Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

IMPROVED REPRESENTATION OF ELECTRICITY COSTS IN THE INTEGRATE MODEL

ZEN MEMO No. 47 – 2023

Magnus Askeland | SINTEF Energi AS

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Norwegian University of Science and Technology (NTNU) | www.ntnu.no
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Preface

Acknowledgements

This memo has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The authors gratefully acknowledge the support from the Research Council of Norway, the Norwegian University of Science and Technology (NTNU), SINTEF, the municipalities of Oslo, Bergen, Trondheim, Bodø, Bærum, Elverum and Steinkjer, Trøndelag county, Norwegian Directorate for Public Construction and Property Management, Norwegian Water Resources and Energy Directorate, Norwegian Building Authority, ByBo, Elverum Tomteselskap, TOBB, Snøhetta, AFRY, Asplan Viak, Multiconsult, Sweco, Civitas, FutureBuilt, Hunton, Moelven, Norcem, Skanska, GK, Nord-Trøndelag Elektrisitetsverk - Energi, Smart Grid Services Cluster, Statkraft Varme, Energy Norway and Norsk Fjernvarme.

The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities

The ZEN Research Centre develops solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contributes to a low carbon society.

Researchers, municipalities, industry and governmental organizations work together in the ZEN Research Centre in order to plan, develop and run neighbourhoods with zero greenhouse gas emissions. The ZEN Centre has nine pilot projects spread over all of Norway that encompass an area of more than 1 million m2 and more than 30 000 inhabitants in total.

In order to achieve its high ambitions, the Centre will, together with its partners:

- Develop neighbourhood design and planning instruments while integrating science-based knowledge on greenhouse gas emissions;
- Create new business models, roles, and services that address the lack of flexibility towards markets and catalyze the development of innovations for a broader public use; This includes studies of political instruments and market design;
- Create cost effective and resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies;
- Develop technologies and solutions for the design and operation of energy flexible neighbourhoods;
- Develop a decision-support tool for optimizing local energy systems and their interaction with the larger system;
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and a testing ground for the solutions developed in the ZEN Research Centre. The pilot projects are Furuset in Oslo, Fornebu in Bærum, Sluppen and Campus NTNU in Trondheim, an NRK-site in Steinkjer, Ydalir in Elverum, Campus Evenstad, NyBy Bodø, and Zero Village Bergen.

The ZEN Research Centre will last eight years (2017-2024), and the budget is approximately NOK 380 million, funded by the Research Council of Norway, the research partners NTNU and SINTEF, and the user partners from the private and public sector. The Norwegian University of Science and Technology (NTNU) is the host and leads the Centre together with SINTEF.

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Abstract

This memo provides a description of new modules for grid interaction in the optimization software Integrate (formerly eTransport). Key design choices are explained and the relevant parameters are described to enable the user to understand how to use the modules as a part of a system in Integrate. An appendix provides mathematical formulations that maps the implementation in AMPL.

Contents

1 Introduction

Integrate has relied on a price for volumetric electricity use in the modelled area in EUR/MWh, and it has been the user's responsibility to include tariffs and other fees in the specified prices. Capacity tariffs have not been included directly but can be indirectly represented through reduced OPEX in investment packages. The limitation is, however, that there is still no incentive for reducing the peak demand as seen by the optimization solver.

Based on these limitations, and the increasing use of capacity-based tariffs to provide incentives for peak load reduction, the grid pricing in Integrate has been revised as described in this document.

The rest of the document is structured as follows. First, the section "Grid pricing practice" describes the price structures commonly used. Thereafter, the section Integrate modules to represent grid interaction" gives a practical description on the Integrate implementation before the section "

The modelled system may contain several such connection points based on how many connections there are with the surrounding grid, and one connection point is typically where metering occurs.

Table 2 provides an overview of the "grid import" module parameters to relate the name in the user interface with the mathematical formulation and the AMPL code and describes what the parameter is used for.

Table 2 Overview of parameters for grid import module

Name	AMPL name	Unit	Description
El cost	El_cost	CURRENCY/ MWh	Price for electricity in the external market during each time step, e.g. Nord Pool spot price.
Max outtake	El_max	MWh/h	Constraint of maximum capacity.
Overusage tariff	IMP_TARIFF_OC	CURRENCY/ MWh/h	Penalty tariff for capacity usage above the subscribed level. If this should not be an option the value should be set higher than the capacity tariff to create a soft constraint requiring the subscribed capacity to be equal to peak load.
Volumetric tariff	IMP_TARIFF_VNT	CURRENCY/ MWh	Volumetric tariff based on energy units imported (similar to el cost) to represent tariffs and taxes.
Capacity tariff	IMP_TARIFF_CT	CURRENCY/ MWh/h	Tariff per unit of capacity. Continuous cost function rather than ladder is assumed.

Similarly, Table 3 provides information for el market parameters.

Table 3 Overview of parameters for el market module

Name	AMPL name	Unit	Description
El load	El_load	MWh	A load can be specified, which commonly may be zero when representing an export node.
Capacity overusage tariff	EXP_TARIFF_OC	CURRENCY/ MWh/h	Penalty tariff for capacity usage above the subscribed level. If this should not be an option the value should be set higher than the capacity tariff to create a soft constraint requiring the subscribed capacity to be equal to peak load.
El price	El_price	CURRENCY/ MWh	Price for electricity in the external market for each time step, e.g. Nord Pool spot price.
Volumetric grid tariff	EXP_TARIFF_VNT	CURRENCY/ MWh	Volumetric tariff based on energy units imported (similar to el cost) to represent tariffs and taxes. Commonly the volumetric tariff for selling to the grid is negative or zero because feed-in reduces system losses.
Capacity grid tariff	EXP_TARIFF_CT	CURRENCY/ MWh/h	Tariff per unit of capacity. Continuous cost function rather than ladder is assumed. Commonly the cost of capacity is zero for exports as capacity-based tariffs may only apply to energy imports.

" provides an example of how to utilize the functionality. This memo is complemented by "

Appendix: Description of mathematical implementation" with technical documentation.

2 Grid pricing practice in Norway

The main driver for grid companies' costs is the need for capacity based on the peak load in the system. Therefore, from July 2022, new rules for how grid costs should be designed were in place[1]. The main change is that while the grid cost historically consists of a fixed fee (NOK/month) and volumetric tariffs (NOK/kWh), electricity users will now to a larger extent be faced with capacity costs (NOK/kW). The underlying motivation for this change is to better align the incentives for electricity users with the upstream costs in the system. Larger consumers, typically companies, have been subject to capacity-based tariffs for some time.

The regulator requires a part of the tariff to be capacity-based but leaves some leeway to the distribution grid companies (DSOs) regarding the final design of the tariff in their area. The overall requirement is that the volumetric tariff (NOK/kWh) should not exceed 50% of the DSO's income and that the fixed payment needs to be based on capacity usage such that the users cover an appropriate part of the overall cost of capacity provision[2].

Most grid companies have chosen to employ the following pricing model:

- A monthly capacity-based fixed fee with capacity intervals
- A volumetric fee for energy which can be lower during some time periods to encourage load shifting to hours with sufficient grid capacity.

The DSO Elvia employs a pricing model which is representative for most DSOs in Norway[3].The capacity-based part of the tariff is shown in Table 1.

Table 1 Elvia's capacity tiers

Fixed fee tier	Peak load (kWh/h)	Cost (NOK/month)	Calculated unit cost (NOK/kW/month)
Tier 1	0-2	125	62.5
Tier 2	2-5	200	40
Tier 3	5-10	325	32.5
Tier 4	10-15	450	30
Tier 5	15-20	575	28.75
Tier 6	20-25	700	28
Tier 7	25-50	1325	26.5
Tier 8	50-75	1950	26
Tier 9	75-100	2575	25.75
Tier 10	100 -	5150	-

[1] https://www.nve.no/reguleringsmyndigheten/kunde/nett/ny-nettleie-fra-1-juli-2022/

[2] https://lovdata.no/forskrift/1999-03-11-302/§14-2

[3] https://www.elvia.no/nettleie/alt-om-nettleiepriser/nettleiepriser-for-privatkunder/

The peak load is determined as the average of the three hours of the month with the highest load, which needs to occur on different days.

In addition there are volumetric fees as follows:

- Day tariff: 06:00 – 22:00: 0.1807 NOK/kWh
- Night tariff: 22:00 – 06:00: 0.1307 NOK/kWh
- Weekend tariff 00:00 – 24:00: 0.1307 NOK/kWh
- Taxes: 00:00 – 24:00: 0.1684 NOK/kWh

3 Integrate modules to represent grid interaction

Two different modules have been developed for representing grid connections, "grid import" and "el market" as depicted in Figure 1.

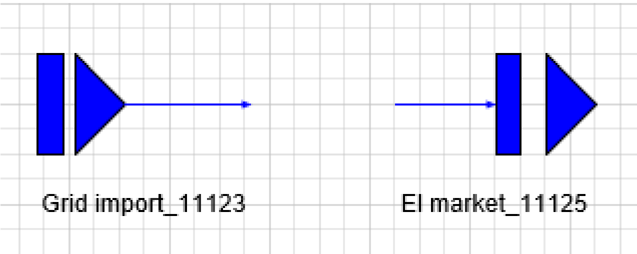

Figure 1 Integrate modules for grid interaction

“Grid import” is to be used for energy purchased from the surrounding grid, while “el market” is to be used for selling energy to the surrounding grid. Note that in the common situation where one connection point has the possibility for both purchasing and selling electricity, it is necessary to connect both to the same busbar as depicted in Figure 2.

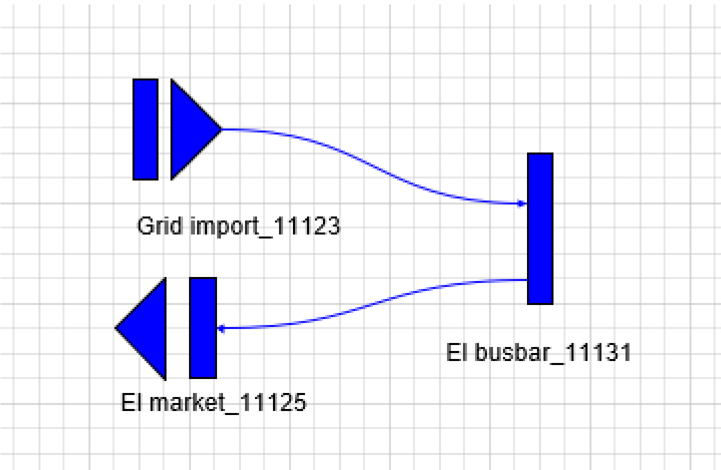

Figure 2 Bidirectional connection point

The modelled system may contain several such connection points based on how many connections there are with the surrounding grid, and one connection point is typically where metering occurs.

Table 2 provides an overview of the "grid import" module parameters to relate the name in the user interface with the mathematical formulation and the AMPL code and describes what the parameter is used for.

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Volumetric tariff	IMP_TARIFF_VNT	CURRENCY/ MWh	Volumetric tariff based on energy units imported (similar to el cost) to represent tariffs and taxes.
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Similarly, Table 3 provides information for el market parameters.

Table 3 Overview of parameters for el market module

Name	AMPL name	Unit	Description
El load	El_load	MWh	A load can be specified, which commonly may be zero when representing an export node.
Capacity overusage tariff	EXP_TARIFF_OC	CURRENCY/ MWh/h	Penalty tariff for capacity usage above the subscribed level. If this should not be an option the value should be set higher than the capacity tariff to create a soft constraint requiring the subscribed capacity to be equal to peak load.
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Capacity grid tariff	EXP_TARIFF_CT	CURRENCY/ MWh/h	Tariff per unit of capacity. Continuous cost function rather than ladder is assumed. Commonly the cost of capacity is zero for exports as capacity-based tariffs may only apply to energy imports.

4 Module validation

The following setup is used to illustrate the use of the modules:

- Market price (import/export): 500 NOK/MWh
- Volumetric import tariff
    - 22-06: 370 NOK/MWh
    - 06-22: 440 NOK/MWh
- Volumetric export tariff: -60 NOK/MWh
- Overusage tariff: 10^12 NOK/MWh/h (avoids any overusage)
- Capacity-based tariff: 0 NOK/MWh/h (to create a baseline)

The system topology is depicted in Figure 3.

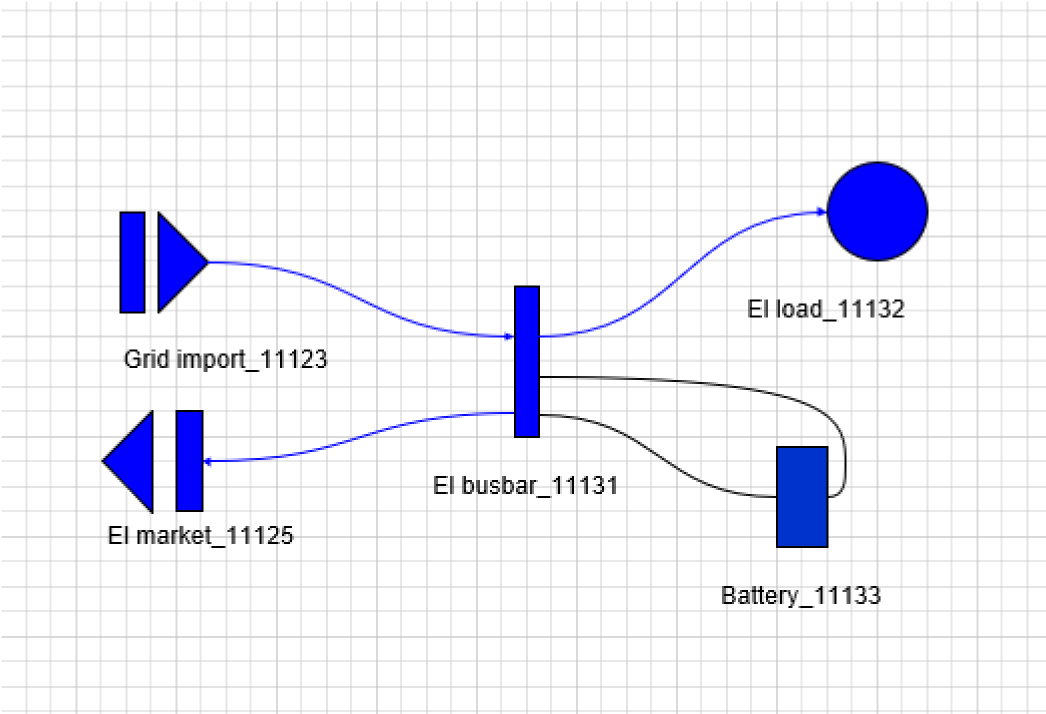

Figure 3 Illustrative example system setup

The battery has a capacity of 5MWh with 10% losses, and the load has a peak in the afternoon as depicted in Figure 4.

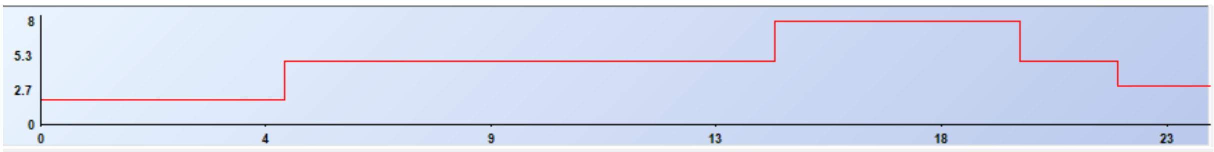

Figure 4 Load profile

This initial setup yields import exactly matching the load profile and no use of the battery because there is no capacity-based tariff in place, and the time-differentiated volumetric tariff does not have large enough price variations to justify the cost of losses. Grid imports are depicted in Figure 5, with a peak load of 8 MWh/h.

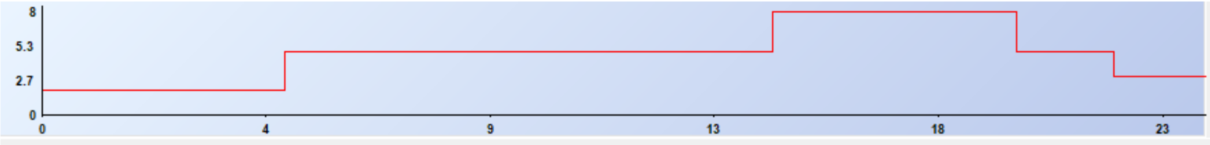

Figure 5 Grid imports without capacity-based tariff

When a capacity-based tariff of 28 000 NOK/MWh/h is specified, there is an incentive to reduce the peak load. The grid imports change due to utilization of the battery to the profile in Figure 6 Grid imports with capacity-based tariffFigure 6 with a peak load of 7.24 MWh/h.

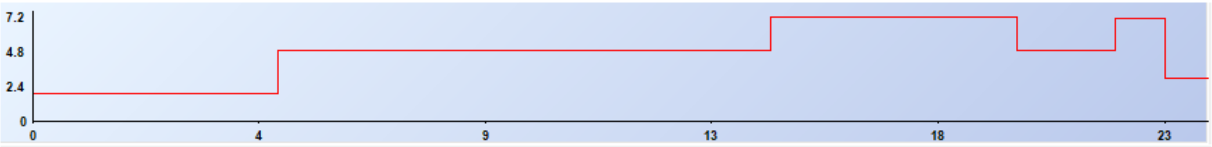

Figure 6 Grid imports with capacity-based tariff

The change in the energy import profile occurs because of the battery. The previously passive battery is now operated according to Figure 7 because the possibility of reducing the capacity-based tariff costs exceeds the cost of energy losses due to operating the battery.

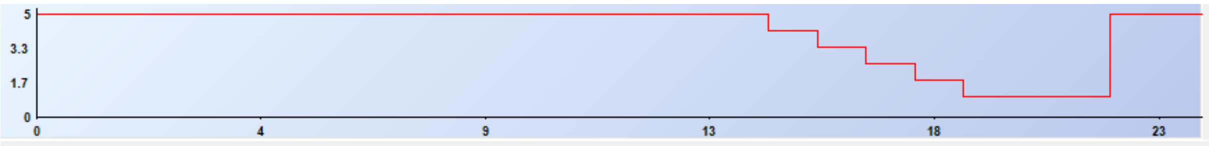

Figure 7 Battery operation with capacity-based tariff

5 Appendix: Description of mathematical implementation

1 Electric source/grid imports (el_source)

This section describes the model formulation of the electric source module (el_sup.mod). This module is used to model the generic electricity supply, i.e. local generation of electricity. It is also used for the grid imports component which is modeled as an electric source with the addition of grid pricing.

1.1 Variables, parameters and sets

Table 1: Mathematical notation of sets for the electric source module

Symbol	Explanation
$El\_supplies$	The set of all electric supplies in the model, Index el_s in the following
$El\_grid\_imports$	Subset of $El\_supplies$ that are also grid imports, Index el_g in the following

Table 2: Mathematical notation of parameters for the electric supply module

Symbol	Explanation	
$El\_max_{el\_s,t}$	Maximum electricity supply	MWh/h
$El\_min_{el\_s,t}$	Minimum electricity supply	MWh/h
$El\_cost_{el\_s,t}$	Price of the electricity	EUR/MWh
$IMP\_TARIFF\_CT_{el\_g}$	Capacity-based import tariff	EUR/MWh/h
$IMP\_TARIFF\_OC_{el\_g,t}$	Excess capacity usage import tariff	EUR/MWh/h
$IMP\_TARIFF\_VNT_{el\_g,t}$	Volumetric import tariff	EUR/MWh

Table 3: Mathematical notation of variables for the electric supply module

Symbol	Explanation	
$el\_usage_{el\_s,t}$	Electricity supply	MWh/h
$imp\_capacity\_usage_{el\_m}$	Peak capacity usage	MWh/h
$imp\_capacity\_subscribed_{el\_m}$	Subscribed capacity	MWh/h
$imp\_oc\_usage_{el\_m,t}$	Capacity over usage	MWh/h

1.2 Contribution to the objective function

The contribution to the objective function varies depending on whether component is an electric supply or an grid import. The following is included for both:

$$Objective^{sub}_{Electric\_Supplies} = \sum_{el\_s,t} El\_cost_{el\_s,t} \cdot el\_usage_{el\_s,t} \tag{1}$$

Which simply states that any energy from the component is subject to the specified cost for each time step.

For grid imports, the following is added to the objective contribution:

$$+\sum_{el\_g,t}\Big(IMP\_TARIFF\_VNT_{el\_g,t}\cdot el\_usage_{el\_g,t}+IMP\_TARIFF\_OC_{el\_g,t}\cdot imp\_oc\_usage_{el\_g,t}$$
$$+\sum_{el\_g}IMP\_TARIFF\_CT_{el\_g}\cdot imp\_capacity\_subscribed_{el\_g} \quad (2)$$

Here, it is possible to import electricity at specified prices. In addition, the grid import module can specify grid costs based on the amount of energy sold and on the capacity usage. The amount of subscribed capacity is optimized and any capacity usage above this level is subject to an overusage fee. If the overusage fee is set significantly higher than the cost of subscribed capacity (as it is by default), there will be no overusage as it will most economical to increase the amount of subscribed capacity.

1.3 Contribution to the emissions

The module has no direct contribution to emissions.

1.4 Network constraints

The network constraint coupling this module to the rest of the system is:

$$\sum_{(i,el\_s)\in Supply2Net} supply\_flow_{i,el\_s,t}+\sum_{(i,el\_l)\in Supply2load} local\_flow_{i,el\_s,t}=el\_usage_{el\_l,t} \quad \forall el\_s,t \quad (3)$$

1.5 Module specific constraints

The following module-specific constraints only apply to grid imports:

$$imp\_capacity\_subscribed_{el\_g}\geq el\_usage_{el\_g,t}-imp\_oc\_usage_{el\_g,t} \quad \forall el\_g,t \quad (4)$$

$$imp\_capacity\_usage_{el\_g}\geq imp\_capacity\_subscribed_{el\_g}+imp\_oc\_usage_{el\_g,t} \quad \forall el\_g,t \quad (5)$$

These specify the need to pay for the capacity usage of the imported electricity. The variable for the subscribed capacity is constrained to take the value of the peak electricity export subtracted the overusage during each hour. There is also a variable for the peak capacity usage so the program can present this value to the user. The capacity usage will be equal to the subscribed capacity if no overusage is incurred.

2 Electric load / market (el_load)

This section describes the model formulation of the electric load module (el_load.mod). This module is used to model electric loads, i.e. sink point for electricity. It is also used for the electric markets component which is modeled as an electric load with the addition of the possibility to sell electricity.

2.1 Variables, parameters and sets

Table 4: Mathematical notation of sets for the electric load module

Symbol	Explanation
El_loads	The set of all electric loads in the model, Index el_l in the following
$El\_markets$	Subset of El_loads that are also electric markets, Index el_m in the following

Table 5: Mathematical notation of parameters for the electric load module

Symbol	Explanation	
$El\_load_{el\_l,t}$	Electric load of electric load el_l in timestep t	MWh
$El\_price_{el\_m,t}$	Price of the electricity sold to the market el_m at timestep t	EUR/MWh
$EXP\_TARIFF\_CT_{el\_m}$	Capacity-based export tariff	EUR/MWh/h
$EXP\_TARIFF\_OC_{el\_m,t}$	Excess capacity usage export tariff	EUR/MWh/h
$EXP\_TARIFF\_VNT_{el\_m,t}$	Volumetric export tariff	EUR/MWh
$Max\_el\_sale_{el\_m,t}$	Maximum amount of electricity sold to market el_m at timestep t	MWh
$El\_deficit\_penalty$	Penalty for deficit of electricity to the loads	EUR/MWh

Table 6: Mathematical notation of variables for the electric load module

Symbol	Explanation	
$el\_deficit_{el\_l,t}$	Deficit of electricity of load el_l at t	MWh
$sold\_el_{el\_m,t}$	Electricity sold from el_m at t	MWh
$exp\_capacity\_usage_{el\_m}$	Peak capacity usage	MWh/h
$exp\_capacity\_subscribed_{el\_m}$	Subscribed capacity	MWh/h
$exp\_oc\_usage_{el\_m,t}$	Capacity over usage	MWh/h

2.2 Contribution to the objective function

The contribution to the objective function varies depending on whether component is an electric load or an electric market. The following is included for both:

$$Objective^{sub}_{Electric\_Loads} = \sum_{el\_l,t} El\_deficit\_penalty \cdot el\_deficit_{el\_l,t} \tag{6}$$

Which simply states that any deficit (energy not supplied) is subject to the penalty cost.
For electric markets, the following is added to the objective contribution:

$$+\sum_{el\_m,t}\Big(EXP\_TARIFF\_VNT_{el\_m,t}\cdot sold\_el_{el\_m,t}+EXP\_TARIFF\_OC_{el\_m,t}\cdot exp\_oc\_usage_{el\_m,t} - El\_price_{el\_m,t}\cdot sold\_el_{el\_m,t}\Big) + \sum_{el\_m} EXP\_TARIFF\_CT_{el\_m}\cdot exp\_capacity\_subscribed_{el\_m} \quad (7)$$

Here, it is possible to sell electricity at specified prices. In addition, the electricity market module can specify grid costs based on the amount of energy sold and on the capacity usage. The amount of subscribed capacity is optimized and any capacity usage above this level is subject to an overusage fee. If the overusage fee is set significantly higher than the cost of subscribed capacity (as it is by default), there will be no overusage as it will most economical to increase the amount of subscribed capacity.

2.3 Contribution to the emissions

The module has no direct contribution to emissions.

2.4 Network constraints

The network constraint is also different in the case of an electric load and electric market.
For electric loads:

$$\sum_{(i,el\_l)\in Net2Load} Connection\_loss\_factor_{i,el\_l}\cdot load\_flow_{i,el\_l,t} + \sum_{(i,el\_l)\in Supply2load} Connection\_loss\_factor_{i,el\_l}\cdot local\_flow_{i,el\_l,t} + el\_deficit_{el\_l,t} = El\_load_{el\_l,t} \quad \forall el\_l\notin el\_m,t \quad (8)$$

For electric markets the sold electricity term is added:

$$\sum_{(i,el\_l)\in Net2Load} Connection\_loss\_factor_{i,el\_l}\cdot load\_flow_{i,el\_l,t} + \sum_{(i,el\_l)\in Supply2load} Connection\_loss\_factor_{i,el\_l}\cdot local\_flow_{i,el\_l,t} + el\_deficit_{el\_l,t} = El\_load_{el\_l,t} + sold\_el_{el\_l,t} \quad \forall el\_l\in el\_m,t \quad (9)$$

2.5 Module specific constraints

The following module-specific constraints only apply to electric markets:

$$exp\_capacity\_subscribed_{el\_m} \geq sold\_el_{el\_m,t} - exp\_oc\_usage_{el\_m,t} \quad \forall el\_m,t \quad (10)$$

$$exp\_capacity\_usage_{el\_m} \geq exp\_capacity\_subscribed_{el\_m} + exp\_oc\_usage_{el\_m,t} \quad \forall el\_m,t \quad (11)$$

These specify the need to pay for the capacity usage of the sold electricity. The variable for the subscribed capacity is constrained to take the value of the peak electricity export subtracted the overusage during each hour. There is also a variable for the peak capacity usage so the program can present this value to the user. The capacity usage will be equal to the subscribed capacity if no overusage is incurred.

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