Supplemental experimental procedures

Kenya Whole Energy System Model end use sectors

In this section, we briefly describe the end use sectors included in the Kenya Whole Energy System Model.

Agriculture – The only demand type considered for the agricultural sector is a generic demand type, obtained from the IEA energy balances [1] and representing fuel consumption to operate the agricultural machinery, expressed in useful energy terms. There is one technology option per fuel type, and fuels considered are diesel, gasoline, and heavy fuel oil.

Commercial sector – A single demand is considered for the commercial sector, and it represents the consumption of electricity for a variety of services in buildings and facilities not classified as residential, industrial, or agricultural. This includes, for example, electricity used for lighting and operating equipment in offices, retail stores, schools, hospitals, hotels, and other public and service-oriented buildings, but it does not consider low temperature heat production, as it is null in the energy balance of reference [1]. A single generic technology with unit efficiency and using electricity as fuel is considered in the model.

Industry – The industrial sector is slightly more complex than the first two. Three different types of demand are considered, as obtained from IEA energy balances [1]: non-metals and cement, food processing, and other processes. The demand for the non-metals and cement subsector can only be covered by technologies using coal as fuel. Similarly, only electricity is considered as an option for the food processing subsector. The other processes subsector includes several different processes, including steel production. Technologies considered are based on various fuels inputs, including coal, electricity, diesel, heavy fuel oil and kerosene.

Residential sector – The residential sector is the most complex sector included in the model, as it also represents the highest share of the final energy consumption in the country. Demands are divided between lighting, cooling, cooking and other. Demand levels are originally obtained from the IEA [1], and have been updated based on data provided by Nuvoni Centre for Innovation Research and the Modern Energy Cooking Services programme[2]. Each demand is split between urban and rural areas, to account for the significant differences in the two areas. Cooling and other demands can only be satisfied by technologies using electricity as an input fuel. Lighting options include both electricity and kerosene. Finally, the cooking sector offers numerous technology options, including different ones for the same type of fuel. For example, e-cooking technologies considered are coil, induction, and electric pressure cookers, while wood stoves can be either traditional or improved, as in the case of charcoal. A complete description can be found in the model's documentation[3].

Transport sector – Transports include national aviation and shipping, the railway system and road transport. The latter is divided between buses, cars, freight, light commercial vehicles, and two- and three-wheelers. Each of the subsector of road transport has three technology options, namely diesel, gasoline, and electricity, except for freight transport, where only diesel and gasoline are considered. Aviation demand can only be satisfied by technologies using jet fuel, shipping by technologies using heavy fuel oil, and electric and diesel trains are considered. Demands are obtained from the IEA energy balances [1] and the Transport Inventory and Greenhouse Gas Emissions Reporting (TrIGGER) tool [4].

Supplemental Tables and Figures

Tables – Modelling results

Table 1 Levelized cost of hydrogen (LCOH) over the nine scenarios simulated.

	LCOH [USD/kg] 2025-2050
S1	3.70
S2	3.36
S3	2.77
S4	3.42
S5	3.12
S6	2.67
S7	3.45
S8	3.16
S9	2.66

Tables – Modelling assumptions

Table 2 Summary of the capital costs for alkaline, proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) electrolysers. Current costs are listed, as well as projections for 2030 and 2050 and the respective sources. Where intervals are given, typical values are shown in brackets. IEA values are given for a generic water electrolysis technology. All values are expressed in USD/kW, reference year 2020.

Technology	Current (2020-2024)	2030	2050	Source	Year
Water electrolysis	China 1000 Global 1750	China 400 Global 440	320-340	IEA[5]	2021
Water electrolysis	China 1070 Global 1640	China 420 Global 610	-	IEA[6]	2023
Water electrolysis	China 1100 Global 2160	China 620 Global 960	-	IEA[7]	2024
Alkaline (10 MW)	1525-2275 (1900)	875	375-475 (475)	DEA[8]	2024
Alkaline (100 MW)	950-1450 (1200)	550	250-350 (300)	DEA[8]	2024
Alkaline (1 GW)	875-1325 (1100)	500	225-325 (275)	DEA[8]	2024
PEM (10 MW)	1525-2275 (1900)	950	400-600 (500)	DEA[8]	2024
PEM (100 MW)	1050-1550 (1300)	650	275-425 (350)	DEA[8]	2024
PEM (1 GW)	950-1450 (1200)	600	250-400 (325)	DEA[8]	2024
SOEC (1 MW)	3200-4800 (4000)	1725	1450	DEA[8]	2024
SOEC (10 MW)	2325-3475 (2900)	1250	1050	DEA[8]	2024
SOEC (100 MW)	1450-2150 (1800)	775	650	DEA[8]	2024
PEM	900-1800	650-1400	400-1000	Blanco et al.[9]	2018
SOEC	785	450	300	Blanco et al.[9]	2018
Alkaline	437-1500 (700)	357-800 (621)	-	ENTSO-E[10]	2022
PEM	613-2000 (1160)	350-1350 (663)	-	ENTSO-E[10]	2022
SOEC	2520-5040 (3083)	715-2500 (1706)	-	ENTSO-E[10]	2022
Alkaline	500-1000	-	200	IRENA[11]	2020
PEM	700-1400	-	200	IRENA[11]	2020
SOEC	2000 (stack)	-	300	IRENA[11]	2020

Table 3 Summary of the efficiencies of alkaline, proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) electrolysers. Current efficiencies are listed, as well as projections for 2030 and 2050 and the respective sources. Where intervals are given, typical values are shown in brackets. IEA values are given for a generic water electrolysis technology. All values are expressed as unit fractions, unless otherwise specified.

Technology	Current (2020-2024)	2030	2050	Source	Year
Water electrolysis	0.64	0.69	0.74	IEA [5]	2021
Water electrolysis	0.65	0.69	-	IEA [6]	2023
Water electrolysis	0.66	0.69	-	IEA[7]	2024
Alkaline	0.65	0.75	0.769	DEA[12,13]	2021
PEM	0.6	0.8	0.9	DEA[12,13]	2021
SOEC	0.74	0.84	0.9	DEA[12,13]	2021
PEM	0.65-0.75	0.7-0.8	0.75-0.86	Blanco et al.[9]	2018
SOEC	0.905	0.949	0.949	Blanco et al.[9]	2018
Alkaline	0.63-0.70	0.65-0.71	-	ENTSO-E[10]	2022
PEM	0.61-0.70	0.63-0.75	-	ENTSO-E[10]	2022
SOEC	0.74-0.81	0.77-0.88	-	ENTSO-E[10]	2022
Alkaline	0.50-0.68 50-78 kWh/kg_{H2}	-	> 0.70 < 45 kWh/kg_{H2}	IRENA[11]	2020
PEM	0.50-0.68 50-83 kWh/kg_{H2}	-	> 0.80 < 45 kWh/kg_{H2}	IRENA[11]	2020
SOEC	0.75-0.85 40-50 kWh/kg_{H2}	-	> 0.85 < 40 kWh/kg_{H2}	IRENA[11]	2020

Table 4 Summary of the stack lifetime of alkaline, proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) electrolysers. Current operational lifespans are listed, as well as projections for 2030 and 2050 and the respective sources. IEA values are given for a generic water electrolysis technology. Values can be expressed in terms of thousands of working hours or years of operation.

Technology	Current (2020-2024)	2030	2050	Unit	Source	
Water electrolysis	50	50	50	khours	IEA[5]	2021
Water electrolysis	50	50	-	khours	IEA[6]	2023
Water electrolysis	50	50	-	khours	IEA[7]	2024
Alkaline	30	30	30	years	DEA[12,13]	2021
PEM	30	30	30	years	DEA[12,13]	2021
SOEC	30	30	30	years	DEA[12,13]	2021
PEM	35-60	40-80	50-100	khours	Blanco et al.[9]	2018
SOEC	2	10	20	years	Blanco et al.[9]	2018
Alkaline	60-75	90-100	-	khours	ENTSO-E[10]	2022
PEM	50-80	60-90	-	khours	ENTSO-E[10]	2022
SOEC	10.0-20	40-60	-	khours	ENTSO-E[10]	2022
Alkaline	60	-	100	khours	IRENA[11]	2020
PEM	50-80	-	100-120	khours	IRENA[11]	2020
SOEC	< 20	-	80	khours	IRENA[11]	2020

Table 5 Capital costs for alkaline, proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) electrolysers considered in this study, based on the values listed in Table 2. All values are given in USD/kW, reference year 2020.

	Conservative				
	2020	**2025**	**2030**	**2040**	**2050**
ALK	2325	2000	1675	1010	350
PEM	2825	2500	2175	1300	425
SOEC	5425	4600	3775	2365	950
	Reference				
	2020	**2025**	**2030**	**2040**	**2050**
ALK	1995	1670	1345	820	300
PEM	2410	2090	1765	1060	350
SOEC	4700	3875	3050	1925	800
	Optimistic				
	2020	**2025**	**2030**	**2040**	**2050**
ALK	1075	750	425	340	250
PEM	1625	1300	975	625	275
SOEC	3975	3145	2320	1485	650

Table 6 Efficiencies for alkaline, proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) electrolysers considered in this study, based on the values listed in Table 3. All values are expressed as unit fractions.

Technology	**Conservative**			**Reference**			**Optimistic**		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
ALK	0.5	0.65	0.7	0.63	0.7	0.73	0.68	0.75	0.77
PEM	0.5	0.63	0.74	0.65	0.7	0.8	0.75	0.8	0.86
SOEC	0.74	0.84	0.85	0.8	0.89	0.9	0.91	0.95	0.95

Table 7 Cell stack operational life for alkaline, proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) electrolysers considered in this study, based on the values listed in Table 4. All values are given in years considering 8000 h/y of operation, or around 90% capacity factor.

Technology	**Conservative**			**Reference**			**Optimistic**		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
ALK	8	11	13	9	12	13	10	13	13
PEM	4	5	6	7	8	11	10	11	15
SOEC	1	5	10	1	6	10	2	7.5	10

Table 8 Nitrogen content, on a mass basis, per type of fertilizer. NPK fertilisers contain various blends of nitrogen, phosphorus and potassium, with nitrogen content ranging anywhere from 1% to 40%. Remaining fertilisers have been split between Others (no nitrogen content) and Others H_2 (some nitrogen content that could be produced through H_2). The full list of fertilisers and their corresponding nitrogen content is given in Table S14.

Fertiliser	**N content [%]**
Calcium Ammonium Nitrate	27
Calcium Nitrate	15.5
Diammonium Phosphate	18
Muriate of Potash	0
NPK	1- 40
Others	0
Others H_2	1- 40
Urea	46

Table 9 Techno-economic parameters for the characterization of the Haber-Bosch process. Investment costs include hydrogen storage at 3.3-4.9 USD/MWh_{H2} to achieve 8000 h/y utilization rate [6]. Most of the energy needed for the process is provided by the exothermic reaction, electricity is needed to power motors, heat exchangers and pressure and temperature control equipment [14].

Parameter	**Value**	**Source**
Efficiency (H_2 to NH_3)	0.98	[14]
Electricity consumption	2.2 GJ/t_{NH3}	[6]
Availability factor	0.95	[6]
Capital cost	770 USD/kW	[6]
Fixed cost	23.1 USD/kW/y	[6]

Table 10 Steel demand in Kenya for the years 2012 to 2022. Data obtained from World Steel Association[15] and Kenya National Bureau of Statistics[16].

Year	Demand [kt/y]	Source
2012	1028	15
2013	1409	15
2014	1436	15
2015	1835	15
2016	1608	15
2017	1465	15
2018	1519	15
2019	1564	16
2020	1738	16
2021	1711	16
2022	1406	16

Table 11 Investment and operating costs for direct reduced iron (DRI) and electric arc furnace (EAF) technologies. DRI can be either natural gas- or hydrogen-based. Capital costs are obtained from Rosner et al.[17], and checked against the latest available data from IEA Global Hydrogen Review [5]. Operating costs are only considered as annual fixed costs and set to 7.5% of the capital costs [5].

Technology	Capital cost [MUSD/kt/y]	Fixed cost [MUSD/kt/y]	Variable cost [MUSD/kt]
DRI-NG	0.750	0.056	0
DRI-H2	0.597	0.045	0
EAF	0.234	0.018	0

Table 12 Energy and materials consumption for the steel making processes. Values are obtained for a direct reduced iron (DRI) and electric arc furnace (EAF) integrated processes as illustrated in Rosner et al. [17], under the assumption that the EAF is working with a 100% sponge iron input and no scrap steel. The latter hypothesis is also well aligned with the IEA's assumption of 5% scrap steel [5].

Technology	Commodity	Consumption
DRI-NG	Natural gas	10.8 GJ/$t_{sponge\ iron}$
DRI-NG	Iron ore	1.54 t/ $t_{sponge\ iron}$
DRI-H2	Hydrogen	9.1 GJ/ $t_{sponge\ iron}$
DRI-H2	Iron ore	1.54 t/ $t_{sponge\ iron}$
EAF	Electricity	2 GJ/t_{steel}
EAF	Sponge iron	1.05 t/t_{steel}

Table 13 Market prices for ammonia and steel in low, current and high market prices scenarios. Sources are listed in the Table.

Commodity	Low	Mid	High	Source
Ammonia [USD/t]	230	450	1200	[18]
Steel [USD/t]	300	800	2000	[19]

Figures – Modelling results

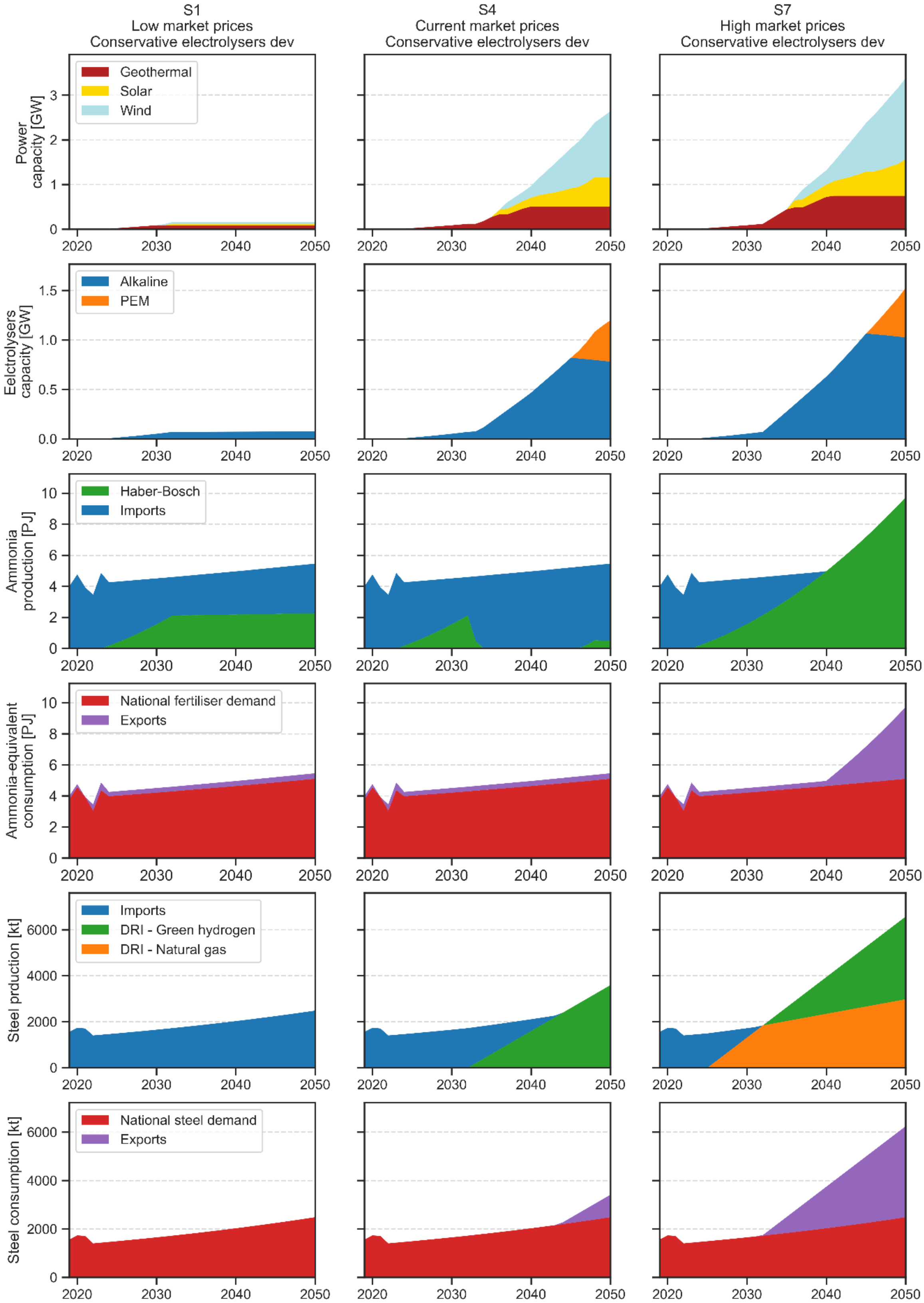

Figure 1 Results of runs based on low market prices for import/export of ammonia and steel (runs 1 to 3). Column 1 shows results for conservative hypothesis on the improvement of water electrolysis technologies, column 2 reference and column 3 optimistic.

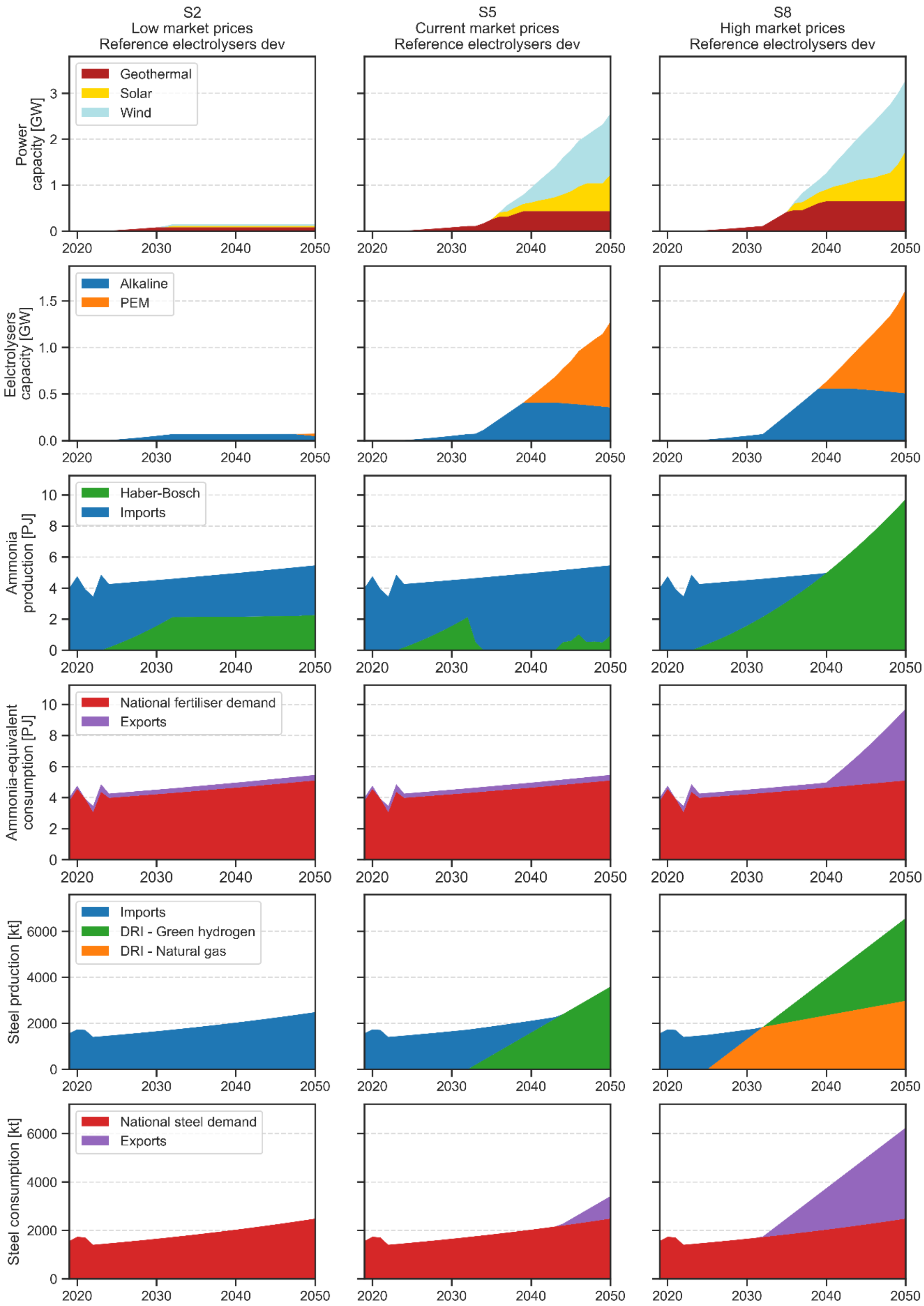

Figure 2 Results of runs based on mid market prices for import/export of ammonia and steel (runs 4 to 6). Column 1 shows results for conservative hypothesis on the improvement of water electrolysis technologies, column 2 reference and column 3 optimistic.

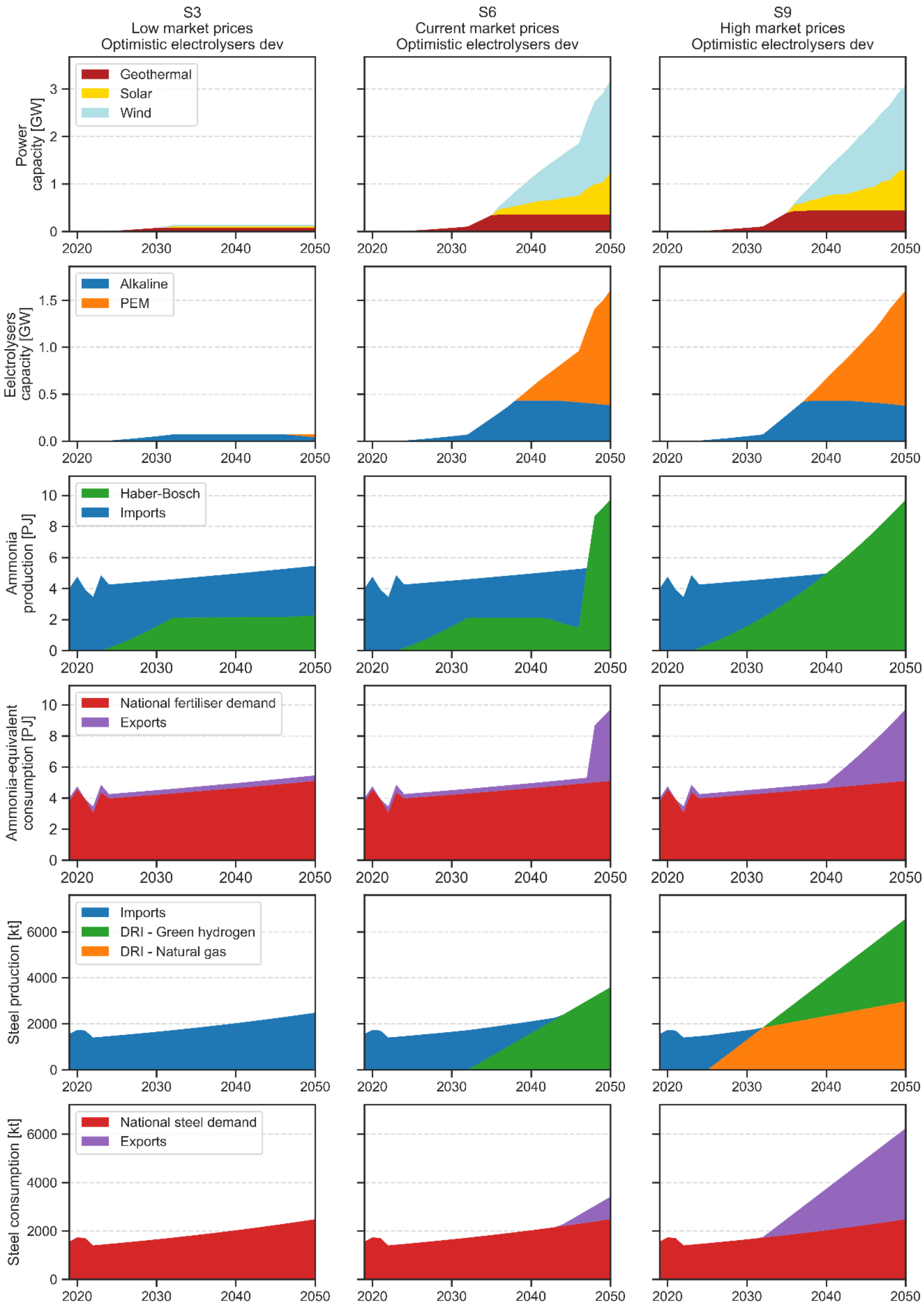

Figure 3 Results of runs based on high market prices for import/export of ammonia and steel (runs 7 to 9). Column 1 shows results for conservative hypothesis on the improvement of water electrolysis technologies, column 2 reference and column 3 optimistic.

Figures – Modelling assumptions

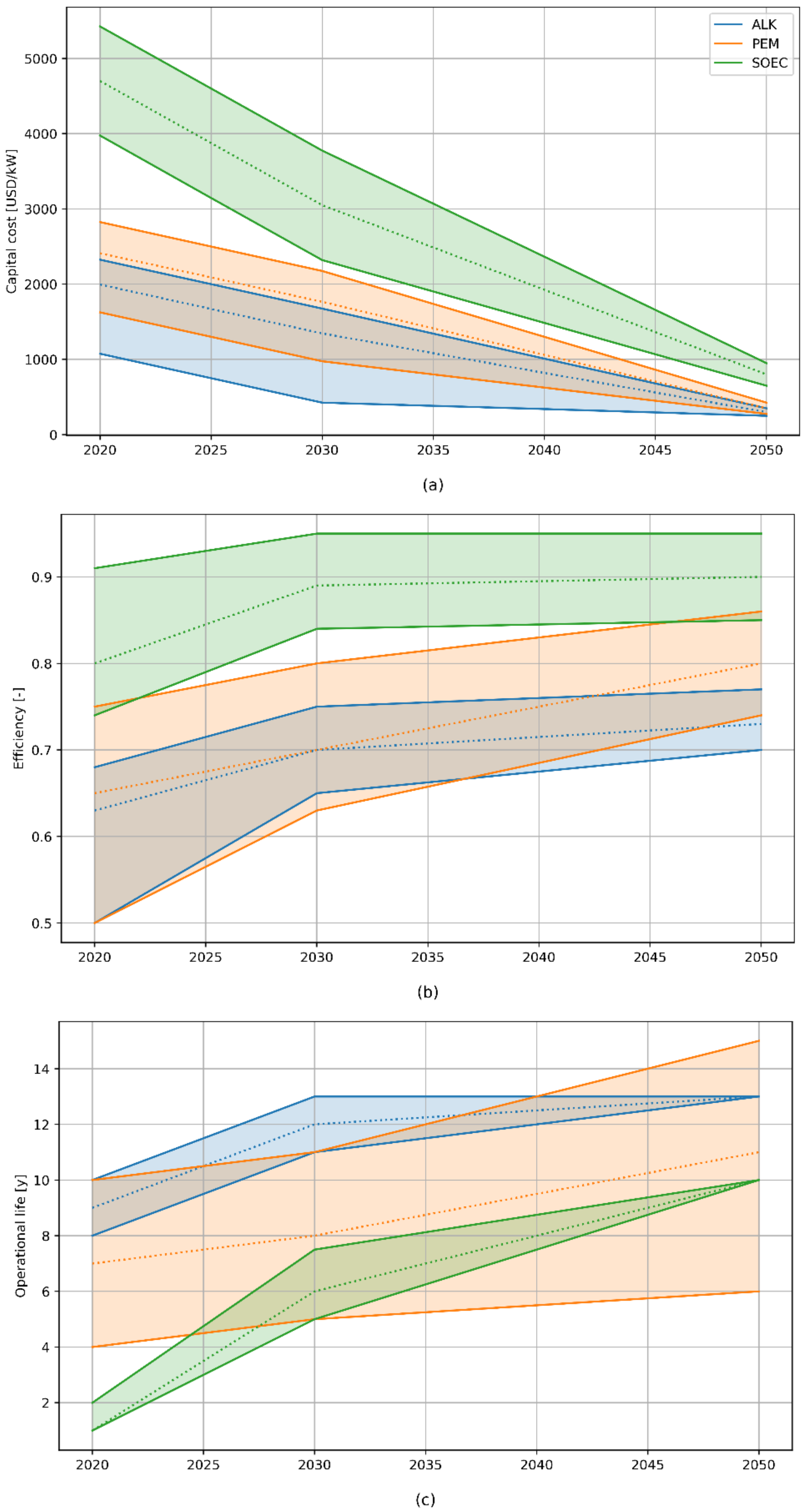

Figure 4 Projected cost reductions (a), improvements in efficiency (b) and improvements in operational stack lifetime for the alkaline (ALK), proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) electrolysers. Based on the literature review summarised in Tables S2 to S4 and on the subsequent values listed in Tables S5 to S7.

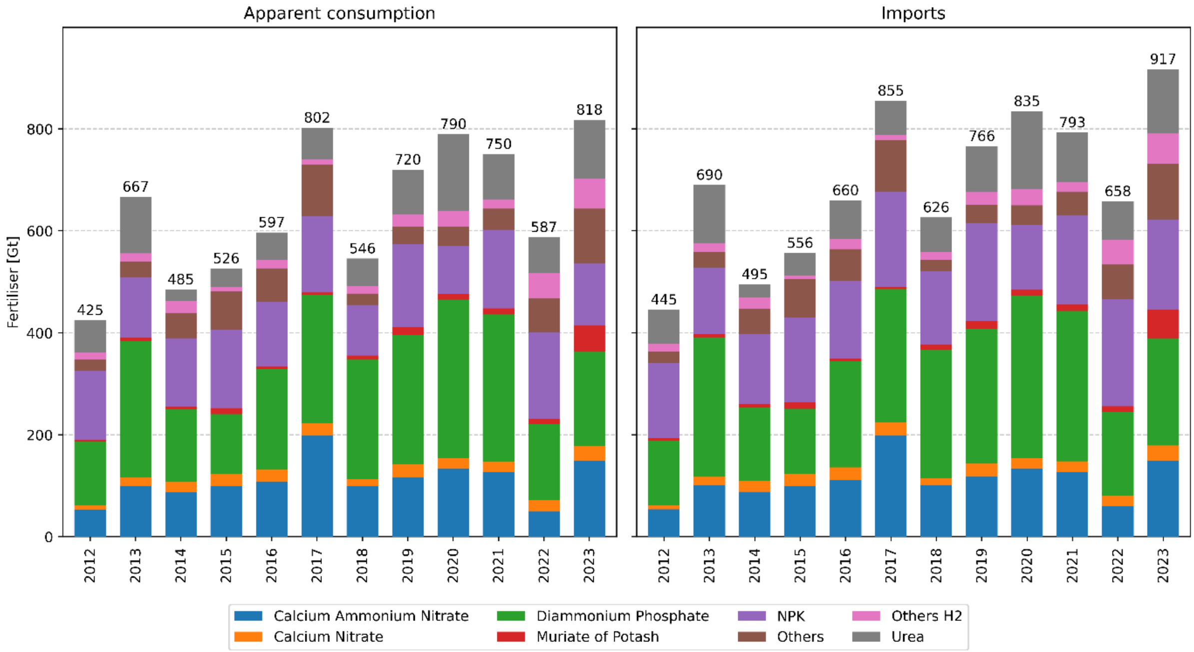

Figure 5 Annual fertilisers apparent consumption and imports in Kenya for the years 2012 to 2023.

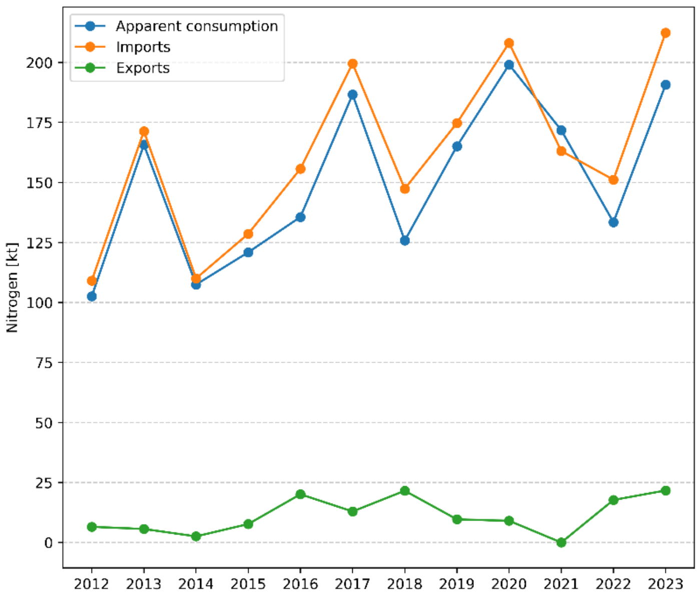

Figure 6 Annual nitrogen consumption, imports and exports in Kenya for the years 2012 to 2023.

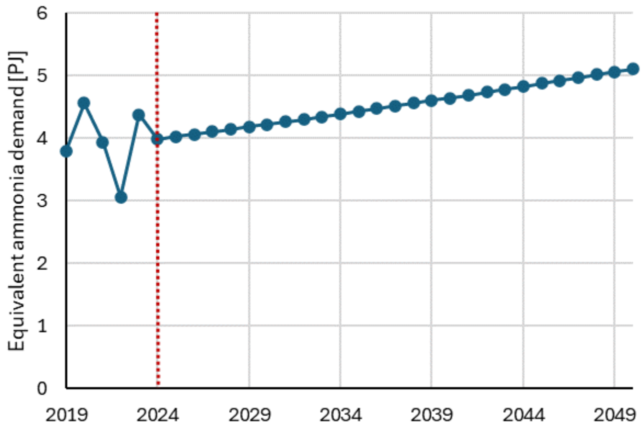

Figure 7 Demand projections for equivalent ammonia demand for nitrogen-based fertilisers in Kenya. The red dotted line separates historical data from the projected figures.

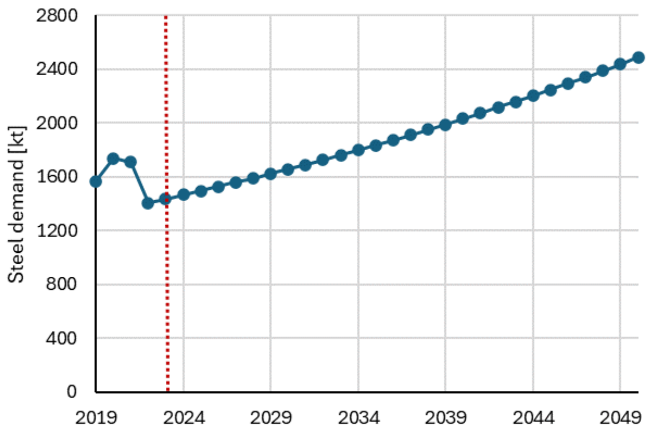

Figure 8 Demand projections for steel in Kenya. The red dotted line separates historical data from the projected figures.

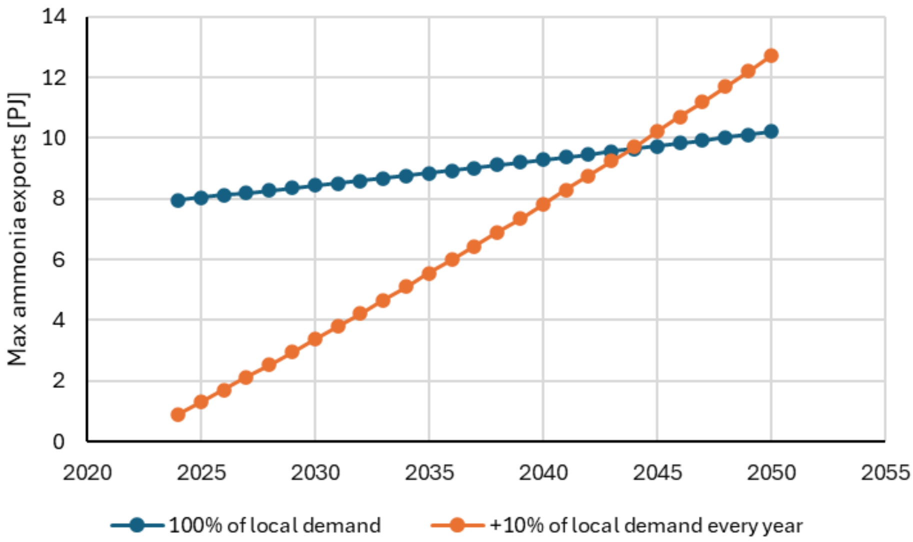

Figure 9 Constraint on maximum ammonia exports in the model. The actual constraint in the model corresponds to whichever constraint is more stringent between the two shown in the figure. The blue line corresponds to exports being equal to local annual demand, while the orange line corresponds to an increase of 10% of local demand every demand, starting from current exports levels.

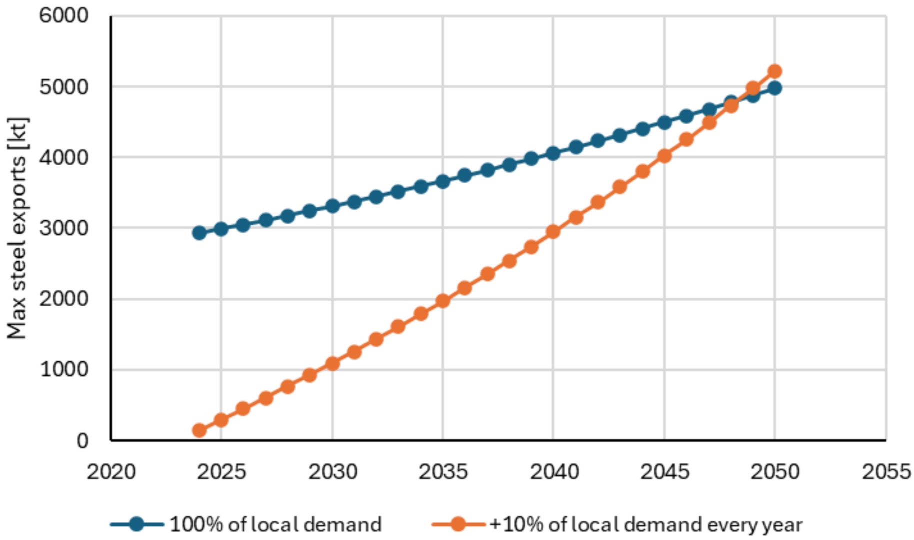

Figure 10 Constraint on maximum steel exports in the model. The actual constraint in the model corresponds to whichever constraint is more stringent between the two shown in the figure. The blue line corresponds to exports being equal to local annual demand, while the orange line corresponds to an increase of 10% of local demand every demand, starting from current exports levels.

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