relevant control can only be organized indirectly, i.e. impacting configurations or other available control parameters often in the form of available setpoints of embedded automation system (not opened for integrators).

The energy measurement framework is planned to be fully implemented at the North Node, specifically at the VTT and UOULU sites. The central controller will facilitate the necessary exchange of data between various components or sub-systems, including solar PV inverters, systems' power supply units, the base station system module, and remote radio heads. PSU may also be a "hybrid entity" controlled by its own "sub-controller" which also takes care of component level control (of several devices, actuators and even several energy resources and storage units). A hierarchical control system is needed. Safety related controls must remain inside critical components like lithium batteries or inverters/chargers.

Integral to this setup are energy measurement devices, such as external meters, which are strategically connected to power outlets to monitor energy usage accurately. The setup also includes open-source 5G environment as part of the 5GTN and energy measurement framework will utilize the open-source environment for experimentation and validation purposes of UC5. This inclusion is vital for the framework as it allows for thorough experimentation, validation, the use of AI/ML tools for assisting in dynamically/non-dynamically RAN configurations changes and providing insights into the framework's performance and adaptability. The comprehensive outline of the North Node 5GTN energy measurement framework can be viewed in Table 5.

Table 5: Summary of North Node 5GTN energy measurement framework

Component	Details
Energy Production	Bi-directional PV-hybrid system, with internal and external meters managed by the Venus GX and Solaredge system controller.
Energy Consumption	Measures energy from wired application servers to wirelessly connected end-user terminals using various meters.
System Control	Central communication module controls energy flow and management based on pre-defined rules.
Data Collection	Utilizes energy meters and dataloggers integrated with applications on servers to collect data.
Technology Integration	Incorporates open-source and commercial 5G technology for testing and validation within the sustainability framework.

3.1.1 Experimental Evaluation of OAI RAN, 5GS Core and USRP radios

Next-generation mobile networks are set to incorporate open-source elements like OAI RAN and Open 5GS core to address the increasing demands for traffic capacity and the integration of new applications. One key strategy being employed is network densification, which involves deploying more base stations to reduce cell sizes, thereby boosting data rates and enhancing connectivity while efficiently using the network spectrum [14]. The OpenAirInterface (OAI) environment, being crucial for future research, will be connected to the energy measurement framework with external meters and an MQTT broker to monitor energy consumption in real-time. The setup includes OAIBOX, which is running with Open 5GS core and ORAN gNB (connected to an external meter). This open-source network is tested using UEs that are connected to the radio unit, such as USRP. Measurement trials will use different ORAN configurations and traffic flows to test the E2E energy consumption of the open-source network. These measures are aimed at optimizing network performance and ensuring sustainable operations in future mobile networks [6].

3.1.2 OAIBOX MAX at 6G-XR North Node

North Node has recently purchased four OAIBOX MAX, which provide the most advanced version of the OAIBOX. Figure 9 illustrates the system components of the OAIBOX MAX also described in detail in D2.1 [7]. The actual OAIBOX, shown in the upper left, integrates the 5G core and gNB. The system includes a network interface card (NIC), a 10 Gb Ethernet card and an SD card filesystem that supports an external universal software radio peripheral (USRP). Note that the USRP is separately connected with the OAIBOX MAX and is not part of it. Additionally, a 5G-ready UE with a pre-programmed 5G SIM card is included. Mobile devices and Quectel Modem can also be used as UEs, and an RF cable kit is available to facilitate over-the-cable connections between the OAIBOX and the UEs. Moreover, the package includes a dashboard offering a web-based platform for real-time 5G network monitoring and management, a 5G lab manual, and some technical support [6].

In Figure 9, the OAIBOX setup is displayed within 5GTN at the North Node. Figure 10 shows the real time energy monitoring of the OAIBOX connected to a USRP N310 device. Both the gNB+core is connected to one output and the radio unit (USRP n310) is connected to the other output. The web interface shown in Figure 10, is accessible using the local IP. Open APIs are used to connect this device with the MQTT broker to send the real time data with the sampling rate of every second to the common broker deployed within the central controller of the energy measurement framework.

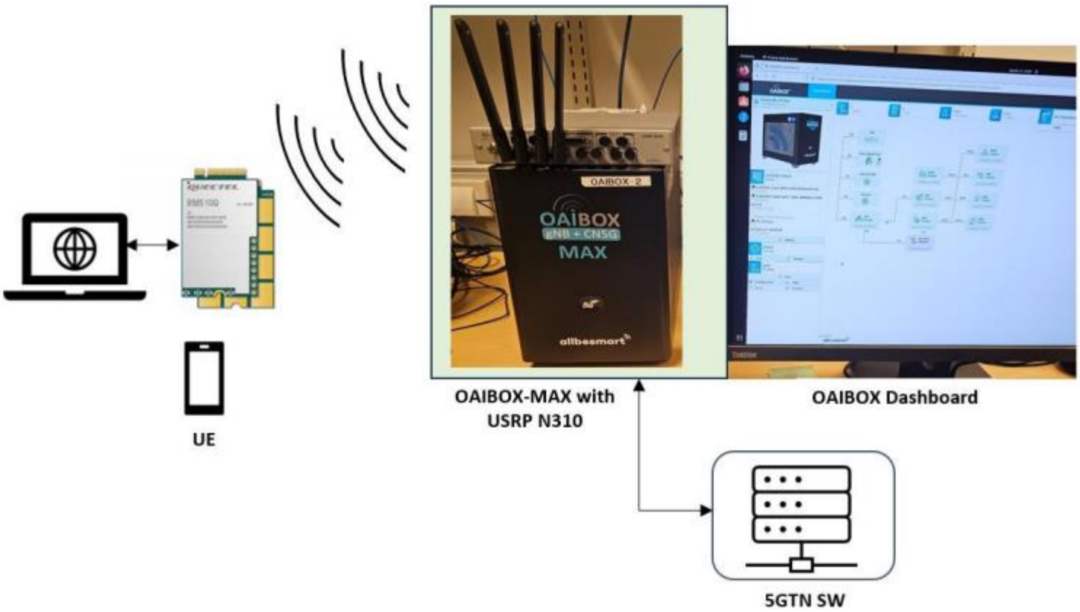

Figure 9: OAIBOX-MAX setup at UOULU 5GTN [7]

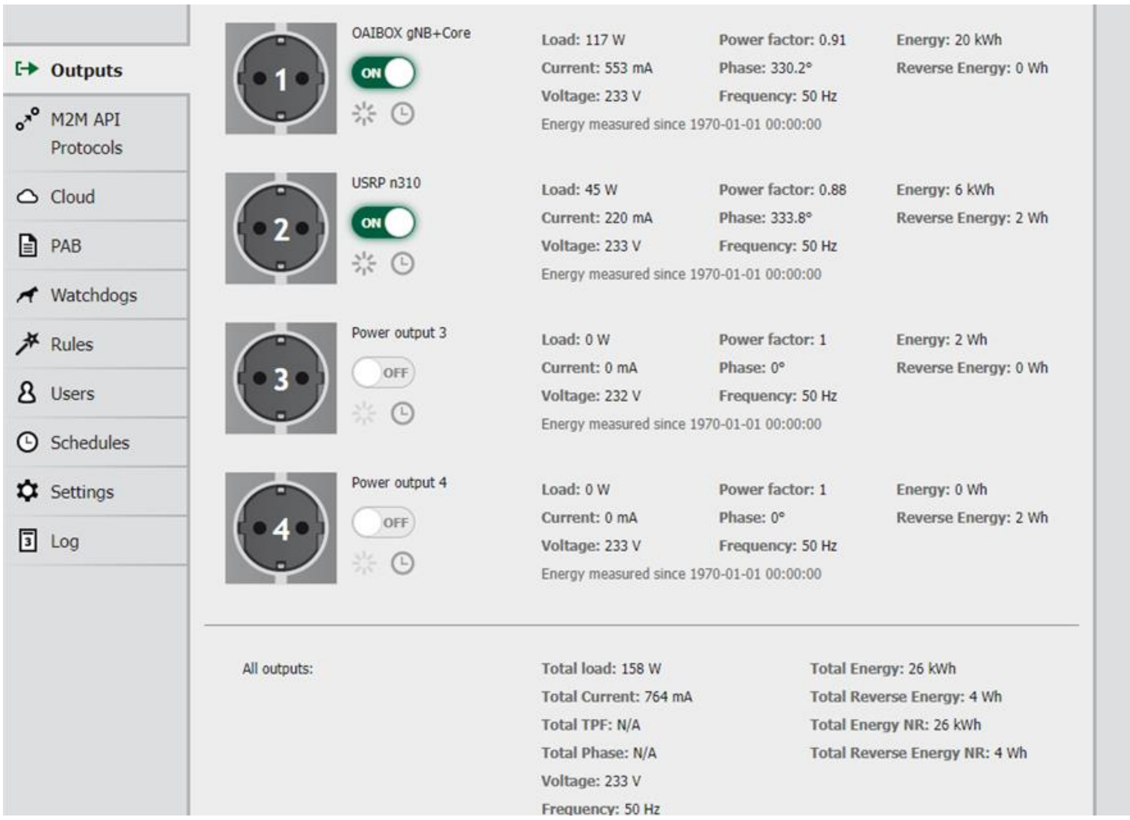

Figure 10: Netio energy meters readings for OAIBOX MAX

3.1.3 Energy saving in OpenRAN using OAIBOX MAX

According to the 5G lab manual [6], various RAN configuration changes can be performed with the OAIBOX, but these changes are currently non-dynamic, meaning the base station must be restarted between adjustments. The potential to make these adjustments dynamically is also being studied. The focus is on configurations that are believed to affect the power consumption of a base station, and the plan includes measuring the power consumption of an OAIBOX MAX device utilizing SDR (USARP models B210 and N310) under different RAN configurations. The results will provide insights into which RAN configuration changes can help conserve energy, making them feasible options for energy optimization.

OAIBOX also allows monitoring of various communications metrics such as bitrate, which will help determine the energy consumption per data bit of an SDR device under different RAN configurations. Four potential open RAN configuration changes aimed at saving energy are being tested with OAIBOX MAX using SDR, and these changes are also considered for traditional RAN. This will allow for comparable energy consumption results between RAN (pico and macro base stations) and open RAN (OAIBOX MAX with SDR).

Restricting the used bandwidth by changing the 5G NR bandwidth to settings like 20 MHz, 60 MHz, or 100 MHz; selecting the TDD frame structure by modifying the slot configuration to contain different numbers of UL and DL slots, with an assumption that less energy is consumed during UL slots (where the UE transmits to the base station) than during DL slots (where the base station transmits to the UE), potentially conserving energy while decreasing DL capacity; restricting the modulation constellation by altering the MCS for UE (in the UL direction) and for the base station (in the DL direction), where the modulation order can be set to automatic mode or to a specific modulation (QPSK, 16QAM, 64QAM, and 256QAM) for uplink and downlink separately, with automatic mode selecting the optimal MCS based on current channel conditions, and a specific modulation set constantly in use, enabling the measurement of energy consumption for different modulations; and selecting the DL MIMO mode in OAIBOX to enable spatial multiplexing for increasing the channel capacity, applying different numbers of transmitting and receiving antennas for the base station and transmitting separate data streams using distinct antennas to increase the data rate, with available configurations including SISO (1x1), MIMO (2x1), and MIMO (2x2).

These RAN configuration changes have already been initially tested as shown in Figure 10 in a non-dynamic manner using two mobile devices as UEs to monitor the effects on maximum data rates and verify that the system operates correctly with different configurations. The next experiment will do detail energy profiling involves connecting an energy measurement device as shown in Figure 11, to separately measure the energy consumption of an OAIBOX MAX device and a USARP device, providing detailed energy consumption information of RF components of gNB. The results of these tests will be presented in the following version of this document which is D5.2. Figure 11 illustrates a setup featuring the OAIBOX MAX integrated within the energy measurement framework. The setup in Figure 11 use Python script to connect to an MQTT broker. A local database stores all energy-related data, which is managed through Grafana installed on the 5GTN server.

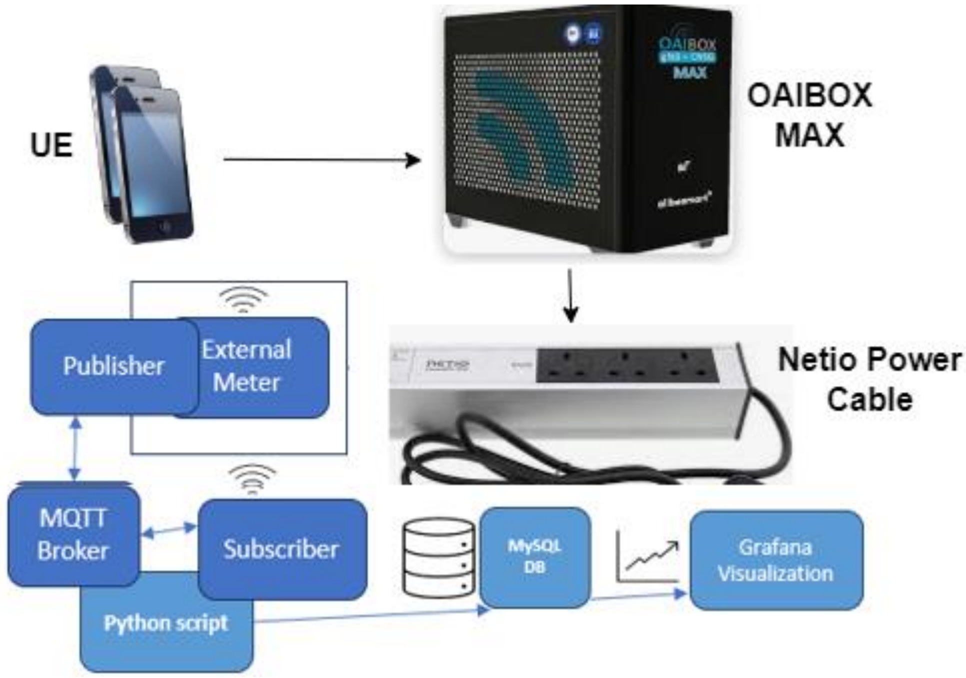

Figure 11: OAIBOX MAX setup with energy measurement framework.

3.2 INTEGRATING ENERGY WEATHER FORECAST FOR 66 HOURS AHEAD

The energy-weather forecast, derived from the HARMONIE model and facilitated by the MetCoOp Ensemble Prediction System (MEPS), allows for multiple forecasts runs that offer both a precise forecast and an estimate of its uncertainty. This data is crucial for the energy management system at both commercial and open-source gNB sites, where it is used to optimize energy usage, storage management, and grid interactions based on predictive analytics of solar generation and weather conditions [15].

3.2.1 Integration with Energy Management Framework

To gain insights of the future solar energy production, the FMI provides energy-weather forecasting interface, depicted in Figure 12. This interface is designed to visualize the predictions of solar power generation for the next 48 hours with seven estimates and the next 18 hours of single power output estimate with total of 66 hours. by allowing users to input specific parameters related to their solar installations. Users can enter details such as the number of solar panels, the nominal output of each panel, inverter capacity, and precise coordinates, along with the orientation and tilt angles of the PV modules. This tailored input helps in generating more accurate site-specific energy-weather forecasts.

Figure 13 shows the FMI’s energy weather forecast web interface for UOULU PV setup for the next 66 hours. Forecasted power outputs are based on seven different fractals, each corresponding to a potential dynamic weather scenario, rather than relying on a single deterministic forecast. Additionally, Figure 13 also shows the accumulated energy over the forecast period, as well as key environmental data including panel and air temperatures, and various radiation measurements such as system global, direct, and diffuse radiations.

Figure 14, presents a Grafana dashboard view of the locally stored energy data and weather fractals from the FMI forecast. This visualization uses the percentage error between the forecasted energy production values and the actual real-time energy production collected from the solar installation.

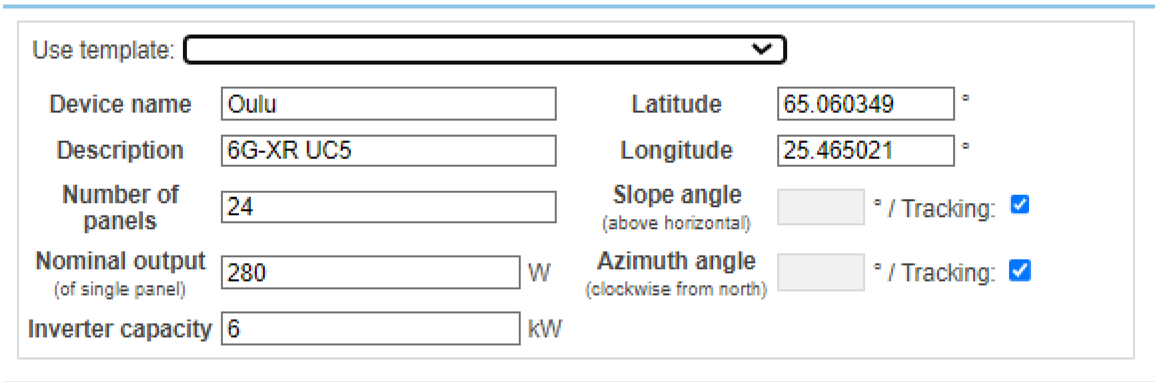

Figure 12: FMI interface for site specific energy-weather forecast

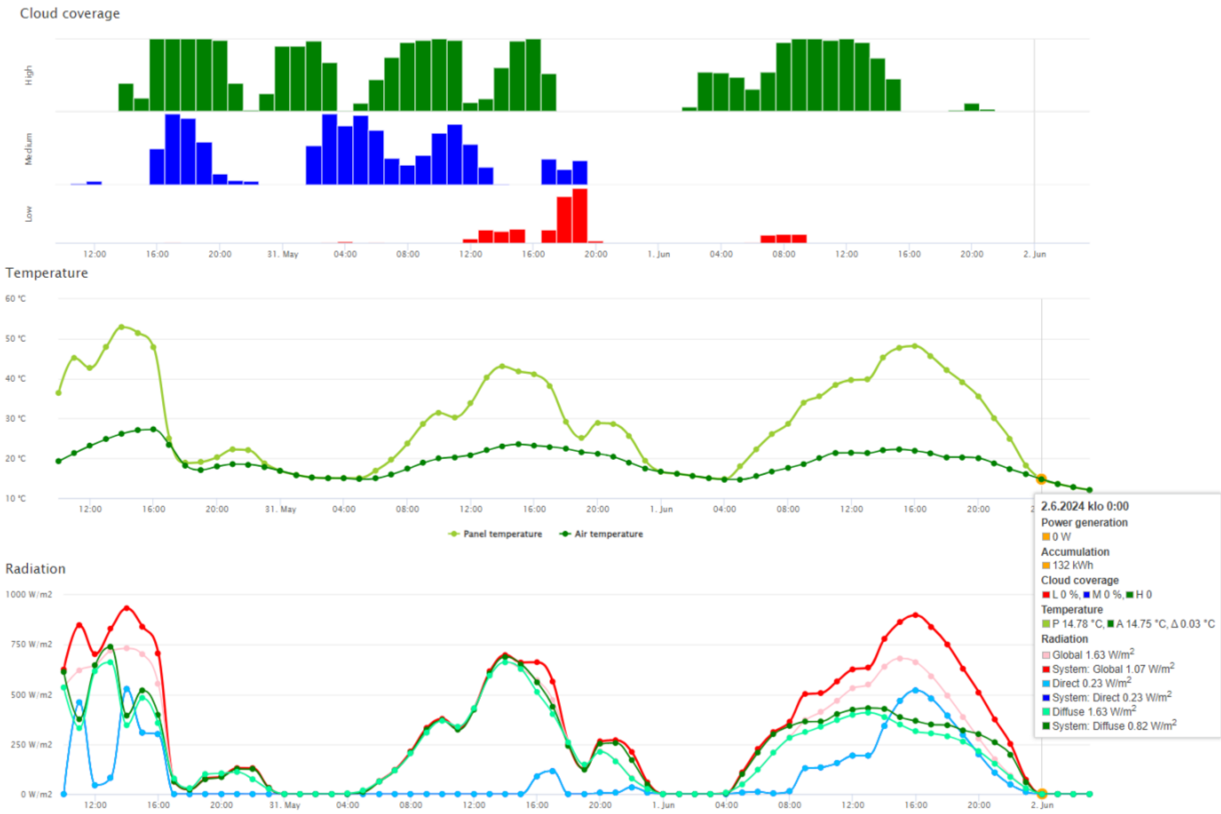

Figure 13: FMI interface for energy weather forecast parameters.

Figure 14: Energy-weather forecast plot of every received parameter.

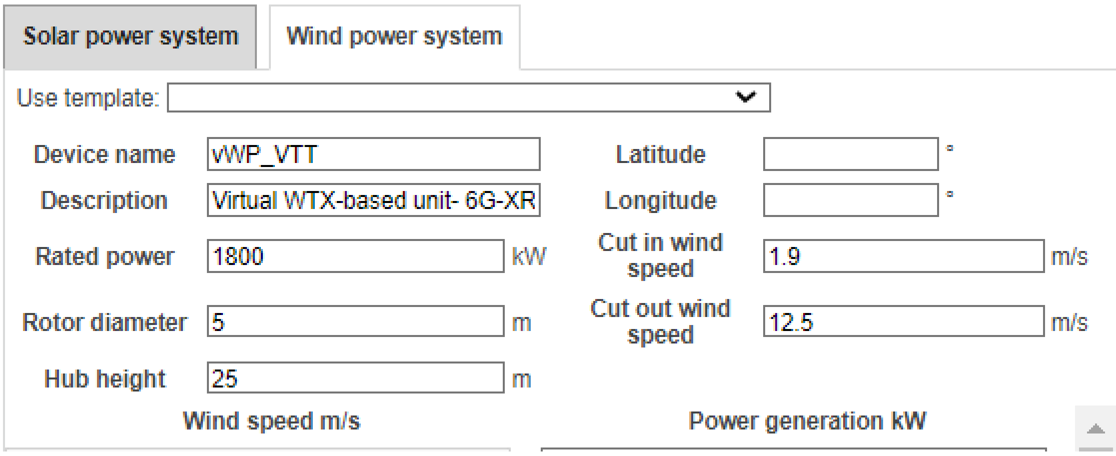

Figure 15: Estimate for virtual Wind power system FMI

The user interface depicted in Figure 15 is the FMI wind power feature, designed to use virtual wind energy production estimation. This platform enables users can also visualize virtual wind power plant by providing parameters like rated power, rotor diameter, hub height, as well as operational wind speeds such as cut-in and cut-out speeds. Additionally, users can input real-time or expected wind speeds to dynamically calculate the potential power generation by wind energy. Some of the features that can be enabled using these forecasts integrated with energy measurement framework are:

Efficient Energy Utilization for gNB: By integrating FMI energy weather forecasts for next 66 hours using FMI APIs, the energy measurement framework can engage power saving measures at gNB sites depending on periods of high solar availability and low availability, thereby reducing reliance on grid electricity during peak sun hours and nighttime. This synchronization minimizes electricity costs and maximizes the use of clean solar energy hence reducing CO2 impact.

Optimal Storage Management: The integrated FMI forecasts aid in the management of dynamic energy storage systems by predicting the accumulated solar production for the next 66 hours. The forecasts are used by the central controller to guide the battery storage system, maintaining power supply continuity keeping charging cycle and health of the battery in optimal state, which can increase their lifespan and efficiency

3.3 ENERGY PRODUCTION ANALYSIS

In this section, the solar energy production and consumption data gathered from the rooftop of the University of Oulu is examined and collected for the training purposes of ML/DL algorithms. These panels are connected to a SolarEdge inverter, which not only converts the DC electricity produced by the panels into AC electricity but also allows for smart monitoring using APIs and power production analysis using a web interface. The data can be fetched with varying sampling rates, from every 15 minutes to hourly energy production data of the accumulated and individual PV modules. Additionally, analysis reports, inverter data, consumption, and meteorological data are also available and can be fetched automatically for real-time constant monitoring and visualization. The SolarEdge setup was installed in July 2020, and all the historic data can be requested with specific sampling rates in CSV format.

Figure 16 shows both solar energy production over a similar period but with higher sampling rate which is monthly accumulated energy date, compared to Figure 17. In Figure 17, the blue spikes represent the daily solar production, which varies significantly day-to-day, largely due to weather conditions and seasonal changes. Both datasets will be used to train algorithms for DL/ML algorithm, to deploy power saving measures more efficiently and forecast energy production and consumption data with more granularity. This dataset also shows that in the energy positive months especially in Nordic conditions base station can run self-sufficiently as off grid-powering system without grid intake.

In VTT's hybrid system, outputs of PV-hybrid's UPS-circuits are equipped with Carlo-Gawazzi ET-112 energy transducers which calculate consumed energy in the circuit every minute and this data is logged and stored to the database in server. Also, real-time sum of all connected meters power is aggregated and stored for further analysis or prospective planning of energy usage.

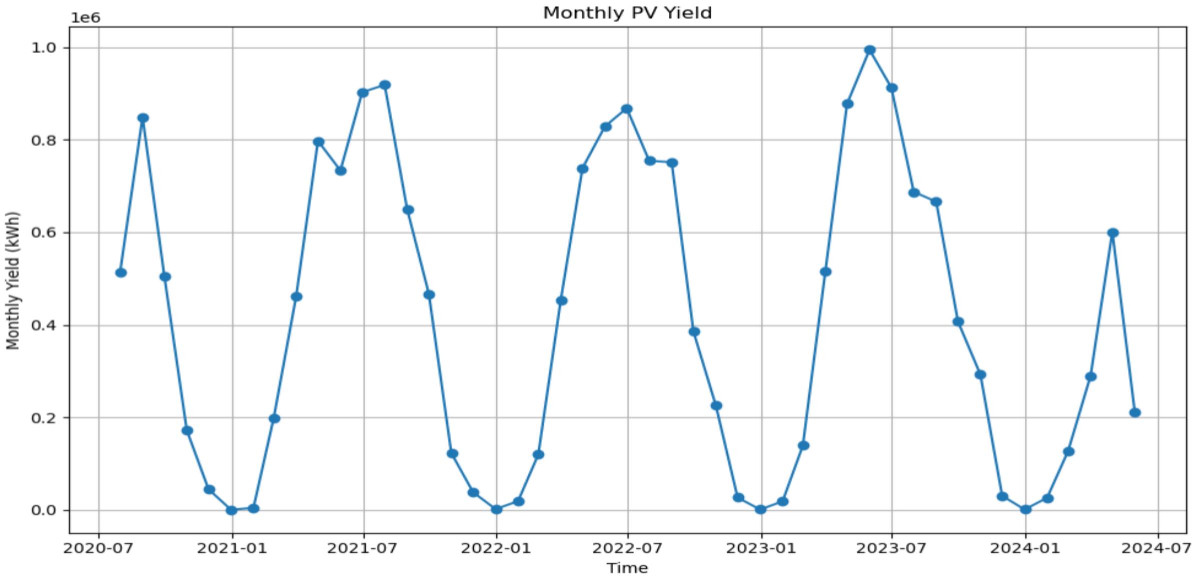

Figure 16: Monthly PV Yield at North-Node

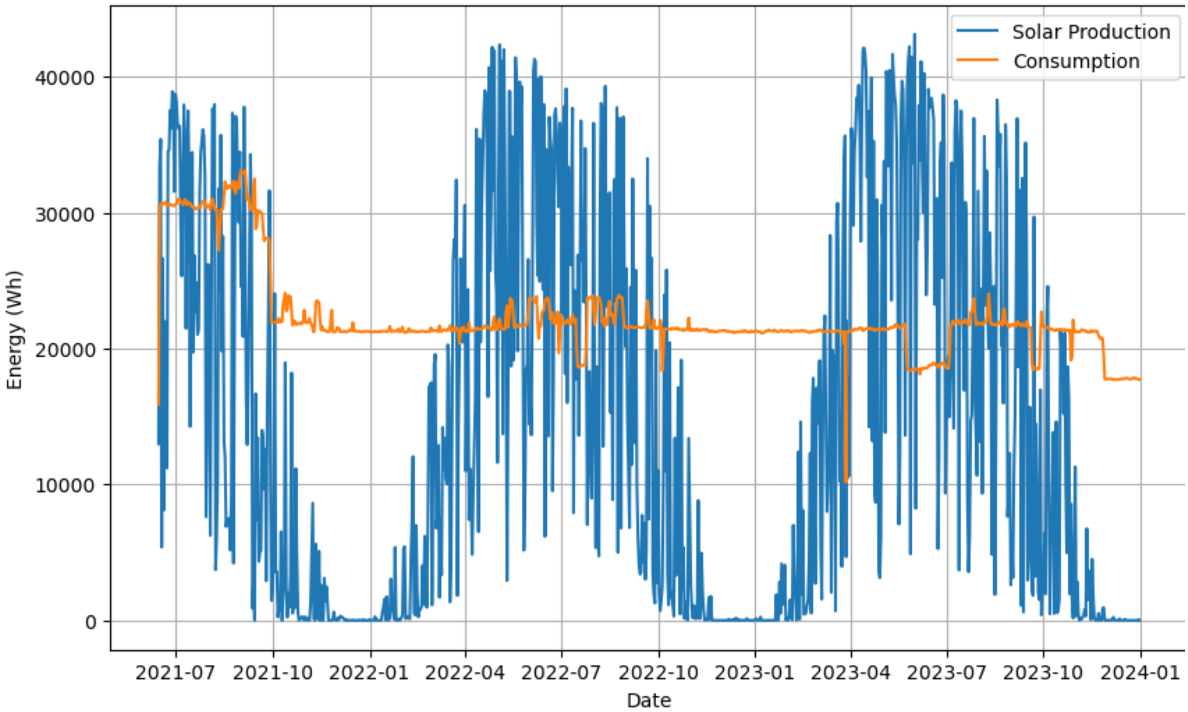

Figure 17: Daily Solar Production vs 5G SA Power Consumption

3.3.1 On-site sensors real-time data

The on-site sensors are important for real-time energy monitoring and for forecasting and estimation of site-specific critical analysis to determine PV array size and wind power. These on-site sensors located at the gNB sites such as solar irradiance and temperate, humidity sensors are integrated within the energy measurement framework at the North Node. For on-site sensors data exchange between the gNB sites, Figure 18 shows the python script which is implemented to automate the collection of sensor data to the deployed MQTT broker at the central controller server. It starts by configuring the MQTT broker's IP address and topic for data publication and sets up the site ID and API key necessary for accessing the SolarEdge API. Upon retrieving the data in JSON format, it publishes the data to the configured MQTT broker (common interface at North Node with sampling rate of every minute. The on-site sensor data consist of solar irradiance sensor for real-time monitoring of direct radiations and two temperature sensors for panel temperature and ambient temperature. The data collection is useful in two ways:

- Historic on-site sensor data can help us train DL/ML algorithms to predict the energy production with more accuracy.
- On-site sensor data with real time monitoring can be useful between the gNB sites at the North Node for activating/deactivating power saving measures.
- Solar irradiance data is useful for scaling the PV modules and sizing the PV array and backup battery size.


```python
import requests
import paho.mqtt.publish as publish
import schedule
import time
import json
from datetime import datetime, timedelta

# MQTT Broker Settings
mqtt_broker = "193.166.32.37"  #  MQTT broker address
mqtt_topic = "energy/sensors"  # MQTT topic to publish
site_id = '1703225'
api_key = 'I8AZZW5B2XGFNM3WSJ8IDA0441Z9TQ9V'

def fetch_sensor_data():
    try:
        # Calculate start and end time
        now = datetime.now()
        endtime = now.strftime('%Y-%m-%d %H:%M:%S')
        starttime = (now - timedelta(minutes=10)).strftime('%Y-%m-%d %H:%M:%S')

        # Fetch sensor data from SolarEdge API
        api_url_sensors = f'https://monitoringapi.solaredge.com/site/{site_id}/sensors?startDate={starttime}&endDate={endtime}&api_key={api_key}'
        response = requests.get(api_url_sensors)
        sensor_data = response.json()

        # Publish sensor data to MQTT broker
        publish.single(mqtt_topic, json.dumps(sensor_data), hostname=mqtt_broker)
        print("Sensor data published to MQTT broker successfully.")
    except Exception as e:
        print("Error fetching or publishing sensor data:", e)

# Schedule job to run every 1 minutes (every 60 seconds)
schedule.every(60).seconds.do(fetch_sensor_data)

while True:
    schedule.run_pending()
    time.sleep(1)
```

Figure 18: Sensor data publish to MQTT broker every 60 seconds

3.3.2 Off-Grid approach using battery energy storage

To run North Node 6G-XR components including gNB sites, remote radios, core and servers in off-grid mode requires careful integration of Battery Energy Storage System (BESS). BESS includes detailed tracking of several critical parameters and KPIs to ensure off-grid usage and completely replying on renewable energy sources (RES). Dynamic BESS requires monitoring of the time since the battery reached its maximum charge and information on insights of the battery charging cycles and usage patterns depending on the gNB load. Events such as automatic synchronization impact the health of the battery and the frequency of low and high voltage spikes and alarms are crucial for addressing potential any issues when it comes to optimal battery management. Here are the key elements to consider:

- Time since last full charge (hh:mm): When the BESS achieved a maximum state of charge (MaxSoC%) or voltage threshold (Vmax).
- Automatic Synchronizations: These events are counted and their impact on battery state of health State of Health (SoH%) is considered, ensuring efficient battery management.
- Low Voltage Alarms: The number of times low voltage alarms are triggered, which can vary based on settings and connected DC-systems, is closely monitored to address potential issues.
- High Voltage Alarms: Like low voltage alarms, tracking the occurrences of high voltage alarms is important, and it depends on the system's settings and connected DC components and gNB load.
- BESS Efficiency KPI: This KPI assesses the system's efficiency by calculating the ratio of discharged energy to charged energy during a specific pre-set period.
- Impact of Monitoring Devices: The influence of monitoring devices and other components connected to the battery side should be considered when evaluating overall system performance and efficiency.
- Real-time Power, Voltage, and Current Monitoring: The BESS's real-time data, including power, voltage, and current from solar chargers, batteries, and DC-load monitoring devices, can be

conveniently tracked using applications like Victron Connect. This real-time data is invaluable for making immediate adjustments and optimizing the system's operation.

3.3.3 Critical Site Analysis

Critical site analysis for the deployment of 6G-XR reference architecture components, specifically for UC5 is a complex process which involves the data collection and forecasting capabilities using on-site sensors, conversion of sunshine into kWh, all kind of system and diffuse radiations, seasonal patterns, shadowing and cloud coverages. To determine the optimal location and number of PV modules, size of the inverter, solar chargers, central controllers, dynamic energy storage capabilities, etc., the load which is gNB sites at the North Node must be determined first. Based on the load requirements and the collected data from the solar irradiance and temperature sensors, the optimal size of the PV array will be determined. Similarly, rated wind power, rotor diameter, hub height, as well as operational wind speeds such as cut-in and cut-out speeds, will be vital for determining the size of the wind turbine

3.3.4 Sizing the required PV array

VTT constructed small PV-hybrid installation in Oulu to clarify all aspects in its operation during the full year and in various environmental conditions. During the planning and construction phase various requirements (e.g. structural issues like mountings, ice-load of modules during winter and safety issues of grid connection, batteries and the whole uninterruptible electricity distribution system) needed to full fill. The farther north we go, the better vertical PV-module installations are. This is due to the reflection of irradiation from snow surface and differences of orbital inclination angle of the sun between the horizontal plane in various locations. For example, during the solar solstice, the highest angle of sun during the midday is in Helsinki 53 degrees and in northern Finland 47 degrees (Rovaniemi), i.e., the deviation from the perpendicular plane to the vertically mounted PV-modules is 6 degrees smaller in Rovaniemi. Comparative maximum angle e.g., in Madrid is 73. This reflects to optimal setup of PV-modules, which is in practice, a compromise of various aspects and local environmental conditions. Even the consumption profile, i.e., when energy is needed during the day could be considered.

Feasibility of the system was checked and inspected from different perspectives and by various experts. Dimensioning of the multifunctional test environment to enable both off-grid and flexible -grid-parallel usage was an essential step in the process. Dimensioning has substantial impact on investment costs and as well control opportunities in daily usage. Flexible operation with the grid interface was an important functionality because the aggregated power of connected E2E-systems was not known in advance, but the modular power supply system was installed permanently. Selected set-up for the laboratory usage and its electrical system's control opportunities enables both controlled grid intake and feed-in depending on the energy balance of the system (surplus or deficit). This way difficult power outages or power curtailments in real off-grid type of trials were avoided (in case the energy balance or sizes of sub-components would not be strictly optimal). Victron Energy's Multiplus-II inverter technology was selected to be applied in this case. It enabled design of controllable and bi-directional AC-energy flows with the grid as well as with the DC-system. Almost uninterruptible (fast <20ms transient time ATS) AC-power distribution to defined E2E-system was realised via 2 distribution cabinets.

Optimal sizing of PV -arrays benefit about experimental 1/min, 1/15min and 1/h datasets on PV-yield during 2023.Monthly datasets about DC-solar charger yield were stored to support scale-up for the full E2E-consumption level. Dataset reveal the real PV-yield (DC-yield to 48VDC system) of vertically wall-mounted southward PV-module setup in VTT Oulu.

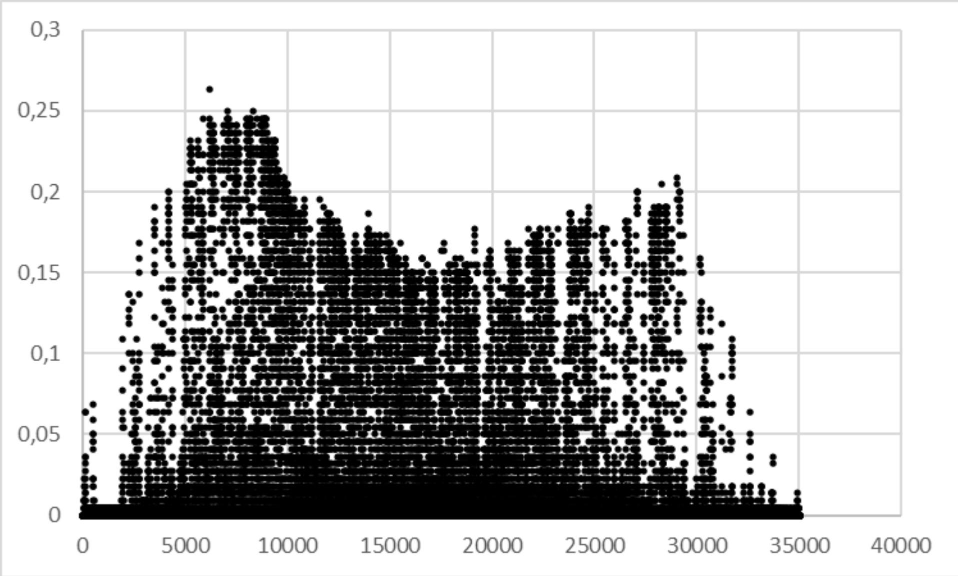

Figure 19: PV-yield Wh/Wp (per installed nominal peak power of the modules) during 15-minute periods in 2023 (VTT's vertical Zencom PV-hybrid installation to south wall in Oulu facility).

In the northern conditions (during the H2 of February to late April) vertical PV-modules were able to harvest reflected irradiation from a surface of snow/ice in the front roof. These reflections increase solar yield in relatively cold condition remarkable way. In the previous picture daily maximum 1/15 min energy yields stand out. This 1/15 min data and its statistical derivatives formulate solid ground for the dimensioning of vertical PV-strings in Oulu -area.

First step in the dimensioning process is to clarify targets e.g., to find overall energy balance (solar yield vs. consumption) in the selected period. Yield can be "matched" to estimated (or measured) consumption in the long dimensioning period (covering e.g., 6-8 months). This period can be called "energy positive dimensioning period" where we investigate also "off-grid" operations in addition to grid-parallel controls. We need this concept because in Nordic conditions there are at least 4 months when solar yield is minimal, and the usage and control pattern of the hybrid system is very different during that time.

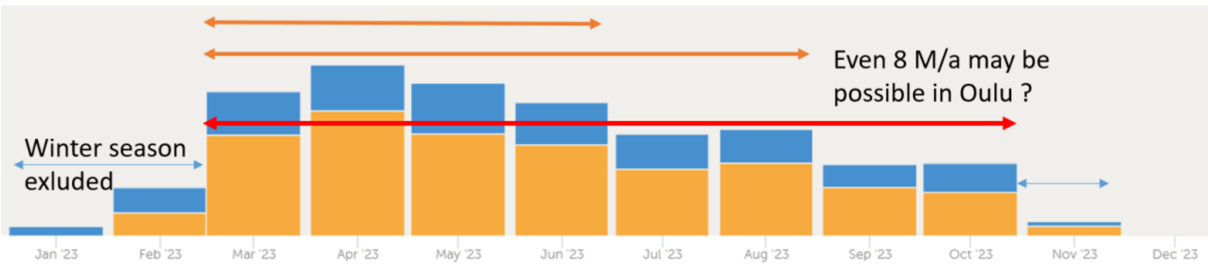

Figure 20: Division of monthly PV-yield during 2023 from January to December

In Figure 20, yellow parts visualize directly used PV-yield and blue parts the proportion of solar yield transferred to battery system and connected DC-loads. Idea about the "dimensioning period" of PV-arrays. (e.g., in Oulu's environmental conditions 6 - 8 months periods starting e.g. from March and ending by September or October is applicable. As a preliminary sizing trial approach 8 months energy positive period was selected as a target for PV -array dimensioning. The hybrid system must adapt to very different usage situations during that period.

Another presumption was made to demonstrate energy balance approach: devices in the PV-supplied "electrical cell" altogether consume averagely 1 kW (which reflect monthly, or even longer-term average measured or estimated energy consumption and is used in the design process as a target level. In practice regional distribution system operators (DSOs) measure all connected entities (e.g., whole macro sites) on hourly basis and that data is available for site owners (telecom -operators). Thus, they are aware about their consumption profiles and longer-term average power levels. This is an easy starting point to dimensioning. In addition to experimental datasets, also tools like PV-GIS service [2], are very useful for the dimensioning of system components, if there is not more detailed information available about the efficiency of the hybrid-system 85 % efficiency factor is necessary to apply. In practice this depend on practical control pattern of loads, share of AC and DC consumptions, converters and amount of energy circulated in the battery circuit. The first step in the dimensioning process is to scale-up experimental monthly PV-yield data or suitable monthly kWh(yield)/kWp(installed nominal power) profile to match estimated long term energy need. In the trial calculation 6 months dimensioning period would result 8,1 kWp PV-array to supply 1kW average load -level in Oulu's site-specific conditions. Correspondingly applying 8 months target period similar approach leads to 9,2 kWp PV-array capable to keep the periodical energy balance positive.

Other experimental rules are:

- Inverter size can be determined based on PV-array's nominal power estimate (if designed to handle loads OFF situation without PV-power curtailment). Warming of the site may be an issue and restrict active power.
- In controllable hybrid installation inverter's AC power can be reduced, when taking DC-charging power and AC (directly connected +DC) loads into account on hourly basis (designing the optimal daily charging scenario and feed-in power profile would require forecasting capabilities)
- In test conditions (Oulu) inverter and DC-charger capacities should be at least 1,3 x sum of PV modules aggregated kWp to be able to harvest detected power peaks. These have occurred during the late winter probably due to the combination of sunny days, snow and ice reflections (on the roof), cold temperatures and low moisture levels in the air.

3.3.5 Battery capacity

Battery technologies have developed a lot during the recent years enabling usage of batteries designed to cyclic usage also in installations where specific back-up batteries were previously used. In practice, there are numerous battery types available and optimized to various use-cases. From the control point of view, battery capacity of the unit is a (fixed) resource which should be used optimal way. Same battery system can be used for various purposes alongside with its prioritized usage. It is also possible to change operative usage or control modes according to changes in the operating environment. Several partly conflicting aspects need to take into account when determinate the size of battery.

To our trial environment, we selected $LiFePO_4$ type of battery blocks with embedded BMS, designed to 6000 cycles and 20 years' service life. Due to the investment costs of this kind of batteries, also the cost of discharged energy is an important factor impacting control principles and overall energy economics of the hybrid installation.

Experimental or simulated hourly (or 1/15 min, 1/min) load and PV-yield profiles are needed as a source information to battery sizing. Also available functionalities reflecting off-grid or bi-directional grid-parallel use-cases should be considered in test calculations. Then by means of time-step based calculations the sufficiency of battery capacity can be tested and ensured in various scenarios (with available functionalities and controls of the system). This can be done also based on power recordings (samples) or taking extreme environmental conditions into account if needed). For example, in practical system we try to keep daily range of SoC% between 25-95% (by means controlled bi-directional energy exchange with the grid). Minimum SoC% could be smaller but in our case 25% level ensures typically few hours operation in worst case conditions (power outage during the dark winter morning when battery is near minimum SoC%).

When thinking off-grid mode, the suitable battery capacity can be estimated by means of PV yield profiles and measured or estimated weekly reference load profiles, which are then scaled to match weekly consumption + losses estimate. In addition, test profiles, which originate or reflect extreme weather periods can be utilized in dimensioning.

Battery sizing procedure was investigated based on one imaginary dataset perhaps reflecting weekly load profile. More specific “tailor-made” weekly reference profiles should be used in real dimensioning exercises. By means of various “reference data sets” operation in case of various traffic patterns could be studied in the later phases of the project. In the dimensioning trial, the weekly consumption dataset was downscaled based on the weekly average to match 1kW + losses 0,18 kW consumption level (η=85%). This consumption dataset could also be recorded from the real base station site by means power quality analyzers or recorders or by applying AC-current loggers. In the PV-GIS system [2], it is also possible to upload specific load-profiles to investigate their impacts on battery sizing by means of sensitivity analysis.

It is important to note that reduced power consumption during the late night reduces the required (expensive) battery capacity. Thus, practical minimum battery size should be determined from cumulated energy during discharging cycles and time on those late-season days (in this trial late October, when PV yield is still slightly bigger than daily consumption taking losses into account).

Another important aspect of the dimensioning is that it must be ensured that the capacities of all system components can handle all” high PV-yield situations” even on exceptional days (e.g., during maintenance of systems, enlargements, and electrical mountings in the laboratory).

Because of the long target period for energy-positive usage, surplus energy in sunny periods accumulate to the system, and it must be:

1) used (e.g., activate intensified cooling or additional loads etc.) or

2) fed into the grid. Accumulated energy must be calculated taking both PV-yield and consumption + charging opportunities into account.

Figure 21 shows how (Energy yield – consumption) develop day by day when “charging cycles with +sign” exceed the energy consumed during the discharging cycle (which determines the minimum battery size). To stabilize this situation excess energy can be fed into the grid during the charging period (pre-planning is needed to optimize costs i.e. feed in during the high-price morning hours is possible if full charging target can be reached later on.) This feed in could be done directly without circulating energy via the battery system.

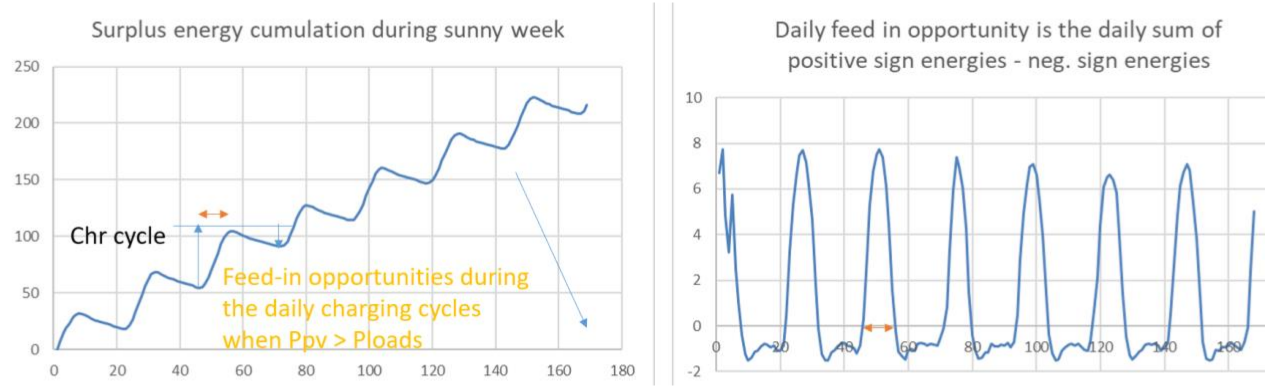

Figure 21: Accumulation of surplus energy on sunny season on weekly level and dimensioning of feed-in opportunities during the charging cycle.

The trial showed how by means of scaled weekly load and yield datasets (April & October were used) minimum inverter size and battery capacities can be determined. Multifunctional and bi-directional inverter capable to operate grid-parallel way enables presumption that power curtailments are not desired or needed and PV- yield should be fully used in AC and DC devices, stored to battery system or feed-in to the local (in house) grid to be used by other nearby appliances. The scheduling of surplus feed-in fits well to working hours and cooling needs during sunny periods.

To calculate feed in power first compare scaled yield - loads equation e.g., on hourly (or 1/15 min) basis and then calculate cumulative sum of daily charging (+signed) and discharging (-) periods. In the trial these were in April: 08-18 charging and 18-08 discharging (ratio 10/14), or during late October 10-16 short charging cycle and 16-10 long discharging period (6/18, due to long dark period needed to find suitable battery size).

Investigating daily discharging period reveal the minimum (applicable) battery capacity needed for the installation to operate in the round the clock- mode (e.g between SoC 15%-95% levels). But this is valid only for days when PV yield is > daily load energy. During the start and end of energy positive design season PV-yield is the restricting factor – not battery size.

In the trial calculation 18-24 kWh nominal battery capacity seem to be suitable and is well fitted to 9,2 kWp PV-system resulting 8 months energy-positive time period enabling long off-grid test run opportunities in VTT Oulu's test premise.

During sunny days, reminder of the difference (energy of the charging cycle – E of discharging cycle) could be fed into the grid during the charging period (in this case <10h and this requires surplus inverter capacity). In the trial calculation max surplus energy was 38 kWh (per day) and it should be fed into the grid during 5-8 h charging period after the break-even point of PV-power and consumption power during typical mornings (corresponding +4,75… 7,6 kW AC inverter power in addition to loads). Thus AC inverter capacity should be suitable to transfer 6,3 - 9,2 kW to AC loads (e.g., 10 kVA in 25C)

Battery data configuration

Utilization of experimental PV-yield data and an imaginary RBS's consumption profile led to the following conclusions:

- Target length of the net energy positive period in Oulu (or high self-sufficiency %) period is 8 months. Longer periods are not feasible.

- PV-modules mounted to vertical walls facing south or similar mast mounted) PV modules can create flatter monthly production power profile through the year and are well sheltered to heavy snow and ice bank (suitable for the environmental conditions on the North Node region).

- Data based dimensioning utilized "Test load profiles" where scaled average power was 1 kW.

- Overall efficiency target >0,85% was taken into account, Pmax of loads was 1,57 kW in the trial calculation. On very high self-sufficiency levels internal losses of the PV-hybrid based power supply unit may increase and as a result a bit lower efficiency factor 0,8 can also be used.

- 8 months energy positive period to this load level requires 9,2 kWp PV-modules (and similar 48V PV to DC -solar charger capacity. Altogether > 9,2 kW and string design, which takes cold conditions (even -40C) and thus elevated open circuit voltage levels of module strings into account.

- At least 200 A(DC) busbar (48V) structure is needed between hybrid's DC components.

- DC to AC inverter capacity should be at least 10 kVA capable to handle maximal feed-in situations at power level 4,7-7,6 kW (thus 3-phase system is required according to Finnish grid-code and local rules).

- Suitable battery capacity would be 24 kWh (nominal, if daily SoC-cycle 15-95% is applied).

Outside the dimensioning period there are 4 excluded winter months when PV-based operation is not possible in practice (daily PV yields << daily consumption of devices). During that season bi-directional AC/DC inverter/charger enable smart utilization of the battery capacity e.g., to charge batteries during the cheapest night (ELSPOT) hours. In charging mode telecom loads are switched through directly to the grid. During the winter season optimized grid intake is necessary to compensate for the energy deficit of the system.

During the winter season:

- Flexible feed-in levels and grid-parallel discharge to loads can be targeted to highest price hours based on day-ahead planning (if price difference is large enough to cover cost of battery degradation).

- Remaining battery capacity can be optimized also to back-up aspect and fulfill set survival requirements (e.g., before storm seasons it is possible to rise remotely minimum SoC-level in the daily charging cycle or even keep batteries full without daily cycling).

In this trial dimensioning exercise batteries charged to 95% SoC would enable 15-16 hours survival time during black-out situation (also during the dark winter season, but only if battery temperature > 13 C. During the energy positive season survival time depend more strongly on weather conditions i.e., several days cumulative solar yield -level.

4 DESCRIPTIVE/INTRODUCTORY ANALYSIS

4.1 POTENTIAL ENERGY CONSERVATION MEASURES/TECHNOLOGIES

One the most recent surveys on RAN energy efficiency is given in [16]. According to it, the best potential for energy savings is expected to be achieved by dynamically switching off cells and carriers (cell sleep modes), by fully utilizing the lean carrier design via discontinuous transmission (DTX), and by dynamic switching off multiple-input multiple-output (MIMO) transmitters. When DTX is enabled and there is no data to be transmitted from the base station, power amplifiers and other RF components can be switched off lowering the idle power consumption. This emphasizes the importance of DTX-aware scheduling. If the served traffic load is low and it can tolerate small delays, it is a good strategy to buffer DL data such that base station can enter DTX for longer periods of time.

A set of experimental measurements were done to evaluate the potential of energy conservation methods at VTT RAN. The reference architecture consisted of a single always-on coverage cell and two capacity cells that can be activated on-demand. The reference architecture is shown in Figure 22. Based on the experiments, the most efficient dynamic energy conservation methods are:

- DTX, which can be turned on permanently as it causes no capacity degradation.
- Capacity cell blocking (light sleep), which stops transmission of all signals and allows turning off power amplifiers (PA) as in DTX for long periods of time.
- Capacity cell deep sleep modes, which allow most of the radio module components to be turned off.
- Reducing the number of active transmitters, which is done autonomously by the base station according to traffic load thresholds.

As an example, the power consumption of the reference standalone architecture with no RRC-connected UEs dropped by 40.6% by enabling DTX and capacity cell deep sleep modes. In this case, the coverage cell is still operational keeping the network available for any UEs. Since the wake-up time from the deep sleep is in the order of minutes, capacity cell deep sleep mode should be used only when the expected traffic load is very low.

Only eMBB subscribers: SA architecture solution

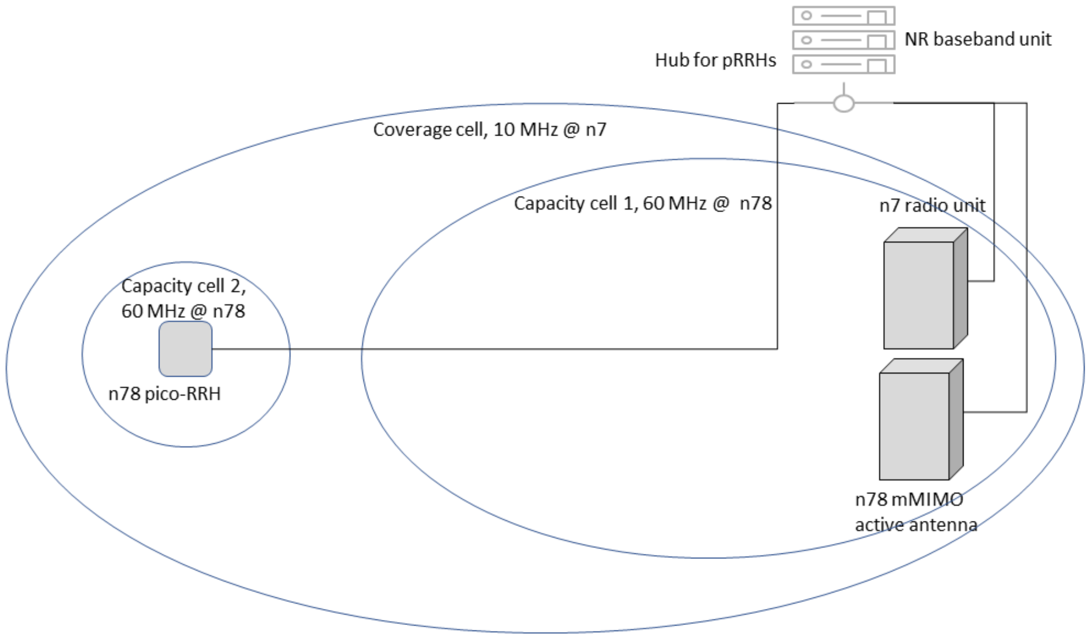

Figure 22: VTT 5G standalone reference architecture.

From the application perspective, several parameters affect energy consumption in server and UEs, especially when considering video streaming applications. Naturally the state-of-the-art processor technology with the used HW can consume less power than older technologies. Video encoding (compression) and decoding with playback are considered the most energy-consuming tasks from the application perspective [5][17]. At the software level, the performance of a video applications can significantly impact both CPU usage and energy consumption. This impact arises from how the application leverages parallelism and threading, as well as the efficiency of the program code. Additionally, combining GPUs with CPUs can lead to energy savings in certain video streaming applications.

Video parametrization is also one important item to be investigated in relation to application energy consumption, which is in our special interest of this project. The efficiency of the parametrization has also some synergy with the used coding technology as the latest coding standardization is more optimized and requires processing higher amount of bits with more complex algorithms [5]. Specifically, the following parameters influence both to server (encoding and packetization) and client (decoding, depacketization and playback) devices:

- Resolution
- Bitrate
- Frame rate
- HDR support
- Bufferization (how much data is uploaded/downloaded due to specific intervals)

It is also notable that the parameter selection done on the server may influence consumption on the client side as well as in the RAN. As an example, according to our first evaluative results, the use of 8K resolution compared to full HD may increase server power usage 35% and client power usage by 50%

when using a general-purpose laptop connected to the North node test environment. A more detailed evaluation in respect to E2E energy efficiency, including RAN, will be provided in D5.2.

4.2 ENERGY OPTIMIZATION

RAN energy optimization problem can be extremely complex as the number of configuration parameters to be adapted can be very large. The optimal solution can be defined as the one minimizing the energy consumption or the operational costs under the constraints of mobile user quality of service. To simplify the problem, it is possible to form a set of cell power saving states that can be used to control the RAN total energy consumption. Consider a hierarchical RAN architecture, where there are coverage cells providing service availability for the given geographical area and a set of overlapping capacity cells providing capacity for the traffic hotspots. In a single sector of a base station site, there is one coverage cell and *N* capacity cells whose coverage areas overlap with the coverage cell but not necessarily with each other. A capacity cell can be in four different states: A) No power saving (DTX still on), B) Autonomous active transmitter reduction enabled, C) Light sleep mode ON, D) Deep sleep mode on. The coverage cell should guarantee network availability and thus only the power saving states A and B are possible for it. The number of power saving states for one sector then becomes $2 \cdot 4^N$. For example, the number of states in the reference architecture shown in Figure 22 becomes 32.

It is possible to estimate the typical power consumption and capacity for the power saving states offline and use this information for the energy optimization problem. The RAN energy optimization problem becomes selecting the optimal set of cell states given the predictions for the local energy availability and for the electricity price as well as the predictions for the traffic requirements and for the location of mobile terminals. Machine learning can be used for the state selection problem or for fine-tuning the parameter values, such as load thresholds for gNB-autonomous actions, within the power saving states.

4.3 VALIDATION OF MEASUREMNT RESULTS

The aim is to execute comparative recordings in relation to fixed installations' most important measurements and other datasets originating from e.g., PV-hybrid's embedded sensors. A preliminary methodology was created, and handheld field measurement instruments were procured and calibrated to enable comparative measurements and data-recordings in the constructed energy measurement framework. That kind of measurements may be useful to reveal potentially malfunctioning measurement devices or erroneously operating "datapipes". Field measurement instruments were calibrated during H1/2024 and their usage was practiced. Applicable power quality analysers, scope-meters, AC+DC voltage + current loggers are capable to record most significant parameters of 1-phase electrical system on weekly basis and thus detect potentially malfunctioning or broken metering units. These activities belong to the task 5.5 and will be executed during the later phases of WP5 work.

4.4 METHODS AND DATASETS TO MEASURE KPIS & KVIS

Historical data-sets (1/15min) were collected and used to estimate preliminary KPIs. A large excel workbook has been used, where various multidimensional time series were processed, checked and interlinked. In further phases of the work, we consider whether the demonstrated KPIs estimation can be implemented above server data (InfluxDB database and Grafana visualizations) more automated way.

The aim is to monitor multidimensional performance of PV-hybrid as a power supply unit of connected E2E telecom loads. For the time being trial analyses were made on monthly basis about:

- energy inputs and outputs (to follow up energy balance and internal losses),
- auxiliary electricity costs (of power intake) and savings by the hybrid PSU,
- cumulative and absolute CO_2 emissions related to the realized and measured power intake,
- self-sufficiency %,
- monthly energy efficiency of PV hybrid as a PSU including realized battery control operations.

Additionally, degradation speed of the battery (i.e., downward trend of state of health, SoH% of the battery blocks) has been monitored.

Introduction of dynamic ESS -feature as an automatic control system of the PV-hybrid during February changed previously managed control patterns. This changed prognoses based control principle is worth of detailed KPI-analysis.

List of KPIs:

-KPI 1: Consumed active energy (kWh):

Note: all devices (in the scope) will be connected to the measurement framework's metering units and their aggregated active power (W) and energy counters sum (Wh) can be calculated and followed-up (as well as individual meters). Data is stored to InfluxDB with time stamps. Only a subset of devices is supplied directly from small PV-hybrid system, but a scale up plan was designed.

KPIs 2,3,4: Absolute active energy (kWh), costs (€) and absolute CO2-savings (g/CO2)

Note: monthly (annual) energy-, cost- and gCO2 emission savings of PV-supplied situation can be compared to normal situation where all devices (AC-loads) would be directly connected to the AC-grid and electricity is procured on hourly ELSPOT-price (OPEX-perspective). Additionally, the value of controllable system (equipped with DESS-controlled hybrid) can be compared to simple grid-tie (grid parallel) AC-inverter alternative based on time-series data.

KPI 5: Monthly self-sufficiency %

Note: Solar share % of total annual energy intake or consumption can be calculated in desired time periods. PV + virtual wind power unit's share, and perhaps PV + virtual Wind + Fuel-cell-unit's energy shares can be estimated. Virtual WP-unit can be reconstructed on weather station m/s wind speed data-stream and real reference wind power units' production curve.

Another challenge is to clarify whether the PV yield's annual share can exceed 70% of annual energy usage taking PV-hybrid's inverter/chargers etc. losses into account. Losses are generated in all electrical transformations (AC/DC, DC/AC) and in the battery. These losses are not linear but can be extracted from energy balance calculations by means of various "envelopes".

KPI 6: Energy efficiency of PSU

Efficiency of the hybrid power supply system acting as a PSU can be followed up (principle: energy outputs / energy inputs in certain period e.g.,1/month follow up or other time frames, taking all control and battery operations into account.

It may be possible to maximize energy efficiency by means of findings from retrospective datasets and analysis results (from the created feed-back loops applying learning by doing changes in control patterns and principles).

In addition to these KPI's, which were specified in WP1 [1], a battery degradation speed should be followed up to reveal the cost for discharged electricity from one battery cycle. This data together with the number of cycles (in full-service life) can be used to estimate costs of battery usage (in the form X snt/kWh). This is an important factor impacting investment and environmental costs and dimensioning, but also daily usage when optimized against hourly electricity price fluctuation.

4.5 E2E ENERGY EFFICIENCY

The E2E energy efficiency using an edge-cloud energy aware service orchestration mechanism is shown in Figure 23. The architecture explains the tasks scheduling and load balancing of different applications using AI tools such as dynamic context switching algorithm and adaptive service orchestration. This mechanism is aligned with applications Quality of Service (QoS) and Quality of Experience (QoE) and energy aware parameters such as forecasted energy availability and energy market prices based on edge-cloud continuum as shown in Figure 23. The architecture also allows to distribute tasks/applications among the three tiers (local edge, edge and cloud) based on the orchestration decision using the parameters such as energy, CPU, GPU; memory and storage. The placement of tasks/applications by the orchestrator is supported by efficiently handling the data among all tiers, using lightweight protocol like MQTT.

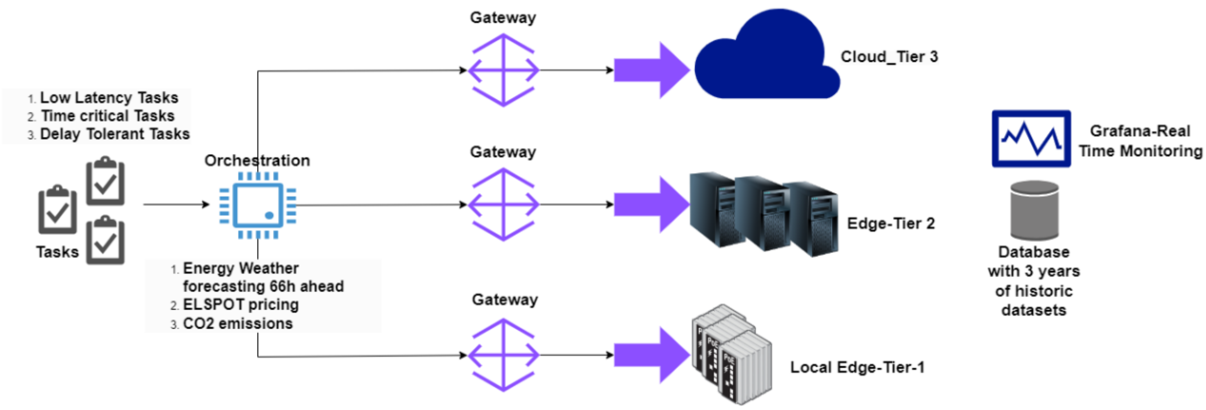

Figure 23: Energy-aware service orchestration

4.5.1 Task scheduling and load balancing

The objective of task offloading and load balancing is to perform E2E energy-efficient operations across the E2E datapath of beyond 5G communication. The utilization of FMI energy weather forecasts is essential for the orchestrator, as shown in Figure 23, to determine the energy availability for the next 66 hours. FMI APIs forecast the energy-related resources for deploying tasks and applications among the three-tier edge-cloud architecture. The forecasted energy parameters include the amount of sunshine in kWh for the next 66 hours, cloud coverage, solar panel and air temperatures, defuse and direct radiations. The orchestrator will utilize these parameters for determining tasks scheduling and load balancing among the three tiers of the proposed architecture in Figure 23.

Similarly, the APIs from ELSPOT's hourly day-ahead electricity market prices and Fingrid, the Finnish national electricity transmission grid operator's estimate of CO2 emissions per kWh of electricity consumed, also play a vital role in energy-aware service orchestration, task scheduling, and load balancing. As shown in Figure 23, the orchestrator can dynamically allocate applications according to the available resources among the three-tier edge-cloud continuum to minimize cost and maximize energy and computing efficiency. These two parameters will assist the orchestration not only in deciding when to buy/sell electricity from the grid based on forecasted energy prices and efficient task scheduling but also in minimizing the carbon footprint using the linked CO2 information from the grid intake.

With the APIs updating the orchestrator on an almost real-time basis, the forecasting capabilities can be enhanced to nowcasting capabilities using ML/DL algorithms. The implementation of this energy-aware service orchestration will be performed using the 6G-XR reference architecture components [1].

5 SUMMARY

Deliverable 5.1 provides a description of the central elements of the constructed sustainability experimentation framework to be used in later phases of 6G-XR project. It describes the specification and architecture of the energy measurement and production frameworks constructed in the North Node for VTT and UOULU sites.

Deliverable 5.1 outlined the 5G trial facilities planned for the 6G-XR project, with a particular emphasis on the hybrid PV infrastructure for the VTT and UOULU sites. It detailed the specifications and 5G architecture for each location, analyzing the current platform capabilities. Crucially, the report charted a roadmap for deploying off-grid powering systems with a focus on hybrid PV infrastructure. This system will be designed for multifunctional operation, supporting both grid-parallel and controllable modes across various self-sufficiency levels depending on load demands and seasonal variations. Chapter 1 is an introductory part describing objectives of the study and structure of the deliverable. In addition, the scope of the experimentation framework, both energy production and consumption sides, are described. The purpose of the experimental energy measurement framework is to enable research and develop activities to develop energy optimization methods including energy production and consumption with advanced methods aiming to boost the decarbonizing the runtime of the mobile networks and services. This way the measurement framework paves the way towards introduction of sustainability experimentation solution including energy forecasting, production, storing and consumption. Chapter 2 presents the state-of-the-art energy measurement framework, providing a detailed specification and functional descriptions of its implementation at both UOULU and VTT sites (North Node). The section elaborates on an E2E energy measurement framework for radio access network infrastructure, application servers, user equipment and tne monitoring systems of the energy production and storage. In addition, it specifies how various nearly real-time metering systems, sensors, renewable energy sources and storages, network components, and APIs for energy forecasting and KPIs have been integrated.

Measurement framework is up and running and ready for upcoming tailor-made trials. The framework is flexible enough to enable enlargements or configuration changes in the E2E-scope if needed. In the created laboratory environment, studies like impact analyses of energy saving functionalities, can be executed by researchers. A subset of E2E-devices, their measurement devices, and embedded sensors' "data pipes", supporting environmental sensors, real-time data pipes from production monitoring systems and supporting data-infrastructure are in place and functioning on both sites of the North Node.

Consumption metering system and auxiliary data systems are capable to store time stamped data and visualize it on real-time basis on desired 1/s basis. Specific datasets and desired periods can also be exported and analysed retrospectively.

Applied solutions (APIs, InfluxDB and Grafana together with mqtt-based data exchange) made it possible to interlink data from the operating context measurements to data-streams originating from external devices and distributed external data services to generate processed datasets and visualize them. This way e.g., indirect impacts of PV-hybrid's control actions on grid intake was processed to time series of CO2- or operative costs. This enables research and development work related to the distributed sub-systems containing multiple, partly interdependent electrical loads (i.e., like several E2E system components) supplied via a resilient microgrid and containing varying degree of alternating primary energy and stored energy from the battery system.

The constructed electricity supply system may integrate various local and renewable energy sources like solar and wind power units together with controllable dynamic energy storage system. Because the system is able to operate flexible way with the bi-directional grid-interface and with varying consumption power levels, performance of various control principles and levels of self-sufficiency can be investigated.

Some supporting data is sampled on 1/min or slower rate to support e.g., long term KPI follow up efforts. Hourly electricity spot pricing and average specific CO_2-emission factors were obtained from external data services to be used in KPI creation. This descriptive report also includes the current and target states of experimentation and validation, along with the functional and non-functional requirements of the overall work package.

Chapter 3 discusses the trials and experimentation infrastructure, with a focus on an approach for powering up the overall E2E test network at desired self-sufficiency level. It presents a high-level architecture and necessary steps for the project and analyses critical site requirements, including sizing the PV array and battery energy storage systems and paves the way towards optimized and smarter operation even in Nordic conditions.

Chapter 4 is a bridge towards the utilization of constructed energy monitoring and data infrastructure and next steps of WP5 work. It elaborates potential energy saving measures and test setups, energy optimization in the wider E2E-scope and additional validation plan of the constructed measurement framework. In addition, the creation process on energy related KPIs is prepared to be implemented according to the research plan.

A set of experimental measurements were done to evaluate the potential of energy conservation methods at VTT RAN. As an example, the power consumption of the reference architecture with no RRC-connected UEs dropped by 40.6% by enabling DTX and capacity cell deep sleep modes. From the application perspective, several parameters affect energy consumption in server and client devices UEs, especially when considering video-related streaming applications. As an example, according to our first evaluative results, the use of 8K resolution compared to full HD may increase server power usage 35% and client power usage by 50% when using a general-purpose laptop connected to the North node test environment. These are only few preliminary examples how this sustainability experimentation framework can be utilized to improve our understanding and knowledge base on energy usage and support efforts to construct energy self-sustainable networks and base stations with 3GPP gNB.

6 REFERENCES

[1] "D1.1 Requirements and Use Case Specifications," 6G-XR project, June 2023.

[2] European Comission, "Photovoltaic Geographical Information System and under it: PVGIS Tools," 2024. [Online]. Available: https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en. [Accessed May 2024].

[3] Ministry of Transport and Communications, "Climate and Environmental Strategy for the ICT Sector in Finland," Available: http://urn.fi/URN:ISBN:978-952-243-595-8, 2021.

[4] Ministry of Transport and Communications, "The ICT sector, climate and the environment : Interim report of the working group preparing a climate and environmental strategy for the ICT sector in Finland," Available: http://urn.fi/URN:ISBN:978-952-243-586-6, 2020.

[5] H. Pihkola, M. Hongisto, O. Apilo and M. Lasanen, "Evaluating the energy consumption of mobile data transfer-from technology development to consumer behaviour and life cycle thinking," *Sustainability ,* vol. 10, no. 7, 2018.

[6] Allbesmart, "OAIBOX, Open source 5G/6G network in a box," 2024. [Online]. Available: https://www.oaibox.com/. [Accessed May 2024].

[7] "D2.1: Orchestration, AI techniques, Endto-end slicing and Signalling for the core," 6G-XR, Feb. 2024.

[8] Victron Energy, "Dynamic ESS – manual," 2024. [Online]. [Accessed May 2024].

[9] Fingrid, "Real-time CO2 emissions estimate," 2024. [Online]. Available: https://www.fingrid.fi/en/electricity-market-information/real-time-co2-emissions-estimate/. [Accessed May 2024].

[10] University of Oulu, "6G Flagship," 2024. [Online]. Available: https://www.6gflagship.com/. [Accessed May 2024].

[11] T. Rauma, M. Lasanen and J. Mäkelä,, "VTT:n 5G-testiverkko Oulussa käyttää nyt aurinkosähköä", Translation: VTT's 5G-Test Network in Oulu utilize now solar power," *VTT's press release,* 5 July 2019.

[12] M. Hongisto, S. J. Rantala, J. Mäkelä, M. Lasanen, J. Huusko, M. Savela and J. Penjala, "Building blocks towards energy self-sufficient / sustained 5G," Poster and demonstration in 5G-seminar, VTT Technical Research Centre of Finland, Espoo, 2019.

[13] Carlo Gavazzi, "Carlo Gavazzi's components and data-sheets of various energy meters," 2024. [Online]. Available: https://www.gavazziautomation.com/. [Accessed May 2024].

[14] W. Azariah, F. A. Bimo , C.-W. Lin, R.-G Cheng, N. Nikaein and R. Jana, "A Survey on Open Radio Access Networks: Challenges, Research Directions, and Open Source Approaches," *Sensor 2024,* vol. 2, no. 3, 2024.

[15] Finnish Meteorological Institute, "New Nordic collaboration to improve weather forecasts," 2024. [Online]. Available: https://en.ilmatieteenlaitos.fi/press-release/436623500. [Accessed May 2024].

[16] D. López-Pérez, A. De Domenico, N. Piovesan, G. Xinli, H. Bao, S. Qitao and M. Debbah, "A Survey on 5G Radio Access Network Energy Efficiency: Massive MIMO, Lean Carrier Design, Sleep Modes, and Machine Learning," *IEEE Communications Surveys & Tutorials,* vol. 24, no. 1, pp. 653-697, 2022.

[17] L. M. P. Larsen, H. L. Christiansen, S. Ruepp, and M. S. Berger, "Toward greener 5G and beyond radio access networks – A survey," *IEEE Open Journal of the Communications Society,* vol. 4, pp. 768-797, 2023.

7 APPENDIX A PV-HYBRID'S TIME SERIES DATA

This appendix A describes exportable 1/minute datapoints' which have been stored to monthly excel files. Currently after the upgrade of VENUS-OS v3.30 some new prognoses and dynamic energy storage system's parameters are documented on 1/hour or 1 per 2 hours basis. DC-metering unit's (BMV-712) cumulative energy counter is read when the number of the counter change (0,01 kWh steps). This below mentioned time series data is originated from the Victron Energy's PV-hybrid's gateway unit and its sub-components. In addition some interlinked and processed data is originated from the VRM-cloud service and external services like ENTSO-E transparency platform (hourly prices) and Solcast-web-service (irradiation). This describes and cover datasets from the power production, storage and control system's side available for the retrospective analysis. Streams can also be used to generate other meaningful datasets by means of simple arithmetical excel calculations. A subset of these can also be monitored nearly real-time basis by means of widgets and Grafana panels. Even smaller subset of data is utilized to control inverter/chargers operations together with the battery system. In addition to these datasets, datapoints from external energy meters and analyzers as well as embedded measurements from devices and external data-services are stored to InfluxDB. Structure of the table depend on connected devices, configuration settings and software versions of the Victron Energy's VRM-cloud-service and version number of the open-source VENUS-operating system in the VENUS-GX device or in other applicable microcontroller orcentral controller device.

Note: when monthly datafiles are combined, alignment of columns must be checked (there may be missing data, due to communication problems). This below mentioned list cover all datapoints related to Victron Energy's VENUS-OS gateway version 3.30 enabling fully automated control of the inverter/charger system by means of dynamic energy storage feature (DESS). Datapoints and structure of the exportable *.log file may change in newer versions.

Instructions to Victron's open-source software can be found here:

https://www.victronenergy.com/live/open_source:start
https://github.com/victronenergy/venus/wiki

V3.30 column No	V3.30 Excel column	SystemDevice and [Insta	Parameter Name	Unit/example	Example (note)	Sampling	Reserved	Reserved	Last row
1	A	timestamp	Europe/Kiev (+03:00)	YYYY-MM-DD hh:mm:ss	2024-05-01 00:00:00	0	0	0	0
2	B	Gateway [0]	VRM Log time offset	s	Typically 1-2 s	0	0	0	0
3	C	Gateway [0]	ESS Scheduled Charging	0	Active/not active	0	0	0	0
4	D	Gateway [0]	Grid setpoint	W	On system boundary	0	0	0	0
5	E	Gateway [0]	Active SOC Limit	%	15-30% used	0	0	0	0
6	F	Gateway [0]	Relay 1 state	0	Open/Closed	0	0	0	0
7	G	Gateway [0]	CCGX Relay 2 state	0	Open/closed	0	0	0	0
8	H	Gateway [0]	DESS hourly restrictions	No restrictions	No Discharge To Grid	No Change From Grid	No Discharge To Grid	No Flow Between Battery and Grid	0
9	I	Gateway [0]	DESS coping strategy	Grid-coping / Target-SOC mode	Battery-coping / Self-consumption mode	0	0	0	0
10	J	Gateway [0]	Dynamic ESS battery capacity	%.2F	0	0	0	0	0
11	K	Gateway [0]	Actual working state of Dynamic ESS	Auto	Off	Blank	0	0	0
12	L	Gateway [0]	SOC target for currently active auto operation	%	25-65 (observed)	0	0	0	0
13	M	Gateway [0]	Dynamic ESS error code	No error	No matching schedule available	0	0	0	0
14	N	Gateway [0]	Battery costs for energy in and out	mu/kWh (mu=monetary unit, €)	May be e.g. 0,07	0	0	0	0
15	O	Gateway [0]	Grid buy price	mu/kWh	May be 0,09€ (From ENTSO-E	Transparency platform	Finnish day ahead ELSPOT pri	+ other cost components)	hourly
16	P	Gateway [0]	Grid sell price	mu/kWh	May be 0,07€ (From ENTSO-E	Transparency platform	Finnish day ahead ELSPOT pri	+ other cost components)	hourly
17	Q	Gateway [0]	Solar Irradiance	W/m²	750	hourly	0	0	0
18	R	Gateway [0]	Solar Irradiance Forecast	W/m²	689	hourly	0	0	0
19	S	Gateway [0]	DESS expected energy to battery flow	Wh	-392	hourly	0	0	0
20	T	Gateway [0]	Default ESS simulated energy to battery flow	Wh	-381	hourly	0	0	0
21	U	Gateway [0]	DESS expected energy to grid flow	Wh	-500	hourly	0	0	0
22	V	Gateway [0]	Default ESS simulated energy to grid flow	Wh	-415	hourly	0	0	0
23	W	Gateway [0]	Default ESS simulated SOC	%	25	hourly	0	0	0
24	X	Gateway [0]	Dynamic ESS scheduled SOC	%	25	hourly	0	0	0
25	Y	Gateway [0]	Total solar forecasted yield for today	Wh	6452	Calculated 1 per 2 hour	0	0	0
26	Z	Gateway [0]	Total solar forecasted yield for today - BETA	Wh	9498	Calculated 1 per 2 hour	0	0	0
27	AA	Gateway [0]	PV Yield model day-ahead accuracy	%	Empty column for future usage	0	0	0	0
28	AB	Gateway [0]	PV Yield model day-ahead accuracy - BETA	%	Empty column for future usage	0	0	0	0
29	AC	Gateway [0]	PV Yield model day-ahead MAPE	%	Empty column for future usage	0	0	0	0
30	AD	Gateway [0]	PV Yield model day-ahead MAPE - BETA	%	Empty column for future usage	0	0	0	0
31	AE	VE.Bus System [261]	Phase rotation	0	Ok	0	0	0	0
32	AF	VE.Bus System [261]	Input voltage phase 1	V	228,8	1/min	0	0	0
33	AG	VE.Bus System [261]	Input current phase 1	A	6,2	1/min	0	0	0
34	AH	VE.Bus System [261]	Input frequency 1	Hz	50,1	1/min	0	0	0
35	AI	VE.Bus System [261]	Input power 1	W	1394	1/min	0	0	0
36	AJ	VE.Bus System [261]	Output voltage phase 1	V	228,8	1/min	0	0	0
37	AK	VE.Bus System [261]	Output current phase 1	A	1,7	1/min	0	0	0
38	AL	VE.Bus System [261]	Output frequency	Hz	50	1/min	0	0	0
39	AM	VE.Bus System [261]	Output power 1	W	395	1/min	0	0	0
40	AN	VE.Bus System [261]	Voltage	V	49,08	1/min	0	0	0
41	AO	VE.Bus System [261]	Current	A	17,7	1/min	0	0	0
42	AP	VE.Bus System [261]	Active input	0	AC Input 1	1/min	0	0	0
43	AQ	VE.Bus System [261]	Active input current limit	A	32	1/min	0	0	0
44	AR	VE.Bus System [261]	AC Input 1 Current Limit	A	32	1/min	0	0	0
45	AS	VE.Bus System [261]	VE.Bus state	0	Bulk	1/min	Absoption	Passthru	Also other
46	AT	VE.Bus System [261]	VE.Bus Error	0	No error	1/min	0	0	0
47	AU	VE.Bus System [261]	Switch Position	0	On	1/min	Off	0	0
48	AV	VE.Bus System [261]	Temperature	0	Ok	1/min	0	0	0
49	AW	VE.Bus System [261]	Low battery	0	Ok	1/min	0	0	0
50	AX	VE.Bus System [261]	Overload	0	Ok	1/min	0	0	0
51	AY	VE.Bus System [261]	Temperatur sensor alarm	0	Ok	1/min	0	0	0
52	AZ	VE.Bus System [261]	Voltage sensor alarm	0	Ok	1/min	0	0	0
53	BA	VE.Bus System [261]	High DC Ripple	0	Ok	1/min	0	0	0
54	BB	VE.Bus System [261]	Temperature L1	0	Ok	1/min	0	0	0
55	BC	VE.Bus System [261]	Low battery L1	0	Ok	1/min	0	0	0
56	BD	VE.Bus System [261]	Overload L1	0	Ok	1/min	0	0	0
57	BE	VE.Bus System [261]	High DC Ripple L1	0	Ok	1/min	0	0	0
58	BF	VE.Bus System [261]	Temperature L2	0	Ok	1/min	0	0	0
59	BG	VE.Bus System [261]	Low battery L2	0	Ok	1/min	0	0	0
60	BH	VE.Bus System [261]	Overload L2	0	Ok	1/min	0	0	0
61	BI	VE.Bus System [261]	High DC Ripple L2	0	Ok	1/min	0	0	0
62	BJ	VE.Bus System [261]	Temperature L3	0	Ok	1/min	0	0	0
63	BK	VE.Bus System [261]	Low battery L3	0	Ok	1/min	0	0	0
64	BL	VE.Bus System [261]	Overload L3	0	Ok	1/min	0	0	0
65	BM	VE.Bus System [261]	High DC Ripple L3	0	Ok	1/min	0	0	0
66	BN	VE.Bus System [261]	Charge state	0	Bulk	1/min	Absoption	Perhaps also Float and Storage	0
67	BO	VE.Bus System [261]	BMS lost	0	No alarm	1/min	0	0	0
68	BP	VE.Bus System [261]	Unequal output distribution in parallel system: L1	0	Ok	1/min	0	0	0
69	BQ	VE.Bus System [261]	Unequal output distribution in parallel system: L2	0	Ok	1/min	0	0	0
70	BR	VE.Bus System [261]	Unequal output distribution in parallel system: L3	0	Ok	1/min	0	0	0
71	BS	VE.Bus System [261]	Unequal mains distribution in parallel system: L1	0	Ok	1/min	0	0	0
72	BT	VE.Bus System [261]	Unequal mains distribution in parallel system: L2	0	Ok	1/min	0	0	0
73	BU	VE.Bus System [261]	Unequal mains distribution in parallel system: L3	0	0	1/min	0	0	0
74	BV	VE.Bus System [261]	Ignore AC input	0	Not ignored	1/min	0	0	0
75	BW	Battery Monitor [512]	Voltage	V	49,09	1/min	0	0	0
76	BX	Battery Monitor [512]	Current	A	14,3	1/min	0	0	0
77	BY	Battery Monitor [512]	Battery temperature	C	24	1/min	0	0	0
78	BZ	Battery Monitor [512]	State of charge	%	23	1/min	0	0	0
79	CA	Battery Monitor [512]	State of health	%	87	1/min	0	0	0
80	CB	Battery Monitor [512]	CVL - Charge Voltage Limit	V	0	1/min	0	0	0
81	CC	Battery Monitor [512]	CCL - Charge Current Limit	A	100	1/min	Stepwise for amount of blocks	0	0
82	CD	Battery Monitor [512]	DCL - Discharge Current Limit	A	100	1/min	Stepwise for amount of blocks	0	0
83	CE	Battery Monitor [512]	Low voltage alarm	0	No alarm	1/min	0	0	0
84	CF	Battery Monitor [512]	High voltage alarm	0	No alarm	1/min	0	0	0
85	CG	Battery Monitor [512]	Low battery temperature alarm	0	No alarm	1/min	0	0	0
86	CH	Battery Monitor [512]	High battery temperature alarm	0	No alarm	1/min	0	0	0
87	CI	Battery Monitor [512]	Cell Imbalance alarm	0	No alarm	1/min	0	0	0
88	CJ	Battery Monitor [512]	High charge current alarm	0	No alarm	1/min	0	0	0
89	CK	Battery Monitor [512]	High discharge current alarm	0	No alarm	1/min	0	0	0
90	CL	Battery Monitor [512]	High charge temperature alarm	0	No alarm	1/min	0	0	0
91	CM	Battery Monitor [512]	Low charge temperature alarm	0	No alarm	1/min	0	0	0
92	CN	Battery Monitor [512]	Internal Failure	0	No alarm	1/min	0	0	0
93	CO	Solar Charger [258]	Voltage	V	49,06	1/min	0	0	0
94	CP	Solar Charger [258]	Current	A	9,6	1/min	0	0	0
95	CQ	Solar Charger [258]	Battery watts	W	1382	1/min	0	0	0
96	CR	Solar Charger [258]	Load state	0	Off	1/min	0	0	0
97	CS	Solar Charger [258]	Charger on/off	0	On	1/min	Off	0	0
98	CT	Solar Charger [258]	Charge state	0	Off	1/min	Ext. Control	May also be: On	0
99	CU	Solar Charger [258]	PV voltage	V	105,61	1/min	0	0	0
100	CV	Solar Charger [258]	PV power	0	1413	1/min	0	0	0
101	CW	Solar Charger [258]	Solar charge current limit	A	60	1/min	0	0	0
102	CX	Solar Charger [258]	MPPT State	Off	MPPT active	1/min	0	0	0
103	CY	Solar Charger [258]	Relay on the charger	Open	Closed	1/min	0	0	0
104	CZ	Solar Charger [258]	Yield today	kWh	10,91	1/min	0	0	0
105	DA	Solar Charger [258]	Maximum charge power today	W	1532	1/min	0	0	0
106	DB	Solar Charger [258]	Yield yesterday	kWh	7,67	1/min	0	0	0
107	DC	Solar Charger [258]	Maximum charge power yesterday	W	1645	1/min	0	0	0
108	DD	Solar Charger [258]	Error code	0	No error	1/min	0	0	0
109	DE	Solar Charger [258]	User yield	kWh	1234,54	1/min	0	0	0
110	DF	Solar Charger [258]	PV Yield Solar Charger Forecast	Wh	1110,15	1/hour	0	0	0
111	DG	Solar Charger [258]	PV Yield Solar Charger Forecast - BETA	Wh	1188,05	1/hour	0	0	0
112	DH	Tank [20]	Tank status	0	Not used	1/min	0	0	0
113	DI	Tank [21]	Tank status	0	Not used	1/min	0	0	0
114	DJ	Tank [22]	Tank status	0	Not used	1/min	0	0	0
115	DK	System overview [0]	#1 Low SOC; discharge disabled	Off	On	1/min	0	0	0
116	DL	System overview [0]	#2 BatteryLife is active	Off	On	1/min	0	0	0
117	DM	System overview [0]	#3 Charge disabled by BMS	Off	On	1/min	0	0	0
118	DN	System overview [0]	#4 Discharge disabled by BMS	Off	On	1/min	0	0	0
119	DO	System overview [0]	#5 Slow charge is active	Off	On	1/min	0	0	0
120	DP	System overview [0]	#6 Charge disabled by user setting	Off	On	1/min	0	0	0
121	DQ	System overview [0]	#7 Discharge disabled by user setting	Off	On	1/min	0	0	0
122	DR	System overview [0]	PV - DC-coupled	W	1339	1/min	0	0	0
123	DS	System overview [0]	AC Consumption L1	W	1321	1/min	0	0	0
124	DT	System overview [0]	Grid L1	W	1456	1/min	0	0	0
125	DU	System overview [0]	DC System	W	380	1/min	0	0	0
126	DV	System overview [0]	Voltage	V	49,87	1/min	0	0	0
127	DW	System overview [0]	Current	A	16,8	1/min	0	0	0
128	DX	System overview [0]	VE.Bus charge current	A	17,9	1/min	0	0	0
129	DY	System overview [0]	Battery Power	W	676	1/min	0	0	0
130	DZ	System overview [0]	VE.Bus charge power	W	956	1/min	0	0	0
131	EA	System overview [0]	Battery SOC	%	35	1/min	0	0	0
132	EB	System overview [0]	Battery state	discharging	charging	1/min	idle	0	0
133	EC	System overview [0]	DVCC Multiple batteries alarm	0	No alarm	1/min	0	0	0
134	ED	System overview [0]	GX Error #48 DVCC with incompatible firmware	0	No alarm	1/min	0	0	0
135	EE	System overview [0]	No grid meter alarm	0	OK	1/min	0	0	0
136	EF	System overview [0]	AC-Input	0	Grid	1/min	0	0	0
137	EG	System overview [0]	Consumption Forecast	Wh	424,51	1/hour	0	0	0
138	EH	System overview [261]	Grid alarm	0	Grid ok	1/min	0	0	0
139	EI	Grid meter [30]	Grid L1 - Power	W	1365	1/min	0	0	0
140	EJ	Grid meter [30]	Grid meter voltage L1	V	228,6	1/min	0	0	0
141	EK	Grid meter [30]	Grid meter current L1	A	6,1	1/min	0	0	0
142	EL	Temperature sensor [23]	Temperature status	0	Open circuit	1/min	0	0	0
143	EM	Temperature sensor [24]	Temperature status	0	Open circuit	1/min	0	0	0
144	EN	DC Load [260]	Battery Voltage	0	49,28	1/min	0	0	0
145	EO	DC Load [260]	Load Current	0	3,9	1/min	0	0	0
146	EP	DC Load [260]	Total energy consumed	kWh	38,83	1/few 3-4 minutes whe	Cumulative counter	0	0
147	EQ	DC Load [260]	Low voltage alarm	0	No alarm	1/min	0	0	0
148	ER	DC Load [260]	High voltage alarm	0	No alarm	1/min	0	0	0
149	ES	DC Load [260]	Low auxiliary voltage alarm	0	No alarm	1/min	0	0	0
150	ET	DC Load [260]	High auxiliary voltage alarm	0	No alarm	1/min	0	0	0
151	EU	DC Load [260]	Low temperature alarm	0	No alarm	1/min	0	0	0
152	EV	DC Load [260]	High temperature alarm	0	No alarm	1/min	0	0	0

Co-funded by the European Union