Faster decarbonization of heavy industries in low-carbon power grids: Using process flexibility for handling grid congestions
Supplementary Information

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S.1 Model formulation

We present the full model formulation used for finding the potential for flexibility of the industries and the associated costs. As the aim is to quantify the added operational costs related to activation of flexibility, the cost functions primarily include terms related to this. Costs related to other energy demands, products, raw materials etc., have not been included. The model is available in GitHub. [1]

Section S.1.1 presents the ammonia & nitric acid process, Section S.1.2 presents the cement process, Section S.1.3 presents the ferroalloy process and Section S.1.4 presents the main cost functions related to the VCM production process. Section S.1.5 presents the nomenclature as well as the parameter values used in the study.

S.1.1 Ammonia & nitric acid

S.1.1.1 Cost functions

The costs of the ammonia producer include the energy costs, emission costs related to natural gas consumption and load shedding costs from production losses.

$$c_{\text{en,amm}} = \sum_t (\text{Cost}_{\text{el}} * p_{\text{amm,t}} + \text{Cost}_{\text{ng}} * g_{\text{amm},t}) \tag{1}$$

$$c_{em,amm} = \sum_t (\text{Cost}_{\text{em}} * em_{\text{amm},t}) \tag{2}$$

$$c_{\text{ls,amm}} = \sum_t (\text{Cost}_{\text{ls,amm}} * (\text{M}^{\text{amm,hb,nh}} * \text{T} - m_{\text{amm,nh},t})) \tag{3}$$

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S.1.1.2 Energy and product links

Total power demand included in the study is the PEM electrolyzers, air separation units, haber-bosch demand, nitric acid compressors and a certain fixed demand. The included natural gas demand is the one related to the synthesis gas process, although there are also other processes which use natural gas. Therefore, the emissions also only account the emissions related to natural gas used in the synthesis gas process.

$$p_{\mathrm{amm},t} = p_{\mathrm{amm,pem},t} + p_{\mathrm{amm,asu},t} + p_{\mathrm{amm,hb},t} + p_{\mathrm{amm,nitric},t} + p_{\mathrm{amm,fix}} \tag{4}$$

$$g_{\mathrm{amm},t} = g_{\mathrm{amm,syn},t} \tag{5}$$

$$h_{\mathrm{amm,hb},t} = h_{\mathrm{amm,syn},t} + h_{\mathrm{amm,pem},t} \tag{6}$$

$$em_{\mathrm{amm},t} = g_{\mathrm{amm},t} * \phi_{\mathrm{ng}} \tag{7}$$

S.1.1.3 PEM electrolyzer & Air separation units

We assume that air separation units operate simultaneously with the PEM electrolyzers, to produce the required nitrogen for the Haber-Bosch process.

$$h_{\mathrm{amm,pem},t} = p_{\mathrm{amm,pem},t} * \eta^{\mathrm{tr}} * \eta^{\mathrm{pem}} \tag{8}$$

$$p_{\mathrm{amm,pem},t} \leq \mathrm{P}^{\mathrm{pem}} * b_{\mathrm{amm,pem},t} \tag{9}$$

$$\alpha^{\mathrm{pem,min}} * \mathrm{P}^{\mathrm{amm,pem}} * b_{\mathrm{amm,pem},t} \leq p_{\mathrm{amm,pem},t} \tag{10}$$

$$p_{\mathrm{amm,asu},t} = p_{\mathrm{amm,pem},t} * \theta_{\mathrm{asu}} \tag{11}$$

S.1.1.4 Synthesis gas production

The hydrogen production capacity of the synthesis gas process has been used to dimension the required PEM capacity. The synthesis gas process has some ramping ability, but this is not used today for process flexibility.

$$h_{\mathrm{amm,syn},t} \leq \mathrm{H}^{\mathrm{syn}} \tag{12}$$

$$h_{\mathrm{amm,syn},t} \geq \alpha^{\mathrm{syn,min}} * \mathrm{H}^{\mathrm{syn}} \tag{13}$$

$$g_{\mathrm{amm,syn},t} \geq \frac{h_{\mathrm{amm,syn},t}}{\theta^{\mathrm{syn}}} \tag{14}$$

S.1.1.5 Haber-Bosch process

In the Haber-Bosch process, the hydrogen and nitrogen from the synthesis gas process, or alternatively from the electrolyzers and the air separation units, is synthesized into ammonia. As there are several process restrictions in the operation, these are incorporated through several constraints, restricting the duration of a load change, the minimum constant operation between load changes and minimum time between two load reductions.

$$p_{\mathrm{amm,hb},t} = \theta^{\mathrm{hb}} * m_{\mathrm{amm,hb,nh},t} * 0.8 + \theta^{\mathrm{hb}} * \mathrm{M}^{\mathrm{amm,hb,nh}} * 0.2 \tag{15}$$

$$m_{\mathrm{amm,hb,nh},t} \leq \mathrm{M}^{\mathrm{amm,hb,nh}} \tag{16}$$

$$m_{\mathrm{amm,hb,nh},t} \geq \mathrm{M}^{\mathrm{amm,hb,nh}} * \alpha^{\mathrm{hb,min}} \tag{17}$$

$$m_{\mathrm{amm,hb,nh},t} - m_{\mathrm{amm,hb,nh},t-1} \leq \delta^{\mathrm{hb}} * \mathrm{M}^{\mathrm{amm,hb,nh}} \tag{18}$$

$$m_{\text{amm,hb,nh},t} - m_{\text{amm,hb,nh},t-1} \geq -\delta^{\text{hb}} * \text{M}^{\text{amm,hb,nh}} \tag{19}$$

$$m_{\text{h2,amm,nh},t} = \frac{m_{\text{amm,hb,nh},t}}{\text{M}_\text{N} + 3 * \text{M}_\text{H}} * 3 * \text{M}_\text{H} \tag{20}$$

$$h_{\text{amm,hb},t} = m_{\text{h2,amm,hb},t} * \text{LHV}_{\text{H}_2} \tag{21}$$

$$m_{\text{amm,hb,nh},t} - m_{\text{amm,hb,nh},t-1} \leq x_{\text{up,amm,hb},t} * \text{M}^{\text{amm,hb,nh}} \tag{22}$$

$$m_{\text{amm,hb,nh},t-1} - m_{\text{amm,hb,nh},t} \leq x_{\text{dn,amm,hb},t} * \text{M}^{\text{amm,hb,nh}} \tag{23}$$

$$(x_{\text{up,amm,hb},t-1} + x_{\text{up,amm,hb},t}) - 1.5 \leq z_{\text{up,amm,hb},t} * 10 \tag{24}$$

$$1.5 - (x_{\text{up,amm,hb},t-1} + x_{\text{up,amm,hb},t}) \leq (1 - z_{\text{up,amm,hb},t}) * 10 \tag{25}$$

$$(x_{\text{dn,amm,hb},t-1} + x_{\text{dn,amm,hb},t}) - 1.5 \leq z_{\text{dn,amm,hb},t} * 10 \tag{26}$$

$$1.5 - (x_{\text{dn,amm,hb},t-1} + x_{\text{dn,amm,hb},t}) \leq (1 - z_{\text{dn,amm,hb},t}) * 10 \tag{27}$$

$$\sum_{i=0}^{\kappa^{\text{hb}}} (x_{\text{up,amm,hb},t+i} - z_{\text{up,amm,hb},t+i}) \leq 1 \tag{28}$$

$$\sum_{i=0}^{\kappa^{\text{hb}}} (x_{\text{dn,amm,hb},t+i} - z_{\text{dn,amm,hb},t+i}) \leq 1 \tag{29}$$

$$x_{\text{up,amm,hb},t} + \sum_{i=0}^{\lambda^{\text{hb}}} (x_{\text{dn,amm,hb},t+i} - z_{\text{dn,amm,hb},t+i}) \leq 1 \tag{30}$$

$$x_{\text{dn,amm,hb},t} + \sum_{i=0}^{\lambda^{\text{hb}}} (x_{\text{up,amm,hb},t+i} - z_{\text{up,amm,hb},t+i}) \leq 1 \tag{31}$$

$$\sum_{i=0}^{\xi^{\text{hb}}} x_{\text{up,amm,hb},t+i} \leq \xi^{\text{hb}} \tag{32}$$

$$\sum_{i=0}^{\xi^{\text{hb}}} x_{\text{dn,amm,hb},t+i} \leq \xi^{\text{hb}} \tag{33}$$

S.1.1.6 Nitric acid production

At the site, there are three large electric compressors used in the nitrid acid production. As there is some compressor overcapacity, it is possible to turn off the smallest of the compressor for around 10 % of the time.

$$p_{\text{amm,nitric},t} = \sum_{c)} p_{\text{amm,nitric},c,t} \tag{34}$$

$$p_{\text{amm,nitric},c,t} = P_c * b_{\text{amm,nitric},c,t} \tag{35}$$

$$\sum_t b_{\text{amm,nitric},c,t} \geq \alpha^c * T \tag{36}$$

$$(b_{\text{amm,nitric},c,t} - b_{\text{amm,nitric},c,t+1}) - 0.5 \leq 10 * x_{\text{amm,nitric},c,t+1} \tag{37}$$

$$0.5 - (b_{\text{amm,nitric},c,t} - b_{\text{amm,nitric},c,t+1}) \leq 10 * (1 - x_{\text{amm,nitric},c,t+1}) \tag{38}$$

$$\sum_{i=0}^{\kappa^{\text{nitric},c}} x_{\text{amm,nitric},c,t+i} \leq 1 \tag{39}$$

S.1.1.7 Other demands

$$p_{\text{amm,fix}} = P^{\text{amm,fix}} \tag{40}$$

S.1.2 Cement

S.1.2.1 Cost functions

The main cost drivers in the cement production site are the energy costs, load shedding costs due to lost production and load change costs related to operation outside nominal working hours. Although operation outside nominal working hours is undesirable, it is included as an option in the study, at a high cost. The cement production also has costs related to other energy carriers, such as natural gas, but they are not included as they are not significantly affected by flexible operation.

$$c_{\text{en,cem}} = \sum_t \text{Cost}_{\text{el}} * p_{\text{cem},t} \tag{41}$$

$$c_{\text{ls,cem}} = \text{Cost}_{\text{ls,cem}} * \sum_t (\text{M}^{\text{cem}} * \text{T} - m_{\text{cem},t}) \tag{42}$$

$$c_{\text{lc,cem}} = \sum_{t,c \in crushers} b_{\text{cem},c,t} * (1 - \text{B}_{c,t}) * \text{Cost}_{\text{lc,cem}} \tag{43}$$

S.1.2.2 Energy and product links

The energy and product linking constraints present how the mass flow of product is distributed through the plant, including the mixing fractions in certain parts of the process. While there is significant overcapacity in the crushers, the raw mill and the cement mills have limited overcapacity, directly reducing the flexibility potential.

$$p_{\text{cem},t} = \sum_m (p_{\text{cem},m,t}) + p_{\text{cem,kiln}} + p_{\text{cem,fix}} + p_{\text{cem,ccs}} \tag{44}$$

$$m_{\text{cem,c1},t} + m_{\text{cem,c2},t} = m_{\text{cem,s1,in},t} \tag{45}$$

$$m_{\text{cem,s1,out},t} = m_{\text{cem,rm},t} \tag{46}$$

$$m_{\text{cem,rm},t} = m_{\text{cem,s2,in},t} \tag{47}$$

$$m_{\text{cem,s2,out},t} = m_{\text{cem,kiln},t} \tag{48}$$

$$m_{\text{cem,kiln},t} = m_{\text{cem,s3,in},t} * \theta^{\text{rm/c}} \tag{49}$$

$$m_{\text{cem,s3,out},t} = \theta^{\text{c/cem}} * (m_{\text{cem,cm1},t} + m_{\text{cem,cm2},t} + m_{\text{cem,cm3},t}) \tag{50}$$

$$m_{\text{cem,cm1},t} + m_{\text{cem,cm2},t} + m_{\text{cem,cm3},t} = m_{\text{cem,s4,in},t} \tag{51}$$

$$m_{\text{cem,s4,out},t} = m_{\text{cem},t} \tag{52}$$

S.1.2.3 Machinery (crushers and mills)

All crushers and mills can be shut on or off in very short time, but they are not able to operate at part load.[2]

$$p_{\text{cem},m,t} = \text{P}^{\text{cem}}_m * b_{\text{cem},m,t} \tag{53}$$

$$m_{\text{cem},m,t} \leq \text{M}^{\text{cem}}_m * b_{\text{cem},m,t} \tag{54}$$

$$\tag{55}$$

S.1.2.4 Silos

There are large silos in which stockpiles of raw materials and finished products are stored.

$$s_{\text{cem},s,t} = s_{\text{cem},s,t-1} + m_{\text{cem},s,\text{in},t} - m_{\text{cem},s,\text{out},t} \tag{56}$$
$$s_{\text{cem},s,1} \leq s_{\text{cem},s,T} \tag{57}$$
$$s_{\text{cem},s,t} \leq \mathrm{S}_s^{\text{cem}} \tag{58}$$

S.1.2.5 Kiln

The kiln operates at a constant load at the site, but for the case study, we have included a small potential for variation in mass flow. However, the power demand is constant regardless of the mass flow.

$$p_{\text{cem,kiln}} = \mathrm{P}^{\text{cem,kiln}} \tag{59}$$
$$m_{\text{cem,kiln},t} \leq \mathrm{M}^{\text{cem,kiln}} * \alpha^{\text{cem,kiln,max}} \tag{60}$$
$$m_{\text{cem,kiln},t} \geq \mathrm{M}^{\text{cem,kiln}} * \alpha^{\text{cem,kiln,min}} \tag{61}$$

S.1.2.6 Other demands

In addition to the above processes, there are some fixed demands at the site. The CCS alternative also has a certain power demand which is included in the Decarbonized case. The potential for flexibility of CCS has not been included in the study, partly due to the constant operation of the kiln.

$$p_{\text{cem,fix}} = P^{\text{cem,fix}} \tag{62}$$
$$p_{\text{cem,ccs}} = P^{\text{cem,ccs}} \tag{63}$$

S.1.3 Ferroalloy

S.1.3.1 Cost functions

The main costs of the ferroalloy producer included in the flexibility consideration are the electricity costs and the costs of load shedding due to production losses.

$$c_{\text{en,mn}} = \sum_t \text{Cost}_{\text{el}} * p_{\text{mn},t} \tag{64}$$
$$c_{\text{ls,mn}} = \sum_p (\text{Cost}_{\text{ls,mn},p} * \sum_t (\mathrm{M}_p^{\text{mn}} * \mathrm{T} - m_{\text{mn},p,t})) \tag{65}$$
$$\tag{66}$$

S.1.3.2 Energy and product links

The energy demand of the ferroalloy producer is simply the sum of the two smelters.

$$p_{\text{mn},t} = \sum_p p_{\text{mn},p,t} \tag{67}$$

S.1.3.3 Smelters

The smelters are normally operated at full load. However, it is possible to reduce the load significantly in relatively short time without affecting the product quality. However, the smelters can not operate at part load over long time, as this could incur significant process interruptions. After a load reduction, it is required to keep the smelters at full load for a certain amount of time before the next possible load reduction.

$$p_{\text{mn},p,t} = m_{\text{mn},p,t} * \theta_p^{\text{mn}} \tag{68}$$
$$p_{\text{mn},p,t} \leq \text{P}_p^{\text{mn}} \tag{69}$$
$$p_{\text{mn},p,t} \geq \text{P}_p^{\text{mn}} * \alpha_p^{\text{min}} \tag{70}$$
$$m_{\text{mn},p,t} \leq \text{M}_p^{\text{mn}} \tag{71}$$
$$p_{\text{mn},p,t} - \text{P}_p^{\text{mn}} * (1 - \epsilon_p^{\text{mn}}) \leq 100 * y_{\text{mn},p,t} \tag{72}$$
$$\text{P}_p^{\text{mn}} * (1 - \epsilon_p^{\text{mn}}) - p_{\text{mn},p,t} \leq 100 * (1 - y_{\text{mn},p,t}) \tag{73}$$
$$\sum_{i=0}^{\omega_p^{\text{mn}}} y_{\text{mn},p,t+i} \geq 1 \tag{74}$$
$$(y_{\text{mn},p,t} - y_{\text{mn},p,t+1}) - 0.5 \leq 10 * x_{\text{dn},\text{mn},p,t+1} \tag{75}$$
$$0.5 - (y_{\text{mn},p,t} - y_{\text{mn},p,t+1}) \leq 10 * (1 - x_{\text{dn},\text{mn},p,t+1}) \tag{76}$$
$$(y_{\text{mn},p,t+1} - y_{\text{mn},p,t}) - 0.5 \leq 10 * x_{\text{up},\text{mn},p,t+1} \tag{77}$$
$$0.5 - (y_{\text{mn},p,t+1} - y_{\text{mn},p,t}) \leq 10 * (1 - x_{\text{up},\text{mn},p,t+1}) \tag{78}$$
$$x_{\text{up},\text{mn},p,t} + \sum_{i=0}^{\kappa_p^{\text{mn}}} x_{\text{dn},\text{mn},p,t+i} \leq 1 \tag{79}$$

S.1.4 Vinyl chloride monomers

S.1.4.1 Cost functions

The full model formulation of the vinyl chloride monomer production process is found in Foslie *et al.*[3], but the main cost functions used in this work are presented here for clarity.

$$c_{en,vcm} = \sum_t (\text{Cost}_{\text{el}} * p_{\text{vcm},t} + \text{Cost}_{\text{ng}} * g_{\text{vcm},t}) \tag{80}$$
$$c_{em,vcm} = \sum_t (\text{Cost}_{\text{em}} * em_{\text{vcm},t}) \tag{81}$$
$$c_{\text{em,lc}} = \sum_t ((LC_{\text{up}} + LC_{\text{dn}}) * \text{Cost}_{\text{lc,vcm}}) \tag{82}$$

S.1.5 Nomenclature & parameter values

Tables 1 to 4 present the variables, indices, abbreviations and parameters used in the model.

Table 1: Model variables

Variable	Description	Unit
p	Power demand	MW
c	Cost	€
g	Natural gas demand	MW
h	Hydrogen demand	MW
em	Emission	ton_{CO_2}
m	Mass flow	ton/h
LC	Load change	-
b	Operation status (on/off)	1/0
s	Storage level	ton
x	Change in process operation	1/0
y	Reduced load	1/0
z	Consecutive load changes	1/0

Table 2: Model indices

Index	Description	Unit
t	Time	h
c	Compressor	-
m	Machinery	-
s	Silo	-
p	Plant	-

Table 3: Model abbreviations

Abbreviation	Description
en	Energy
amm	Ammonia & nitric acid industry
mn	Ferroalloy (manganese)
vcm	Vinyl chloride monomer
el	Electricity
ng	Natural gas
ls	Load shedding
lc	Load change
hb	Haber-Bosch
nh	Ammonia
pem	PEM electrolysis
asu	Air separation unit
nitric	Nitric acid
fix	Fixed demands
syn	Synthesis gas
tr	Transformer
min	Minimum
max	Maximum
up	Up (ramping)
dn	Down (ramping)
kiln	Cement kiln
ccs	Carbon capture & storage
c1,c2,c3	Crushers 1–3
s1,s2,s3,s4	Silos 1–4
rm/c	Rawmeal to clinker
c/cem	Clinker to cement
cm1,cm2,cm3	Cement mills 1–3
cem	Cement
em	Emissions

Table 4: Parameters used in the case study

Parameter	Description	Unit	Value
$\mathrm{Cost}_{\mathrm{el}}$	Electricity cost	€/MWh	49.0 [4]
$\mathrm{Cost}_{\mathrm{ng}}$	Natural gas cost	€/MWh	52.0 [4]
$\mathrm{Cost}_{\mathrm{em}}$	Emission cost	€/$\mathrm{ton}_{\mathrm{CO_2}}$	164.0 [4]
$\mathrm{M}^{\mathrm{amm,hb,nh}}$	Nominal production of ammonia	ton/h	58.3 [5]
T	Duration of analysis	h	168
ϕ_{ng}	Emission factor of natural gas	$\mathrm{ton}_{\mathrm{CO_2}}$/MWh	0.202 [6]
η^{tr}	Transformer efficiency	-	0.95 [7]
η^{pem}	PEM efficiency	-	66 % [3]
$\mathrm{P}^{\mathrm{amm,pem}}$	PEM capacity at ammonia industry	MW	-
$\mathrm{P}^{\mathrm{amm,fix}}$	PEM capacity at ammonia industry	MW	14
$\alpha^{\mathrm{pem,min}}$	Minimum PEM load	-	10 % [8]
θ_{asu}	ASU power consumption per PEM power	-	0.008 [9]
$\mathrm{H}^{\mathrm{syn}}$	Hydrogen production capacity of synth. gas process	MWh/h	-
$\alpha^{\mathrm{syn,min}}$	Minimum operation of synthesis gas process	-	80 % [10]
θ^{syn}	Natural gas consumption per hydrogen production	-	0.659 [11]
θ^{hb}	Haber-Bosch power consumption per ammonia	MW/ton	0.64 [9]
$\alpha^{\mathrm{hb,min}}$	Minimum operation of Haber-Bosch	-	60 % [10]
δ^{hb}	Maximum ramping of Haber-Bosch	-/h	20 % [12]
M_{N}	Molar mass of nitrogen	ton/mol	14.01e-6
M_{H}	Molar mass of hydrogen	ton/mol	1.008e-6
$\mathrm{LHV}_{\mathrm{H_2}}$	Lower heating value of hydrogen	MWh/kg	33.3
ξ^{hb}	Maximum successive hours of load increases/reductions	h	5
κ^{hb}	Minimum time between load increases/reductions	h	150 [10]
λ^{hb}	Minimum constant operation	h	24 [10]
P_c	Power demand of compressor c	MW	
α^c	Minimum operation of compressor c	-	90–100 %
$\kappa^{\mathrm{nitric},c}$	Minimum up time of nitric acid production unit	h	24
$\mathrm{M}^{\mathrm{cem}}$	Nominal cement production	ton/h	181.6 [2]
$\mathrm{B}_{c,t}$	Normal working hour	-	0/1
$\theta^{\mathrm{rm/c}}$	Ton raw meal per ton clinker	-	1.56 [13]
$\theta^{\mathrm{rm/c}}$	Ton clinker per ton cement	-	0.787 [2]
$\mathrm{P}^{\mathrm{cem}}_{c1}$	Power of cement crusher 1	MW	1.855 [2]
$\mathrm{P}^{\mathrm{cem}}_{c2}$	Power of cement crusher 2	MW	1.855 [2]
$\mathrm{P}^{\mathrm{cem}}_{rm}$	Power of raw mill	MW	5.0 [2]
$\mathrm{P}^{\mathrm{cem}}_{kiln}$	Power of kiln	MW	5.0 [2]
$\mathrm{P}^{\mathrm{cem}}_{cm1}$	Power of cement mill 1	MW	1.0 [2]
$\mathrm{P}^{\mathrm{cem}}_{cm2}$	Power of cement mill 2	MW	3.5 [2]
$\mathrm{P}^{\mathrm{cem}}_{cm3}$	Power of cement mill 3	MW	5.0 [2]
$\mathrm{M}^{\mathrm{cem}}_{c1}$	Capacity of cement crusher 1	ton/h	350 [2]
$\mathrm{M}^{\mathrm{cem}}_{c2}$	Capacity of cement crusher 2	ton/h	350 [2]
$\mathrm{M}^{\mathrm{cem}}_{rm}$	Capacity of raw mill	ton/h	244 [2]
$\mathrm{M}^{\mathrm{cem}}_{kiln}$	Capacity of kiln	ton/h	223 [2]
$\mathrm{M}^{\mathrm{cem}}_{cm1}$	Capacity of cement mill 1	ton/h	16 [2]
$\mathrm{M}^{\mathrm{cem}}_{cm2}$	Capacity of cement mill 2	ton/h	74 [2]
$\mathrm{M}^{\mathrm{cem}}_{cm3}$	Capacity of cement mill 3	ton/h	104.5 [2]
$\mathrm{S}^{\mathrm{cem}}_{s1}$	Storage capacity of cement silo 1	ton	100,000 [2]
$\mathrm{S}^{\mathrm{cem}}_{s2}$	Storage capacity of cement silo 2	ton	20,000 [2]
$\mathrm{S}^{\mathrm{cem}}_{s3}$	Storage capacity of cement silo 3	ton	80,000 [2]
$\mathrm{S}^{\mathrm{cem}}_{s4}$	Storage capacity of cement silo 4	ton	67,000 [2]

$\alpha^{\text{cem,kiln,max}}$	Maximum operation of cement kiln	-	105 % [14]
$\alpha^{\text{cem,kiln,min}}$	Minimum load of cement kiln	-	95 % [14]
$P^{\text{cem,fix}}$	Fixed demands of cement production site	MW	1.0 [2]
$P^{\text{cem,ccs}}$	Power demand for cement CCS	MW	16.0 [15]
$P^{\text{mn}}_{\text{FeMn}}$	Maximum power capacity of ferromanganese smelter	MW	38 [16]
$P^{\text{mn}}_{\text{SiMn}}$	Maximum power capacity of silicomanganese smelter	MW	32 [16]
$\theta^{\text{mn}}_{FeMn}$	Power consumption per ferromanganese production	MWh/ton	2.5 [17]
$\theta^{\text{mn}}_{SiMn}$	Power consumption per silicomanganese production	MWh/ton	4.5 [17]
α^{min}_{p}	Minimum load of manganese production smelter	-	60% [16]
ϵ^{mn}_{p}	Allowed power demand variation of smelter	-	0.1 %
ω^{mn}_{p}	Maximum down time of smelter	h	4 [16]
κ^{mn}_{p}	Minimum time between load reductions	h	12 [16]

S.2 Power flow

The power flow model consists of seven nodes connected by a power grid. In this section we describe how they are connected, and the affiliated net load of each node.

S.2.1 Node data

The net load data for each node consists of a combination of power generation data and load data. The insufficiency of locally produced electricity to serve the local loads is covered by the transmission grid.

The nodes incorporated in the model are the following:

- B1 - Holen (slack node)
- B2 - Arendal (slack node)
- B3 - Rød
- B4 - Grenland
- B5 - Bamble
- B6 - Porsgrunn
- B7 - Hasle

The lines between the nodes are the following:

- L1 - Arendal - Bamble
- L2 - Bamble - Grenland
- L3 - Grenland - Rød
- L4 - Bamble - Porsgrunn
- L5 - Porsgrunn - Rød
- L6 - Holen - Rød

- L7 - Rød - Hasle

The regional transmission grid, the node- and line numbering, as well as the location of the different end-user categories and generation are presented in Fig. 1.

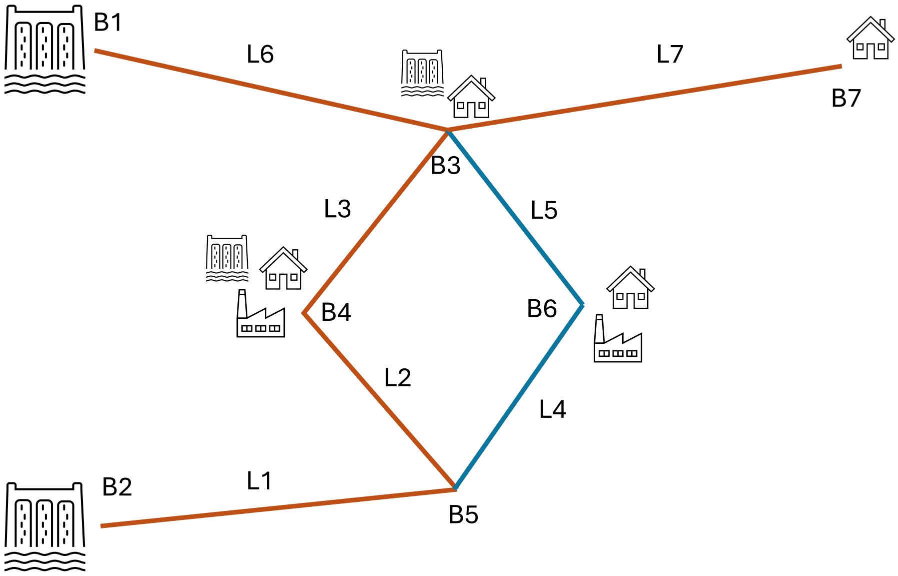

Figure 1: Overview of nodes and lines in the transmission grid. Red lines represent 420 kV, while blue lines represent 300 kV.

In the following, the generation and load data for each node is described. Note that the industry area "Herøya" is located below the B6 node.

S.2.1.1 Generation

The buses B1 and B2 are two slack nodes as these represent generation-dominated areas in the Norwegian power systems. Further, there are two nodes with power generation in the system, namely B3 and B4. In cooperation with the local grid company, we have mapped the relevant hydro power plants larger than 2 MW of installed capacity, and allocated them to the correct node using the *NVE Atlas*, which provides an overview of the Norwegian transmission grid and power plants.[18] The power plants have also been classified as either *Hydro Run-of-river* or *Hydro Water Reservoir*, and are presented in Table 5.

Table 5: Installed hydro power capacities

	B4	B3
Hydro Run-of-river	74 MW	65 MW
Hydro Water Reservoir	208 MW	111 MW

All these power plants are located in the Norwegian price zone NO2, covering the southern parts of Norway. In order to estimate production profiles for the power plants, data from the same week has been obtained from ENTSO-E, which provides hourly generation data from the two different hydro power types in the price zone.[19] The same website provides information regarding the total installed capacity of the types in the price zones, which has been used to scale the local production to the total capacities.

S.2.1.2 Load

While the industry loads are generated in the industry flexibility model, the other general demand in the area is estimated. This applies to the nodes B3, B4, B6 and B7. The local grid company, Lede, has provided us with the peak net load data of the nodes B3, B4 and B6 for the hour of the year with highest net load.[20] The net load is the power flow from the transmission grid to the local grid, and is a result of the local demand and the local power generation.

$$p_{net} = p_{demand} - p_{generation} \tag{83}$$

$$p_{net} = (p_{industry} + p_{other}) - p_{generation} \tag{84}$$

With knowledge of the power generation and industry load at each node, as well as the maximum net load, the general load from primarily residential and some commercial end-users can be calculated in the maximum net load hour. This data is presented in Table 6. The ferroalloy and VCM producers are allocated to the B4 node, while the ammonia and cement producers are allocated to the B6 node. To generate load series for the general load, this has been assumed to have a similar profile as the overall consumption of the price zone NO1 in Norway, consisting primarily of residential and commercial demand.

Table 6: Load data in peak net load hour, week 5

Bus	p_{net}	p_{ind}	p_{oth}	p_{gen}
B4	30.6 MW	-	114.5 MW	83.9 MW
B3	164.7 MW	168.8 MW	125.0 MW	129.1 MW
B6	305.5 MW	97.8 MW	207.7 MW	-

The final node, B7, represents the export from the area towards the neighbour price zone, NO1. In the transmission grid, the cross-border flow between NO2 and NO1 is distributed between two main channels, both with one 420 kV transmission line and multiple smaller lines. We have therefore estimated, based on qualitative data from area plans of the system operators, that the total cross-border flow is distributed equally between the north and south channels.[21–23] The load data for B7 is therefore found by using 50 % of the cross-border flow reported between NO2 and NO1 in the period, as obtained from ENTSO-E.[24]

S.2.2 Model parameters

S.2.2.1 Line data

The maximum capacities of the seven transmission system lines have been determined through open source reports from the TSO (Statnett) as well as dialogue with the local DSO (Lede). Although relatively precise, they are to a small degree approximate numbers. This is to avoid publishing power system-sensitive information. The voltage levels are openly available at the energy regulator's online map database [c]. Based on these capacities and voltage levels, the remaining necessary technical specifications were set using[25]. First, the maximum current capacity was calculated, allowing us to select the appropriate overhanging lines, i.e., the line specification that has the current rating closest to our calculated maximum current capacities. Therefrom, the resistance, reactance and capacitance were set using the same line from the transmission line table. The specific line data used can be found in Table 7 and were created using the "create_line_from_parameters"-function in pandapower.

[c] https://atlas.nve.no/

Table 7: Technical specifications of the transmission lines.

#	Capacity [MW]	Nominal voltage [kV]	Current capacity [kA]	Resistance [Ω/km]	Reactance [Ω/km]	Capacitance [nF/km]
L1	2 200	420	3.024	0.025	0.324	11.426
L2	2 200	420	3.024	0.025	0.324	11.426
L3	2 200	420	3.024	0.025	0.324	11.426
L4	900	300	1.732	0.040	0.413	8.97
L5	900	300	1.732	0.040	0.413	8.97
L6	2 200	420	3.024	0.025	0.324	11.426
L7	2 200	420	3.024	0.025	0.324	11.426

S.2.2.2 Transformer data

The transformers were created using the “create_transformer_from_parameters”-function in pandapower. They are not limiting the power flow in the area, and are therefore not of particular interest. They have been set with the technical specification as shown in Table 8.

Table 8: Technical specifications of the transformers

Bus	HV bus	LV bus	Capacity	Open loop losses	Iron losses [kW]
B3	420 kV	300 kV	900 MVA	4 %	60 kW
B5	420 kV	300 kV	900 MVA	4 %	60 kW

S.3 Power flow results

Below are the results of the power flow analysis when checking the N-1 criterion fulfillment for transmission line tripping for all transmission lines.

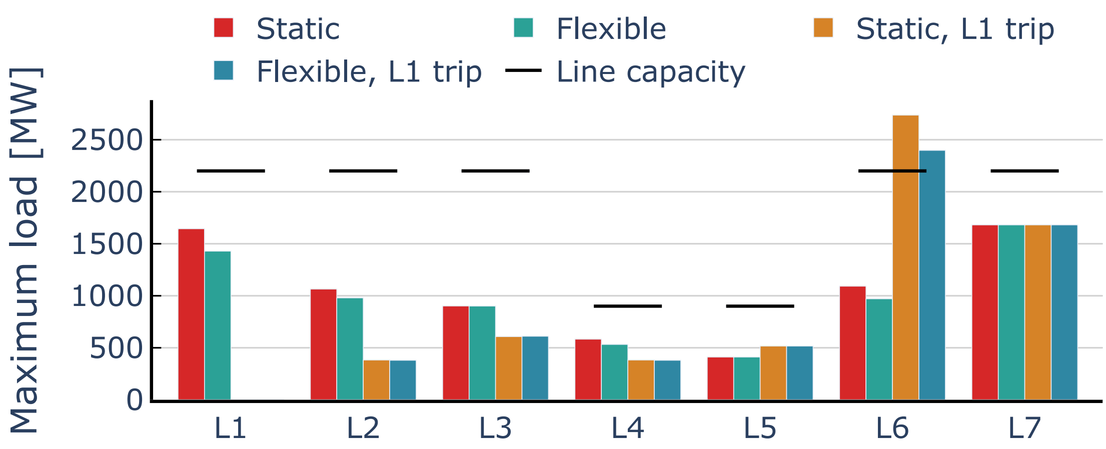

Figure 2: Maximum hourly load on all lines in the case of line tripping of L1.

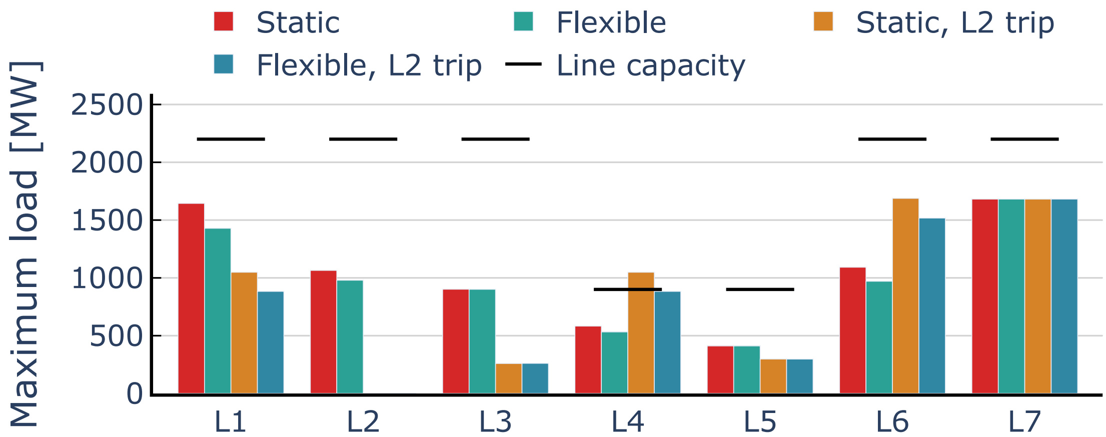

Figure 3: Maximum hourly load on all lines in the case of line tripping of L2.

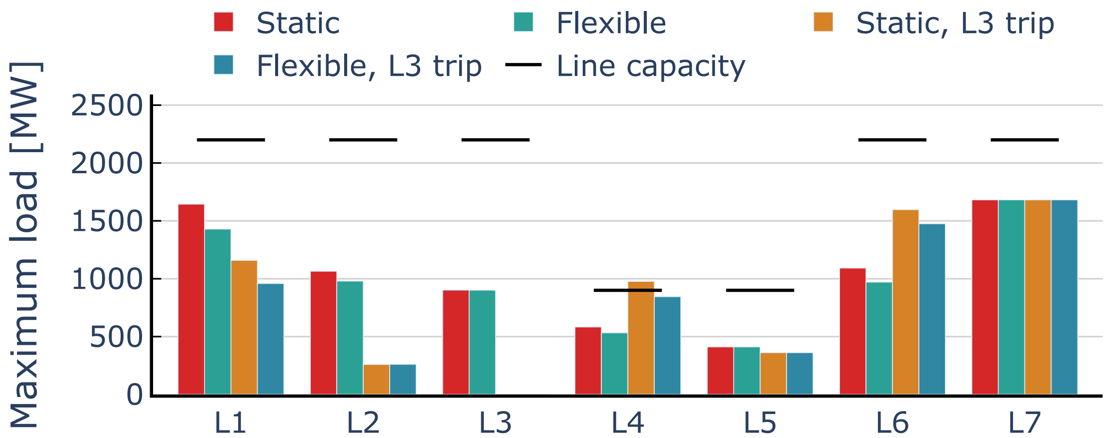

Figure 4: Maximum hourly load on all lines in the case of line tripping of L3.

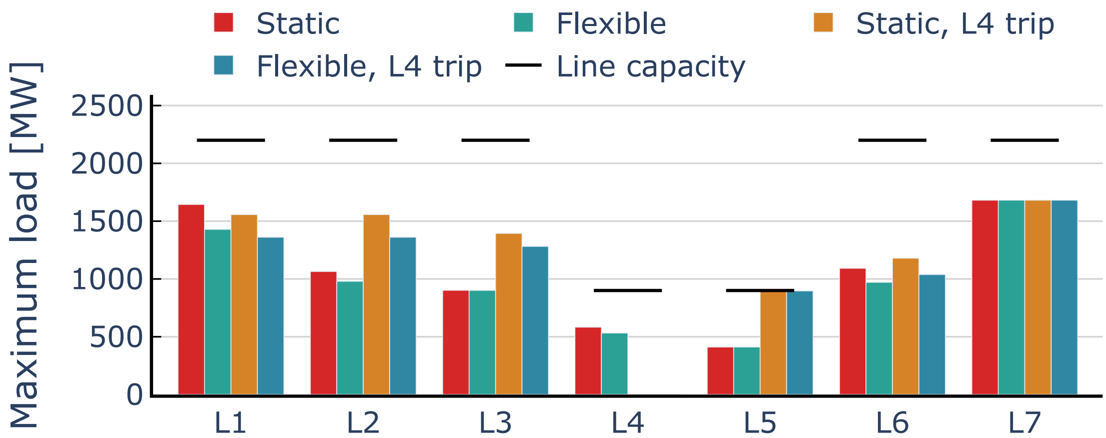

Figure 5: Maximum hourly load on all lines in the case of line tripping of L4.

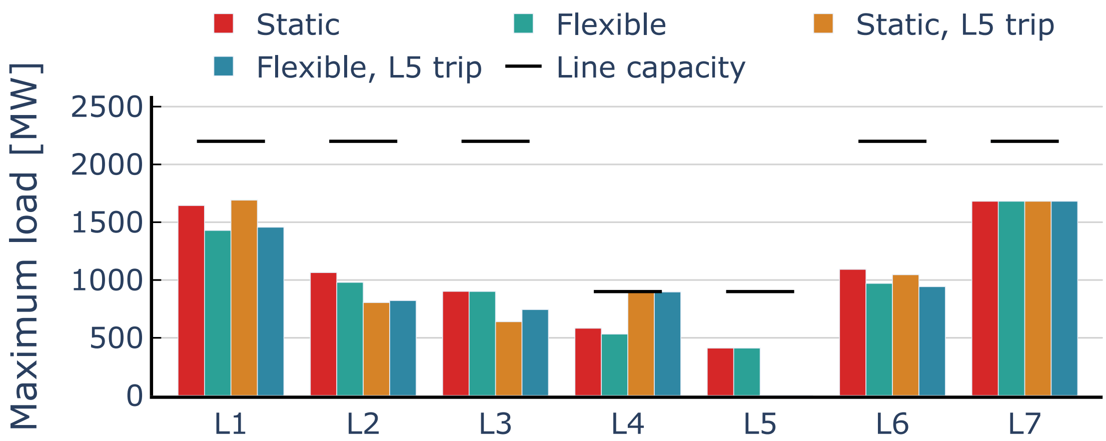

Figure 6: Maximum hourly load on all lines in the case of line tripping of L5.

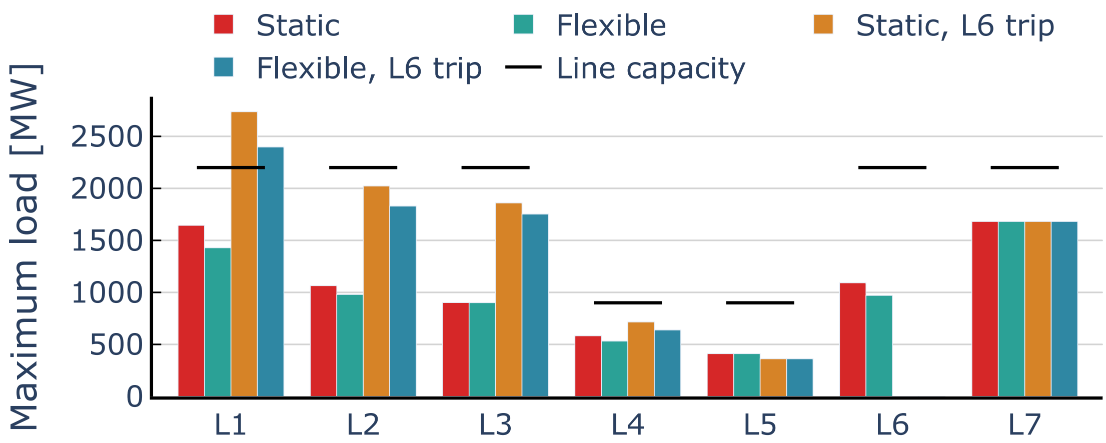

Figure 7: Maximum hourly load on all lines in the case of line tripping of L6.

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