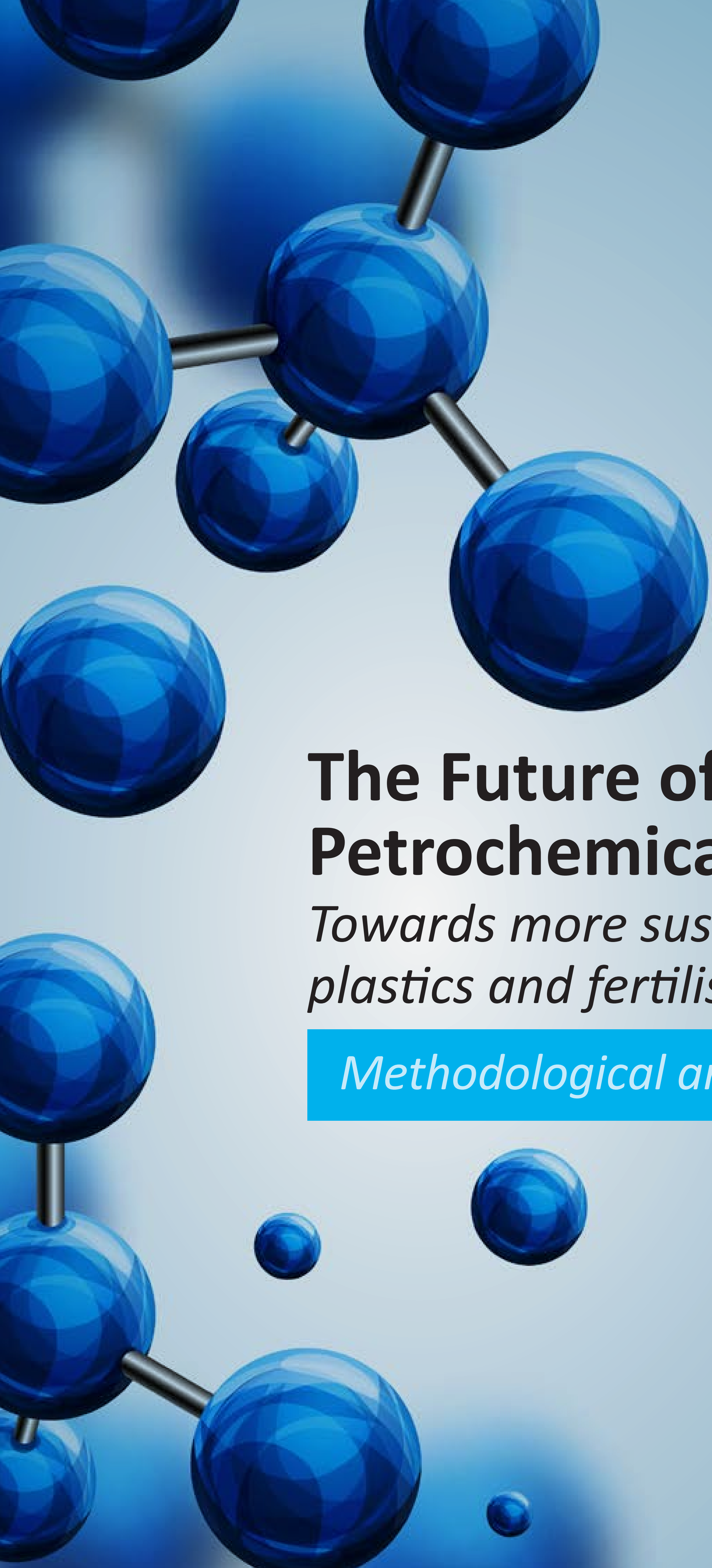

International Energy Agency
Secure
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The Future of Petrochemicals

Towards more sustainable plastics and fertilisers

Methodological annex

INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 7 association countries and beyond.

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Table of contents

1. Scenario analysis

Two contrasting futures for the chemical sector are explored in this analysis. The first is shaped by the projection of the current trajectory, informed by existing and announced policies (the *Reference Technology Scenario* - RTS, Chapter 4 of the main publication). The second is rather different. It stipulates up-front a more sustainable end-point and examines the course by which it might be realised (the *Clean Technology Scenario* – CTS, Chapter 5 of the main publication).

Reference Technology Scenario

The RTS is a modelled projection of what might take place in the chemical sector between now and 2050. The modelling is based on cost-optimal decisions on the equipment and operation of the industry. It occurs within an energy price and chemical demand context informed by the range of existing and announced policies and by established behavioural and other exogenous considerations.

The assumptions made about the future of the wider energy system are broadly in line with those of the International Energy Agency's (IEA) New Policies Scenario, featured in the World Energy Outlook (IEA, 2017). That scenario aims to provide a sense of where today's policy intentions seem likely to take the energy sector. It incorporates the policies and measures that governments around the world have already put in place, and the effects of announced policies, as expressed in official targets or plans.

The RTS is the baseline scenario used for this modelling, but it and the projections made therein are not forecasts. Whereas the IEA makes short-term forecasts for certain fuels and technologies, it does not make long-term forecasts. The modelling horizon (2050) and approach (constrained cost optimisation of technologies that are, at least, at the demonstration stage or beyond) in this publication are two important factors that make the results unsuitable to use as a forecast.

Technologies and policies can change rapidly, without much forewarning, and in 2050, there are likely to be new technologies available, the precursors of which have yet to be conceived in a laboratory. Prices for many fuels, such as oil and gas, tend to move in cycles, rather than follow consistent trends, and the markets in which they are traded remain out of equilibrium for extended periods. By contrast, the modelling underpinning this publication and that of the wider energy system informed by the *World Energy Outlook*, achieve equilibrium in these markets in the long-term. Despite these reservations, the approach adopted offers important insights into a range of possible futures for the chemical sector. The insights suggest where the best opportunities lie and what form of intervention might most profitably be addressed by policy makers

Clean Technology Scenario

The CTS was generated using the same tools and methodologies as those of the RTS. For example, process choices are still based on minimising capital investment and fuel costs, but with the addition of various constraints. The key additional constraint is that the model requires direct CO_2 emissions to be reduced by 45% by 2050, compared to current levels, despite a 40% increase in primary chemical output.

This is not the only additional constraint. The assumptions made about the extent of the required mitigation of other environmental impacts, such as those related to air pollution and water and about other aspects of the future energy system, are in line with those adopted in the IEA

Sustainable Development Scenario. Featured for the first time in the World Energy Outlook (IEA, 2017), the Sustainable Development Scenario takes a fundamentally different approach from the New Policies Scenario of the World Energy Outlook, to which the RTS is aligned.

The Sustainable Development Scenario takes as its starting point a vision of where the energy sector needs to go and works back from that to the present, rather than projecting forward from today's trends. The Sustainable Development Scenario contributes to the achievement of three core goals (derived from the energy-related aspects of the United Nations Sustainable Development Goals):

- universal access to modern energy services by 2030, including not only access to electricity but also clean cooking
- objectives of the Paris Agreement on climate change, including a peak in greenhouse gas emissions being reached as soon as possible, followed by a substantial decline in such emissions
- a large reduction in other energy-related pollutants, to deliver a dramatic improvement in global air quality and a consequent reduction in premature deaths from household air pollution.

These goals have direct implications for sectors beyond the energy sector, including the chemical sector, mainly by raising prices or lowering the availability of certain fuels. For example, the increased demand for liquefied petroleum gas (LPG), relative to other oil products, for clean cooking in developing economies limits the supply available to other sectors, and increases its price.

2. Demand for primary chemicals

Demand for primary chemicals (high value chemicals, HVC: ethylene, propylene, benzene, toluene and mixed xylenes; methanol and ammonia) within the analysed time horizon is an exogenous input to the technology model. These demand curves are estimated on the basis of country- or regional-level data for gross domestic product (GDP), disposable income, short-term industrial capacity, current materials consumption, regional demand saturation levels derived from historical demand intensity curves, and resource endowments. At the regional level, demand is translated into production considering latest observed trade patterns are maintained at similar levels over time. Total production is simulated by factors such as process, age structure (vintage) of plants, and stock turnover rates. Primary chemical production projections were distributed to a wide international network of chemical sector stakeholders for comment and subsequent refinement.

Future demand for primary chemicals is highly uncertain, so the sensitivity of the core results is explored using a "high demand variant" for each scenario. By 2050, production levels in the high demand variants are approximately 25% higher than those of the core scenario results. Figure A.1 displays the production projections used to generate the core RTS results at a regional level, along with the global projections for the CTS and high demand variants of both the RTS and CTS. The sensitivity analysis results are presented in section 4 of this annex.

Recycling assumptions

The plastics included within the scope of the recycling analysis are polyethylene terephthalate, high-density polyethylene, polyvinyl chloride, low-density polyethylene, polypropylene and polystyrene. The production levels of these key thermoplastics are the same in the RTS and the CTS, but the share of plastic demand met via secondary production increases in the CTS, thereby providing primary chemical savings, relative to the RTS. The key parameters pertaining to the recycling analysis are summarised in Table A.1.

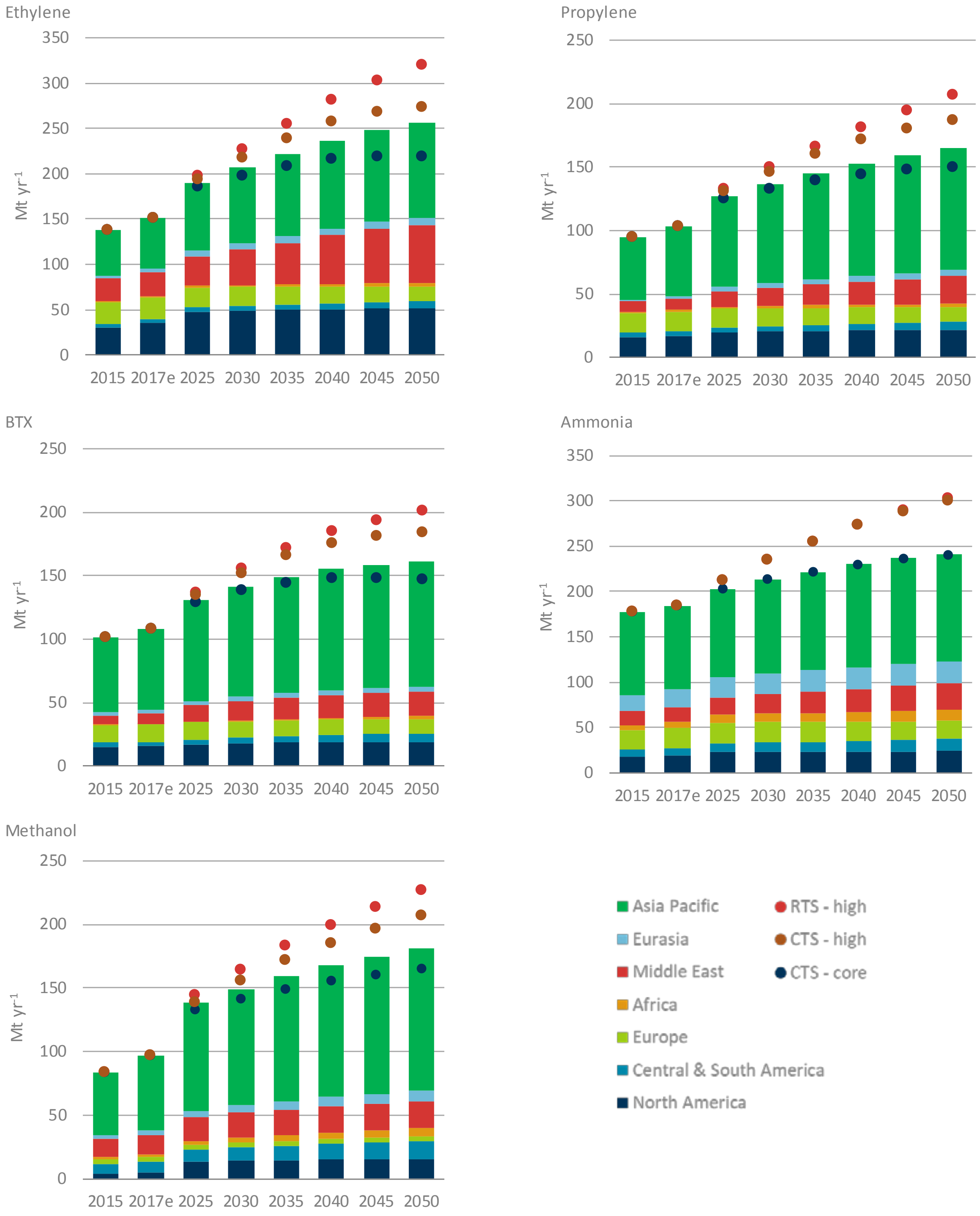
Table A.1 • Summary of key recycling parameters

			RTS		CTS	
Global averages for all resins	2015	2017e	2030	2050	2030	2050
Secondary plastic production (Mt)	25	27	42	69	63	159
Collection rate	14%	15%	17%	18%	26%	41%
Yield rate	73%	73%	74%	75%	78%	84%
Displacement rate	33%	33%	33%	33%	48%	67%
Primary chemical savings (Mt)	-	-	-	-	16	70
HVCs (Mt)	-	-	-	-	15	67
Ammonia (Mt)	-	-	-	-	>0	2
Methanol (Mt)	-	-	-	-	>0	2

Note: HVCs = high value chemicals.

The three factors shown in Table A.1 – the collection, yield and displacement rates – are multiplicative, meaning that improvements are needed across the board to effect significant reductions in virgin primary chemical demand. Initial recycling rates are informed by various data sources (OECD, 2018; Plastics Europe, 2017) and consultation with chemical sector experts. Available plastic waste for recycling is calculated using estimates of historic demand, and average product lifetimes (Geyer et al., 2017). Primary chemical savings are calculated using a translation matrix derived from (Levi and Cullen, 2018).

Figure A.1 • Production projections for the core results and high demand variants



Sources: METI (2016), *Future Supply and Demand Trend of Petrochemical Products Worldwide*, Tokyo, www.meti.go.jp/policy/mono_info_service/mono/chemistry/sekkajyukyuudoukou201506.html; IFA (2018), International Fertilizer Association Database, http://ifadata.fertilizer.org/ucSearch.aspx; expert elicitation. “2017e” is the estimated base year in the modelling. Results are provided for both 2017e and 2015 in this annex, with the 2017e values often involving a degree of interpolation.

3. Technology modelling

This section provides an overview of the methodology employed to generate the results underlying the analysis of the main publication, along with details of key modelling inputs. Where information is provided on key parameters in the main publication (e.g. typical process yields are provided in Chapter 2), this is not repeated here.

Overview of methodology

The modelling results that underpin this publication are generated using a cost-optimisation (TIMES-based) model of the chemical sector. The aim of the modelling architecture is to facilitate technology decision making on a least-cost basis, specifically, discounted capital investment and fuel costs.

The TIMES-based linear optimisation model of the chemical and petrochemical sector is one of five industry technology models the IEA uses to examine energy-intensive sectors (iron and steel, chemicals and petrochemicals, cement, pulp and paper, and aluminium).

The chemical sector TIMES model covers 39 model regions (seven aggregated reporting regions) and a detailed portfolio of technology options for the production of primary chemicals (HVCs, methanol and ammonia) (see Table A.3). Primary chemicals account for around two-thirds of the sector's overall energy consumption. The remaining energy consumption in the sector, which is distributed across thousands of different products and facilities, is modelled using a simulation module.

Each technology characterised in the model for primary chemical production is defined with different parameters, including yields, capital expenditure, fixed operational expenditure, energy performance by fuel, emissions levels by unit of energy use and by product for feedstock-related emissions, construction and decommissioning times, installed capacity and vintages of plants.

The model is driven by the need to satisfy regional demands for primary chemicals, which are projected and translated to their producing regions exogenously. The model must satisfy these demands, while conforming to various scenario-specific constraints, such as limits on the availability of certain fuels and on CO_2 emissions (allowing for the need to supply urea plants with CO_2 feedstock).

The model interacts with other models in the IEA via price signals (e.g. for fuels), available alternative feedstocks (e.g. COG). The integrated and iterative approach is aimed at providing a coherent scenario that takes account of the complex interdependencies within the energy system. For this publication, the wider energy system context is provided by results from the World Energy Model, the latest results of which are described in the World Energy Outlook (IEA, 2017).

Model regions

Table A.2 • Model regions for reporting results

Region	Countries and territories within region
North America	Canada, Mexico and United States.
Central and South America	Argentina, Bolivia, Bolivarian Republic of Venezuela, Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay.
Europe	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, United Kingdom, Albania, Belarus, Bosnia and Herzegovina, Gibraltar, Iceland, Israel***, Kosovo**, Montenegro, Norway, Serbia, Switzerland, Former Yugoslav Republic of Macedonia, Republic of Moldova, Turkey* and Ukraine.
Africa	Algeria, Egypt, Libya, Morocco, Tunisia, Benin, Botswana, Cameroon, Republic of the Congo, Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania, Togo, Zambia, Zimbabwe.
Middle East	Bahrain, the Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, the Syrian Arab Republic, the United Arab Emirates and Yemen.
Eurasia	Russian Federation, Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.
Asia Pacific	Australia, Bangladesh, China, Chinese Taipei, India, Japan, Korea, Democratic People's Republic of Korea, Mongolia, Nepal, New Zealand, Pakistan, Sri Lanka, Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam.

* Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue". Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus. ** This designation is without prejudice to positions on status, and is in line with United Nations Security Council Resolution 1244/99 and the Advisory Opinion of the International Court of Justice on Kosovo's declaration of independence. *** The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Key modelling inputs

Table A.3 • Technology investment costs and technology readiness levels (TRLs)

Technology description	Primary product	CAPEX (2016 USD/t product)	OPEX (% of CAPEX)	TRL
Ethane steam cracking	High value chemicals	1 487	2.5%	9
Naphtha steam cracking	High value chemicals	2 057	2.5%	9
LPG steam cracking	High value chemicals	1 900	2.5%	9
Gas oil steam cracking	High value chemicals	2 328	2.5%	9
Naphtha catalytic cracking	High value chemicals	3 000	2.5%	8
Ethanol dehydration	Ethylene	1 328	2.5%	8/9
Propane dehydrogenation	Propylene	1 691	2.5%	9
Methanol to olefins	Ethylene, propylene	1 000	2.5%	8/9
Methanol to aromatics	BTX aromatics	1 000	2.5%	7
Ammonia via steam methane reforming	Ammonia	860	2.5%	9
Ammonia via oil partial oxidation	Ammonia	1 203	2.5%	9
Ammonia via coal gasification	Ammonia	2 063	5.0%	9
Ammonia via biomass gasification	Ammonia	6 000	5.0%	6/7
Methanol via steam methane reforming	Methanol	295	2.5%	9
Methanol via oil partial oxidation	Methanol	295	2.5%	9
Methanol via coal gasification	Methanol	710	5.0%	9
Methanol via COG reforming	Methanol	295	2.5%	9
Methanol via biomass gasification	Methanol	4 900	5.0%	6/7
Concentrated stream CO_2 capture	Captured CO_2	50	40.4%	9
Dilute stream CO_2 capture	Captured CO_2	272	7.4%	7/8
Electrolyser (2015)	Hydrogen	9 383	3.5%	8/9
Electrolyser (2030)	Hydrogen	4 632	3.5%	8/9
Electrolyser (2050)	Hydrogen	2 312	3.5%	8/9
Air separation unit	Nitrogen	9	2.5%	9
Ammonia synthesis unit	Ammonia	95	2.5%	9
Methanol synthesis unit	Methanol	44	2.5%	9

Note: HVCs = High Value Chemicals, CAPEX = Capital Expenditure, OPEX = Operational Expenditure. CAPEX is expressed per unit of primary product capacity. OPEX is expressed as a percentage of CAPEX. The electrolyser is the only technology for which CAPEX declines over time. Electrolyser CAPEX figures for 2015, 2030 and 2050 correspond to USD 1400/kWe, USD 780/kWe and USD 480/kWe respectively, on an electrical input basis. Storage and transport costs for CO_2 are incorporated into the OPEX percentage, as to send the appropriate cost signal to the model for this technology. The percentages account for combined transport and storage costs of USD 20/tCO_2 captured.

Table A.4 • Electrolytic technology assumptions

			Elec. SEC (GJ/t)				Efficiency (HHV, %)			
Process route	Component	Output	2015	2017e	2030	2050	2015	2017e	2030	2050
Ammonia	Air separation	Nitrogen	3.1	3.1	3.1	3.1	-	-	-	-
	Synthesis	Ammonia	1.4	1.4	1.4	1.4	-	-	-	-
	Electrolyser	Hydrogen	-	-	-	-	66%	67%	72%	82%
Methanol	Synthesis	Methanol	1.5	1.5	1.5	1.5	-	-	-	-
	Electrolyser	Hydrogen	-	-	-	-	66%	67%	72%	82%

Note: Elec. = electricity; HHV = higher heating value.

Table A.5 • Process energy intensities

			SEC range (GJ/t)			BPT (GJ/t)		
Process	Primary product(s)	Range	Fuel	Steam	Elec.	Fuel	Steam	Elec.
Ethane steam cracking	HVCs	High	29.2	2.4	1.9	-	-	-
		Average	17.1	-0.1	0.8	13.6	-1.4	0.3
		Low	13.6	-3.0	0.3	-	-	-
Naphtha steam cracking	HVCs	High	19.4	0.8	1.5	-	-	-
		Average	14.6	-0.3	0.9	13.1	-1.4	0.3
		Low	12.0	-2.1	0.3	-	-	-
LPG steam cracking	HVCs	High	27.2	1.9	1.5	-	-	-
		Average	18.6	-1.7	0.4	13.5	-1.4	0.3
		Low	13.6	-2.8	0.3	-	-	-
Gas oil steam cracking	HVCs	High	21.5	-1.7	0.3	-	-	-
		Average	17.8	-2.1	0.3	12.0	-1.4	0.3
		Low	14.8	-2.5	0.3	-	-	-
Naphtha catalytic cracking	HVCs	Average	10.9	-1.2	0.3	10.9	-1.2	0.3
Ethanol dehydration	Ethylene	Average	1.6	45.5	1.9	1.6	45.5	1.9
Propane dehydrogenation	Propylene	Average	10.7	2.7	0.1	8.9	2.2	0.1
Methanol to olefins	Ethylene, propylene	Average	11.4	-2.1	0.2	5.9	-1.1	0.2
Methanol to aromatics	BTX aromatics	Average	11.4	-2.1	0.2	5.9	-1.1	0.2
Ammonia via SR (natural gas)	Ammonia	High	32.4	-5.5	0.3	-	-	-
		Average	26.3	-9.3	0.3	13.5	-4.8	0.3
		Low	15.6	-11.4	0.3	-	-	-
Ammonia via POX (oil)	Ammonia	High	32.6	-6.3	2.0	-	-	-
		Average	27.9	-8.4	2.0	20.5	-6.3	2.0
.		Low	20.6	-9.7	2.0	-	-	-
Ammonia via GSF (coal)	Ammonia	High	29.6	-1.3	3.7	-	-	-
		Average	23.6	-1.5	3.7	19.6	-1.3	3.7
		Low	19.6	-1.9	3.7	-	-	-
Ammonia via GSF (biomass)	Ammonia	Average	26.3	-1.7	5.0	26.3	-1.7	5.0
Methanol via SR (natural gas)	Methanol	High	16.9	-2.5	0.3	-	-	-
		Average	15.7	-2.8	0.3	11.6	-2.1	0.3
		Low	13.8	-3.0	0.3	-	-	-
Methanol via POX (oil)	Methanol	Average	14.8	-2.9	2.0	10.1	-2.1	2.0
Methanol via GSF (coal)	Methanol	Average	26.9	-5.5	3.7	20.8	-4.4	3.7
Methanol via SR (COG)	Methanol	Average	26.9	-5.5	3.7	20.8	-4.4	3.7
Methanol via GSF (biomass)	Methanol	Average	28.0	-5.9	5.0	28.0	-5.9	5.0
Conc. stream CO_2 capture	Captured CO_2	Average	0.0	0.0	0.4	0.0	0.0	0.4
Dil. stream CO_2 capture	Captured CO_2	Average	0.0	3.2	0.5	0.0	3.2	0.5

Note: HVC = High Value Chemicals, SR = Steam Reforming, GSF = Gasification, POX = Partial Oxidation, COG = Coke Oven Gas, Conc. = Concentrated, Dil. = Dilute, SEC = Specific Energy Consumption, Elec. = Electricity. Where no significant regional variance in SEC is presented only currents estimates of the global average are presented. SEC and BPT values are presented on a gross basis, i.e. without any credits for recycled fuel gas.

Oil feedstock price assumptions

The energy system contexts for the RTS and CTS are provided by the IEA's New Policies Scenario and Sustainable Development Scenario respectively. These contexts include price assumptions for crude oil and other non-oil product energy carriers, details of which can be found in the latest edition of the World Energy Outlook (WEO, 2017). A more detailed description of the methodology for deriving individual oil product prices is provided here.

The choice of feedstock for chemicals production can be determined by various factors, but there is no doubt that the price trajectory of different oil products is one of the most important ones, especially for high-value chemicals production. The model assumes the long-term price trajectory of major petrochemical feedstocks (naphtha, ethane and LPG) derived based on their historical relationship with oil prices, with specific adjustments applied to reflect anticipated market developments.

The model uses the IEA long-term oil prices defined in the World Energy Outlook 2017 as a basis, which are expressed in year-2016 dollars. The RTS and the CTS take the oil prices from the wider IEA's New Policies Scenario and the Sustainable Development Scenario respectively. In the RTS, there is an upward drift in the oil price over the period to 2050 to reflect the need to move to higher cost oil to satisfy increasing demand. However, in the CTS, oil prices turn its direction in the mid-2020s and continue to head downward reflecting lower demand than in the RTS.

As feedstock prices vary by region, the model delivers price trajectories for the three major regional groupings: exporting regions, Europe and Asia Pacific. In general, exporting regions include the Middle East, North America and Eurasia. The prices for Europe were applied to the European countries, as well as those in Africa and Central and South America.

In principle, the prices for exporting regions were derived based on the historical relationship between IEA oil prices and product prices between 2001 and 2016. The prices for importing regions such as Europe and Asia Pacific were calculated by adding transportation costs to the exporting region prices. While this methodology works well for certain oil products such as naphtha, history may not provide a good guidance for future prices in the cases of ethane and LPG given the substantial changes occurred in the market due to the shale revolution in the United States. For instance, US ethane prices have been formed at around 40% of IEA oil prices between 2001 and 2010, but in the aftermath of the shale boom, the ratio relative to oil prices went down to as low as 10% in 2013, which rose slightly to 20% in 2016. Reflecting the onsets of multiple US ethane crackers planned to come online in the late 2010s and early 2020s, the model assumes a gradual increase of the ratio to 35% over the period to 2025.

The same logic was applied to LPG prices. For LPG prices in importing regions, respective transportation costs were added to the prices in exporting regions. However, we introduced an additional premium for ethane prices in Europe and Asia Pacific given that the source of ethane export is limited to North America and that the incremental room for exports from North America is increasingly squeezed over time with tightening NGLs supply and growing domestic demand.

Below is the summary of methodologies applied to derive the long-term price assumptions for individual oil products in the RTS.

Naphtha

- Exporting regions: IEA oil prices x multiplier derived from the historical relationship between oil prices and European naphtha prices between 2001 and 2016
- Europe: the same prices with exporting regions
- Asia Pacific: exporting region prices + transportation cost ($2/bbl)

Ethane

- Exporting regions: IEA oil prices x multiplier derived from the historical relationship between oil prices and US ethane prices between 2001 and 2016 (where the multiplier gradually increases over the period to 2025)
- Europe: exporting region prices x premium factor + transportation cost ($5/bbl)
- Asia Pacific: exporting region prices x premium factor (higher than that of Europe) + transportation cost ($6/bbl)

LPG

- Exporting regions: IEA oil prices x multiplier derived from the historical relationship between oil prices and US LPG prices between 2001 and 2016 (where the multiplier gradually increases over the period to 2025)
- Europe: exporting region prices + transportation cost ($4/bbl)
- Asia Pacific: exporting region prices + transportation cost ($5/bbl)

Table A.6 • Oil products price assumptions in the RTS

Product ($2016/bbl)	Region	2020	2025	2030	2040	2050
Crude oil		72	83	94	111	124
Naphtha	Exporting regions	65	75	84	100	111
	Europe	65	75	84	100	111
	Asia Pacific	67	77	86	102	113
Ethane	Exporting regions	23	29	33	39	43
	Europe	30	38	40	49	57
	Asia Pacific	34	47	49	65	79
LPG	Exporting regions	45	53	61	71	80
	Europe	49	57	65	75	84
	Asia Pacific	50	58	66	76	85

The approach applied in the CTS is similar with that in the RTS, but there is an important caveat to be taken into consideration in relation to LPG. In this scenario, the supply of LPG is noticeably lower than that in the RTS due to lower natural gas production and lower refinery utilisation. Meanwhile, the appetite for LPG is stronger in many sectors, for example, clean cooking and LPG in transport, implying that the availability of LPG for feedstock use can be reduced compared to the RTS. We therefore assumed a multiplier for LPG to increase beyond 2025 out to 2035, ending up at a slightly higher level than in the RTS.

Table A.7 • Oil products price assumptions in the CTS

Product ($2016/bbl)	Region	2020	2025	2030	2040	2050
Crude oil		66	72	69	64	62
Naphtha	Exporting regions	59	65	62	57	56
	Europe	59	65	62	57	56
	Asia Pacific	61	67	64	59	58
Ethane	Exporting regions	22	25	24	22	22
	Europe	27	32	30	29	29
	Asia Pacific	30	36	34	34	35
LPG	Exporting regions	41	46	44	43	41
	Europe	45	50	48	47	45
	Asia Pacific	46	51	49	48	46

4. Tabulated results

Global results

Table A.8 • Global energy and technology results

Fuel/feedstock/process	*RTS*				*CTS*			
	2015	2017e	2030	2050	2015	2017e	2030	2050
Process energy consumption (Mtoe)	184	199	239	236	184	198	228	186
Coal	59	65	82	86	59	65	64	20
Oil	4	3	1	0	4	3	0	0
Gas	107	115	137	129	107	115	148	156
Electricity	14	15	19	20	14	15	16	11
Heat	0	0	0	0	0	0	0	0
Bioenergy	0	0	0	0	0	0	0	0
Other renewables	0	0	0	0	0	0	0	0
Feedstock consumption (Mtoe)	492	531	696	864	492	530	678	773
Coal	49	53	67	76	49	53	53	16
Oil	376	405	526	654	376	404	501	571
Gas	66	71	97	119	66	72	114	170
Electricity	0	0	0	0	0	0	5	9
Heat	0	0	0	0	0	0	0	0
Bioenergy	1	1	6	15	1	1	5	7
Other renewables	0	0	0	0	0	0	0	0
HVCs (Mt)	212	234	319	399	212	233	307	348
Naphtha steam cracking	122	127	164	215	122	127	150	163
Ethane steam cracking	47	54	84	86	47	54	78	65
LPG steam cracking	29	31	29	42	29	31	34	41
Gas oil steam cracking	3	4	2	0	3	4	2	0
Propane dehydrogenation	6	9	19	18	6	10	14	7
Naphtha catalytic cracking	0	0	2	8	0	0	10	50
Ethanol dehydration	1	1	5	14	1	1	4	6
Methanol to olefins/aromatics	4	7	14	17	4	7	17	15
Ammonia (Mt)	177	183	214	242	177	183	213	240
Natural gas steam reforming	109	116	150	178	109	116	160	230
Oil partial oxidation/steam reforming	5	4	2	0	5	4	0	0
Coal gasification/partial oxidation	64	63	62	64	64	63	48	0
Biomass gasification	0	0	0	0	0	0	0	0
Electrolysis	0	0	0	0	0	0	5	10
Methanol (Mt)	83	97	149	182	83	97	158	179
Natural gas steam reforming	37	41	64	84	37	42	90	142
Oil partial oxidation/steam reforming	2	2	2	0	2	2	0	0
Coal gasification/partial oxidation	33	43	71	87	33	42	54	22
COG steam reforming	10	10	12	12	10	10	12	12
Biomass gasification	0	0	0	0	0	0	0	0
Electrolysis	0	0	0	0	0	0	2	4

Note: HVC = High Value Chemicals, SR = Steam Reforming, GSF = Gasification, POX = Partial Oxidation, COG = Coke Oven Gas, BDH = Bioethanol Dehydration, STC = Steam Cracking, PDH = Propane Dehydrogenation, NCC = Naphtha Catalytic Cracking, MTO/MTA = Methanol to Olefins/Methanol to Aromatics.

Regional results

Table A.4 contains the modelling results for feedstock energy consumption related to primary chemical production, at the regional level.

Table A.9 • Regional feedstock results

Region/feedstock	*RTS*				*CTS*			
	2015	2017e	2030	2050	2015	2017e	2030	2050
World (Mtoe)	492	531	696	864	492	530	678	773
Coal	49	53	67	76	49	53	53	16
COG	5	5	6	6	5	5	6	6
Other Coal	44	48	62	70	44	48	47	10
Oil	376	405	526	654	376	404	501	571
Naphtha	243	253	327	435	243	252	310	396
Ethane	64	75	116	119	64	75	107	90
LPG	61	70	79	100	61	70	80	85
Gas oil	7	8	3	0	7	8	3	0
Other Oil	0	0	0	0	0	0	0	0
Gas	66	71	97	119	66	72	114	170
Electricity	0	0	0	0	0	0	5	9
Imported heat	0	0	0	0	0	0	0	0
Bioenergy	1	1	6	15	1	1	5	7
North America (Mtoe)	64	76	104	113	64	76	102	103
Coal	0	0	0	0	0	0	0	0
COG	0	0	0	0	0	0	0	0
Other Coal	0	0	0	0	0	0	0	0
Oil	56	66	87	95	56	65	82	84
Naphtha	7	9	13	17	7	9	13	21
Ethane	30	36	59	52	30	35	53	37
LPG	18	20	14	26	18	20	15	25
Gas oil	1	1	1	0	1	1	1	0
Other Oil	0	0	0	0	0	0	0	0
Gas	9	10	17	18	9	10	19	18
Electricity	0	0	0	0	0	0	0	0
Imported heat	0	0	0	0	0	0	0	0
Bioenergy	0	0	0	1	0	0	1	1
Europe (Mtoe)	85	84	74	62	85	84	71	54
Coal	0	0	0	0	0	0	0	0
COG	0	0	0	0	0	0	0	0
Other Coal	0	0	0	0	0	0	0	0
Oil	75	73	62	51	75	73	57	40
Naphtha	55	53	46	39	55	53	40	30
Ethane	4	5	6	5	4	5	7	5
LPG	12	11	8	6	12	11	8	4
Gas oil	4	4	2	0	4	4	2	0
Other Oil	0	0	0	0	0	0	0	0
Gas	10	10	11	11	10	10	10	6
Electricity	0	0	0	0	0	0	4	8
Imported heat	0	0	0	0	0	0	0	0
Bioenergy	0	0	0	1	0	0	0	1

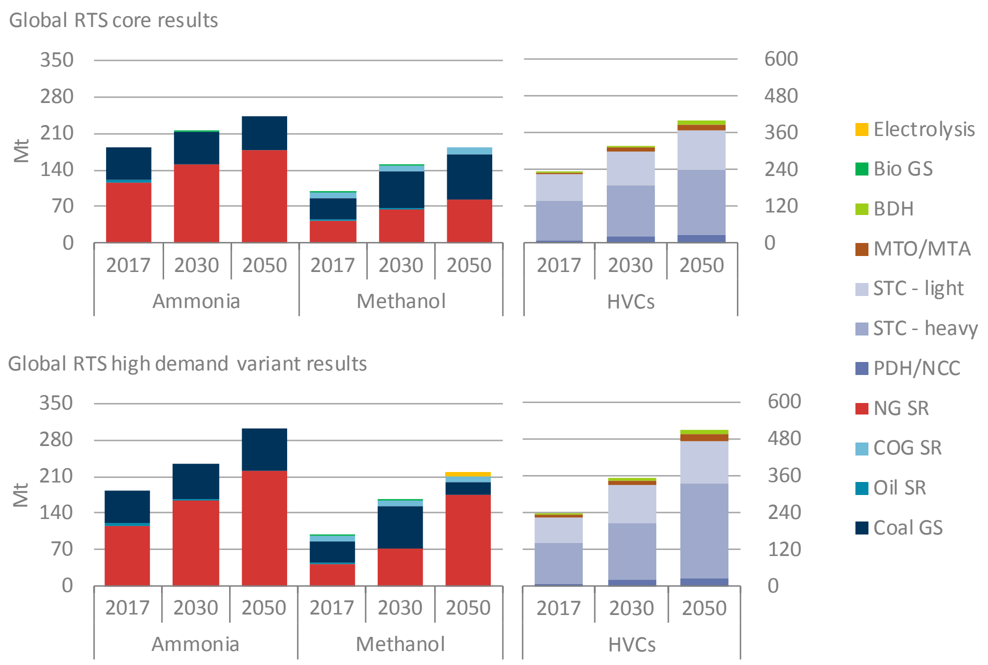
Region/feedstock	*RTS*				*CTS*			
	2015	2017e	2030	2050	2015	2017e	2030	2050
Middle East (Mtoe)	66	70	100	170	66	70	98	155
Coal	0	0	0	0	0	0	0	0
COG	0	0	0	0	0	0	0	0
Other Coal	0	0	0	0	0	0	0	0
Oil	53	56	81	147	53	56	76	132
Naphtha	16	16	21	71	16	16	21	74
Ethane	22	24	40	47	22	23	35	36
LPG	15	16	19	28	15	16	20	22
Gas oil	0	0	0	0	0	0	0	0
Other Oil	0	0	0	0	0	0	0	0
Gas	13	14	19	23	13	14	21	23
Electricity	0	0	0	0	0	0	0	0
Imported heat	0	0	0	0	0	0	0	0
Bioenergy	0	0	0	0	0	0	0	0
Asia Pacific (Mtoe)	230	251	349	425	230	250	339	375
Coal	49	53	67	76	49	52	53	16
COG	5	5	6	6	5	5	6	6
Other Coal	44	48	62	70	44	48	47	10
Oil	166	182	255	305	166	182	249	269
Naphtha	146	156	220	267	146	156	212	237
Ethane	6	6	5	7	6	6	6	7
LPG	12	17	29	32	12	17	30	25
Gas oil	3	3	1	0	3	3	1	0
Other Oil	0	0	0	0	0	0	0	0
Gas	14	15	23	31	14	16	35	85
Electricity	0	0	0	0	0	0	0	1
Imported heat	0	0	0	0	0	0	0	0
Bioenergy	0	0	4	13	0	0	3	4
ROW (Mtoe)	46	51	70	95	46	51	68	86
Coal	0	0	0	0	0	0	0	0
COG	0	0	0	0	0	0	0	0
Other Coal	0	0	0	0	0	0	0	0
Oil	26	28	41	57	26	28	38	47
Naphtha	18	18	26	42	18	18	24	34
Ethane	3	4	6	8	3	4	5	5
LPG	4	6	9	8	4	6	8	8
Gas oil	0	0	0	0	0	0	0	0
Other Oil	0	0	0	0	0	0	0	0
Gas	20	22	28	36	20	22	30	39
Electricity	0	0	0	0	0	0	0	0
Imported heat	0	0	0	0	0	0	0	0
Bioenergy	1	1	1	1	1	1	1	1

Notes: LPG = liquefied petroleum gas; COG = coke oven gas; ROW = rest of the world.

Sensitivity analysis results

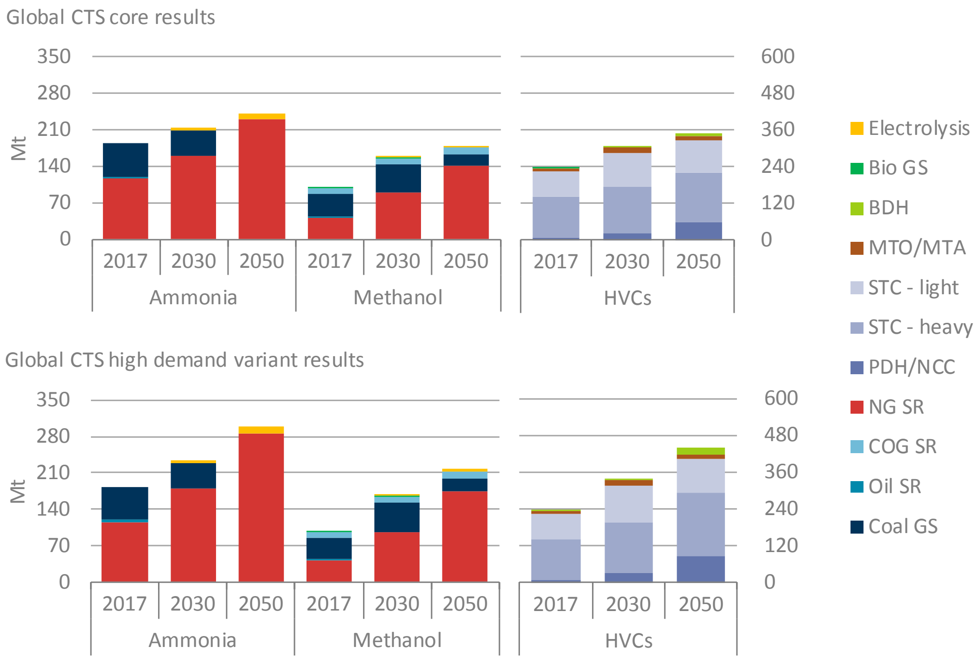
The sensitivity of the results is explored using the high demand variants presented in section 2 in this annex. The aim is to ascertain whether the feedstock and technology selections associated with the core results of this publication would change dramatically if demand for primary chemicals exceeded our core estimations in each scenario. A summary of the sensitivity analysis is provided by Figures A.2-A.4, which display only minor changes in the technologies and feedstocks utilised.

Figure A.2 • Global sensitivity results for the RTS



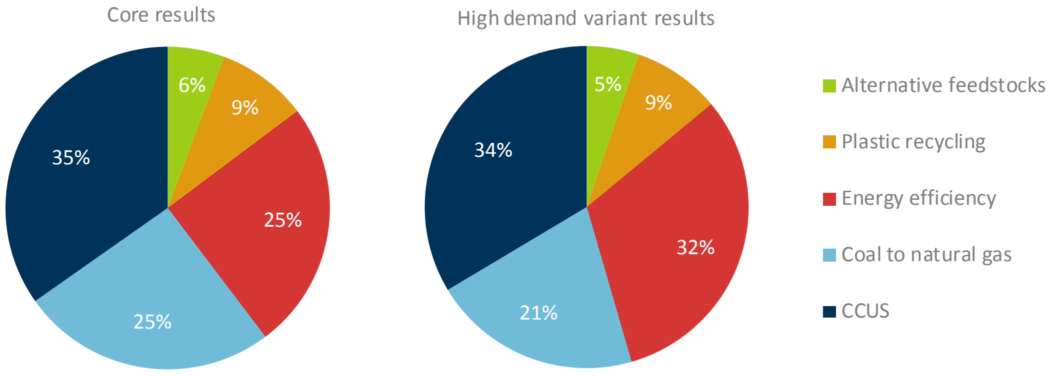
Notes: BDH = bioethanol dehydration; Bio = bioenergy; COG = coke oven gas; GS = gasification; NG = natural gas; PDH = propane dehydrogenation; MTO/MTA = methanol-to-olefins/aromatics; NCC = naphtha catalytic cracking; SR = steam reforming; STC - heavy = naphtha and gas oil steam cracking; STC - light = ethane and liquid petroleum gas steam cracking.

Figure A.3 • Global sensitivity results for the CTS



Notes: As per previous figure.

Figure A.4 • Sensitivity of emissions mitigation lever contributions



Notes: The decomposition of mitigation levers is performed in the same manner for the high demand variants (right pie) as for the core results (left pie).

5. Air pollutants

The levels of air pollutant emissions in this report have been estimated using an extension of the analysis conducted for previous IEA studies (IEA, 2016a; IEA, 2017). These were originally performed in conjunction with the International Institute of Applied System Analysis, using the GAINS model (Amann et al., 2011).

Only air pollutants resulting from the combustion of fuels within the chemical sector are included within the scope of this publication's results. Regional intensity factors are derived for each model region, fuel and year, and then applied to the process energy results for primary chemical production. The scope of air pollutants considered includes nitrous oxides (NO_x), sulphur dioxide (SO_2) and fine particulate matter ($PM_{2.5}$).

6. Water demand assessment

We project two distinct types of water use: withdrawal (volume of water removed from a source) and consumption (volume of water withdrawn that is not returned to the source). Water withdrawal is by definition, always greater than or equal to consumption. For this analysis, 'water' refers to accessible freshwater. While we recognize that non-freshwater sources are already being used, either to replace or complement freshwater, in many places the use of alternative sources is at a nascent stage or is not yet economic, relative to freshwater, and is not quantified in this analysis.

Direct water demand for primary chemical production

Direct water demand estimates for primary chemical production includes water uses as feedstock. This occurs in primary chemical production processes such as steam reformers and steam crackers. As some of these processes occur at high temperature and pressure, high-purity freshwater is a necessity. Intensity factors were calculated for these processes and then applied to the activity levels for each process in each region, using various data sources and expert consultation (Nel Hydrogen, 2018; Levi and Cullen, 2018). Water demand for process heating is excluded due to the wide range of possible configurations for steam systems across chemical sites.

Indirect water demand for primary energy production

In order to quantify the water requirements for primary energy production, we conducted a comprehensive review of published water withdrawal and consumption factors for relevant stages of oil, natural gas, coal and biofuels production for World Energy Outlook 2016. Water factors were taken from the most recent sources available, and as much as possible from operational rather than theoretical estimates. These were then compiled into source-to-carrier ranges for each fuel (excluding hydropower),[1] disaggregated by production chain, and applied across the energy demand projections from the least-cost technology chemicals model (see Box 2.3) at an equivalent level of disaggregation by scenario and model region. The water factors applied are generally global, with the exception of biofuels, where factors range widely depending on where feedstock is grown.

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[1] The IEA does not present ranges for withdrawals and consumption for hydropower. While a majority of the water withdrawn is returned to the river, hydropower's water consumption varies depending on a range of factors. Thus the amount consumed is site specific and a standardised measurement methodology is not yet agreed, though researchers are developing methodologies.

The production chains were disaggregated as follows:

- Oil- conventional oil (primary and secondary recovery), arctic, NGLs, extra heavy oil bitumen, kerogen, tight, coal-to-liquids, gas-to-liquids, enhanced oil recovery (by various methods);
- Natural gas- conventional gas, shale, tight, coal-to-gas, coalbed methane, and;
- Biofuels- sugarcane ethanol, corn ethanol, lignocellulosic ethanol, soybean biodiesel, rapeseed biodiesel and palm oil biodiesel.

Indirect water demand from power generation

In order to quantify the water requirements for power generation, we conducted a comprehensive review of published water withdrawal and consumption factors for electricity generation technologies by cooling system type. Water factors were taken from the most recent sources available, and as much as possible from operational rather than theoretical estimates. Water factors compiled did not account for water used to produce the input fuel, as this may be supplied outside of the country where power is generated.

These average water factors were applied to the World Energy Outlook 2016 (IEA, 2016b) projections for power generation in each scenario, region and generating technology, disaggregated by cooling system, by fresh and non-fresh water type, using present shares based on information from Platts. Technologies were further broken down into existing and new capacity. In most cases shares of cooling technologies were held constant, with several exceptions where known policies and plans were accommodated (including the United States, China and India). The cooling systems included were once-through, wet cooling tower, wet cooling pond, dry and hybrid. The water factors for primary energy production and power generation were sent to a group of peer-reviewers for further review.

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