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Horizon Europe

EUROPEAN COMMISSION

European Climate, Infrastructure and Environment Executive Agency (CINEA)

Grant agreement no. 101136131

SHIFT to Direct Current

Deliverable D2.1
Network Design Tool for DC Solutions

Document Details

Due date	31-03-2025
Actual delivery date	31-03-2025
Lead Contractor	EDF
Version	1.0
Prepared by	Elsy EL SAYEGH, Amel ADDALA, Rémi LEMBEYE (EDF), Pedro COSTA, Manuel Pedro NETO (INESC), Motaz AYIAD (NEW), Javier IGLESIAS (HITCH), Nicolas ROUSSELET (NEXNS), Katharina HETZENECKER (RWTH)
Reviewed by	Kilian DREXLER (FRAUN), Lina RUIZ (NEXNS)
Dissemination Level	Public

Project Contractual Details

Project Title	Shift to Direct Current
Project Acronym	Shift2DC
Grant Agreement No.	101136131
Project Start Date	01-12-2023
Project End Date	31-05-2027
Duration	42 months

Document History

Version	Date	Contributor(s)	Description
0.1	14-01-2025	EDF	Table of Contents
0.2	03-03-2025	EDF, NEW, INESC, NEXNS, RWTH	Internal draft
0.3	17-03-2025	EDF	Internal review
1.0	31-03-2025	FRAUN, NEXNS	Final version

Disclaimer

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Acknowledgment

This document is a deliverable of Shift2DC project. Shift2DC has received funding from the European Union´s Horizon Europe programme under grant agreement no. 101136131.

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Executive Summary

The **SOL23 Direct Current (DC) Network Design Tool**, developed within the Shift2DC project (WP2, Task T2.1), provides a methodology for the:

- **Electrical sizing** of DC networks (cross-section of cables, nominal power of converters)
- **Performance evaluation** (energy losses, voltage distribution, etc.) of DC networks.

The tool addresses the lack of open-source solutions tailored to DC systems, offering functionalities for load flow (LF) analysis, component sizing, and Key Performance Indicator (KPI) assessment. It is particularly suited for Low Voltage Direct Current (LVDC) applications in data centers, buildings, industrial facilities, and ports, where DC networks can offer efficiency and reliability benefits.

The deliverable is structured as follows:

- **Chapter 1** introduces the tool and its scope, objectives, and requirements, emphasizing its role in the Shift2DC project.
- **Chapter 2** presents the "Read me" of the tool. It details the installation steps, the file structure, the usage, the operational workflow, and the limitations of the tool.
- **Chapter 3** outlines the input data structure of the tool, categorizing parameters essential for network modeling, load flow, and sizing.
- **Chapter 4** describes the sizing methodology, highlighting the algorithm steps, including the load flow calculations. It also presents the time-step load flow under droop control as a key feature for performance evaluation.
- **Chapter 5** presents the performance assessment methodology, focusing on energy, efficiency, and economic KPIs, which quantify the benefits of DC networks compared to Alternative Current (AC) alternatives.
- **Chapter 6** presents the summary of the main findings and conclusions.

The **SOL23 tool** is implemented in **Python**, leveraging power system modeling libraries such as *pandapower*, and is designed to be accessible to engineers and researchers without deep expertise in DC networks. Starting with a Technology Readiness Level (TRL) equal to 3, the developments aim to enhance its capabilities and usability, with a target TRL of 6.

This deliverable serves as a **comprehensive guide to the tool**, providing a foundation for further refinement and application in real-world DC network design.

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Acronyms

AC	Alternating Current
AFE	Active Front-End
Al	Aluminum
CAPEX	Capital Expenditures
Cu	Copper
COS	CurrentOS
C&I	Commercial and industrial
DAB	Dual Active Bridge
DC	Direct Current
EMI	Electromagnetic interference
EMS	Energy Management System
EU	European Union
EUR	Euros
EV	Electric Vehicle
GUI	Graphical user interface
HVAC	Heating, Ventilation, and Air Conditioning
IEC	International Electrotechnical Commission
ILC	Interlink Converter
IW	Inter-tripping Wire
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LF	Load flow
LVDC	Low Voltage Direct Current
ODCA	Open DC Alliance
OPEX	Operational Expenditures
PDU	Power Distribution Units
PF	Power flow
PV	PhotoVoltaic
PVC	PolyVinyl Chloride
SLD	Single-line diagram
SST	Solid-State Transformer
TRL	Technology Readiness Level
UC	Use Case
UPS	Uninterruptible Power Supply
WP	Work Package
XLPE	Cross-linked polyethylene

1 Introduction

This chapter introduces the main characteristics and motivations for the development of a tool supporting the design of DC grids namely the main components such as cables and inverters/converters.

1.1 Scope, Overview, and Objectives of the Deliverable

Deliverable Context

This deliverable (D2.1) results from the first task (T2.1 - Network Design Tool for DC Solutions) in the second Work Package (WP2) of the Shift2DC project. It presents the development of a tool designed to support the sizing and performance analysis of DC networks. The main characteristics of the tool are the following:

Problem Addressed

- Existing network design tools mainly address AC systems and are not optimized for DC systems.
- There is a lack of open-source design tools for DC systems evaluating DC implementation benefits at an early stage[1].

Main Objective

- The development of a design tool for DC networks, enabling sizing, evaluation, and comparison of their benefits.

Expected Advantages

- The tool offers a robust framework for the preliminary design and analysis of DC systems compared to conventional AC radial networks[2]. For a given use case, the tool provides:
    1. Electrical sizing of cables (cross-section [mm²]) and converters (nominal power [kW]),
    2. Evaluation of KPIs.
- The tool assists stakeholders in making informed decisions regarding the transition to and implementation of DC solutions.

Applications

- The tool applies to LVDC networks across multiple sectors, such as data centers, buildings, industrial applications, and ports, where DC technology can offer significant advantages in terms of energy efficiency, operational costs, and sustainability.

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[1] To our knowledge, only *etap* commercial design tool is capable of DC network static sizing and loss calculation.

[2] We assume that existing tools already handle the design of AC networks.

Requirements

Several important characteristics and requirements must be considered during the development of the DC network design tool:

- The tool must integrate **static models** of specific devices, such as converters and DC cables, which are vital elements of DC grids. This is necessary for conducting feasibility studies and assessments. Voltage control strategies should be implemented in the models of all converters as an option to ensure accurate voltage level and power loss calculations.
- The tool must be able to implement various DC **ecosystem rules** (Current/OS (COS)[3] and Open Direct current alliance (ODCA)[4]).
- The tool must cover a **wide range of applications,** including data centers, buildings, industrial applications, and ports.
- The tool should not require **specific in-depth knowledge** of DC technologies (end-users will be researchers, developers, or engineers).
- The tool is preferable to be **open source**.
- The tool should **output:**
    1. **Electrical sizing** of the DC solution under examination, performing power flow (PF) calculations.
    2. **Performance analysis** of the DC solution, including economic, environmental, and efficiency KPIs.

Programming Language

- The network design tool was developed from scratch in Python. Existing Python libraries for power systems modeling were used to accelerate the development process (e.g., Panda power[5]).

Scope

- Commercial and Industrial (C&I) applications.

TRL

- **Starting TRL:** 3
- **Target TRL:** 6

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[3] Current/OS

[4] Open Direct Current Alliance

[5] https://pandas.pydata.org/pandas-docs/stable/index.html

1.2 Relationship with Other Deliverables

This deliverable (D2.1) of task T2.1 of WP2 is closely linked to the outcomes of task **T1.4 of WP1** and is essential for **WP4**, and WP5 (Figure 1-1):

- On the one hand, task T2.1 builds upon the specifications defined in task T1.4.
- On the other hand, task T2.1 enables the design of DC solutions that will guide the sizing of the demonstrators in WP4. In addition, task T2.1 allows for evaluating the performance of DC solutions, supporting studies in WP5 about innovation, standardization, and cost-benefit analysis.

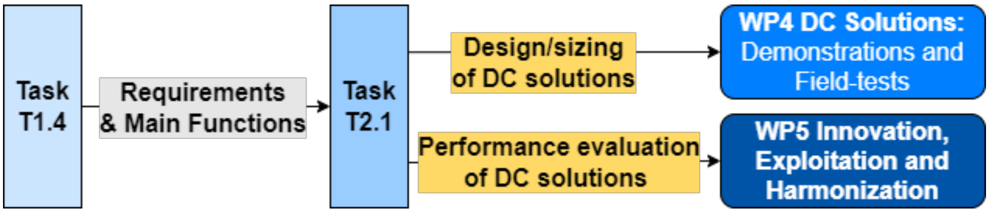

Figure 1-1 Interdependencies of task T2.1 with other project deliverables.

1.3 Structure of the Deliverable

This deliverable is structured around six chapters:

- **Chapter 1**: Introduction and presentation of the deliverable objectives.
- **Chapter 2**: “Read me” of the design tool developed in T2.1.
- **Chapter 3**: Description of the inputs of the design tool.
- **Chapter 4**: Description of the electrical sizing calculation in the design tool.
- **Chapter 5**: Description of the performance evaluation in the design tool.
- **Chapter 6**: Summary of the main findings and conclusions.

2 Read me of the Design Tool

This section provides a comprehensive overview of the tool's architecture, detailing its key components and functionalities. Additionally, it offers clear guidelines for the installation process, ensuring a correct setup and optimal configuration.

2.1 Overview of the Design Tool

The network design tool developed in Task 2.1 of WP2 is a Python-based application that assists in the design/sizing and performance evaluation of DC networks. The tool enables users to analyze different configurations and scenarios to assess the feasibility and benefits of implementing DC solutions.

2.2 Installation of the Tool

Link of the Project Git

- The link to download the design tool on the project git: SHIFT2DC/dc_design_tool

Prerequisites

- Python 3.10.0. Make sure you have Python 3.10.0 installed. Download it here.

Installation Steps

1. Clone the repository:
        - `git clone [REPO_URL]`
        - `cd [PROJECT_FOLDER]`
2. Create a virtual environment:
    - Linux/macOS:
        - `bash`
        - `python3.10 -m venv venv`
    - Windows:
        - `cmd`
        - `py -3.10 -m venv venv`
3. Activate the virtual environment:
    - Linux/macOS:
        - `bash`
        - `source venv/bin/activate`
    - Windows:
        - `cmd`
        - `.\venv\Scripts\activate`
4. Install dependencies:
        - `pip install -r requirements.txt`
5. Usage/Running the Tool:
    - Fill in the input files described in section 2.4.1.
    - Run the `main.py`
    - With the virtual environment activated:
        - `python main.py`
6. Virtual Environment (Reminders):
    - To exit the virtual environment:
        - `deactivate`
7. To delete the virtual environment:

    - Remove the venv folder from your project directory.
8. Contribution:
    - Ensure you use Python 3.10.0 and the virtual environment.
    - Install dependencies from requirements.txt.
    - Verify your Python version before contributing:
        - *python --version*

The installation guide described above can be found in README.md in the dc_design_tool folder.

2.3 File Structure in the Tool

The design tool consists of several Python scripts organized as follows:

- main.py: Main execution script that integrates all functionalities.
- utilities_create.py: Network creation functions.
- utilities_kpis.py: Functions for computing efficiency, economic, and environmental KPIs.
- utilities_load_flow.py: Load flow calculations.
- utilities_assets_profile.py: Assets profile generation.
- utilities_net_topology.py: Network topology handling.
- utilities_plot_save.py: Saving and plotting.
- utilities_read.py: File reading and input parsing.
- utilities_worst_case_sizing.py: Worst-case sizing calculations.

2.4 Usage of the Tool

2.4.1 Input Files

Input Files

- input_file_grid_data.xlsx: Defines the network topology, loads, and other parameters.
- catalog_cable.xlsx: Contains the available cables and their specifications.
- catalog_converter.xlsx: Contains the available converters and their specifications.

2.4.2 Running the Tool

Running the Tool

- Execute main.py to run the full workflow:
    - *python main.py*
- This script will do the following:
    - Read input files and create an initial DC network.
    - Size the network based on worst-case scenarios (details in section 4).
    - Evaluate the sized network's performance on worst-case scenarios.
    - Perform time-step load flow analysis.
    - Compute and save KPIs.

2.4.3 Output Files

Output Files

- output_sizing_results_file.xlsx: Contains the results of network sizing.
- output_sizing_results_plot_network.html: Visualizes the network topology.
- output_evaluation_results_scenario_'x'_file.xlsx: Contains the load flow results for the sized network under scenario 'x' (where x = 1, 2, 3) defined in the input Excel file.
- output_evaluation_results_scenario_'x'_plot_network.html: Visualizes the load flow results for the sized network under scenario 'x' (where x = 1, 2, 3).
- output_timesteps_LF_results.xlsx: Contains the load flow results with droop control, considering time-series data of the sized network.
- output_kpis_results_file.xlsx: Stores the calculated KPIs.

2.5 Architecture and Operational Workflow of the Tool

The operational workflow of the DC solution design tool is illustrated in Figure 2-1.

Inputs (details in Chapter 3):

- **User-defined grid data input file** (input_file_grid_data.xlsx): Defines the network topology, assets data and profiles (loads, generators, etc.), converters, DC ecosystem, and other parameters (details in section 3.1).
- **Catalog/Library for cables** (catalog_cable.xlsx): Specifications and technical parameters of available DC cables (details in section 3.2).
- **Catalog/Library for converters** (catalog_converter.xlsx): Specifications and technical parameters of available AC/DC, DC/AC, and DC/DC converters (details in section 3.2).

Calculations fulfilled by the tool and their respective Outputs:

1. **Design/sizing analysis** of DC solutions (details in Chapter 4):
    - Preliminary sizing of the cables (cross-sections) of the network.
    - Preliminary sizing of the converters (nominal power) of the network.
2. **Performance evaluation** of DC solutions (details in Chapter 5):
    - Evaluation of efficiency KPI (details in section 5.1).
    - Evaluation of environmental KPI (details in section 5.2).
    - Evaluation of economic KPI (details in section 5.3).

Thanks to these two main functionalities, the tool allows users to compare different configurations by simulating various load and generation profiles.

It is important to note that, to perform these calculations, the tool uses power flow analysis to compute voltage profiles, current distributions, and power losses.

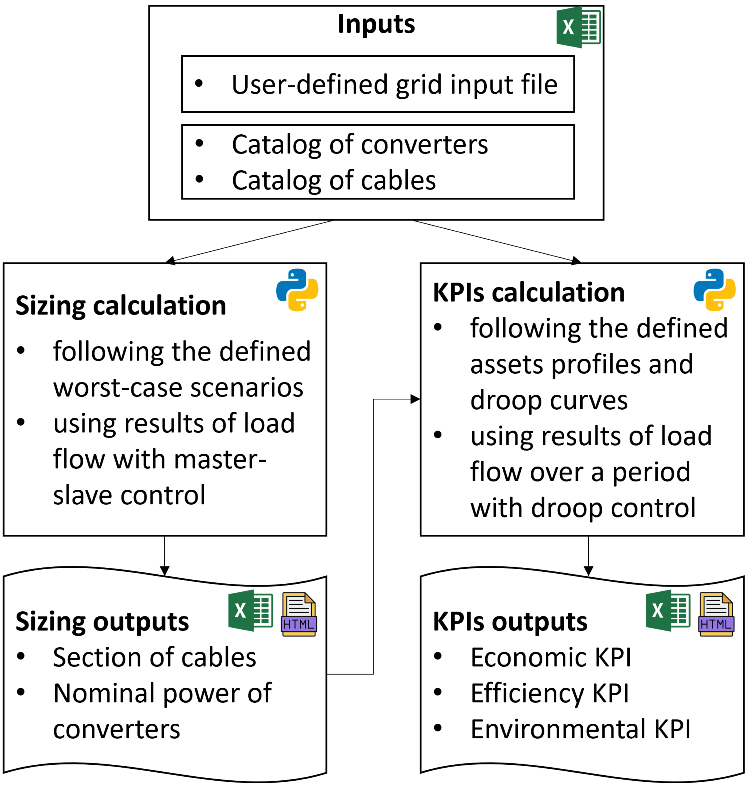

Figure 2-1 Diagram describing the operational flow of the design tool.

2.6 Limitations

Capacity limits of the tool:

- **Architecture selection**: The proposed methods only consider unipolar architecture is supported. Bipolar and meshed architecture are not included.
- **Limited by database**: The accuracy of results depends on the availability and quality of input data (especially cable and converter libraries). Detailed and more accurate models can be introduced by the users of the tool.
- **Protection scheme and short circuit current calculation**: The tool does not model transient behaviors or protection schemes; earthing system and short-circuit calculations are not included. A methodology will be proposed in Deliverable 2.2 addressing this need.
- **AC network comparison**: The design tool in T2.1 is focused on DC networks. It assumes that the user can size and evaluate the performance of the equivalent AC network with existing AC tools. Therefore, to compare the performance of the DC network and its equivalent AC network, the user must input the capital expenditures (CAPEX), and total energy consumed of the AC grid over an equivalent period. This allows comparison KPIs to be calculated.
- **Converter voltage control**: All converter models include voltage control strategies and efficiency curves for accurate voltage and power loss calculations. However, droop control for the main AC/DC converter is not yet functional due to the need for one slack bus[6] in the power flow calculation. This may be addressed in future updates.
- **Dynamic voltage control:** The tool does not support dynamic adjustments to the droop curve in real time. Non-convergence issues may occur, requiring the Energy Management System

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[6] Reference voltage bus

(EMS) or secondary regulation authority to modify the droop curve. The absence of dynamic droop control may also be addressed in future updates.

2.7 Conclusion

This chapter provides an overview of the design tool, outlining its installation, structure, usage, and architecture. The following chapters will provide more detailed explanations of the inputs, sizing methodologies, and performance evaluations implemented within the tool.

3 Inputs of the Design Tool

This section details the input data required for the execution of the proposed tool. At the current version, input data is performed through an Excel fille including all the information. However, other sources of data can be developed in future applications, namely in the WP4 to include the developed tool in Digital Twins.

3.1 Input File – Read Me

This section presents the “read me” of the input Excel file **input_file_grid_data.xlsx**.

3.1.1 Excel File Overview

This Excel input file describes the DC grid topology and key parameters for:

- Cables and converters sizing.
- KPIs calculations.

It is designed to help users systematically model a DC grid and its associated components.

Remarks

- This file contains multiple sheets described in Section 3.1.2, each serving a specific purpose for grid description.
- The user is invited to follow the instructions described in Section 3.1.3 to ensure accurate modeling and reliable results.

3.1.2 Sheets Description

Table 1 provides a breakdown of each sheet’s purpose of the DC Network Design Tool

Table 1 - Sheet Descriptions for the DC Network Design Tool

Sheet Name	**Purpose**
Read me	Present the Excel file and the filling guide.
Glossary	Define the parameters of all sheets.
Use Case (UC) Definition	Define project and use UC details.
Assets Nodes	List all nodes in the grid with their associated assets.
Converters	List all converters in the grid with their associated data.
Lines	List all lines in the grid with their associated data.
User-defined Assets Profiles	Define the assets profiles.
Default Assets Profiles	List the default assets profiles.
Default Droop Curves	List the default droop curves.

Remarks on Input Requirement

- The sheets contain **color-coded** cells to indicate **input requirements**:

🟥	**Mandatory fields** must be completed by the user.
🟨	**Conditional fields** must be filled only if a specific condition applies.
🟩	**Optional fields** can be filled in at the user's discretion.

- **User input fields** are left **white** for clarity. Users must only modify white cells to prevent errors or inconsistencies in the design tool.

3.1.3 Filling Guide

Once the Single Line Diagram (SLD) is ready, use it to complete the input sheets:

Step 1: Draw a SLD.
A SLD is crucial for preparing and organizing input data. It should include:

a. **Assets**: DC loads, Photovoltaic (PV) systems, storage systems, Electric Vehicle (EV) chargers, AC loads, AC grids.
b. **Lines**: All DC cables connecting the assets.
c. **Converters**: AC/DC, DC/AC, and DC/DC converters (Power Distribution Units (PDU), PV, Storage, EV).
d. **Nodes**: Mark and number each connection point.

Step 2: Add and Number Nodes in the Grid.
Nodes are essential reference points in the grid. Follow these guidelines:

- Assign a node number **at each asset's connection point**.
- Place a node **at the end of each line** where it connects to another asset, component, or converter.
- Number nodes **at converter input and output** to maintain accuracy.
- Grid points at the same voltage level are defined by the same node number.
- Use consistent and sequential numbering to avoid duplicate identifiers.

Step 3: Fill the Sheets using the SLD.
Once the SLD is ready, use it to complete the input sheets:

- **Step 3.a: "UC Definition" Sheet**
    - Enter the project name, class, ecosystem, grid architecture, and worst-case definitions.
- **Step 3.b: "Assets Nodes" & "User-defined Assets Profiles" Sheets**
    - Define node number, asset type, operating voltage, power, capacity, and associated converter.
    - Fill user-defined assets profiles if needed.
- **Step 3.c: "Converters" Sheet**
    - Specify converter types, nodes, nominal power, voltage levels, efficiency, voltage control mode, and droop curve.
- **Step 3.d: "Lines" Sheet**
    - Provide line connections (start and end nodes), length, and section.

Key Considerations

- Node numbers must match the SLD to avoid inconsistencies.
- Grid points at the same voltage level are defined by the same node number.
- Use the "Glossary" sheet to check input requirements (Mandatory, Optional, or Conditional).
- Follow color coding for fields in the Excel file.

Summary

- Start with a well-defined SLD.
- Number nodes consistently at every asset, line, and converter.
- Use the SLD to fill the sheets accurately.
- Follow input requirements to complete data for the simulation.

3.1.4 Zoom on the Parameters

This section lists the parameters in each sheet. In addition, the “Glossary” sheet presents a table of parameter descriptions, with comments and instructions for filling in each parameter.

UC Definition Sheet:

- **Project name**: Name of the project for identification.
    - Mandatory, User-defined input
- **Use case**: Purpose of the project.
    - Mandatory, select from predefined options: Local consumption maximization, Resilience.
- **Project class**: Classification of the project/application.
    - Mandatory, select from predefined options: Commercial, Industrial, Port, Residential.
- **Ecosystem**: Ecosystem type impacting voltage drop definition (±2% for CurrentOS, ±5% for ODCA).
    - Mandatory, select from predefined options: CurrentOS, ODCA.
- **Poles**: Grid architecture type.
    - Optional, select from predefined options: Unipolar, Bipolar, Meshed.
- **Total PV power installed [kW]**: The total power of PV installed in the grid.
    - Optional, User-defined input.
- **Total EV charging station size [kW]**: The total EV charging station size.
    - Optional, User-defined input.
- **Number of DC voltage levels**: The number of DC voltage levels in the grid.
    - Optional, User-defined input.
- **Number of AC/DC converters**: The number of AC/DC converters in the grid.
    - Optional, User-defined input.
- **Number of DC/AC converters**: The number of DC/AC converters in the grid.
    - Optional, User-defined input.
- **Number of PDU DC/DC converters**: The number of PDU DC/DC converters in the grid.
    - Optional, User-defined input.
- **Number of PV DC/DC converters**: The number of PV DC/DC converters in the grid.
    - Optional, User-defined input.
- **Number of storage DC/DC converters**: The number of storage DC/DC converters in the grid.
    - Optional, User-defined input.
- **Number of EV DC/DC converters**: The number of EV DC/DC converters in the grid.
    - Optional, User-defined input.
- **Operating temperature (degrees Celsius)**: Operating temperature of the installation.
    - Mandatory, User-defined input.
- **Material**: Conductor material (Aluminum/Copper).
    - Mandatory, select from predefined options: Aluminum (Al), Copper (Cu).
- **Insulation**: Conductor insulation type.
    - Mandatory, select from predefined options: PolyVinyl Chloride (PVC), Cross-linked polyethylene (XLPE).
- **Cable sizing security factor [%]** : Security factor for cable sizing (details in section 4.1, step 3).
    - Mandatory, User-defined input.
    - Cables size will be increased by this factor commonly set at 5% as a margin.
- **AC/DC converter sizing security factor [%]** : Security factor for AC/DC converter sizing.
    - Mandatory, User-defined input.
    - Converter size will be increased by this factor commonly set at 10% as a margin.

- **Other converters sizing security factor [%]**: Security factor for other converters (DC/AC, PDU DC/DC, PV DC/DC, Storage DC/DC, and EV DC/DC) sizing.
    - Mandatory, User-defined input.
- **Loads expansion factor [%]**: Loads expansion factor for cables and PDU converter sizing.
    - Mandatory, User-defined input.
    - [0-100], if less than 100%, we consider loads are not used simultaneously.
- **Loads power factor [%]** : Loads power factor % of the maximum power for cables and converters sizing defined in a worst-case scenario.
    - Mandatory, User-defined input.
- **PV power factor [%]** : PV power factor % of the installed capacity for cables and converters sizing defined in a worst-case scenario.
    - Mandatory, User-defined input.
- **EV power factor [%]** : EV Charging station consumption % of the maximum power for cables and converters sizing defined in a worst-case scenario.
    - Mandatory, User-defined input.
- **Storage duration at nominal power [hours]**: Storage duration at nominal power for storage sizing required by the user, defined in a worst-case scenario.
    - Mandatory, User-defined input.
- **Storage power contribution [%]** : Storage power contribution % of the maximum power for cables and converters sizing defined in a worst-case scenario.
    - Mandatory, User-defined input.
- **Simulation time step [minutes]**: Time step for annual load flow simulations.
    - Mandatory, select from predefined options: 5, 10, 15, 20, 30, 60 minutes.
- **Simulation period [days]**: Time step for annual load flow simulations.
    - Mandatory, User-defined input.
- **Total energy generated in AC grid [MWh]**: Total energy generated in AC grid for KPIs comparison over an equivalent period.
    - Optional, User-defined input.
- **Efficiency of AC grid [%]**: Efficiency of the AC grid for KPIs comparison.
    - Optional, User-defined input.
- **Total CAPEX of AC grid [kEUR]**: Total CAPEX of AC grid for KPIs comparison.
    - Optional, User-defined input.
- **Total weight of AC grid kg]**: Total weight of AC grid for KPIs comparison.
    - Optional, User-defined input.
- **Total emissions of AC grid [kg CO2]**: Total lifecycle CO2 emissions of AC grid for KPIs comparison.
    - Optional, User-defined input.

Assets Nodes Sheet:

- **Component type**: Type of asset.
    - Mandatory, select from predefined options: DC Load, PV, Storage, EV, AC Load, AC Grid.
- **Node number**: Unique identifier for the node.
    - Mandatory, User-defined input.
- **Node type**: Node type, modeling for the load flow.
    - Mandatory, select from predefined options: “V”, “P”, storage, gen.
- **Operating nominal voltage**: Operating nominal voltage of the node.
    - Mandatory, User-defined input.
- **Maximum Power**: Maximum power consumed/generated by the asset.
    - Mandatory, User-defined input.
- **Capacity**: Capacity of the asset.
    - Mandatory, User-defined input.
- **Droop curve of asset**: Droop curve of the asset for voltage control.
    - Mandatory, select from predefined options: not applicable, default non-dynamic, default dynamic, user-defined non-dynamic, user-defined dynamic.
- **Directly linked converter**: Name of the converter directly linked or associated with the node.
    - Mandatory, User-defined input.
- **Node number for directly linked converter**: Unique identifier for the converter directly linked or associated with the node.
    - Mandatory, User-defined input.
- **Asset profile type**: Type of profile per asset.
    - Mandatory, select from predefined options: not applicable, user-defined, default PV profile, default EV load, default DC office plug non controllable load, default DC office plug controllable load, default DC lighting, default 12h controllable load with continuous droop, default non controllable HVAC, default server load, default 12h industrial process, default 24h industrial process, default boat load.

Converters Sheet:

- **Converter name**: Name of the converter associated with the node.
    - Mandatory, User-defined input.
- **Node_i number**: Unique identifier for the starting node of the converter connection.
    - Mandatory, User-defined input.
- **Node_j number**: Unique identifier for the ending node of the converter connection.
    - Mandatory, User-defined input.
- **Converter type**: Converter type.
    - Mandatory, select from predefined options: AC/DC Converter Isolated, AC/DC Converter Non-Isolated, DC/AC Converter, PDU DC/DC Converter Isolated, PDU DC/DC Converter Non-Isolated, PV DC/DC Converter, Storage DC/DC Converter, EV DC/DC Converter.
- **Voltage level V_i [V]**: Voltage level for the starting node of the converter connection.
    - Conditional (on converter type), User-defined input.
- **Voltage level V_j [V]**: Voltage level for the ending node of the converter connection.
    - Mandatory, User-defined input.
- **Nominal power [kW]**: Nominal power of the converter.
    - Optional (if already sized/fixed, otherwise the tool will design the converter), User-defined input.

- **Efficiency curve**: Efficiency curve of the converter.
    - Mandatory, select from predefined options: default, user-defined.
- **Efficiency curve if user-defined**: User-defined efficiency curve.
    - Conditional (on efficiency curve type), User-defined input.
- **Voltage control mode**: Voltage control strategy for the converter.
    - Mandatory, select from predefined options: master-slave control, droop control.
- **Droop curve**: Droop curve of the converter.
    - Mandatory, select from predefined options: not applicable, default non-dynamic, default dynamic, user-defined non-dynamic, user-defined dynamic.
- **Droop curve if user-defined**: User-defined droop curve.
    - Conditional (on droop curve type), User-defined input.

Lines Sheet:

- **Node_i number**: Unique identifier for the starting node of the line.
    - Mandatory, User-defined input.
- **Node_j number**: Unique identifier for the ending node of the line.
    - Mandatory, User-defined input.
- **Line length**: Length of the line connecting node i and node j.
    - Mandatory, User-defined input.
- **Resistance**: Resistance of the line connecting node i and node j.
    - Optional (if already sized/fixed, otherwise the tool will design the cables), User-defined input.

User-defined Assets Profiles Sheet:

- **Datetime**: Datetime.
    - Optional, User-defined input.
- **Node \ Time step**: Node number of the asset and time step number.
    - Mandatory, User-defined input.

3.2 Cables Catalog

This section presents the “read me” of the cable catalog file: **catalog_cable.xlsx**. The data already included in the catalogue is indicative since the real values only can be included after the validation of the manufacturers. A new cable will be developed and tested in Task 3.1 and it is expected that more accurate values can be included during the project.

3.2.1 Overview

The design tool provides the basic design of the DC grid with a preliminary sizing of cables. This deliverable helps to give a frame of the potential cable product portfolio. The main criteria that need to be specified is the maximum carrying current capacity of the cables.

The ampacity calculation for low voltage DC cables is based on the standard IEC-60287 for single insulated (XLPE or PVC), single conductor core (Aluminum or copper). However, it does not take into account installation rules where different reduction factors would affect the current carrying capacity.

3.2.2 Assumptions & Parameters in the Catalog

Typical data in the catalog of DC cables (NEXANS[7]):

- **Cross section** [mm²].
- **Conductor material**: Al / Cu - Note: This will be predetermined for the design.
- Maximum surrounding Temperature of the cable [°C].
- **Maximum current capacity**: Imax [A] (result of the model calculation).
- **Resistance** R for various operating temperatures T°C [Ω/m].

Assumptions:

Nexans defines the cable types as follows:

- Cable type = Cu for section = 0,5 to 95 mm²
- Cable type = Al for section = 120 mm² and over

The choice between copper and aluminum is related to the size of the conductors (not to the cable's location in the installation). To reduce costs, larger cross-sections are only available with aluminum conductors.

As this is a simplified design tool, it was decided not to consider all the installation conditions that influence current capacity.

For a future version of the catalog, the following information will be integrated:

- Voltage level.
- Unipolar or Bipolar.
- Incorporation (Y/N) of the inter-tripping Wire (IW).
- Protection against Electro Magnetic Compatibility (if required).
- Cable design for indoor/outdoor installations.
- Fire performance level.

3.3 Converters Catalog

This section presents the "read me" of the converter catalog file **catalog_converter.xlsx**.

3.3.1 Overview & Description of Converters

To perform electrical sizing analysis and assess performance (e.g., the maintenance cost of the main AC/DC converter and measures that guarantee continuous power supply of critical loads), it is necessary to **develop specific libraries that contain static models and data for the converters** under study, including at least the following types:

- AC/DC converters
- DC/DC converters
- DC/AC converters

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[7] https://www.nexans.com/

AC/DC Converters

The AC/DC converter rectifies the AC to DC. In the simplest configuration, the AC/DC converter only operates in unidirectional mode, allowing the current to travel in just one direction, as shown in Figure 3-1. Main AC/DC Converters named Active Front End (AFE) are bidirectional.

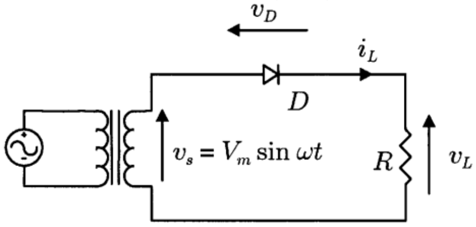

Figure 3-1 Topology of a typical rectifier converter [1].

Depending on the type of AC supply and the arrangement of the rectifier circuit, the output voltage may require additional smoothing to produce a uniform, steady voltage. The rectifier can be unidirectional or bidirectional, isolated or non-isolated.

For the project application, the rectifier will be connected at low voltage (400 V_{AC}), converting it to several voltage ranges depending on the final device, ecosystem, and application, ranging from 350 to 700 V_{DC} in the distribution buses. Additionally, it will be available in isolated/non-isolated and unidirectional/bidirectional. It will be depicted as shown in Figure 3-2.

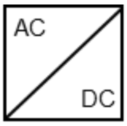

Figure 3-2 AC/DC converter (non-isolated).

DC/DC Converters

The DC-DC converters will be responsible for adapting the voltage and controlling the power to (from) the common DC bus to the different loads (sources). At the same time, they will provide additional functionalities:

- Reducing the AC voltage ripple on the DC output voltage below the required level.
- Providing isolation between the input source and the load (if required).
- Protecting the supplied system and the input source from electromagnetic interference (EMI).

The converters will integrate a control algorithm for the proper sharing of power when operating in parallel as expected. The droop control method can be easily implemented for parallel operation, and it is selected for the applications.

DC/DC non-isolated converters

A non-isolated (transformer less) Buck-Boost converter is shown in Figure 3-3. The converter consists of a DC input voltage source V_S, a controlled switch S, inductor L, diode D, filter capacitor C, and load resistance R. Through the control of the switch S, the output voltage and power are controlled.

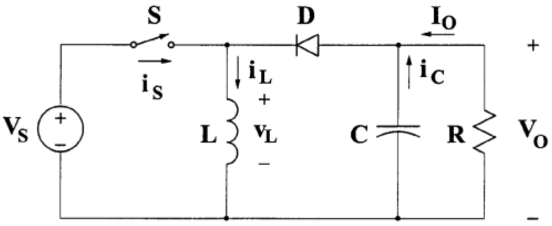

Figure 3-3 Topology of a typical DC/DC non-isolated converter [1].

It will be depicted as shown in *Figure **3**-**4***.

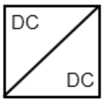

Figure 3-4 Symbol for a DC/DC non-isolated converter.

DC/DC isolated converters

In many DC power supplies, galvanic isolation between the DC or AC input and the DC output is required for safety and reliability.

The isolated condition refers to a type of converter able to translate a direct voltage to a direct voltage, providing galvanic isolation. This means there is no direct conduction path between the input and output, so energy flows through a field rather than via an electrical connection.

An economical means of achieving such isolation is to employ a transformer version of a DC-DC converter. To perform the voltage conversion, it is necessary to create an alternating voltage within the converter. This is achieved through a power electronic circuit that creates a variable magnetic flux and variable voltage accordingly, which is then rectified, as shown in Figure 3-7.

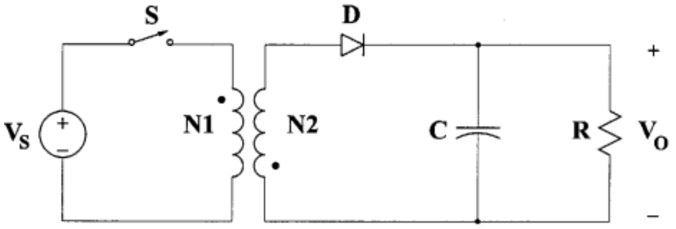

Figure 3-5 Topology of a typical DC/DC isolated converter [1].

It will be depicted as shown in *Figure **3**-**6***.

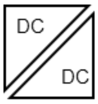

Figure 3-6 Symbol for a DC/DC isolated converter.

The isolated converter can be designed with different topologies depending on the power and required performance. A typical design for higher power is depicted in *Figure **3**-**7***. Known as a Dual Active Bridge (**DAB**) **converter,** it is a highly efficient isolated bidirectional DC/DC converter. This equipment is also known as a Solid-State Transformer (SST).

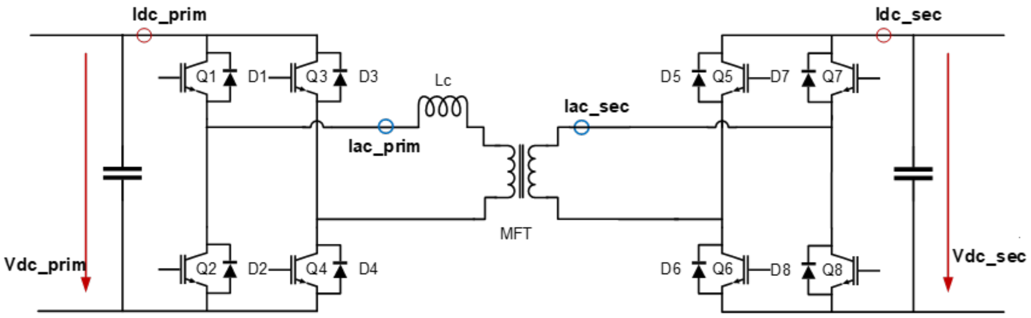

Figure 3-7 Internal diagram of a Dual Active Bridge DC/DC isolated converter.

The isolated converter can operate at different switching frequencies, up to kHz, depending on the application. By increasing the switching frequency, it is possible to achieve a reduction in the size and weight of the transformer while maintaining the same power and high efficiency, which makes it very attractive for specific applications in which the footprint and size ratio are critical requirements. Additionally, the turns ratio of the transformer can be used to adjust the output voltage level.

3.3.2 Assumptions & Parameters in the Catalog

The impedance and losses of **AC/DC, DC/AC, and DC/DC converters** vary depending on the power flow, making them critical elements to model using the classical load flow theories. In this task, the global DC network is divided into *N* subnetworks each time separated by a converter. This allows the application of the classical load flow equations to each subnetwork (refer to Section 4.2.2.4). In the transition from the downstream to the upstream grid, the flowing current, and an approximate piecewise-linear function of the efficiency curve, as shown in *Figure **3**-**8*** (Converters losses are function of the load), are used to deduce the converter losses. These losses are depicted as fictive load in the upstream grid added to the standby losses which are fixed and constant. This assumption allows static simulations using classical load flow theory without specifying the details of the electronic design. The internal topology is not addressed, so it will not be possible to select variables like half-bridge, full-bridge, Dual Active Bridge, etc.

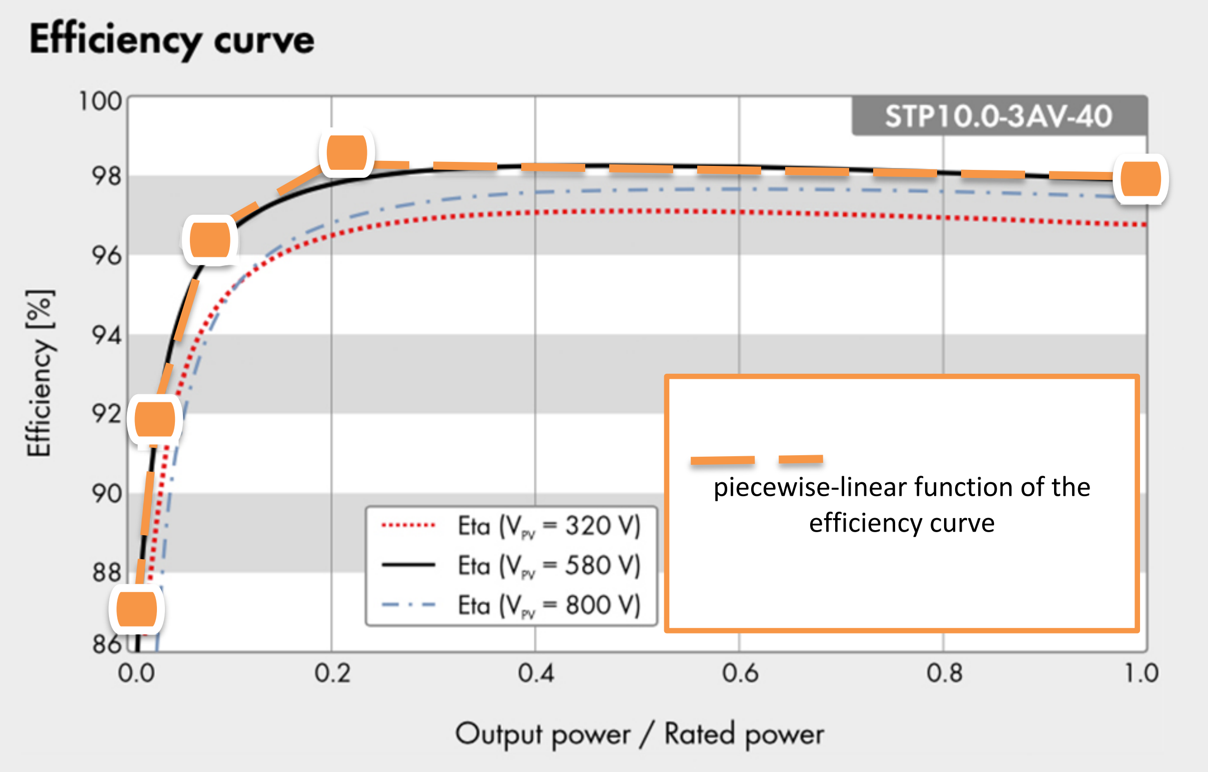

Figure 3-8 Example of an efficiency curve of an industrial converter.[8]

In the design tool, DC/DC converters are categorized as:

- **PDU DC/DC converters**: Interface between primary and secondary DC voltage levels.
- **PV DC/DC converters**: Used in PV systems to optimize energy extraction.

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[8] Efficiency and Derating, Technical information, SMA Catalog.

- **Storage DC/DC converters**: Manage power exchange between battery storage and the grid.
- **EV DC/DC converters**: Regulate power flow between EV chargers and the grid.

Each type has specific efficiency characteristics, voltage control strategies (droop control or fixed voltage mode/master-slave mode), and bidirectional capabilities for energy storage applications.

The design tool includes a predefined library of standard converter models, along with the option to input user-defined performance parameters. It integrates these parameters into simulations to assess system efficiency, losses, and cost implications.

The parameters available in the catalog to specify the converters will be:

- **Converter type**: AC/DC Converter Isolated, AC/DC Converter Non-Isolated, DC/AC Converter, PDU DC/DC Converter Isolated, PDU DC/DC Converter Non-Isolated, PV DC/DC Converter, Storage DC/DC Converter, EV DC/DC Converter.
- **Ecosystem**: CurrentOS/ODCA.
- **Stand-by losses** [W]
- **Voltage level V1 and Voltage level V2**: Input and output rated voltages [V]
- **Nominal power** [kW]
- **Efficiency curve** as follows: [Xi;Yi], i={1,2,3,4}, with X= Factor of Nominal Power (%), Y=Efficiency (%)
- **Approximate cost** [k€]
- **Product carbon footprint** [kg CO2-eq per year]
- **Weight** [kg]

Note that the voltage control mode and the droop curve of the converter are fixed in the sheet “Converters” of the input file.

4 Electrical Sizing & Load Flow Algorithms

The present section describes the implemented load flow algorithms and the electrical sizing methods used to determine the cable sections and the power ratings of the converters.

4.1 Workflow of the Electrical Sizing Calculation

One key functionality of the T2.1 tool is the sizing of a DC grid. To achieve this, a sizing algorithm was developed to obtain a preliminary design of the DC grid, including the sizing of cables and converters. *Figure **4-1*** presents the high-level workflow for the sizing calculations, which is detailed in this section.

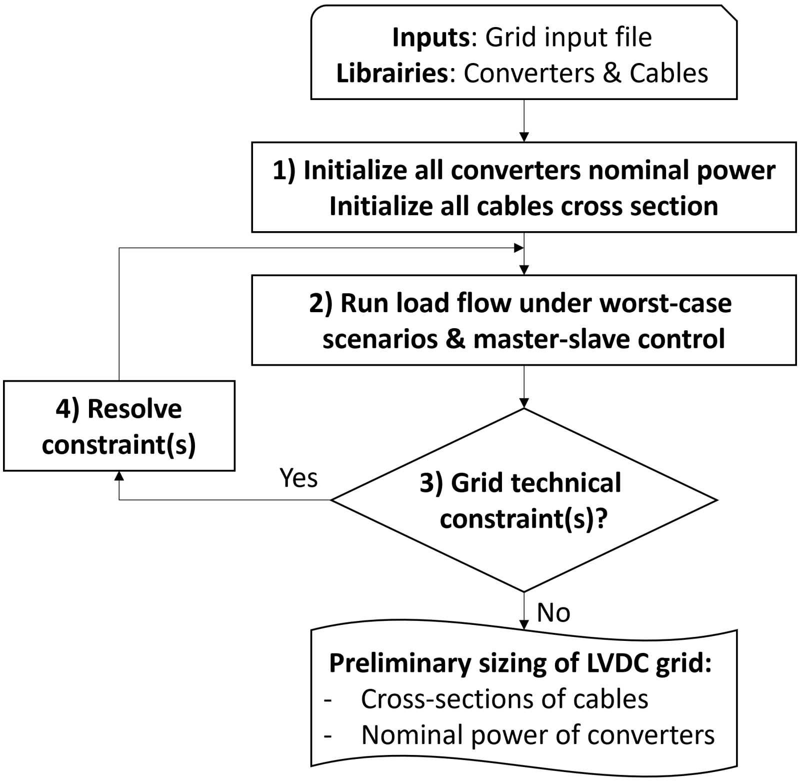

Figure 4-1 High-level workflow for sizing of converters and cables.

Inputs (detailed in Chapter 3):

- **User-defined grid data input file** (input_file_grid_data.xlsx) (detailed in Section 3.1).
- **Catalog/Library for cables** (catalog_cable.xlsx) (detailed in Section 3.2).
- **Catalog/Library for converters** (catalog_converter.xlsx) (detailed in Section 3.3).

Electrical Sizing Algorithm:

- **Step 1: Initialization of all converters' nominal power and all cables' cross-section.** This step is needed to get the efficiency curves of converters and the resistances of cables.
    - The cross-sections of cables are initially set to the largest available section in the catalog while respecting user-defined constraints (e.g., material selection: Alu/Cu, insulation type: PVC/XLPE).
    - For converters, the smallest available unit is selected from the catalog, considering the required type and input and output ranges.

- **Step 2: Load Flow Calculation under Worst-Case Scenarios and Master-Slave Control**. This step is essential to compute the voltages and the currents at the nodes of the DC grid.
    - **Worst-case scenarios** are pre-defined in the input file and represent the most critical operating conditions for the DC grid. These scenarios ensure that all components are sized adequately to handle extreme conditions [2]. The following three worst-case scenarios are considered:
        - **Worst-case scenario 1 aiming to size the storage system DC/DC converter:**
            - If the battery and its converter are not already sized, a first iteration is performed with the AC grid OFF and a user-defined load percentage.
        - **Worst-case scenario 2 aiming to size cables and PDU DC/DC, DC/AC, PV DC/DC, and EV DC/DC converters:**
            - Asset converters (PV and EV DC/DC converters): Sized based on the maximum load power.
            - PDU converters: Sized to handle the total load plus an expansion factor.
            - Cables: Sized to cover the maximum power demand for each use (load or generation). For cables aggregating multiple loads, an expansion factor is applied.
        - **Worst-case scenario 3 aiming to size cables and AC/DC converter:**
            - The AFE[9] converter power is determined after setting the battery power based on the user's desired load percentage.
    - **Load flow equations** for DC networks under master-slave control are detailed in Section 4.2.2. The *runpp* AC load flow function of *pandapower* was used as a basis for the developments in T2.1 and was adapted for our case (see Section 4.2.2.4 for all details).

- **Step 3: Technical Constraint Checking.** The load flow results are analyzed to determine if the grid design is technically feasible, i.e., if it meets technical constraints:
    - **Current constraints in converters:** The power handled by each converter (increased by the sizing security factor if defined by user) must not exceed its nominal capacity.
    - **Current constraints in cables:** The current (increased by the sizing security factor if defined by user) through each cable must be lower than the maximum admissible current of its cross-section.
    - **Voltage constraints at nodes:** Voltages at all nodes must remain within acceptable limits as defined by the regulatory framework (e.g., Current OS or ODCA ecosystems).

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[9] Depending on the ecosystem, AFE can be named ILC for InterLink Converter

- **Step 4: Resolving constraints.** If constraints are violated, modifications are applied in the following order:
    - **Converter Sizing Adjustment**:
        - If a converter exceeds its current limit, its nominal power is increased based on the power observed in the load flow and a user-defined security factor: $P_{conv_{new}} \geq P_{conv_{loadflow}} \times securityFactor$
    - **Cable Sizing Adjustment:**
        - Cables are resized systematically, prioritizing adjustments from the downstream (farthest from the slack bus) to the upstream (closest to the slack bus).
        - The process involves iteratively decreasing the cable cross-section and rerunning the load flow until a constraint violation occurs. The last valid configuration is then retained.
        - If the section of a downstream line becomes larger than that of an upstream line, the upstream line is increased accordingly, and the process is repeated.

Outputs:

- Preliminary sizing of the cables (cross-sections) of the network.
- Preliminary sizing of the converters (nominal power) of the network.

As depicted in *Figure **4-1***, power flow calculations are iterated until all electrical constraints are resolved (voltage drops, over current). Therefore, as mentioned in Step 2 of the workflow, section 4.2 presents the load flow for the DC grid.

An illustration of the sizing algorithm outputs is presented in **Appendix A.**

4.2 Load Flow for DC Grid

4.2.1 Objective of the Load Flow & Types of DC Grid Control

One of the fundamental components of the sizing algorithm is the accurate calculation of **load flow** within the targeted electrical network. Load flow analysis plays a crucial role in determining power distribution, voltage stability, and overall system performance. To effectively size electrical components, it is essential to have a thorough understanding of the network topology, configuration, and load flow constraints. This ensures that the system operates efficiently and maintains stability under various operating conditions.

In this work, **load flow calculations are systematically presented to support the network sizing process**. The calculations consider both AC and DC load flow methodologies, addressing their unique characteristics and constraints.

Two Types of DC Grid Control: DC networks can be controlled using different strategies to ensure power balance and stability. This section explores two primary control methods:

1- **Master-Slave Control**: A hierarchical control method where a designated master converter regulates voltage while slave converters control current. This is the only control that will be considered for the sizing load flow calculations (section 4.2.2).

2- **Droop Control**: A decentralized control strategy that allows multiple converters to share power dynamically by adjusting their output voltage based on load conditions. This control will be considered for the KPIs evaluation of the DC network (Section 4.2.3).

4.2.2 Mathematical Model for the Load Flow under Master-Slave Control

This section presents the load flow of a DC grid under master-slave control, which is essential for the electrical sizing algorithm (see *Figure **4-1***).

The implementation follows the structure outlined below:

1- AC Load Flow Calculations: This section provides a detailed analysis of power flow in AC networks, considering parameters such as voltage magnitudes, phase angles, and real and reactive power flows.
2- Assumptions for DC Load Flow Calculations: Since DC networks operate differently from AC systems, specific assumptions are required to simplify the analysis.

4.2.2.1 Alternated Current Load Flow Equations

The state of the art on AC load flow [3] is presented in five main elements: power injection (active and reactive), power flow (active and reactive), and current flow. Once these values are estimated then the system state variables (voltage magnitude and the phase angles) of the network nodes can be found. Understanding AC load flow provides the foundation for developing DC load flow calculations.

An AC network with *N* nodes has (*2N-1*) state variable (x_{ac}): as follow:

$$x_{ac} = \begin{bmatrix} 0 & \theta_1 & \dots & \theta_N \\ V_0 & V_1 & \dots & V_N \end{bmatrix}$$

Where *V* and θ are the voltage magnitude and phase angles values respectively of all nodes from *0* to *N*, considering that node 0 has phase angle (θ_0) zero and assumed to be the slack bus.

Based on that, an iterative solver can be executed to evaluate the system state variable by solving the following load flow equations from the measurement function $h(x)$. The measurement function combines all the following non-linear equations.

Active power injection $h_1(x)$ at node i:

$$h_1(x) = \sum_{j\in N} P_{ij} = V_i \sum_{j\in N} V_j\left(G_{ij}\cos(\theta_{ij}) + B_{ij}\sin(\theta_{ij})\right)$$

Reactive power injection $h_2(x)$ at node i:

$$h_2(x) = \sum_{j\in N} Q_{ij} = V_i \sum_{j\in N} V_j\left(G_{ij}\sin(\theta_{ij}) - B_{ij}\cos(\theta_{ij})\right)$$

Active power flow $h_3(x)$ from node i to node j:

$$h_3(x) = P_{ij} = V_i^2\left(G_{ij} + G_{sh_i}\right) - V_iV_j\left(G_{ij}\cos(\theta_{ij}) + B_{ij}\sin(\theta_{ij})\right)$$

Reactive power flow $h_4(x)$ from node i to node j:

$$h_4(x) = Q_{ij} = -V_i^2\left(B_{ij} + B_{sh_i}\right) - V_iV_j\left(G_{ij}\sin(\theta_{ij}) - B_{ij}\cos(\theta_{ij})\right)$$

Current flow $h_5(x)$ from node i to node j:

$$h_5(x) = I_{ij} = \frac{\sqrt{P_{ij}^2 + Q_{ij}^2}}{V_i}$$

If the shunt admittance $(G_{sh_i} + jB_{sh_i})$ is ignored, then:

$$h_5(x) = I_{ij} = \sqrt{(G_{ij}^2 + B_{ij}^2)(V_i^2 + V_j^2 - 2V_iV_j\cos(\theta_{ij}))}$$

where i and j are the 'from' and 'to' nodes respectively, V_i is voltage magnitude and θ_i is phase angle of node i, and $\theta_{ij} = \theta_i - \theta_j$. $(G_{ij} + jB_{ij})$ is the (i, j) element of the complex admittance matrix, while $(G_{sh_i} + jB_{sh_i})$ is the i_{th} shunt admittance.

4.2.2.2 Assumptions for Direct Current Load Flow Equations

AC load flow equations are inherently non-linear due to their dependence on phase angles between network nodes. However, by applying certain assumptions and simplifications, these equations can be adapted to represent DC load flow, significantly reducing their complexity. The key assumptions for this transformation are as follows [4]:

1- **No phase angle components**: Unlike AC systems, DC networks do not have phase angles associated with voltage and current. This assumption eliminates the trigonometric (sine and cosine) components from the equations, simplifying the overall mathematical formulation.
2- **Frequency-free admittance matrix**: Since DC systems operate at zero frequency, reactive elements such as inductance and capacitance do not contribute to power flow calculations. As a result, only the resistive components remain in the admittance matrix, further simplifying the equations and making them linear.

Based on these points, AC load flow equations can be transformed into a more straightforward DC load flow model, which is particularly useful for analyzing DC grids and microgrids.

4.2.2.3 DC Load Flow Equations

The transformation from AC to DC drop out the reactive components from the measurements function $h(x)$. As a result, $h(x)$ present only three elements as follow:

Power injection $h_1(x)$ at node i

$$h_1(x) = \sum_{j \in N} P_{ij} = V_i \sum_{j \in N} V_j(\rho G_{ij})$$

Power flow $h_2(x)$ from node i to node j

$$h_2(x) = P_{ij} = V_i^2(\rho G_{ij} + G_{sh_i}) - V_iV_j(\rho G_{ij})$$

Current flow $h_3(x)$ from node i to node j:

$$h_3(x) = I_{ij} = \frac{\sqrt{P_{ij}^2 + 0}}{V_i} = \frac{P_{ij}}{V_i} = \rho G_{ij}(V_i - V_j)$$

Where ρ is 1 for monopolar and 2 for bipolar.

Furthermore, the state variables of the system (x_{dc}) are phase angle-free and depend only on voltage, as shown below:

$$x_{dc} = [V_0 \quad V_1 \quad \dots \quad V_N]$$

4.2.2.4 Application of Load Flow in the Design Tool

The design tool leverages the *runpp* function from *pandapower*, which was originally intended for balanced AC power flow calculations. To adapt it for DC load flow simulations, specific considerations and transformations are applied, as outlined below.

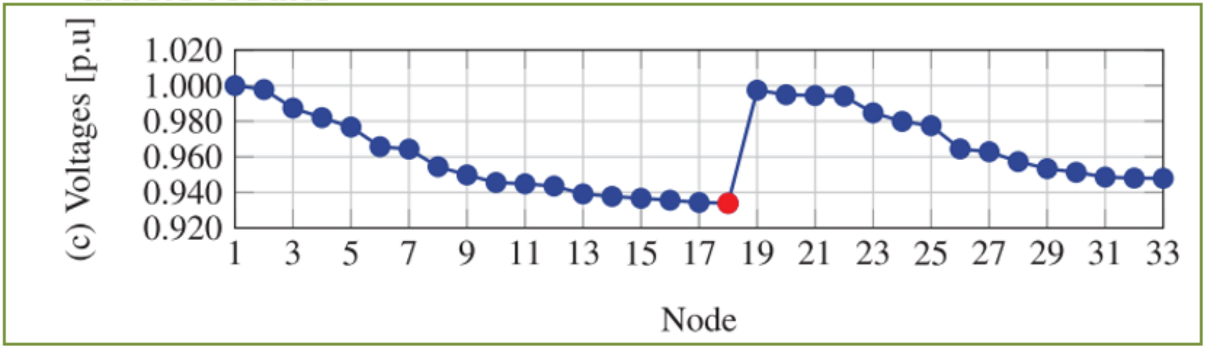
Reactive Parameters

As previously mentioned in 4.2.2.2, DC power flow calculations should not account for reactive elements such as inductance and capacitance. To ensure proper handling of DC networks using *pandapower*, the following parameters are set in the *runpp* function:

- $x\_ohm\_per\_km = 1e - 20$: Effectively neutralizing reactance in lines.
- $c\_nf\_per\_km = 0$: Eliminating capacitance effects.

To verify this assumption, we run a load flow using *pandapower* on a 33-node test system from the article [5] and compare the results. *Figure **4**-**2*** shows that the voltage profiles obtained by *pandapower* match those in the article, thus validating the use of *runpp* for DC powder flow.

article results



panda power results

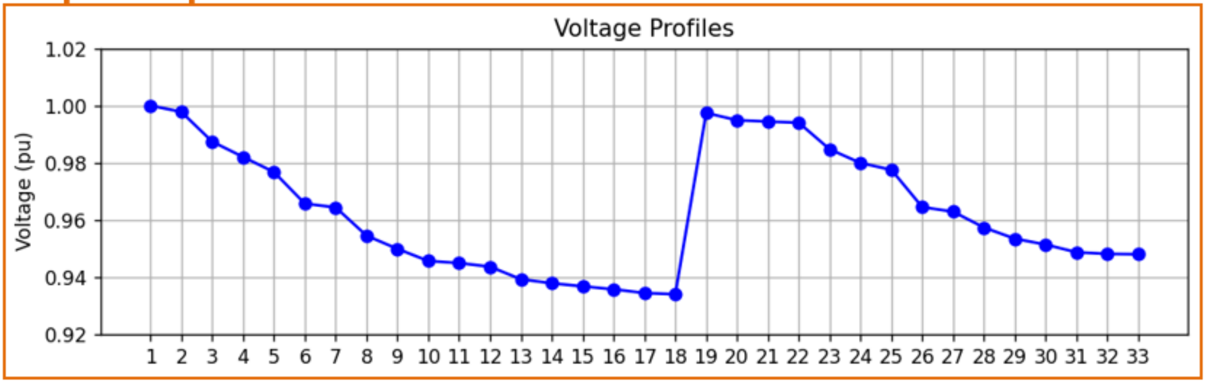


Figure 4-2 Comparing DC load flow results: article vs. pandapower (adapted from[5]).

Power Scaling Adjustments

Since *runpp* is designed for balanced AC power flow (three-phase symmetric calculation), adjustments are needed to correctly represent DC power calculations. The transformations applied include:

- Active Power Scaling:
    - The relationship between AC and DC power is given by: $P_{AC} = \sqrt{3}UI\cos\varphi, P_{DC} = VI$
    - Assuming that the AC line-to-line voltage corresponds to the DC voltage level $U = V$, we had to scale input powers by $\sqrt{3}$ before running the power flow.
    - After obtaining results, the computed power values are then scaled back by $\frac{1}{\sqrt{3}}$ to return to DC units.
- Losses Calculations:
    - In AC networks, power losses are calculated as: $P_{losses,AC} = 3RI^2$
    - In DC networks, power losses are calculated as: $P_{losses,DC} = 2RI^2$
    - To correctly map AC-based loss calculations to DC, a conversion factor of $\frac{2}{3}$ is applied to obtain accurate DC losses.

Integration of Converters in the Load Flow

Pandapower natively supports elements such as lines, transformers, generators, and loads, but does not provide dedicated models for power converters. To address this limitation, the following methodology is implemented:

- Network Partitioning:
    - The DC grid is divided into subnetworks based on converter connections.
    - Each subnetwork is treated as an independent system for power flow calculations.
- Iterative Load Flow for Converters:
    - The *perform_dc_load_flow* function manages the iterative resolution of power flow with converters.
    - If droop control is enabled, an iterative loop adjusts voltage levels until convergence is reached (details in section 4.2.3).
    - The method ensures that power exchanges between subnetworks are correctly computed.
- Converter Representation:
    - Converters are modeled indirectly by adjusting power injections at buses based on their efficiency curves.
    - Upstream subnetworks are linked to downstream networks through emulated external grids.
    - Power transfer calculations are performed through fictive loads, and results are updated iteratively to reflect accurate operating points.
- Load Flow Execution:
    - Each subnetwork is processed sequentially.
    - The *runpp* function is applied to each isolated network with the necessary DC adjustments.
    - Results from upstream subnetworks are propagated to downstream subnetworks to ensure proper convergence.

4.2.3 Mathematical Model for the Load Flow under Droop Control

This section presents the load flow of a DC grid under droop control, which is essential for the performance and KPIs evaluation of the DC network that will be detailed in Chapter 5.

4.2.3.1 Background

Several approaches for voltage control exist, such as linear and non-linear droop control [6]. The former method is easier to implement. Nevertheless, there are some drawbacks of linear droop, such as weak voltage regulation and unbalanced current sharing.

To overcome this issue, authors in [7] and [8] proposed a linear piecewise droop control approach. This approach uses a mathematical piecewise function, where each segment is linear, and the slopes of the segments can vary. This allows for more flexible control by adjusting the droop characteristics across different operating ranges. The method was experimentally tested, and the results demonstrate that, under various load conditions, the linear piecewise droop control ensures better current sharing and voltage regulation, outperforming the single-slope droop control. Additionally, the droop control method stated in CurrentOS standard and ODCA system specification corresponds to the linear piecewise droop control method.

4.2.3.2 Basic Formulation of Linear Piecewise Droop Control

The basic formulation of linear piecewise droop control used in this work is the relation between voltage and power regarding a given piecewise function. To better understand the previously stated, *Figure* ***4-3*** illustrates a function $f(\mathrm{V})$ regarding the droop control of an EV charger with bidirectional power flow, where V is the voltage imposed on the EV charger. Note that for better understanding, the axes were switched.

The output power P is function $f(\mathrm{V})$ that can be mathematically stated as:

$$f(\mathrm{V}) = \begin{cases} \mathrm{P}_1, \mathrm{V} \in [\mathrm{V}_1, \mathrm{V}_2[\\ \theta_1 \times \mathrm{V} + \eta_1, \mathrm{V} \in [\mathrm{V}_2, \mathrm{V}_3[\\ 0, \mathrm{V} \in [\mathrm{V}_3, \mathrm{V}_4[\\ \theta_2 \times \mathrm{V} + \eta_2, \mathrm{V} \in [\mathrm{V}_4, \mathrm{V}_5[\\ \mathrm{P}_6, \mathrm{V} \in [\mathrm{V}_5, \mathrm{V}_6] \end{cases}$$

Where θ and η are the slopes and y-intercepts, respectively, of droop control. As shown in *Figure* ***4-3***, the piecewise function can also be defined by six coordinates. The figure above shows an example for an EV Charger.

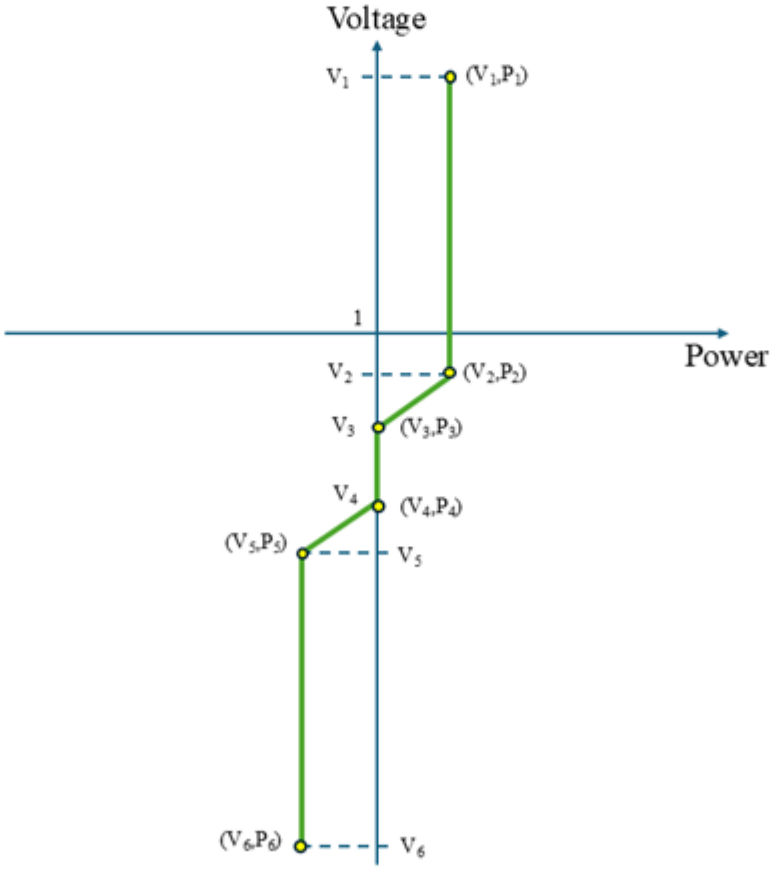


Figure 4-3 Droop control of an EV charger.

4.2.3.3 Methodology of Power Flow Analysis Considering Droop Control

At this stage, the integration of the droop curves into the PF algorithm is carried out **iteratively**. Since the droop curves define the asset power, the process begins by providing the nominal power values of the assets to the PF algorithm, which then calculates the bus voltages. These voltages are compared with the droop curve, and the next iteration is initiated by using the power value derived from the droop curve interpolation in the PF calculation to obtain updated bus voltage values. Convergence is achieved when the voltage variation between iterations falls below a specified threshold.

The steps are the following:

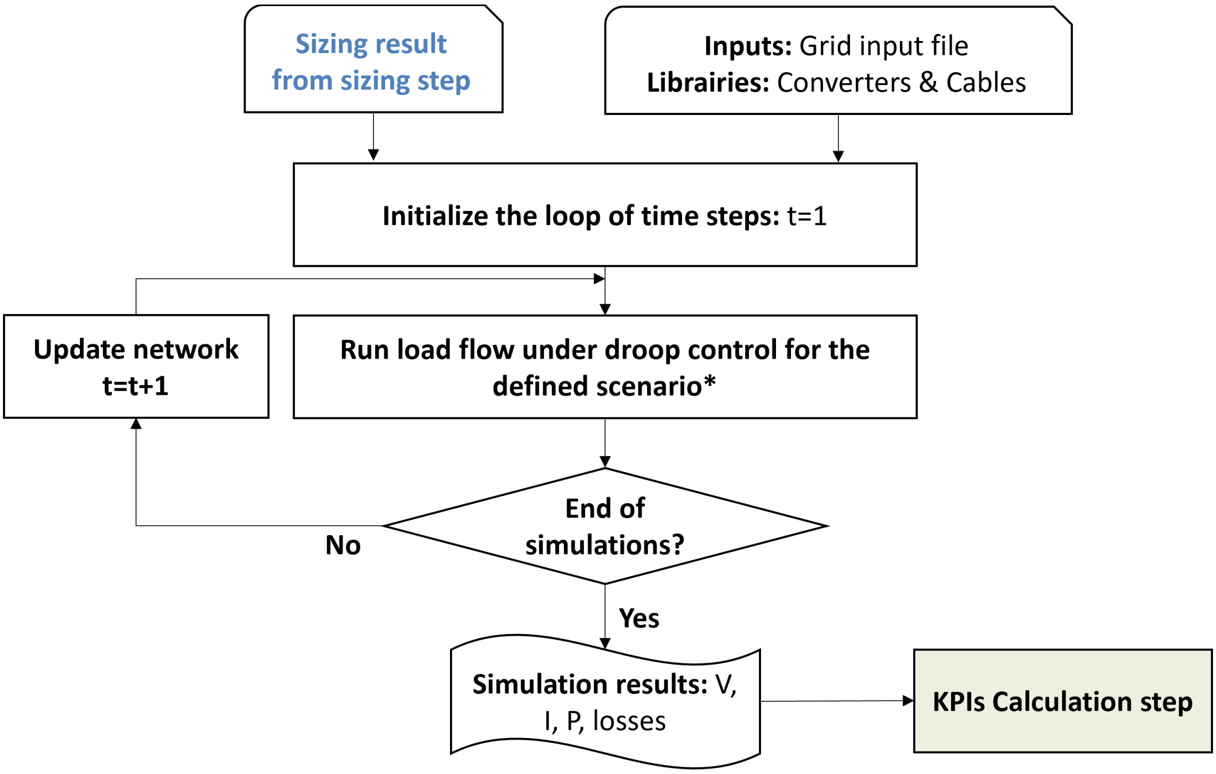
1. Initialization of grid components.
2. Performing the PF computation.
3. Obtaining bus voltages.
4. Obtaining new assets powers by interpolation.
5. PF reevaluation.
6. Verification of bus voltages deviation error between iterations.

The iterative process is given by steps 3 to 6 and stops if step 6 is verified against the tolerance value.

4.2.3.4 Time-Step Load Flow under Droop Control

Objective

As depicted in *Figure* ***4-4***, the time-step load flow simulation under droop control is essential for evaluating the performance (e.g., power losses) and KPIs of the DC network over a defined period (details in Chapter 5). This process provides insights into power flow, energy losses, and voltage regulation at each time step, accounting for changes in the network's conditions.



**Defined scenario = Defined load & production curves*

Figure 4-4 High-level workflow of time-series load flow under droop control.

Why Time-Step Load Flow?

To accurately model the operation of the DC network, it is crucial to assess how the system behaves over time rather than relying solely on single operating points analysis.

- The time-step load flow allows for capturing voltage and current fluctuations at each time step, which are vital for ensuring the reliability and efficiency of the system.
- By simulating power flow at each time step, we can track how power is distributed across the network, ensuring that the converters and cables are operating within their limits. This assessment also helps identify periods of high losses or inefficiencies, which could be critical for improving system design or operational strategies.
- The time-step load flow also allows the evaluation of energy losses in the network components (e.g., cables, converters), which is necessary for calculating efficiency and identifying potential points of failure or opportunities for optimization.

This time-step load flow under droop control provides a comprehensive view of how the DC network operates over time, enabling a detailed evaluation of its dynamic performance.

How is the Time-Step Load Flow Performed?

Time Step Loop (Figure 4-4):

- **The simulation proceeds step-by-step over the specified duration**. The total duration and time step are provided as input (in the “UC Definition” sheet, cf. Section 3.1.4). At each time step, the network conditions are updated to reflect the current state of the system.
- **Load Flow with Droop Control**: The load flow at each timestep is calculated using the droop control strategy (described in Section 4.2.3.3), which adjusts the power delivery based on the voltage and load conditions. Non-convergence of droop control can possibly be observed requiring dynamic change of droop characteristics. However, this functionality is not supported by the design tool.
- **Network Update**: At each time step t, the network model is updated to reflect changing conditions, including generation and consumption profiles, which may vary over the simulation period (details in the following paragraph).

Generation and Consumption Profiles Principle

- **Reminder: Two options for assets profiles**: user-defined (the user can enter the asset profile in the sheet “User-defined Assets Profiles”) or default. Cf. section “Zoom on the Parameters 3.1.4” and more precisely « Asset profile type » parameter: not applicable, user-defined, default PV profile, default EV load, default DC office plug non controllable load, default DC office plug controllable load, default DC lighting, default 12h controllable load with continuous droop, default non controllable Heating, Ventilation, and Air Conditioning (HVAC), default server load, default 12h industrial process, default 24h industrial process, default boat load.
- **Inputs profiles for power flow over a period (with droop control):**

$$P_{asset}(t) = P_{asset}^{ref}(t) \times P_{asset}^{nominal} + N_{asset}(t)$$

  - $P_{asset}(t)$: power profile of the asset.
  - $P_{asset}^{ref}(t)$: reference power profile of the asset (each type of asset has its reference power profile: user-defined or default)
  - $P_{asset}^{nominal}$: nominal power of the asset.
  - $N_{asset}(t)$: noise with variance that depends on the type of the asset when the profile is set by default.
- **Assumptions:**
  - If the asset profile is **default** and the simulation period < 365 days (e.g., 10 days) → We use the default daily profile and replicate it for the defined number of days (considering that we start from January), and we integrate a noise that respects the seasons (winter, summer) and day types (weekday, weekend, vacation).
  - If the asset profile is **default** and the simulation period = 365 days → We generate an annual profile from January to December that integrates a noise that respects the seasons (winter, summer) and day types (weekday, weekend, vacation).
  - If the asset profile is **user-defined** → We check if the length of the defined profile is consistent with the specified time step and simulation period. If yes, the asset profile is taken equal to the user-defined profile. If not, the tool displays an error.

Key Outputs in output_timesteps_LF_results.xlsx

- **Network State at Each Time Step**: The time-step simulation generates a series of network snapshots, each representing the state of the system at a specific point in time. These snapshots are essential for detailed analysis and comparison of system performance over time.
- **Results for Performance Evaluation**: For each time step, the simulation results include information on energy production, consumption, losses, and voltage levels. These results will be used to evaluate KPIs and provide insights into the system's overall efficiency and performance.

5 KPIs Calculation

As discussed in Section 4.2.3.4, the results of the time-step load flow under droop control are critical for evaluating the performance of the network across the simulation period. These evaluations, which include energy losses, voltage distribution, and power distribution, are essential for calculating the KPIs discussed in this chapter, where the network's efficiency and performance will be quantitatively assessed.

5.1 Efficiency KPIs

5.1.1 Objective & Assumptions

Objective

- Assess the efficiency of the DC grid by evaluating energy generation, consumption, and losses.
- Compare the efficiency of the DC grid with an equivalent AC grid.

Assumptions

- The efficiency ratio is calculated as the ratio of total consumed energy to total generated energy.
- Losses in cables and converters contribute to overall inefficiency.
- The total simulation time step is provided in minutes and converted to hours.
- Efficiency of the AC grid is provided as an input for comparison.

5.1.2 KPIs Calculated

KPIs Calculated

- **Total Generated Energy [MWh]:**
    - Sum of power from generation sources (e.g., PV, discharging storage, slack bus) over the simulation period.
    - Formula: $E_{gen} = \sum\left(P_{sgens} + P_{discharge} + P_{slack}^{+}\right) \times \Delta t$
- **Total Consumed Energy [MWh]:**
    - Sum of power consumed by loads and charging storage over the simulation period.
    - Formula: $E_{cons} = \sum\left(P_{loads} + P_{discharge} + P_{slack}^{-}\right) \times \Delta t$
- **Total Losses in Cables [MWh]:**
    - Sum of power losses in cables over the simulation period.
    - Formula: $E_{loss,cables} = \sum P_{loss,cables} \times \Delta t$
- **Total Losses in Converters [MWh]:**
    - Sum of power losses in converters over the simulation period.
    - Formula: $E_{loss,converters} = \sum P_{loss,converters} \times \Delta t$

- **Efficiency Ratio [%]:**
    - Ratio of total consumed energy to total generated energy.
    - Formula: $\eta = \frac{E_{cons}}{E_{gen}} \times 100$
- **Energy Savings [MWh] and [%]:**
    - Difference in total generated energy between DC and AC grids.
    - Formula: $E_{savings} = E_{gen,AC} - E_{gen,DC}$
    - Formula: $\%E_{savings} = \frac{E_{savings}}{E_{gen,AC}} \times 100$

For an example simulation case comparing the efficiency of DC and AC grids using MATPOWER, refer to **Appendix B.**

5.2 Environmental KPIs

5.2.1 Objective & Assumptions

Objective

- Evaluate the environmental impact of the DC grid based on material weight and lifecycle emissions.

Assumptions

- The weight of cables and converters contributes to environmental impact.
- Lifecycle emissions are computed based on predefined emission factors.

Limitations

- The weight of protection devices is not considered. DC protection devices weights are expected to vary at this level of the technology development. A future improvement of this tool would be to add protection devices weight to the KPI.
- Avoided $CO2$ emissions thanks to energy savings are not considered in this KPI being highlighted in the efficiency KPI.

5.2.2 KPIs Calculated

KPIs Calculated

- **Total Weight of Components (kg):**
    - Sum of the weight of all cables and converters.
    - Formula: $W_{total} = W_{cables} + W_{converters}$
- **Weight of Cables (kg):**
    - Computed based on material type (Cu or Al) and length. Since the cable catalog does not include weight parameters, the code uses default weight per meter for Al and Cu cables (in kEUR/m) as defined below:
        - $default\_weight\_cable\_al\_per\_m = 1$
        - $default\_weight\_cable\_cu\_per\_m = 2$
    - Formula: $W_{cables} = \sum L_{cable} \times W_{per\_m}$

- **Weight of Converters (kg):**
  - Computed based on nominal power and specific weight per kW. If the installed converter is listed in the converter catalog, the code uses the weight parameters from the catalog. Otherwise, it applies a default weight per kW (in kEUR/kW) as defined below:
    - $default\_weight\_converter\_kg\_per\_kw = 1$
  - Formula: $W_{converters} = \sum Pnom_{converter} \times W_{per\_kW}$

- **Total Lifecycle Emissions (kg CO2):**
  - Sum of emissions from cables and converters. Since the cable and converter catalogs do not include emission parameters, the code uses default emission factors per kg for cables and converters (in kg CO2/kg) as defined below. However, note that the converter catalog was designed in a way to integrate this parameter, but the necessary data is not available.
    - $emission\_factor\_converter\_kg\_co2\_per\_kg = 5.0$
    - $emission\_factor\_cable\_kg\_co2\_per\_kg = 3.0$
  - Formula: $CO2_{total} = CO2_{cables} + CO2_{converters}$
- **Weight Difference with AC Grid (kg, %):**
  - Difference in total weight between DC and AC grids.
  - Formula: $W_{diff} = W_{total,AC} - W_{total,DC}$
  - Formula: $\%W_{diff} = \frac{W_{diff}}{W_{total,AC}} \times 100$
- **Lifecycle Emissions Difference with AC Grid (kg CO2, %):**
  - Difference in total lifecycle CO2 emissions between DC and AC grids.
  - Formula: $CO2_{diff} = CO2_{total,AC} - CO2_{total,DC}$
  - Formula: $\%CO2_{diff} = \frac{CO2_{diff}}{CO2_{total,AC}} \times 100$

A detailed Life Cycle Assessment (LCA) of the demonstrators will be performed in Task 5.3.

5.3 Economic KPIs

5.3.1 Objective & Assumptions

Objective

- Analyze the investment cost of the DC grid and compare it with the AC grid.
- Analyze the operational cost of the DC grid and compare it with the AC grid.

Assumptions

- CAPEX includes costs for converters and electrical infrastructure costs (protection devices, switchgears, cables, earthing...).
- Operational expenditures (OPEX) include maintenance costs for cables and converters over their lifetime.
- The total CAPEX of the AC grid is provided as input for comparison.

5.3.2 KPIs Calculated

KPIs Calculated

- **Total CAPEX [kEUR]:**
    - Sum of costs for converters and electrical infrastructure costs, such as protection devices, switchgears, cables, and earthing.
    - Formula: $CAPEX_{total} = CAPEX_{cables} + CAPEX_{converters}$
- **CAPEX for Cables [kEUR] :**
    - Computed based on cable type and length. Since the cable catalog does not include cost parameters, the code uses default cost per meter for Al and Cu cables (in kEUR/m) as defined below:
        - $default\_cost\_cable\_al\_per\_m = 0.001$
        - $default\_cost\_cable\_cu\_per\_m = 0.002$
    - Formula: $CAPEX_{cables} = \sum L_{cable} \times c_{per\_m}$
- **CAPEX for Converters [kEUR] :**
    - Computed based on nominal power and cost per kW. If the installed converter is listed in the converter catalog, the code uses the cost parameters from the catalog. Otherwise, it applies a default cost per kW (in kEUR/kW) as defined below:
        - $default\_cost\_per\_kw = 2$
    - Formula: $CAPEX_{converters} = \sum Pnom_{converter} \times c_{per\_kW}$
- **CAPEX Difference with AC Grid [kEUR] or [%]:**
    - Difference in total investment costs between DC and AC grids.
    - Formula: $CAPEX_{diff} = CAPEX_{total,AC} - CAPEX_{total,DC}$
    - Formula: $\%CAPEX_{diff} = \frac{CAPEX_{diff}}{CAPEX_{total,AC}} \times 100$
- **Total OPEX [kEUR] :**
    - Sum of maintenance costs for cables and converters over their lifetime (20 years).
    - Formula: $OPEX_{total} = OPEX_{cables} + OPEX_{converters}$
- **OPEX for Cables [kEUR] :**
    - Computed based on annual maintenance[10] cost per meter and cable length. Since the cable catalog does not include cost parameters, the code uses default cost per meter for Al and Cu cables (in kEUR/m) as defined below:
        - $default\_cost\_cable\_al\_per\_m = 0.00002$
        - $default\_cost\_cable\_cu\_per\_m = 0.00003$
    - Formula: $OPEX_{cables} = \sum L_{cable} \times c_{maint\_per\_m} \times lifetime$
- **OPEX for Converters [kEUR] :**
    - Computed based on annual maintenance cost per kW and nominal power. Since the converter catalog does not include maintenance cost parameters, the code uses default cost per kW (in kEUR/kW) as defined below:
        - $default\_cost\_PV\_converter = 0.05$
        - $default\_cost\_EV\_converter = 0.07$
        - $default\_cost\_ACDC\_converter = 0.06$
        - $default\_cost\_DCAC\_converter = 0.06$
        - $default\_cost\_storage\_converter = 0.08$
    - Formula: $OPEX_{converters} = \sum Pnom_{converter} \times c_{maint\_per\_kW} \times lifetime$

---

[10] Maintenance costs cover periodical inspections, replacement costs or annual fees of maintenance, etc.

OPEX savings [kEUR] can be calculated by the user using **the energy savings KPI** (refer to KPI calculated in Section 5.1.2) and the **electricity price** of the considered country: $OPEX_{savings} = E_{savings} \times c_{keur\_per\_MWh}$

For a more detailed breakdown of the economic KPIs, including additional assumptions and methodologies, refer to **Appendix C**. Given the current maturity level of DC components, some economic parameters have been estimated based on assumptions due to limited available cost data.

6 Conclusion & Perspectives

This deliverable (D2.1) presented the results of Task 2.1, “Network Design Tool for DC Solutions,” as part of the Shift2DC project.

The development of the SOL23 DC Network Design Tool within the Shift2DC project addresses the growing need for a structured and accessible approach to DC network design and evaluation. This tool provides a comprehensive methodology for the electrical sizing, load flow analysis, and performance assessment of DC networks, offering key insights into their preliminary design, efficiency, and feasibility compared to conventional AC systems.

Through the implementation of static models for DC cables and converters, voltage control strategies, and KPI calculations, the tool enables users to evaluate the technical and economic performance of DC networks. The time-step load flow simulation under droop control enhances the tool's accuracy in analyzing real-world operational conditions, while the KPI evaluation framework facilitates a direct comparison with AC alternatives.

Despite its current capabilities, the tool has some limitations that could be addressed in future developments. The focus on DC networks assumes that users can independently evaluate AC networks with existing tools, which may require additional integration efforts. Furthermore, the droop control functionality of the main AC/DC converter is not yet fully implemented, limiting the accuracy of power-sharing mechanisms. These areas present opportunities for further research and refinement.

Future enhancements should focus on extending the tool’s functionality, improving user accessibility, and increasing its TRL. Potential improvements include:

- Full implementation of droop control to enable better stability.
- Expansion of the tool’s scope to incorporate other DC grid architectures (e.g., bipolar) and hybrid AC/DC networks for broader applicability.
- Graphical user interface (GUI) development to improve usability and accessibility for engineers and researchers.

By providing an open-source and structured approach to DC network design, the SOL23 tool contributes to the advancement of DC power systems in various sectors, including data centers and industrial facilities. With continued development and validation, it has the potential to become a reference tool for engineers and researchers seeking to optimize DC network architectures for future energy systems.

7 References

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APPENDIX A: Example of the Sizing Outputs for the Building Demonstrator

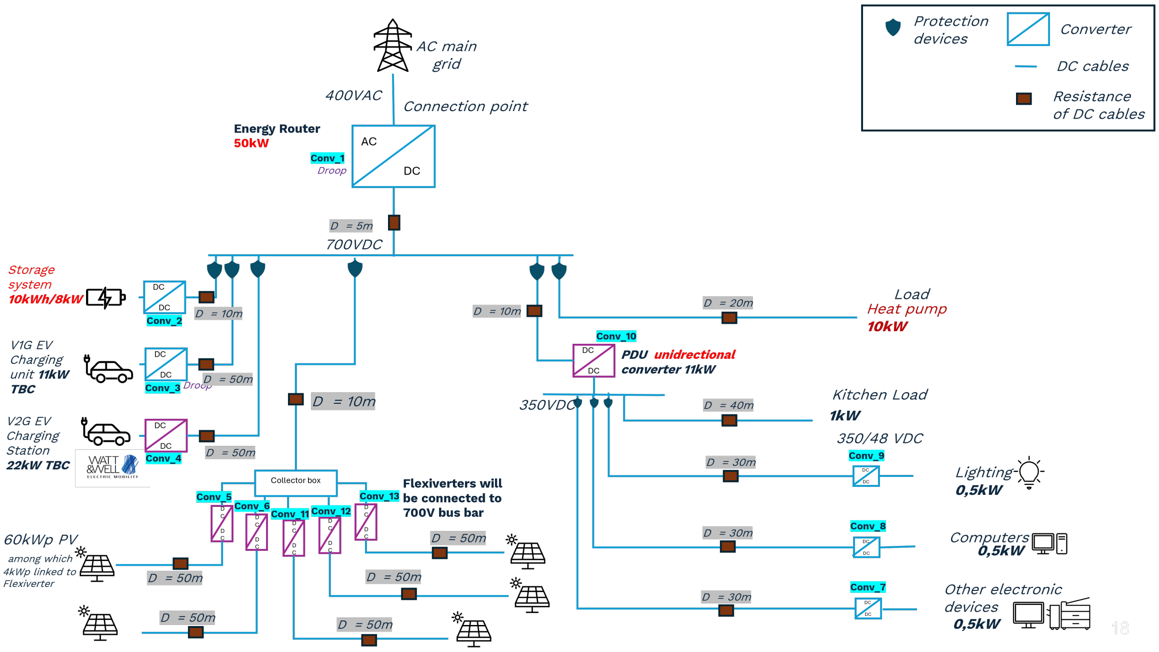


Figure A-0-1 Single line diagram associated with the presented sizing results.

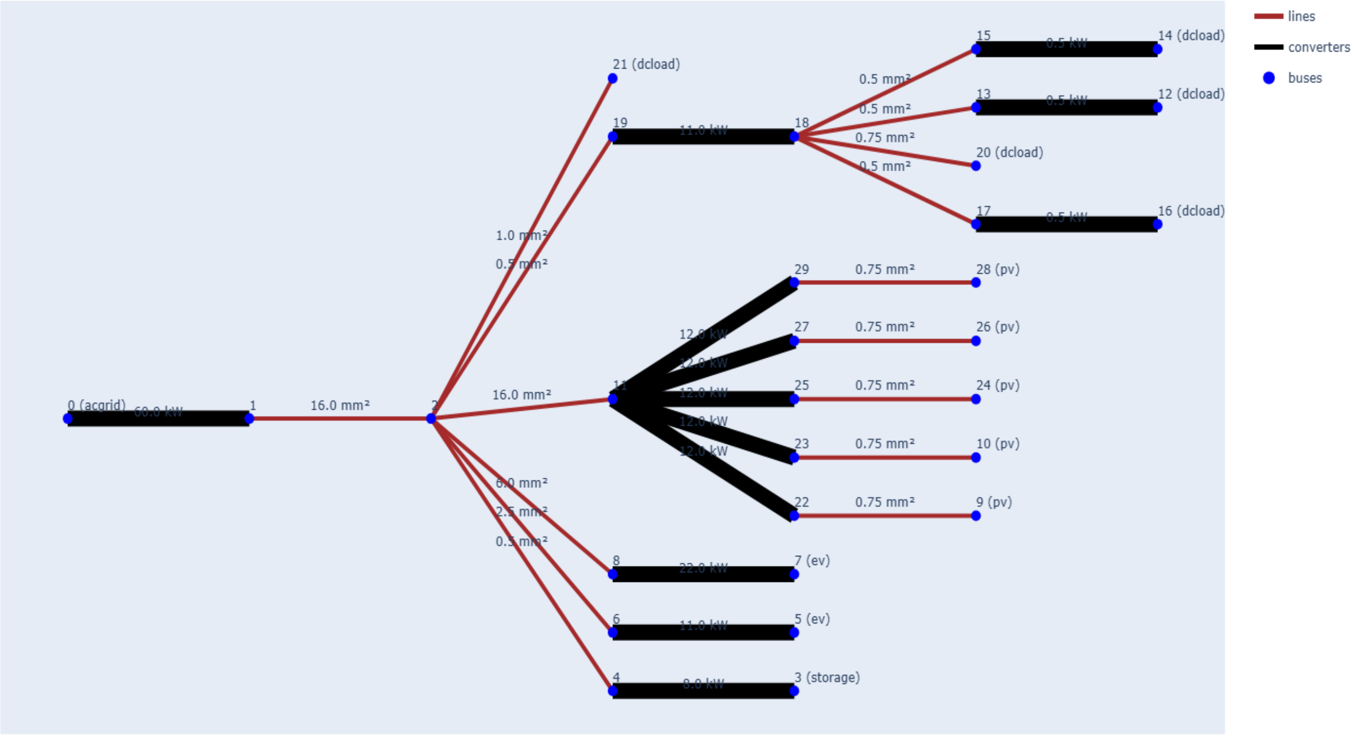


Figure A-0-2 Example of a sizing output for the building demonstrator.

APPENDIX B: Example Case for Efficiency Comparison of DC & AC Grids

Objective

- Assessing performance of the DC grid design by answering the following questions:
  - How much of the generated power can be fed into the grid?
  - How much more power needs to be accounted for, for connecting power consumers to the grid?
  - How efficient is the power distribution in the grid structure?
- If possible, enabling efficiency comparison of the DC grid and an equivalent AC system.

Assumptions

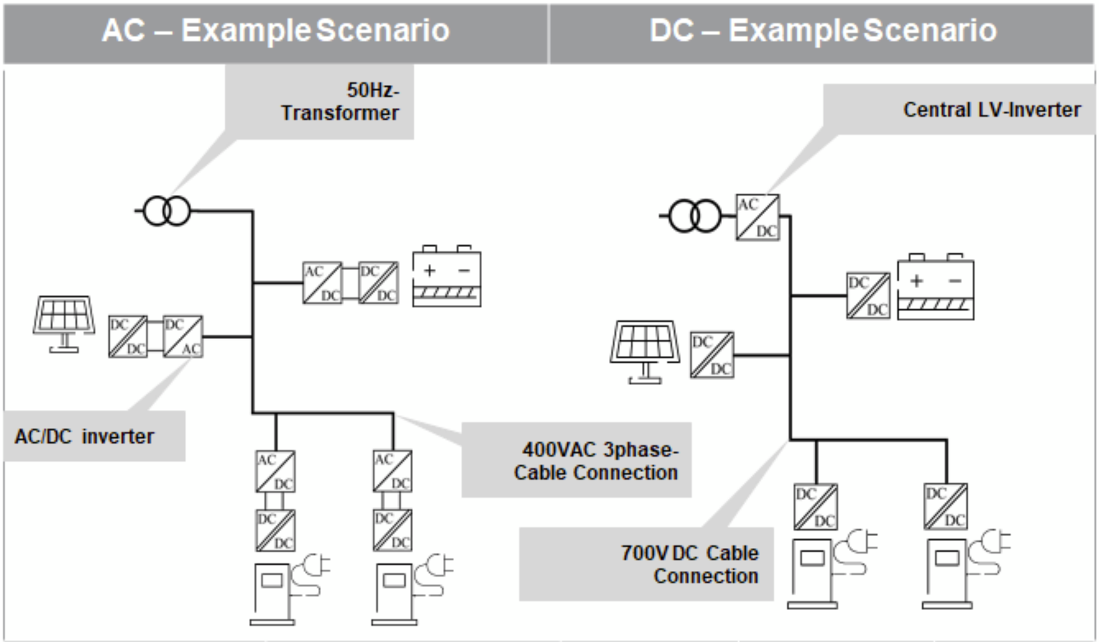
- For the AC equivalent scenario, the same DC-DC converters are used, as for the DC grid, plus additional AC/DC inverters, as illustrated by Figure B- 1 below.
- It is assumed that the distances between the grid nodes for the AC equivalent case are the same as for the AC grid design.
- The RMS value AC line-to-line voltage is assumed to be 400V, thus, the RMS line-to earth voltage is assumed to be 230V.

Inputs

- Load profiles of the electrical loads and power generation plants connected to the DC grid.
- Efficiency curves of the DC/DC converters chosen for the connection of the electrical loads and power generation plants to the DC grid.
- Efficiency curves of the AC/DC converters that would be needed additionally to connect the electrical loads and power generation plants to an AC grid.
- DC cable losses from the DC power-flow calculation.
- AC cable losses from the AC power-flow calculation, if available.
- Load profile of the central inverter connecting the DC grid under investigation to the surrounding grid infrastructure.

Methodology

1. Calculate the loss power occurring in the converters by interpolating the efficiency curve at the location of the operating power according to the load profile.
2. Using the calculated losses, derive the power that is withdrawn or fed into the grid connection point. For devices consuming power, the power at the grid connection point is increased by the losses occurring in the converter, for power generation plants, the power available at the grid connection point is reduced by the power losses in the converter.
3. The obtained power at the grid connection points serves as input for the power flow calculation.
4. The DC power flow calculation outputs the cable losses and the load profile of the central inverter.
5. The losses in the central inverter (AFE) can be calculated using the method described in step1.



	Transformer/Central LV-Inverter	Battery	PV feed in	EV-Charger
Transformer/Central LV-Inverter		20m		
Battery	20m		40m	
PV feed in		40m		40m
EV-Charger			40m	

Figure B- 1 Example of a DC grid and its AC equivalent counterpart.

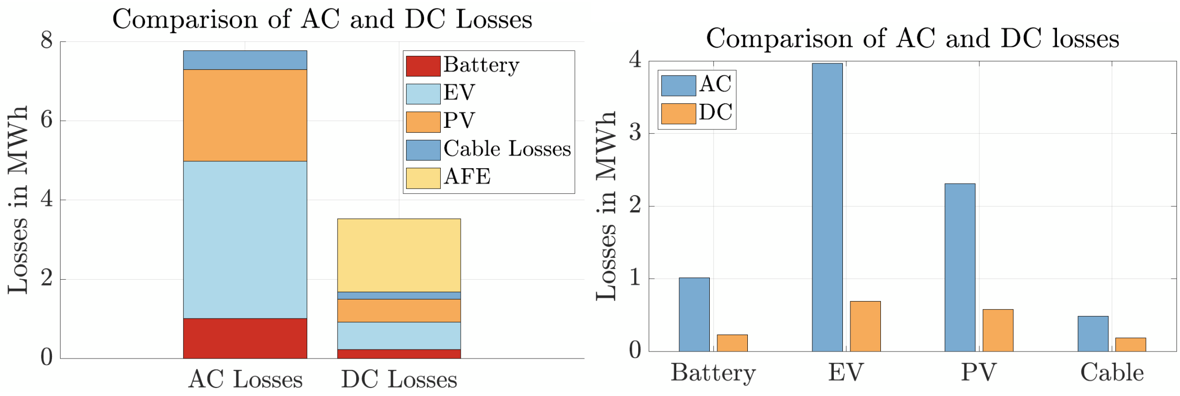


Figure B-2 Loss energy of the different grid elements of the DC and the AC example grid.

The total losses from Table 2 comprise the sum of all losses depicted in the figure above for the two scenarios, respectively. Note that the losses in the central inverter (AFE) of the DC-scenario depend on the sizing of the battery or other energy storage systems within the grid system. These results are illustrative as they depend mainly on the efficiency curves considered for the converters. For this example, the efficiency curves are arbitrary and theoretical due to the lack of industrial products on the market. Thus, Figure B-2 illustrates the study case only without any deduction on the general efficiency for DC systems that will be conducted in Task 5.3.

Energy distributed via grid system is defined as the sum of the energy that is generated by all power plants in the grid system E_{gen} and the sum of energy consumed by all electrical loads E_{cons} in the grid system. As it is assumed that the load profiles for the DC and AC scenarios are the same, E_{grid} is equal for both scenarios.

$$E_{grid} = \sum E_{gen} + \sum E_{cons}$$

The system efficiency is calculated using the equation below.

$$\eta_{system} = 1 - \frac{E_{loss}}{E_{grid}}$$

The "*PV energy at grid node*" is defined as the ratio between the overall PV energy available at grid node and the overall PV energy generated by the PV power plant. This indicates how much of the generated power will be available to the grid. The "*EV-charger energy at grid node"* is defined as the ratio between the energy withdrawn from the grid at the grid connection point of the converters of the EV-charger and the energy consumed by the EV-charger according to its load profile from the input data. According to the table below, it can be seen, that in the example case the additional AC/DC inverter stages in the ac-scenario increase the energy demand by more than 10%, for the EV charger, while reducing the PV energy available to the grid by over 7%.

The cable losses of the DC grid structure are an output of the DC-power flow calculation. The AC-cable losses in Table 2 were obtained by using the AC-power flow calculation in MatPower[11]. As the distances between the grid nodes of the example range between 20m and 40m and the power at the grid nodes is at maximum 25 kW, the cable losses are quite low.

Table 2 - Overview of efficiency KPIs calculated for the example case.

	AC	DC
Total Losses E_{loss} [MWh]	7,771	3,53
E_{grid} [MWh]	69,061	69,061
System efficiency η_{system}	88,74%	94,89%
PV Energy at Grid Node	92,63 %	98,15%
EV-Charger Energy at Grid Node	110,51%	101,83%
Cable Losses [MWh]	0,484	0,1839
Cable Losses /Energy distributed via grid	0,68%	0,27%

---

[11] https://github.com/MATPOWER/matpower

APPENDIX C: Detailed Economic KPI Definitions and Assumptions

Objective

The economic KPIs are established to assess the financial impact of converting an AC system into a DC system. These KPIs help quantify the expected economic benefits and changes associated with the transition. The evaluation focuses on several critical factors, including:

1. **CAPEX**: The initial investment required for infrastructure modifications, including equipment costs and installation expenses.
2. **OPEX**: The ongoing costs associated with system operation, such as energy consumption, maintenance, and personnel.
3. **System Loss Reduction**: A comparison of power losses between AC and DC systems to determine potential efficiency gains and cost savings.
4. **Maintenance Frequency**: The expected change in maintenance requirements, considering the reliability and durability of DC components.
5. **Average Downtime**: The impact on system availability, including potential reductions in outages due to fewer components and improved efficiency.

Assumptions

There are a few assumptions used in the backbone of the economic KPIs. These assumptions are as follows:

1. CAPEX is the accumulation of the equipment and installation costs of the converters (e.g., Uninterruptible Power Supply (UPS)), the protection devices, cables, and earthing. Additionally, it includes any additional regulatory fees.
2. OPEX covers the maintenance, downtime, and consumption (with losses) aspects.
3. The changes (expected reduction) on the losses are fully based on the improvement of the system efficiency.

Methodology

The main inputs for the economic KPIs are the following:

1. Number of converters (UPS) and their rated power.
2. Protection devices and switchgear unit.
3. Length of the cables, for cables cost estimation.
4. Additional electrical infrastructure costs, such as earthing.
5. Any additional fees, permit, or regulatory fees.
6. Downtime cost per event and count of downtime events for AC and DC.
7. AC and DC total system losses.
8. Assets lifetime and annual maintenance cost.

The different KPIs are calculated based on their nature as follows:

1. **CAPEX**: since it represents the accumulated cost before operation, then it can be estimated as follows:

$$CAPEX = \sum_{i=0}^{N} ConvCost(i) + \sum_{i=0}^{N} InfrasCost(i) + \sum_{i=0}^{K} CableCost(i) + PermitComplianceCost$$

Where N is the number of converters, $ConvCost$ represents the cost of the converters and their installation, K is number of cables, $InfrasCost$ covers all infrastructure costs such as protection devices, $CableCost$ represents the cost of the cables, and lastly the $PermitComplianceCost$ covers all additional costs.

In more detail, the $ConvCost$ is estimated as follows:

$$ConvCost(i) = EquipmentCost(i) + InstallationCost(i)$$

Where the equipment cost, and the installation cost are estimated using a polynomial function interpolated from APC Galaxy VS UPS reference values for different rated power[12].

$$EquipmentCost(i) = -0.4026 * Rated_{kW} * Rated_{kW} + 141.81 * Rated_{kW} + 5894$$

$$InstallationCost(i) = 125 * Rated_{kW}$$

The cable cost $CableCost$ is a function of the cable length and the cost of the selected cable type from the database.

2- **OPEX**: three KPIs represent the OPEX as follows:

   a. Total Maintenance Cost Over Lifetime (MCOL)

   $$MCOL = AnnualMaintenaceCost * Lifetime$$

   b. Annual energy consumption cost

   $$C = EuroperkWh * \text{Annual energy consumption}$$

Total OPEX is the summation of the previous 2 elements for all assets available.

3- **AC to DC transition**: these KPIs are mainly dependent on the efficiency of the AC system vs the DC system.

   a. Conversion Efficiency Savings (CES)

   $$CES = \left(1 - \frac{DCSystemLosses}{ACSystemLosses}\right) * 100$$

   b. Energy Cost Savings (ECS)

   $$ECS = (ACEnergyConsumption - DCEnergyConsumption) * PriceperkWh$$

   c. Operational Downtime Savings (ODS)

   $$ODS = (ACDowntimeEvents - DCDowntimeEvents) * DowntimeCostperEvent$$

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[12] https://www.apc.com/us/en/product-range/65772-galaxy-vs/#products