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# Future availability and demand for oil gas and key minerals

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# 18. Future availability and requirement for oil gas and key minerals

*Kimon Keramidas, Alban Kitous, Bradford Griffin*

**To provide quantitative information on the potential tensions for energy supply and access other raw materials for the EU in the next three decades, world dynamic modelling with a detailed regional coverage was chosen. The modelling work conducted in POLINARES was made with the use of the POLES model. The work can be broken down in two segments: work related to energy raw materials demand and supply; and work related to minerals demand. The outputs of the POLES model were used to provide an informed view of the challenges and opportunities that might arise in the future for the provision of energy services and for the access to energy resources, notably through the use of such metrics as energy intensity and energy dependence.**

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## 18.1. Introduction

To provide quantitative information on the potential tensions for energy supply and access other raw materials for the EU in the next three decades, world dynamic modelling with a detailed regional coverage was chosen. The modelling work conducted in POLINARES was made with the use of the POLES model (see Appendix A.1 for description). Work can be broken down in two segments: work related to energy raw materials demand and supply; and work related to minerals demand.

POLES was used in a conventional way to illustrate potential futures of the world economy and implications for the supply and demand of energy. In collaboration with WP3, the 4 Future World Images developed in WP3 were transcribed in POLES by interpreting and approximating qualitative descriptions into quantified data that drive the model, in the fields of macro-economics, investment climate, technologies, and regional and global geopolitics. The model outputs were used to provide an informed view of the challenges and opportunities that might arise in the future for the provision of energy services and for the access to energy resources, notably through the use of such metrics as energy intensity and energy dependence.

Originally an energy model, POLES was also extended in the scope of POLINARES to include the demand of certain minerals (steel, copper). A methodology was set up to produce this demand endogenously in POLES (or refine it, as was the case for steel), and was implemented in the model. Additionally, other model outputs related to energy were used within WP2 to assess the demand of other minerals (e.g. neodymium, gallium, lithium). This information provided views on the shifting dynamics in a world of fast developing economies, on the importance of new commodities markets linked to emerging technologies, and put in perspective European demand with that of other regions of the world.

## 18.2. Using POLES in POLINARES: Energy and scenarios

### 18.2.1. Overview: quantifying Future World Images

The four Future World Images (FWIs) were set up in POLINARES WP3 using a discourse on international relations, institutions, trade rules, the weight of the State, the importance of private ownership, and other topics with a qualitative description. The aim of the work in WP2 is to replicate these Images in a quantified way in the fields of energy and minerals in order to illustrate their implications.

The possibilities that could offer the modelling of the energy (and minerals) system in POLES were used to interpret and implement certain aspects of the FWIs in the modelling:

1. The qualitative statements from WP3 were converted into parameters in the scenario inputs for POLES, which would transform the model outputs. To that end, we chose appropriate topics and themes that could cover a wide range of issues on POLES and developed a conversion matrix between descriptive qualifications and quantitative factors.
2. The qualitative valuation of these factors (e.g. high; medium; low) is converted into quantified factors. The factors are multiplying (smaller or larger than one) or additive (positive or negative) and their values depend on the parameter and the region considered. They are applied to reference values for model variables and so correspond to a deviation from that reference. A qualitative description of the reference values was initially provided for indication and context.
3. The set of values for these factors was inserted in the model, and their values were fine-tuned based on their impact.

For each FWI, or POLES scenario, we created projections up to 2040 and extracted a set of indicators to describe the future supply and demand of energy. We identified countries or country groupings to which we applied appropriate values for each of the factors in the matrix. The groupings were:

- Europe: EU-27 plus periphery (Norway, Switzerland, Iceland, Balkans) and Turkey
- North America: USA and Canada
- Latin America: includes Mexico
- China
- India
- Rest of Asia: includes South and Southeast Asia
- OECD Pacific: Japan, Korea, Australia, New Zealand
- CIS: includes Russia
- Middle East & North Africa
- Rest of Africa: includes South Africa

This aggregation scheme covers the entire globe. If, in specific cases we needed additional finer distinctions in specific parameters, we introduced differences for sub-parts of the above, including:

- Russia
- Brazil
- Mexico
- South Africa
- Turkey
- Gulf (i.e. Saudi Arabia, Iran, Iraq, Kuwait, UAE)

The Future World Images have two principal dimensions: an economic axis (prevalence of market forces; prevalence of State forces); and a political axis (integration and globalization; competition and regionalization).

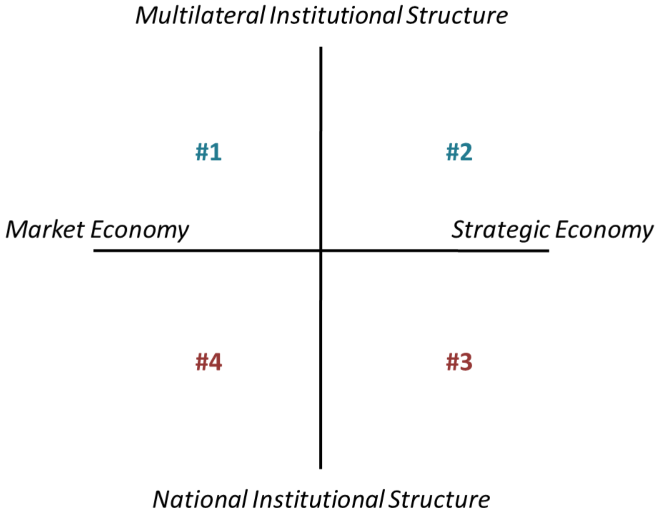


**Figure 1: Future World Images**

We identified six large groupings of issues in which to establish an interface between qualitative descriptions and quantitative parameters: macroeconomic drivers; resources (geological availability of energy); supply of fossil fuels (political availability of energy); investment climate (encompassing decision-making from both public and private actors); technological development; and climate-related issues.

Global development shares a common pathway in each of the four FWIs until approximately 2015. After that time, each Image begins to progressively diverge from the others. Between 2025 and 2040, the FWIs display distinct profiles and reflect the qualitative differences driving each scenario. Discussions of when to begin the divergence between FWIs gradually moved earlier (to 2015) to acknowledge the uncertain state of current world affairs and due to the nature of the POLES model, which is based on long-term averages and does not easily accommodate very rapid change.[1]

### 18.2.2. Macroeconomic drivers

Gross Domestic Product (GDP) and population are two essential drivers of energy demand. GDP per capita (i.e. average annual income) is an important driver of energy needs in the POLES model and a driver of structural changes in the economy of a region (industrialization and progressive shift to a service-based economy).

For population, a single data set was chosen for all four FWIs: the 2010 update of the United Nations Population Division scenario with a medium fertility rate.[2] The use of a single data set allows us to avoid issues such as the effect of education and income growth on fertility, which can be argued to have both positive and negative effects, and has the added benefit of comparability between scenarios.

For annual GDP growth, we took data from International Monetary Fund projections for the short-term (up to 2016).[3] For the longer term, we used Enerdata projections that assume a gradual convergence of GDP per capita growth (in constant 2005 USD, in purchasing power parity) towards a leader of total factor productivity (chosen here as the USA) and a gradual convergence of purchasing power across countries towards parity.[4]

[1] Historical observations indicate that many energy and infrastructure systems cannot be altered in structural ways at less than decadal timescales.
[2] World Population Prospects: the 2010 Revision, UNPD. http://esa.un.org/unpd/wpp/index.htm
[3] World Economic Outlook Database: the April 2011 Edition, IMF. http://www.imf.org/external/pubs/ft/weo/2011/01/weodata/index.aspx
[4] Both of these convergences take place over a long period and are fully realized beyond the time horizon of the modelling exercise done for POLINARES.

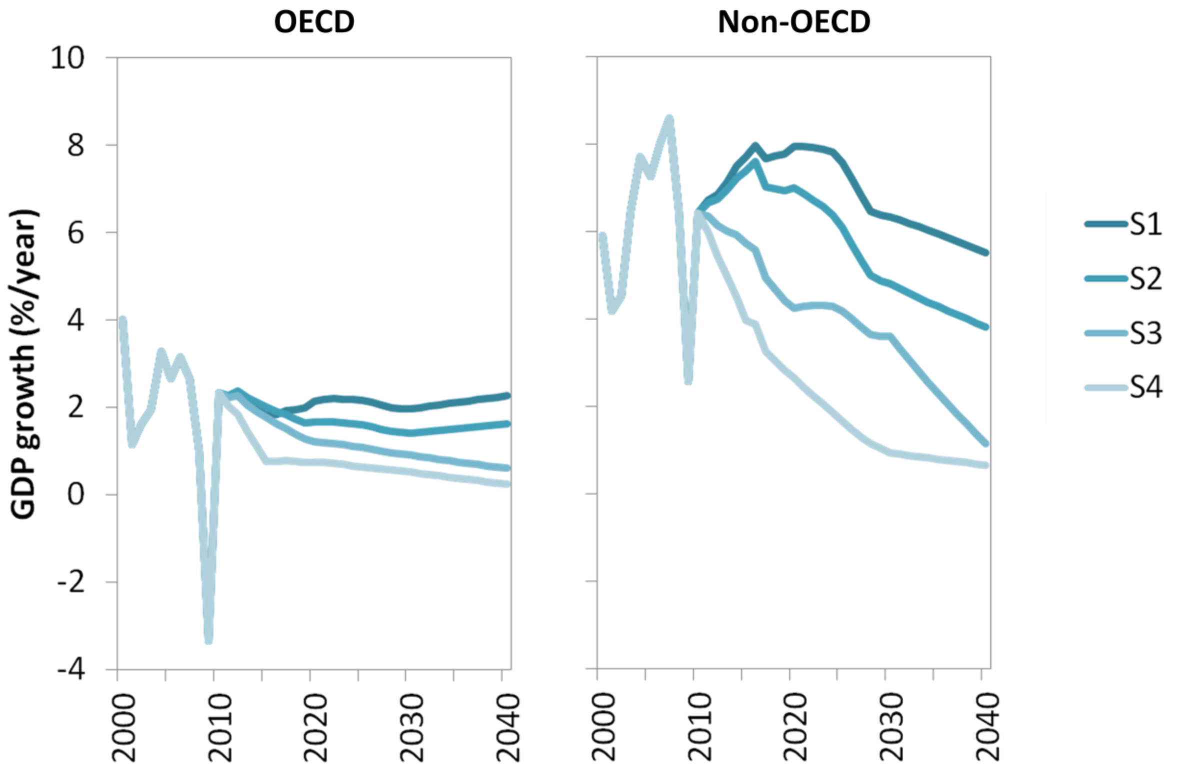


Figure 2: Average annual GDP growth in OECD and non-OECD across the 4 scenarios (%/year)

### 18.2.3. Resources

**Fossil fuels**

For purposes of inter-comparability, we chose to use the same data set of geologically present resources for oil and gas across scenarios. Differences in the oil and gas supply in the scenarios come from political and economic factors, and not from geologic factors. Thus, the nature of the scenarios is more suitable to describe issues of "peak-demand" for oil rather than "peak-supply".

The Ultimately Recoverable Resources (URR) per producing country or region for conventional resources were taken from annual BGR surveys, which correspond to middle- to high-end estimates compared to figures available elsewhere in the literature, taking into account future discoveries. [5] For non-conventional oil resources figures from national estimates were used. Currently in POLES, modelling of non-conventional oil resources includes Canada (tar sands), USA (shale oil), and Venezuela (extra-heavy oil).

Coal is considered to be a material whose supply will not be constrained by its resource base in the time frame of these scenarios. Costs of coal production can increase with a rise in production over time; however they are not related to the geologic availability of the material itself.

[5] Bundesanstalt für Geowissenschaften und Rohstoffe

**Uranium**

Similar to above, the same figure for uranium resources was used across scenarios. A figure of 23.5 Mt for world resources was chosen, as it corresponds to a middle estimate of resources, taking into account future discoveries.

**Biomass**

Estimates of the global potential for biomass depend greatly on assumptions on surface yield and land use. Expanding land surfaces for the purposes of growing energy crops can be limited by the perceived unacceptability of losing agricultural surfaces, as well as natural woodlands or grasslands. A central estimate totalling about 200 EJ/year of potential was used across all four scenarios.

### 18.2.4. Investment: power generation

To address issues of capital availability and differences between public and private investment preferences, discount rates for different types of technologies were examined.

Power generation technologies were grouped in three categories based on their capital intensity and technological maturity:

- **Nuclear and large hydro**: These are large capital-intensive technologies that have been associated, historically, with state participation in their financing via direct funding or indirectly via companies with a large State participation as their shareholders.
- **Fossil fuels-based generation** (oil, gas, coal): These are the least capital-intensive technologies and the technology group which is most mature. Efficiency and cost improvements are foreseen; however they are incremental rather than radical and smaller in scale compared to renewables. They can be associated with both State and private actors.
- **Renewables** (wind, solar, biomass, small hydro): These technologies have the highest potential for improvement and cost reduction in the future and are often associated with State subsidies for their support. Presently, they are capital-intensive (per unit of power installed); however the typical power plant size is smaller than for nuclear and large hydro, which makes them more accessible to independent private actors.

**Differentiated discount rates** between scenarios and technologies reflect the ease of access of actors to capital for investment in the power sector. In a scenario where the State is a strong actor in investments in the power sector, discount rates are lower on average (e.g. S2); in a scenario where market forces are left to manage investments, preference will turn to projects with a shorter return on investment and discount rates will be higher on average (e.g. S1).

Additionally, wealth and capital availability will influence the perception of risk and will impact discount rates: a scenario with low access to capital and geopolitical tensions will increase discount rates and make technologies such as nuclear nearly prohibitive (e.g. S4).

Conversely, geopolitical tensions with a strong State will act as a stimulus towards higher energy independence and will encourage a decrease of discount rates in chosen technologies (e.g. S3).

Thus, discount rates were also differentiated per region based on regional preferences for technologies and fuel resources. For example, States in resource-constrained regions such as Europe or OECD Pacific might choose to encourage (i.e. lower the discount rates in) renewables more than fossil fuel technologies.

### 18.2.5. Investment: technology and energy efficiency

The modelling includes assumptions on technological improvements and energy efficiency improvements across regions by default. Technology costs decrease, use of energy per unit of value added decreases, and the combined effect through all sectors is a convergence of energy intensity across world regions.

Several competing factors influence the way these assumptions were modified for the POLINARES scenarios.

- S1 & S2: A cooperative world encourages technological diffusion and provides a solid basis for technological R&D. Ease of access to capital by state or market players enables innovation.
- S1 & S4: Predominant market forces stimulate competition and innovation.
- S3: Energy security concerns push efficiency measures that decrease dependence to foreign energy sources.
- S3 & S4: Low access to capital constrains the ambitions for innovation. Instability and risk perception, political or economic, discourages technological diffusion.

The first two factors combine to make S1 a “high tech” world with high energy efficiency. Conversely, the last two factors combine to make S3 a world where technologies remain costlier but where energy efficiency is a policy priority. S2 and S4 then follow in the order of most to least efficient scenario.

The parameters that were changed include:

- **Power generation**: Investment costs for select technologies (nuclear and renewables). Also, drivers of technological improvements (elasticities) that accelerate cost decreases thanks to learning-by-searching and learning-by-doing (for all technologies).
- **Final demand sectors**: Annual improvements in energy efficiency, differentiated across sectors: industry, buildings, transport.

### 18.2.6. Fossil fuel supply

The availability and distribution of different types of fossil fuels are strong drivers of development over the next several decades. Due to the current global reliance on fossil fuels as the major form for energy supply, and the slow structural change which can occur in energy supply infrastructure, growth or decline in fossil fuel use will have significant impacts on the world energy and geopolitical systems. Modelling of fossil fuel supply included the fluidity of oil and gas markets, amount of investment in production capacities for different world regions, the strength of constraints on non-conventional oil development, and preferential trade of gas and coal resources.

More or less fluid markets will allow state or private actors differing access to oil and gas resources. While access to resources is generally not a problem during prosperous economic times, access might be limited for political reasons when spare economic capital is constrained. If the State plays a large role in determining resource allocations (S3), then the global oil and gas market fluidity is likely to be quite low as countries try to protect national endowments. If market forces are more prevalent (S4), then more open economies will benefit from what resource trade is available, while State-led countries will tend to be more isolated. Modelling of market fluidity was based on elasticities to oil and gas prices.

The Gulf region supplies the majority of world oil and gas resources, but its ability to continue doing so in the future will be constrained by the level of investment in production capacity. The necessary level of investment to maintain, or increase, Gulf oil and gas production may or may not be occurring currently, so there is reason to consider various scenarios. Modelling of Gulf investment in production capacity for POLINARES assumed that sufficient investment occurs in strong growth scenarios (S1 & S2), but that it will be constrained otherwise. In S3, Gulf investment allows capacity to increase somewhat to 2015, then it stalls and remains constant until 2025, and after declines for the rest of the model period. The situation is considered to be even more dire in S4, where investment is frozen at 2015 levels and production capacity falls steadily between 2015 and 2040.

A lower economic constraint (associated to environmental damage) was attributed to non-conventional oil resources when conventional oil production was reduced by falling Gulf capacity investment. This lower constraint on non-conventional oil development reflects societal and political choices to try to maintain world oil supply and offset rising fuel costs, by accepting the greater environmental damages that come with tar sands, extra-heavy oil, and shale oil development.

Depending on the level of State direction for gas development, we model preferential trade routes for particular regions. For example, in S2 when global economic growth is quite strong and driven by State-led economies, China will be a major resource consumer. To reflect its political and economic clout, China will have preferential gas trade from Russia over trade to Europe.

### 18.2.7. Climate change

Climate policies beyond the current implementation were not included as part of the FWIs. A global agreement, or significant multi-lateral agreements, on the reduction of GHG emissions were not considered likely to occur within the timeframe of the POLINARES study. Consequently, a global carbon price does not develop in any of the scenarios.

## *18.3. Using POLES in POLINARES: Minerals*

In the scope of POLINARES, POLES, while being primarily an energy model, was used to develop the demand side of some key materials derived from raw minerals. This was achieved in collaboration with other partners in WP2.

### 18.3.1. Overview: Methodology

The work conducted allows POLES outputs to be used in two ways to derive demand for materials:

- **Direct model outputs**: Demand is modelled endogenously in POLES. This approach is best suited for materials that are used in a variety of sectors, so as to make the best use of POLES' sectoral description of the economy and link key drivers to the demand of a material for that sector. This method is the sum of two approaches:
    - ***Bottom-up approach***: For the uses that can be linked to sectors explicitly modelled in POLES (road transport, construction, power sector)
    - ***Top-down approach***: For the more diffuse uses that cannot be linked to sectors explicitly modelled in POLES (for example mass market products, high tech IT, medical equipment, …)

  Certain base minerals were chosen for this approach, based on their importance in the overall economy: steel and copper.

- **Derived from model outputs**: Demand for a material or mineral can be calculated ex-post by using certain model outputs, which can be used as drivers for the demand of a material for a particular use. This approach is best suited for materials that are used in new and emerging technologies related to energy – technologies which are modelled in POLES. The market share in the total demand of these materials for these uses today is small but is expected to grow in the future. However, the demand for the other uses cannot be readily estimated with POLES outputs. Minerals that can be estimated with this method include minerals in wind turbines, in photovoltaic panels, in nuclear power plants, in hybrid and electric vehicles.

### 18.3.2. Bottom-up approach (sectoral demand)

This approach applies to minerals or materials demand in uses that can be linked to sectors explicitly modelled in POLES. Sectoral demands calculated independently are aggregated in a total demand.

The sectors where this was applied are the transport sector, the construction sector and the power sector.

The demand for each sector depends on:

- Act: an **activity indicator** that will determine the relative increase or decrease of demand compared to last year. This is an indicator that does not necessarily cover the entire sector but is representative of the sector and its evolution. For example, surfaces in residential for the construction sector.

- a **specific consumption indicator** that provides the changes in the ways the material is used in that sector over time. Specific consumption can decrease (via technological improvements, efficiency or substitution by another material for example) or it can increase (new uses, trade-offs between materials). For example steel use in new construction can decrease (a move towards more lumber and glass in construction) or can increase (a move towards more steel instead of concrete). When the sector at hand can be further split into sub-sectors, for example types of buildings, this specific consumption indicator can be further disaggregated into:
    - Coef std: a specific consumption indicator for a standard building (e.g. kg of steel per square meter of household surface)
    - Coef type: a ratio signifying the relative difference of material needed for a different type of building compared to the standard building (e.g. low energy consumption building)
    - Coef var: a variable providing the changes of the first indicator over time

Thus demand per sector follows a similar equation. For a sector i constituted of subsectors j for year t:

$$Cons_{i,t} = \sum_{j} Act_{j,t} \cdot Coef\ std_{t} \cdot Coef\ type_{j} \cdot Coef\ var_{j,t}$$

The following table shows the activity indicators that we chose for our modelling of steel and copper demand.

**Table 1: Sectors and drivers for materials demand, bottom-up approach**

| Sector | Driver | Steel | Copper |
|---|---|---|---|
| **Transport** | New sales of private cars, annually | X | X |
| **Construction** | Newly built and renovated surfaces in residential, annually | X | X |
| **Power sector** | New power capacities installed, annually | | X |

Private cars and new or renovated construction in the residential sector are good indicators for the entirety of the activity in the transport and construction sectors, respectively. Private cars can be split in sub-sectors of conventional ICE vehicles, plug-in hybrids and full electric vehicles. Surfaces in the residential sector can be split into newly built and renovated, and also in standard energy consumption, 'medium' energy consumption and 'low' energy consumption buildings. Newly installed power capacities require copper both in the machinery involved but also in the power lines connecting the capacities to the grid. Data was not sufficient to include a separate demand for steel in the power sector.

Since the perimeter of the drivers do not necessarily correspond to the whole of the sector (e.g. private cars do not cover the whole of transport), the specific consumption indicator might not necessarily correspond to useful figures (e.g. kg of copper per vehicle).

A survey of literature provided figures for the split of demand between sectors in recent historical years. Most of the data found was for OECD countries. In order to ensure a world coverage of the modelling, the split in all countries and regions was done by estimating the shares from neighbouring countries, from countries with a similar economic development, or by subtracting OECD figures from figures on the world to obtain figures for non-OECD. The lack of data, the insufficient disaggregation and the differences in the definitions of the sectors between countries is evident in the spread of the values obtained.

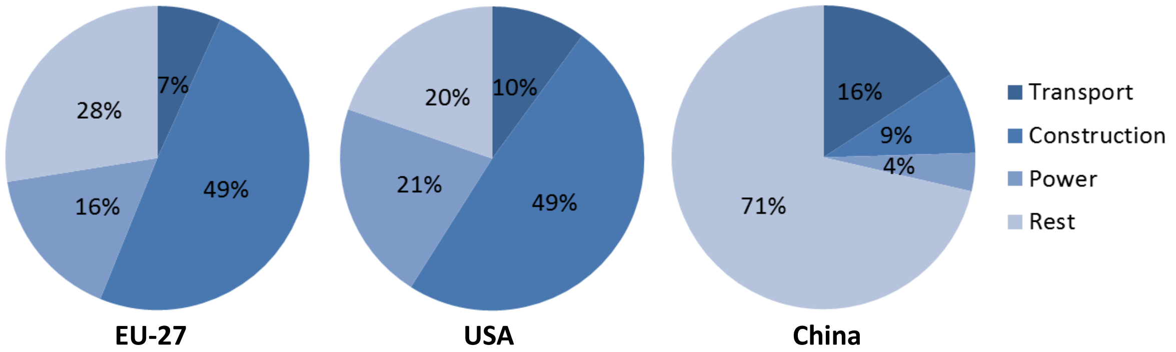


**Figure 3: Sectoral split of copper demand for EU-27, USA and China, 2003-2008 averages**

The sectoral split allowed to infer values for the specific consumption indicators in historical years (Coef std). Own assumptions were used for the other coefficients:

Coef type: Between sub-sectors (i.e. vehicle and building types):

- Steel: a single value was taken across all types.
- Copper: a single value was taken in buildings; for vehicles, a factor of 1.5 was taken for hybrids and 2 for electric vehicles.

Coef var: For the evolution of specific consumptions over time:

- Private cars: Over all vehicle types, an average of 0.5% less steel used per year; copper was kept constant.
- Surfaces: Constant for standard consumption buildings, an average of 1% less steel used per year for medium and low consumption buildings; copper was kept constant.
- Power: copper was kept constant.

Sources used were WP2 partners, international and national institutes or trade federations of the steel and copper industries, surveys and markets reports and industry reports. For steel: USGS, Eurofer, Japan Iron and Steel Federation, American Iron and Steel Institute, Shanghai Futures Exchange, South

African Iron and Steel Institute, CIRED (France), CSN (Brazil), MKM (Russia), Severstal (Russia). For copper: International Wrought Copper Council, International Copper Study Group, FEDEM (France).

Thus total sectoral demand of steel is the sum of the demand for transport and for construction; for copper it is the sum of all three sectors. To this demand we have to add a "residual" demand to obtain the total material demand of a country or region, for which a different method was used.

### 18.3.3. Top-down approach (intensity of use)

This approach applies to the uses of the minerals or materials that cannot be described by the methodology above, uses that cannot be easily linked to sectors explicitly modelled in POLES. For theses diffuse uses, the activity indicator that we have chosen is the richness of the country or region at hand: people and economies tend to consume more as they get richer.

Our modelling followed the concept of Intensity of Use, which has been discussed considerably in the literature, particularly in steel (Steel Intensity Curve: IISI, 1974[6]; Duisenberg, 1985[7]; Sadler, 2003[8]). The Intensity of Use curve relates material use in the economy (consumption per unit of GDP) with the level of economy development in that country (GDP per capita). It distinguishes several phases:

1. A very low level in a pre-industrialized economy
2. A rapid rise, associated with the development of industry and the installation of infrastructure
3. A levelling-off, that may be due to new demand coming from the replacement of antiquated infrastructure but not a growth of that infrastructure; this has been observed to take place in economies now well developed, e.g. in 1941 for steel in the USA (Labys, 2004[9])
4. A decline, associated to a shift towards a more services-based economy
5. A long-term stabilization; it is interesting to note that consumption does not reach zero, however a stable consumption per capita can eventually lead to a closed circular economy

This behaviour is modelled with the following equation:

$$\frac{Cons}{GDP} = \left(\frac{GDP}{Cap}\right)^{\alpha} \cdot exp\left(\beta \cdot \frac{GDP}{Cap}\right) + Floor$$

Where the α, β and Floor parameters have to be calibrated to fit an intensity of use behaviour (per country/region). The predominance of the terms is illustrated in the figure below.

[6] International Iron and Steel Institute (1974), *Steel Intensity and GNP Structure*. Brussels, Belgium.
[7] Duisenberg, H. (1985), "*Long-Term Forecasting Models for Steel Demand*", Communication, 12th International Conference if the Applied Econometric Association. Zaragoza, Spain.
[8] Sadler, A. (2003), *Demande Internationale de Produits Sidérurgiques, Croissance et Développement*, Ph.D. dissertation, Université de la Méditerranée. Marseille, France.
[9] Labys, W.C. (2004), *Dematerialization and Transmaterialization: What Have We Learned?*, Research Paper 2004-1, West Virginia University Regional Research Institute Research Paper Series. Morgantown, WV, USA.

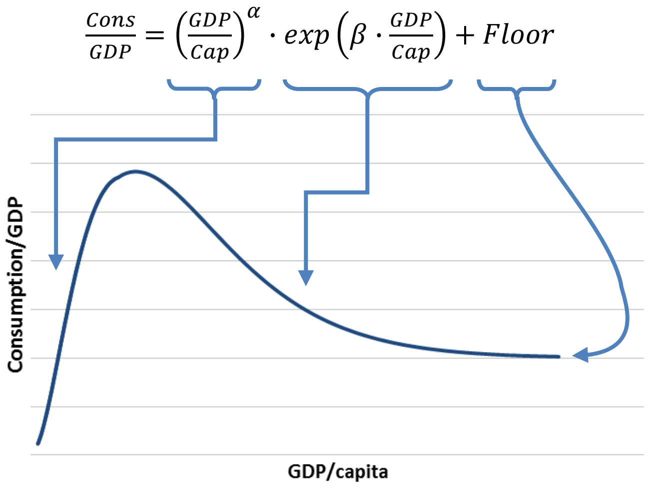


Figure 4: Schematic of the Intensity of Use concept

While this approach was developed for considering the entirety of material consumption in an economy, we applied it to only the “residual” part of consumption that is not described by the sectoral approach.

For each country/region, the different parameters were calibrated in order to recreate an Intensity of Use behaviour, taking into account historic behaviour in the past and the speed (in years) with which the transitions between phases would be reached in the future (using in-house GDP/capita development figures), and checking that figures of consumption per capita were also coherent. The work was conducted for steel and copper.

The application of this method showed a rather good fit in historical data and between OECD and non-OECD regions for both steel and copper, and made apparent such phenomena such as the collapse of the FSU in the 1990s or the rise of China and the Asian economies in the 2000s.

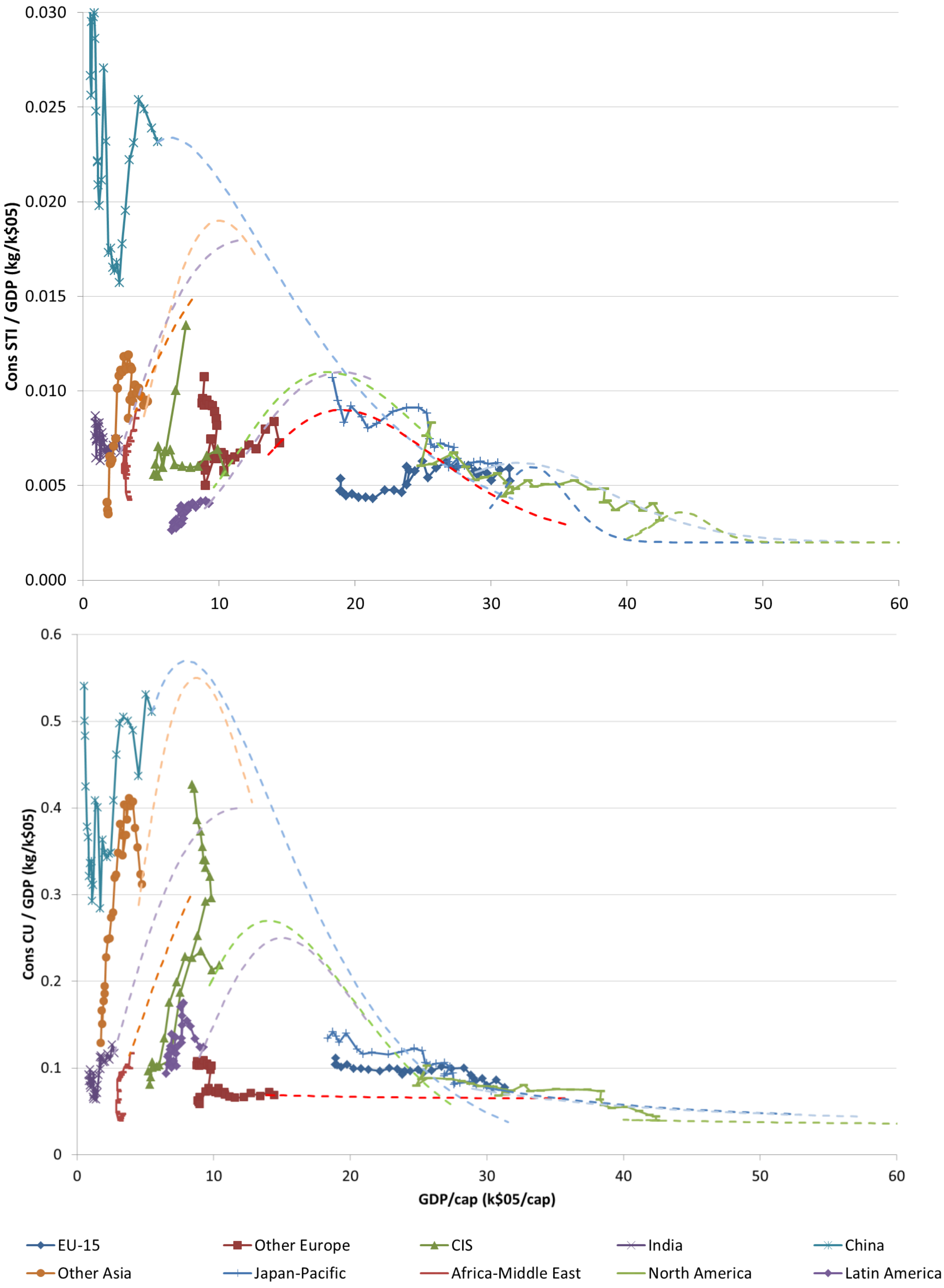


**Figure 5: Intensity of Use per world region for residual demand for steel and copper, historical and projection (1980-2050)**

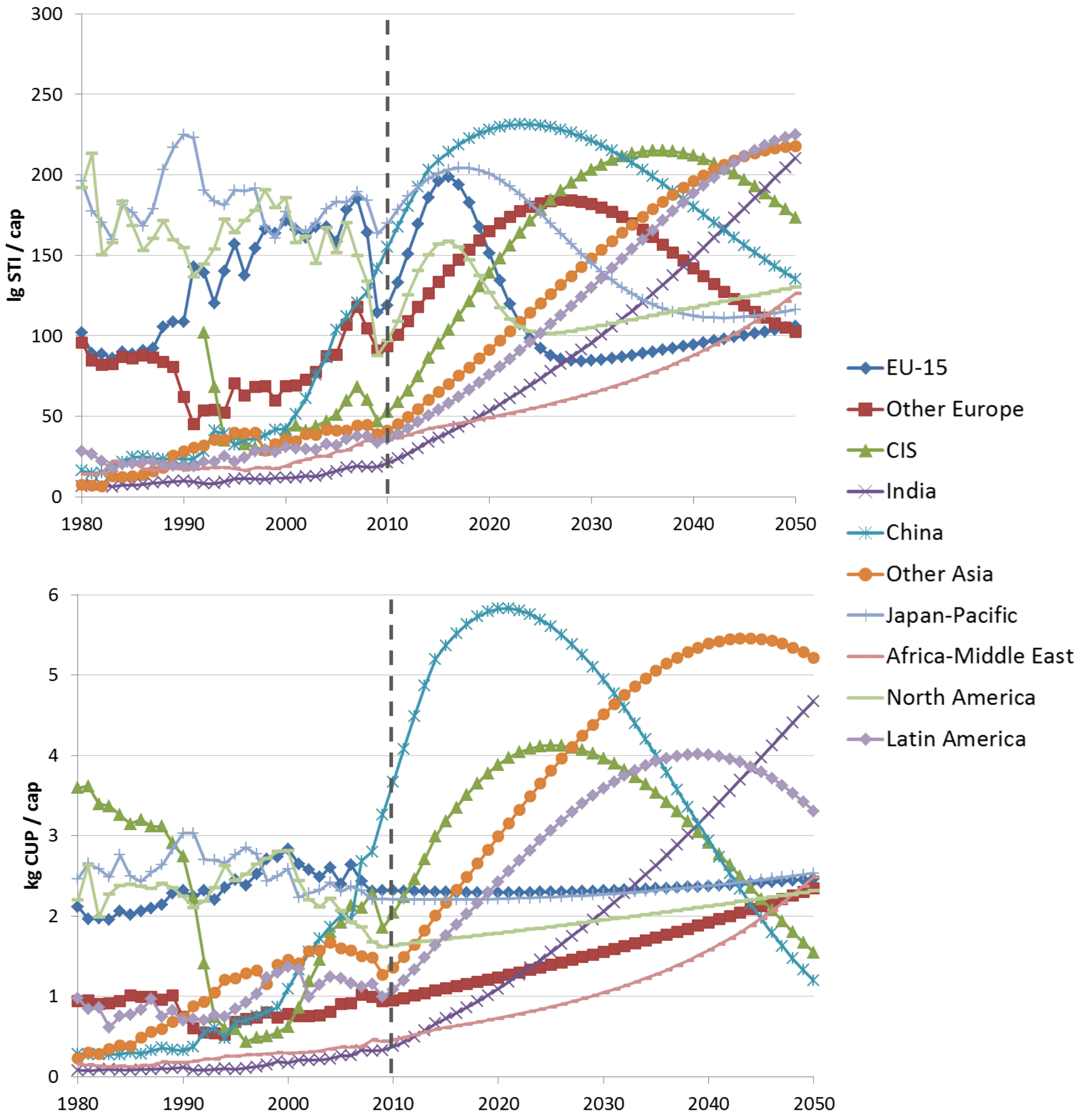


Figure 6: Steel and copper consumption per capita in residual uses, historical and projection (1980-2050)

The parameters thusly obtained were there used as input assumptions for the modelling of the Future World Images, using the GDP and population data of the FWIs. It is interesting to note that several world regions (India, Africa) do not reach a “peak-demand” within the time frame of the POLINARES study with the economic growth assumptions used here (close to FWI S1).

The “residual” demand is then added to the sectoral demands to obtain the total material demand of a country or region.

### 18.3.4. Indirect approach (derived from technologies)

This last approach uses the technological description of energy-related technologies readily available in POLES to provide information on demand for specific minerals, an approach particularly useful for new and emerging technologies.

The method is similar to the bottom-up approach described above, only that the conversion from the activity indicators to minerals demand is exogenous. Activity indicators in this case are annual newly installed or sold units of particular technologies (MW, or vehicles), which are model outputs; information on the present and future mineral content of these technologies can then be applied to infer demand for that mineral per country or region.

A list of so-called 'minerals-intensive' technologies is provided below.

**Table 2: List of POLES technologies useful for minerals demand**

| Technologies | Minerals |
|---|---|
| Nuclear fission | Zirconium |
| Photovoltaic panels | Indium, Tellurium, Gallium |
| Concentrated solar power | Silver |
| Wind turbines | Neodymium, Dysprosium |
| Plug-in hybrid and full electric vehicles | Lithium, Lanthanum, Cobalt, Neodymium, Dysprosium |

## 18.4. Main findings: Energy

The emphasis placed on energy throughout society will increase in the coming decades. Short of a bold move towards reducing GHG emissions that could be chosen for a variety of reasons, from the environment to energy security, total primary energy demand will expand with a growing share for fossil sources; fuel prices will rise significantly; and global trade of energy will dramatically alter those countries with secure sources of supply. To some degree, these changes will occur regardless of assumptions concerning the influence of markets and states on world economies, or whether we find ourselves in a more cooperative or conflict-prone society. However, energy intensity, trade flows, and GHG emissions vary a great deal between the explored scenarios of future circumstances.

### 18.4.1. Primary Energy and Energy Intensity

#### 18.4.1.1. *"Cooperative" scenarios (S1 & S2)*

Total demand for energy continues to grow at a steady yearly increase of 1-3% between 2010 and 2040 in both of the cooperation scenarios (S1 and S2), compared to an average of 2%/year over the last 20 years (1990-2010). Total demand is approximately 22 Gtoe by 2040 (compared to 12 Gtoe in 2010), and like the current situation, demand is still dominated by fossil sources (see Figure 7).

- **Fossil fuels**: The sum of oil, natural gas, and coal (primary fossil sources) increases in magnitude from 10 Gtoe in 2010, to 16 Gtoe (S1 & S2) by 2040. Despite this enormous boost in demand for fossil resources over the next three decades, the share of oil, gas, and coal in the primary energy mix falls somewhat from 80% to 72% (S1) or 75% (S2). Increased fossil demand is almost entirely due to additional gas and coal, which are each consumed at approximately twice the 2010 levels. The demand for oil does not undergo such a large increase though. The 36% (S1) and 28% (S2) increases in oil demand follow a similar pattern to the additional oil used in the transportation sector, where it may be difficult to reduce demand and larger structural change is needed to decrease fossil fuel use over the long term.

- **Nuclear**: Nuclear power experiences a strong increase in energy consumed over the study period (although quite modest compared to the increases in other energy forms). Between 2010 and 2040, nuclear increases by 1.0 Gtoe and 0.6 Gtoe in S1 and S2, respectively. Strong GDP growth in both of the cooperative scenarios, and an investment atmosphere conducive to lending large sums of capital provide the main drivers for expansion of nuclear power. Given that a carbon price does not exist in these scenarios and nuclear is a very capital intensive technology, increases of 140% (S1) and 85% (S2) are considerable.

- **Renewables**: Renewable energy sources, including biomass, hydropower, wind, solar, and geothermal provide an increasing share of the primary energy mix. In 2010, renewables provided approximately 14% of the total energy demand and increase to

20% (S1) and 19% (S2) by 2040. Expansion of the renewables sector represents an increase of approximately 2.5 times in energy production; primary energy from renewables by 2040 is 4.5 Gtoe (S1) and 4.2 Gtoe (S2), respectively.

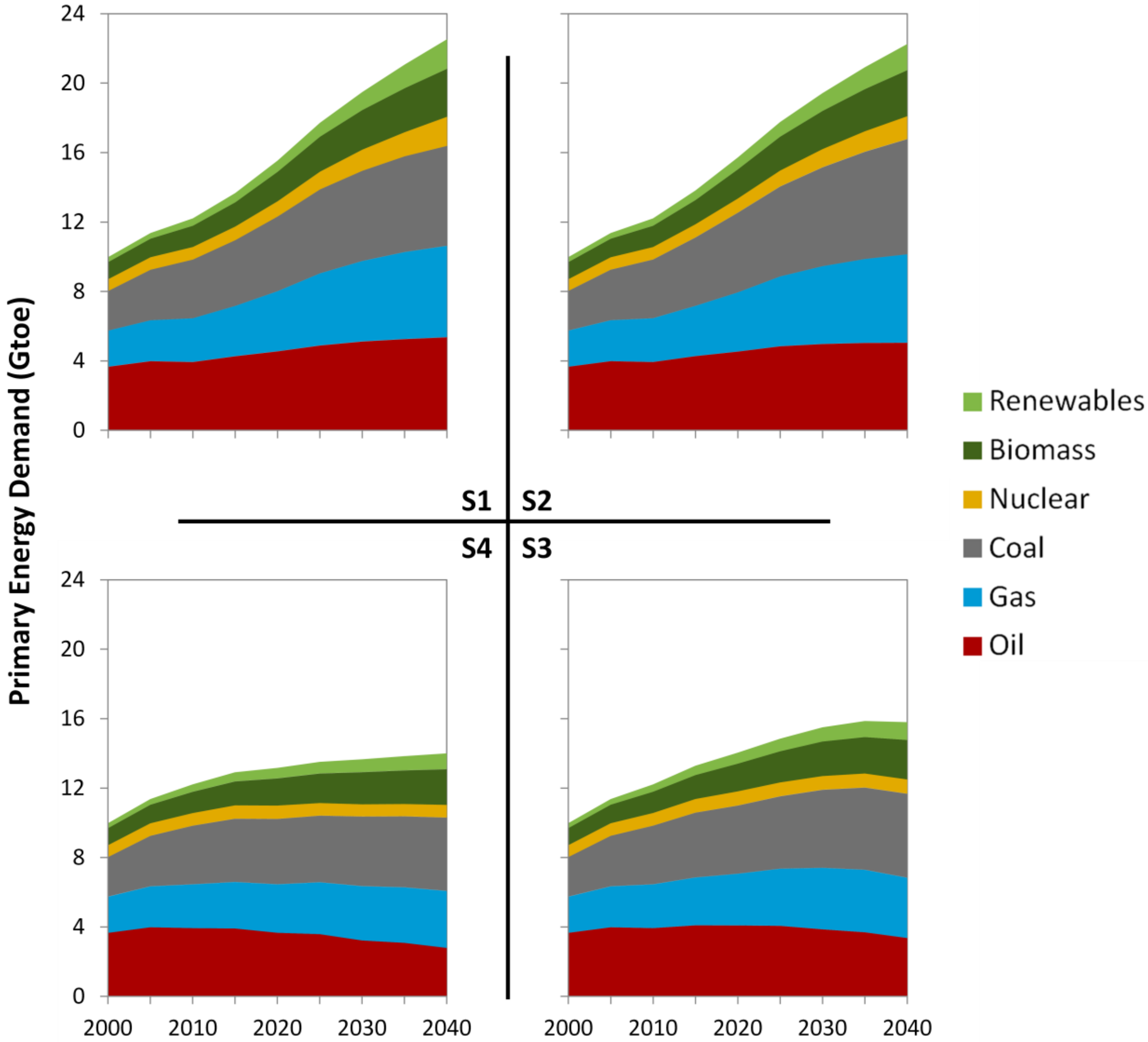


Figure 7: Primary Energy Demand

### 18.4.1.2. *"Conflictual" scenarios (S3 & S4)*

The two conflict scenarios present more variation between market and state-led economies, but both scenarios follow a similar pattern of reduced consumption in all energy forms. The lower growth (S3) or stalling economy (S4) assumptions have a very strong influence on total consumption.

In S3, total demand only increases to 16 Gtoe by 2040 and appears to reach a plateau by 2035. This flattening of total energy demand roughly corresponds to the peak in combined demand for oil, gas, and coal, which is mostly due in this scenario to reduced production of oil and gas from key supplier regions sensible to conflict, such as the Middle East and North Africa. Total primary energy demand growth averages 1-2% between 2010 and 2030, but falls to 0-1% growth for the following decade (2030-2040).

The lowest economic growth situation, S4, has very little increase (and even has reductions) in each of the primary energy sources, as well as for overall energy demand. Between 2020 and 2040, total energy demand grows by an average of only 0.5% per year. Over this same period, gas and coal each increase yearly by 0.9% and 0.5%, respectively, while oil decreases at a similar rate of 1% per year.

- **Fossil fuels**: Demand for natural gas and coal each rise by approximately 40% between 2010 and 2040 in S3, and by 32% and 24%, respectively, in S4; these two sources sustain the observed growth of fossil fuels to 2035. Primary oil demand sees somewhat more modest gains of 30% (S3) and 15% (S4) over this period. Fossil fuels still make up three-quarters of total primary demand by the end of the study period, however, their share has continued to decline since 2010. Despite great differences in the volumes involved, the total share of fossil fuels in the conflict scenarios is within the same range as in the cooperation scenarios.

- **Nuclear**: Total consumption of nuclear power stays roughly constant around 0.8 Gtoe (S3) and 0.7 Gtoe (S4), with new production only replacing that from retired plants. This is due to low cash flow availability in these scenarios, which limits the role of such capital-intensive options. As a share of total primary energy demand, nuclear does not vary much, remaining between 5-6%.

- **Renewables**: As in the cooperation scenarios, renewable energy sources experience substantial growth over the next three decades. The unavailability of cheap oil and gas from conflict-prone regions, volatile international oil price, and energy security concerns provide strong drivers for this growth in OECD countries. While the total energy demand does not increase much because of the difficult economic conditions, renewables make up an increasing share of total energy, reaching 21% (S3 and S4) of primary energy by 2040, a share only slightly higher than in the cooperation scenarios. Development of wind and solar production drives much of the growth in the renewables sector, but biofuel consumption also experiences tremendous gains, going from 0.06 Gtoe in 2010, to 0.4 Gtoe (S3) and 0.3 Gtoe (S4) by 2040.

#### 18.4.1.3. *Energy Intensity*

The energy consumed per unit of GDP produced in the economy is reported as the energy intensity of a region or sector. As economic growth is slower across the scenarios from S1 to S4, fewer and fewer resources are available to invest in research and development of more energy-efficient technologies. This leaves only energy prices to drive the majority of energy intensity reductions. However, since energy prices are generally lower in the scenarios with lower consumption, at the world level energy intensity increases from S1 to S4 (see Figure 8).

In 2010, approximately 180 toe were consumed per million dollars ($2005ppp) of GDP. By 2040, the level of world energy intensity falls in each of the scenarios:

**Table 3: Energy intensity - global average and annual evolution (toe/M$05ppp)**

| toe/M$05 | 1980 | 2010 | 2040 | *1980-2010* | *2010-2040* |
|---|---|---|---|---|---|
| **S1** | 269 | 180 | 93 | *-1.3%* | *-2.3%* |
| **S2** | | | 112 | | *-1.6%* |
| **S3** | | | 119 | | *-1.4%* |
| **S4** | | | 144 | | *-0.7%* |

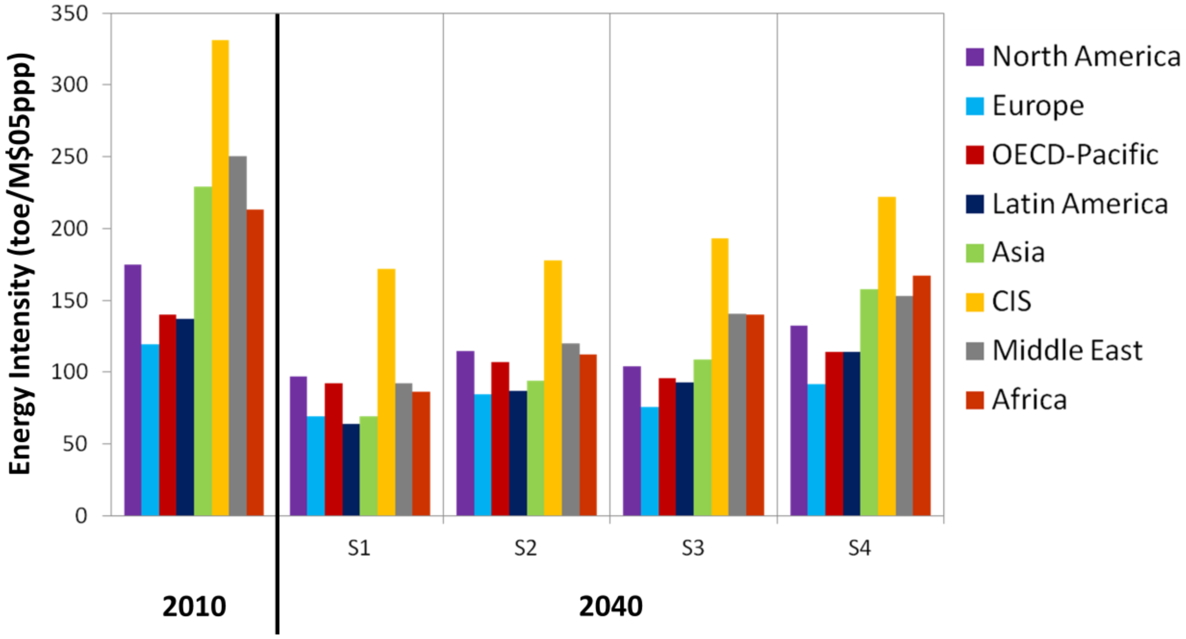


**Figure 8: Energy Intensity**

Non-OECD countries (Latin America, developing Asia, CIS, Middle East, and Africa) follow the global pattern well. When economic resources are easily available (S1 and S2) and energy prices are higher because of increased consumption, energy efficiency is also higher. Reduced economic growth and lower prices (S3 and S4) result in less energy efficiency. Physical resource constraints do not have a large effect in non-OECD regions because they tend to be resource abundant areas and are often suppliers of energy goods. While Asia is largely a consuming region given its rapidly growing demand, it is still endowed with significant resources; examples like coal, which is abundant, have large potentials for energy efficiency improvement.

In OECD countries, a similar pattern from lowest (S1) to highest (S4) energy intensity is evident, as in non-OECD countries. For the most part, these countries do not have as much easily exploitable energy resources and have a higher dependence on imports from volatile regions, where sudden political or social shifts may halt supply (e.g. the Libyan revolution recently interrupted the supply of 1.1 mb/d of oil to the European market). Thus, in the state-led and conflict-prone scenario, S3, energy security concerns come to dominate OECD energy efficiency developments, and result in an energy intensity lower than in S2 where conflict is less apparent. Energy intensity in the other conflict scenario, S4, is also reduced from what it would otherwise have been, but the disorderly nature of market forces and the low energy prices in this scenario prevent significant improvements.

### 18.4.2. Fuel prices and demand response

#### 18.4.2.1. *International fuel prices*

Over time, non-renewable energy prices are likely to climb as we exploit the resource base and additional discoveries become more and more costly to extract. During the overall upward trend, price will fluctuate as a result of supply and demand dynamics within the market. Changes can be relatively smooth or show considerable variation if scarcity develops, either through higher than expected consumption or insufficient supply. While the prices shown here reflect expected annual averages, within a year we can expect considerable variability; potentially increasing in conflict-prone or outright conflictual cases with exacerbated market tensions.

Scenarios S1 and S2 display smoothly increasing prices for oil (Figure 9) and gas (European market price shown in Figure 10). A stable rise in price reflects a sufficient supply of resources to meet the energy demands of the economy. The costs of extraction, transportation, and production may be increasing, which directly impact the price level, but crises are less likely to develop in a cooperative world. Smooth transitions between supplying regions (e.g. from the Middle East to North America) and resource types (e.g. from conventional to unconventional oil) help to mitigate shortages.

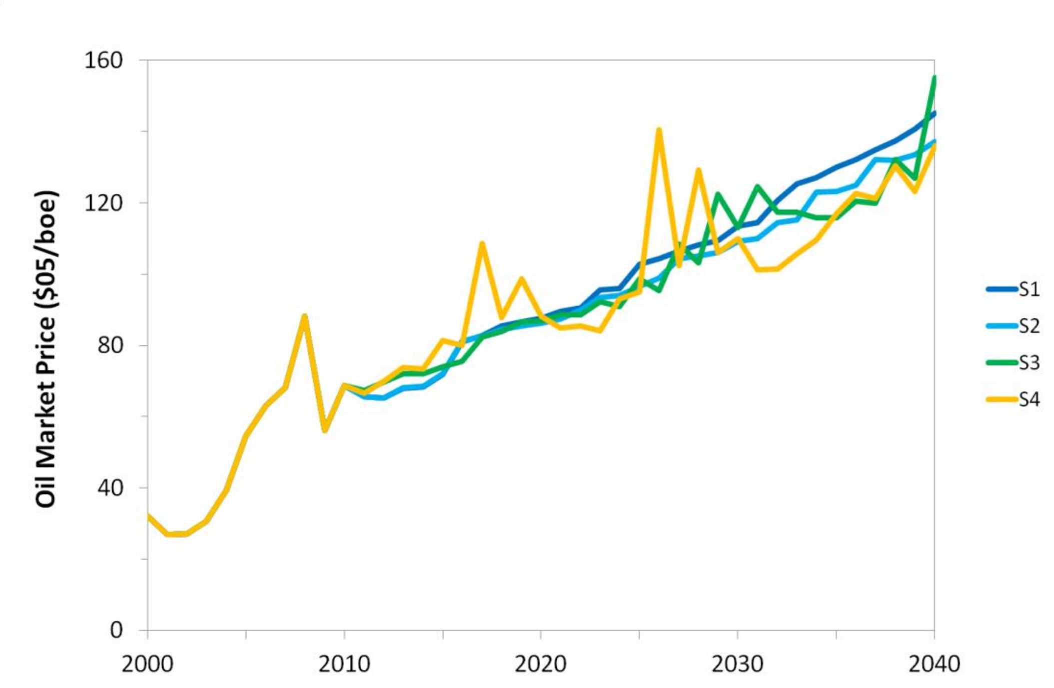


Figure 9: International Oil Market Price

While all of the scenarios display a similar degree of average price increase, when the ability of supplying regions to consistently provide adequate quantities of oil and gas is constrained market prices become volatile. Scenarios S3 and S4 reflect the inability of conflict-prone regions, such as countries in the Persian Gulf or North Africa, to provide the same share of oil, and to a lesser extent natural gas, in the future compared to today. In 2010, the Gulf region provided approximately 29% of the world's oil. In the cooperative scenarios, where the Gulf region is stable and investment in production capacity continues as world oil demand evolves (reaching over 100 mb/d by 2040), the share of oil provided by the Gulf alone will be over 45% (45-50 mb/d), while that of OPEC reaches approximately 57% (58-63 mb/d). With this level of market share, if OPEC and the Gulf states are able to maintain cohesion, they are likely to retain significant influence over the world oil price.

But, if between 2010 and 2040 the Gulf cannot boost its production level of low cost oil, its share of world production does not grow quickly, as in S3 (33% of world production, 21 mb/d, by 2040), or if its share even declines, as in S4 (21%, 12 mb/d, by 2040), shortages in global supply occur and price volatility develops as a result.

Price spikes are more apparent in the market for oil than those for gas. This is mainly because oil supply is dominated by just a few large providers, and oil is considered to trade on a global market where the actions of one actor impact all others regardless of geographic distance. Less volatility exists for gas prices than oil price in the conflict scenarios since there are more regions supplying natural gas, many of which are perceived to be more stable producers in the coming decades. Additionally, a large part of gas trade tends to be dominated by long-term fixed-price contracts rather than spot prices as in oil trade, which dampens the ability for volatility to develop. Finally, oil and gas uses are increasingly diverging with oil largely being limited to mobile uses, whereas gas tends to dominate stationary uses (such as power generation and industry). This reduces the interchangeability of the two fuels, and therefore the correlation between the two prices, and gas is less impacted by the dramatic fluctuations of oil prices.

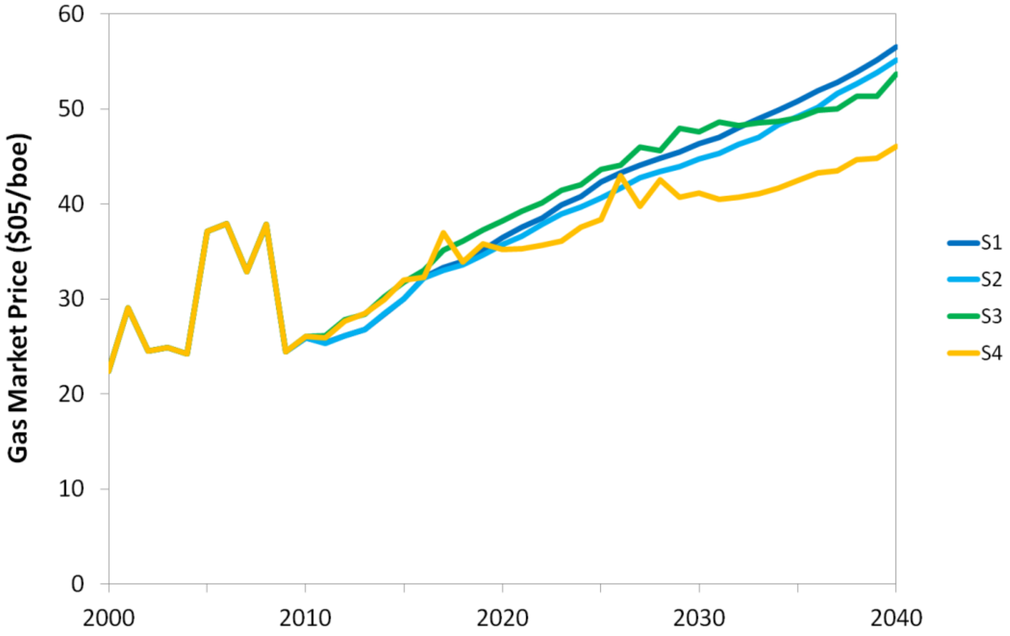


Figure 10: European Gas Market Price

### 18.4.2.2. *Final demand sectors*

Consumption follows broadly similar patterns across the different scenarios. Final energy use increases for most regions in the cooperative, high economic growth scenarios, S1 and S2. Final demand stays flat or falls in the conflict, resource-limited scenarios, S3 and S4. Below, a deeper look at several regions in the scenarios highlights these trends.

Results from North America in a very high economic growth scenario, S1, demonstrate how the OECD generally becomes increasingly efficient, even as development is strong and GDP increases. This trend is evident for North America (and the broader OECD) for each scenario except S4, where total North American consumption stays remarkably constant until 2040. Industry final demand shows the most variation across scenarios. For most, industry consumption falls by 0-3.5%/year for oil, gas, and electricity use. Coal consumption rises in all scenarios as an inexpensive alternative to other energy forms (given that no price is placed on carbon emissions). For North America, coal offers an abundant domestic energy source which overtakes all other energy carriers, except gas, by 2040 in S1. Depending on air quality regulations, this switch could adversely affect urban residents' health.

Other significant trends include the switch in the residential and agricultural sectors from gas heating to electricity; and the general efficiency improvement for transport. Overall consumption increases in buildings and agriculture across most scenarios; except in S3, where demand for unconventional North American oil diverts supply away from domestic residential uses and overall final demand decreases over time as a result. Electrification of heating in buildings occurs to some extent in each scenario, to the detriment of gas. The transport sector follows a very similar trend in each scenario, with small consumption improvements to 2020 and then rapid decrease in final demand to 2040. Most of the reductions occur in private road transport, while rail and freight consumption varies depending on the particular scenario.

**Table 4: Final Consumption – North America (S1)**

| North America – S1 | | | | | |
|---|---|---|---|---|---|
| | | | | Annual % change | |
| Mtoe/year | 2009 | 2020 | 2040 | 2009-2020 | 2020-2040 |
| **Total final consumption** | **1649** | **1668** | **1535** | **0.1%** | **-0.4%** |
| **Industry** | **457** | **457** | **416** | **0.0%** | **-0.5%** |
| *Oil* | *162* | *128* | *75* | *-2.1%* | *-2.6%* |
| *of which, non-energy uses* | *134* | *110* | *64* | *-1.8%* | *-2.7%* |
| *Gas* | *137* | *149* | *120* | *0.8%* | *-1.1%* |
| *Coal* | *30* | *42* | *87* | *3.1%* | *3.7%* |
| *Electricity* | *84* | *83* | *73* | *-0.1%* | *-0.6%* |
| **Buildings & Agriculture** | **562** | **594** | **620** | **0.5%** | **0.2%** |
| *Gas* | *208* | *200* | *140* | *-0.4%* | *-1.8%* |
| *Electricity* | *271* | *293* | *339* | *0.7%* | *0.7%* |
| **Transport** | **630** | **618** | **499** | **-0.2%** | **-1.1%** |
| *Private road* | *381* | *346* | *216* | *-0.9%* | *-2.3%* |
| *Air* | *57* | *52* | *46* | *-0.8%* | *-0.6%* |

China exemplifies the strong growth of state-led economies in S2. To achieve such a high level of GDP total final consumption more than doubles between 2009 and 2040, with particularly strong growth until 2020. Final demand in industry, residential and agriculture, and transport increases to fuel the growth boom. In industry, the massive escalation of gas and electricity demand offsets the peak and decline of oil and coal consumption. An even more pronounced upward trend for gas and electricity consumption is evident in the residential and agricultural sectors. Since both natural gas and electricity are network technologies, this level of increased consumption will need to be accompanied by a massive expansion of the distribution infrastructure.

Private road transportation will drive most of the additional demand in the transport sector, especially between 2009 and 2020 with annual growth rates of 14%. Because most of the demand increase is due to the proliferation of personal vehicles as Chinese GDP per capita rises, oil will be required for nearly all of the additional fuel demand.

Table 5: Final Consumption – China (S2)

| China – S2 | | | | | |
|---|---|---|---|---|---|
| | | | | Annual % change | |
| Mtoe/year | 2009 | 2020 | 2040 | 2009-2020 | 2020-2040 |
| **Total final consumption** | **1572** | **2599** | **3862** | **4.7%** | **2.0%** |
| **Industry** | **930** | **1470** | **1807** | **4.2%** | **1.0%** |
| *Oil* | *125* | *169* | *131* | *2.8%* | *-1.3%* |
| *of which, non-energy uses* | *74* | *103* | *80* | *3.1%* | *-1.3%* |
| *Gas* | *29* | *62* | *175* | *7.2%* | *5.3%* |
| *Coal* | *566* | *765* | *698* | *2.8%* | *-0.5%* |
| *Electricity* | *173* | *408* | *659* | *8.1%* | *2.4%* |
| **Buildings & Agriculture** | **485** | **733** | **1390** | **3.8%** | **3.3%** |
| *Gas* | *26* | *106* | *402* | *13.6%* | *6.9%* |
| *Electricity* | *84* | *181* | *410* | *7.2%* | *4.2%* |
| **Transport** | **157** | **396** | **665** | **8.8%** | **2.6%** |
| *Private road* | *44* | *188* | *257* | *14.1%* | *1.6%* |
| *Air* | *11* | *25* | *63* | *7.7%* | *4.7%* |

Energy security plays the largest role in S3, where more pronounced global conflict and state-led economies create the conditions to reduce dependence on foreign energy sources. Europe pursues energy efficiency measures in most sectors under high growth, cooperative scenarios, but demand reductions are even larger in S3. Given Europe's lack of major fossil resources and relatively substantial demand, energy consumption reduction is an important element of energy security policy.

The EU industry pursues steady reductions in consumption of all fuels, except for coal which is not prone to rapid price increases or volatility, making it less of an energy security concern. The residential and agricultural sectors consume less overall, but achieve this through a switch away from gas and increased electricity use. Again, this follows from an EU energy security policy to use more domestic sources, in this case more electricity from nuclear and renewables.

**Table 6: Final Consumption – Europe (S3)**

| EU-27 – S3 | | | | | |
|---|---|---|---|---|---|
| | | | | Annual % change | |
| Mtoe/year | 2009 | 2020 | 2040 | 2009-2020 | 2020-2040 |
| **Total final consumption** | **1171** | **1105** | **914** | **-0.5%** | **-0.9%** |
| **Industry** | **388** | **348** | **267** | **-1.0%** | **-1.3%** |
| *Oil* | *128* | *96* | *48* | *-2.6%* | *-3.4%* |
| *of which, non-energy uses* | *91* | *71* | *35* | *-2.2%* | *-3.5%* |
| *Gas* | *94* | *83* | *54* | *-1.1%* | *-2.1%* |
| *Coal* | *40* | *45* | *50* | *1.1%* | *0.5%* |
| *Electricity* | *89* | *86* | *72* | *-0.3%* | *-0.9%* |
| **Buildings & Agriculture** | **462** | **445** | **395** | **-0.3%** | **-0.6%** |
| *Gas* | *165* | *141* | *85* | *-1.4%* | *-2.5%* |
| *Electricity* | *138* | *144* | *148* | *0.4%* | *0.1%* |
| **Transport** | **320** | **312** | **252** | **-0.2%** | **-1.1%** |
| *Private road* | *158* | *151* | *105* | *-0.4%* | *-1.8%* |
| *Air* | *8* | *7* | *5* | *-1.2%* | *-1.7%* |

#### 18.4.2.3. *Power generation sector*

The electricity generation sector is especially sensitive to changes in input fuel prices. New generation capacity is added based on national preferences (e.g. coal in China, or feed-in-tariffs that increase competitiveness of renewables in Europe), but also in response to the outlook for different fuel costs. Higher prices for oil and gas precipitate a faster transition to other sources of electricity generation, namely nuclear, renewables, and coal (see Figure 11).

In 2010, OECD and non-OECD countries each generate approximately 10 000 TWh of electricity. Both regions increase their power generation between 2010 and 2040; the OECD expands by 15% (to 12 000 TWh), while the non-OECD generates substantially more, adding 75% (to 18 000 TWh).

In the absence of any efforts to curb emissions or reflect externalities linked to carbon content with the price of fuels, the coal price remains lower and more stable than those of other fuels. This makes coal a cheap and scalable source of power, and a preferred fuel in both emerging and developed economies. The coal share in power generation remains fairly stable across all of the scenarios, with 40-45% in non-OECD countries and 35% in the OECD.

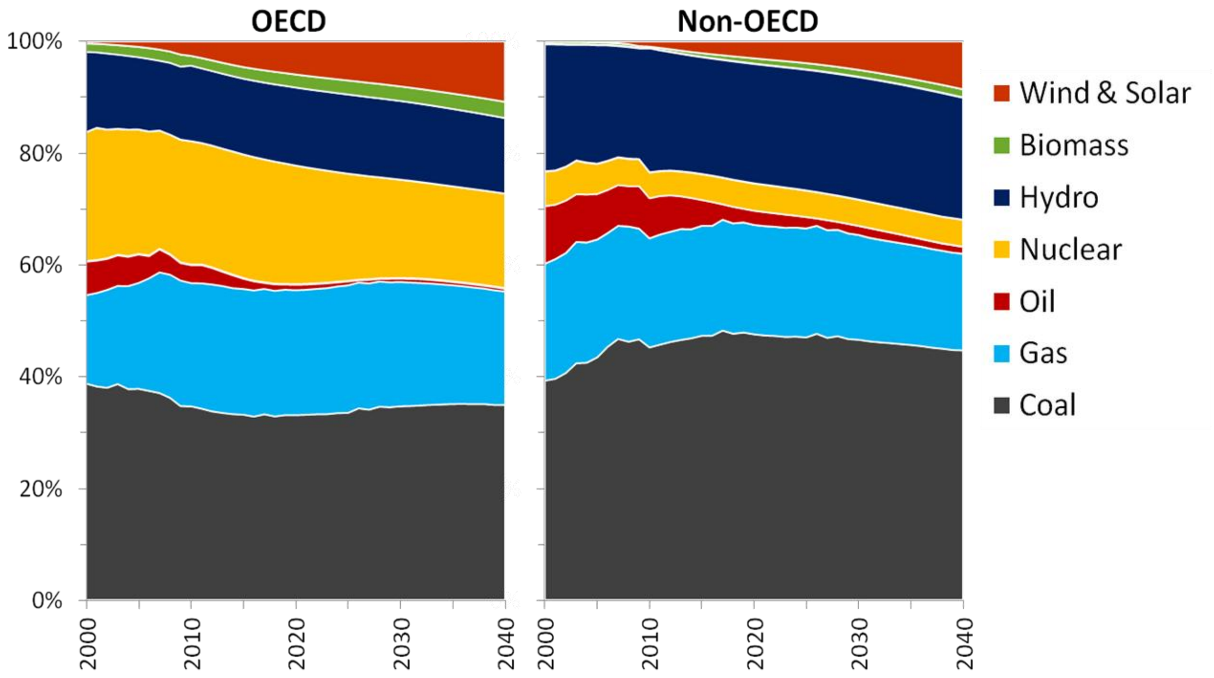


Figure 11: Input Fuel Shares for Electricity Generation: OECD & Non-OECD (S4)

### 18.4.3. Energy trade flows: Oil and Gas

#### 18.4.3.1. *Volumes of trade*

Oil products and natural gas are currently traded around the globe in international and regional markets with very large amounts of capital transferred between regions for energy goods. In an economically prospering world, in 2040, the Middle East and CIS can expect to be earning at least $3 trillion/year in combined revenues from the export of oil and gas. This is a considerable increase compared to the combined $0.6 trillion/year earned recently (2005), due both to an increase in traded volumes and an increase in the prices of these commodities.

Conversely, major importing areas, notably China, India, and other modernising Asian countries, will be required to pay almost the same costs to import energy in support of their development (Figure 12). Scenarios of slower or stagnant economic growth (S3 and S4) indicate much reduced oil export revenues for the Middle East and CIS. Their combined revenue will fall to $1.5 trillion and $1.2 trillion, respectively, representing an opportunity loss of revenue of 50-60%, compared to a cooperative scenario such as S1. Almost all of the reduction in revenue will be at the expense of the Middle East, which suffers if political stability cannot be maintained in the region.

#### 18.4.3.2. *Expenditure & revenue as a share of GDP*

Oil import costs and export revenues appear very different when considered as a percentage of GDP (see Figure 13).

For Europe, OECD Pacific, and Asia oil import cost shares remain remarkably stable over time and across scenarios. Each region spends approximately 2% of GDP on importing oil between 2010 and 2040. This is within the values observed historically for OECD economies, although it represents an increase for Asian economies compared to past decades. For Asia in particular, a stable share of oil expenditures observed beyond this decade exists only because the sharp increase in oil imports tracks with the rapid growth of the overall economy.

In North America and Latin America, depending on the scenario, each area is either an importer or exporter with associated costs or revenues; however, monetary flows do not exceed 1.5% of GDP either way.

For the main oil exporting regions there is much more variation of the weight of export revenues in their economies. The CIS manages to maintain a fairly stable share of around 7-9% of GDP, except in S4 where it becomes increasingly reliant on income from oil exports (13% of GDP by 2040). For Africa, despite maintaining relatively stable export revenues over time in all scenarios, the share of GDP falls from 6% in 2010 to 0-2% by 2040. Finally, the Middle East relies less over time on oil exports in most scenarios, but they still provide a sizable portion of GDP. Export revenues fall from 18% of GDP in 2010 to between 10-14% by 2040, except in S2, where income from oil exports actually grows to provide 22% of GDP. Strong oil demand in China and India drives most of the S2 expansion; these countries are considered to prosper more in a state-led world. These GDP shares compare well with historical values observed in recent decades (e.g. Middle East oil export revenues accounted for an average 16% of GDP over 1990-2010), and in some cases even increases despite the considerable economic growth of these regions.

#### 18.4.3.3. *Drivers of growth and geopolitical consequences*

**Oil**

Total world trade of crude oil and oil products amounted to 1.6 Gtoe in 2010 (1.7 Gtoe in 2005). As oil prices rise and demand experiences strong growth in the cooperative scenarios, S1 and S2, international trade of oil will climb to 3.0 Gtoe and 2.7 Gtoe, respectively, by 2040. Almost all of the expansion in imports will occur in developing countries in Asia. For the cooperative scenarios especially, economic growth rates in China and India remain at very high levels. Neither of these countries has large oil or gas reserves and must import the majority of their needs. Massive expansions of personal vehicle fleets will drive much of the increase in oil imports. Even in the conflict scenarios, personal vehicle use will grow strongly and drive an expansion of Asian oil imports by 2 (S3) to 1.5 (S4) times.

**Gas**

Gas trade follows a similar pattern to that of oil: the CIS and the Middle East send the majority of exported gas via pipeline and LNG tanker to developing Asian countries, for consumption in the power generation and residential sectors. Electrification of many expanding cities will create a very strong demand for natural gas. While Russia and the rest of the CIS do not match the Middle East for revenue earned from gas exports, their share of this market is much greater than for oil. This is partly a result of significant gas resources in the CIS, but is also due to the geographic proximity of the region to both Europe and China. Expansion of the existing pipeline network will provide a certain level of 'locked-in' trade between these regions. Much of the expansion of Middle East gas exports will necessarily be LNG trade.

**Regional blocs**

**North America**: In all of the scenarios, North America will continue to develop its unconventional resources and eventually become self-sufficient in terms of oil and gas consumption (with the exception of S4, where the Americas gas market price remains too low to induce sufficient production capacity expansion to avoid the need to import gas). A North American 'energy island' is driven by two associated factors: high global consumption and energy security. These factors are covered in detail in the following section, however each appears to result in the increased development of unconventional oil resources (i.e. Canadian oil sands and U.S. shale oil)[10]. As global oil price and consumption rise, continued investment in unconventional oil production will occur. This will happen from an economic investment standpoint, but could also be driven by concerns for the security of energy supply. For example, the U.S., which currently imports 1.3 Mtoe/day, has made obtaining stable sources of oil supplies a strong policy objective.

[10] Unconventional gas resources do not yet exist in the POLES model, but they are likely to contribute further to North America's energy self-sufficiency in the coming decades.

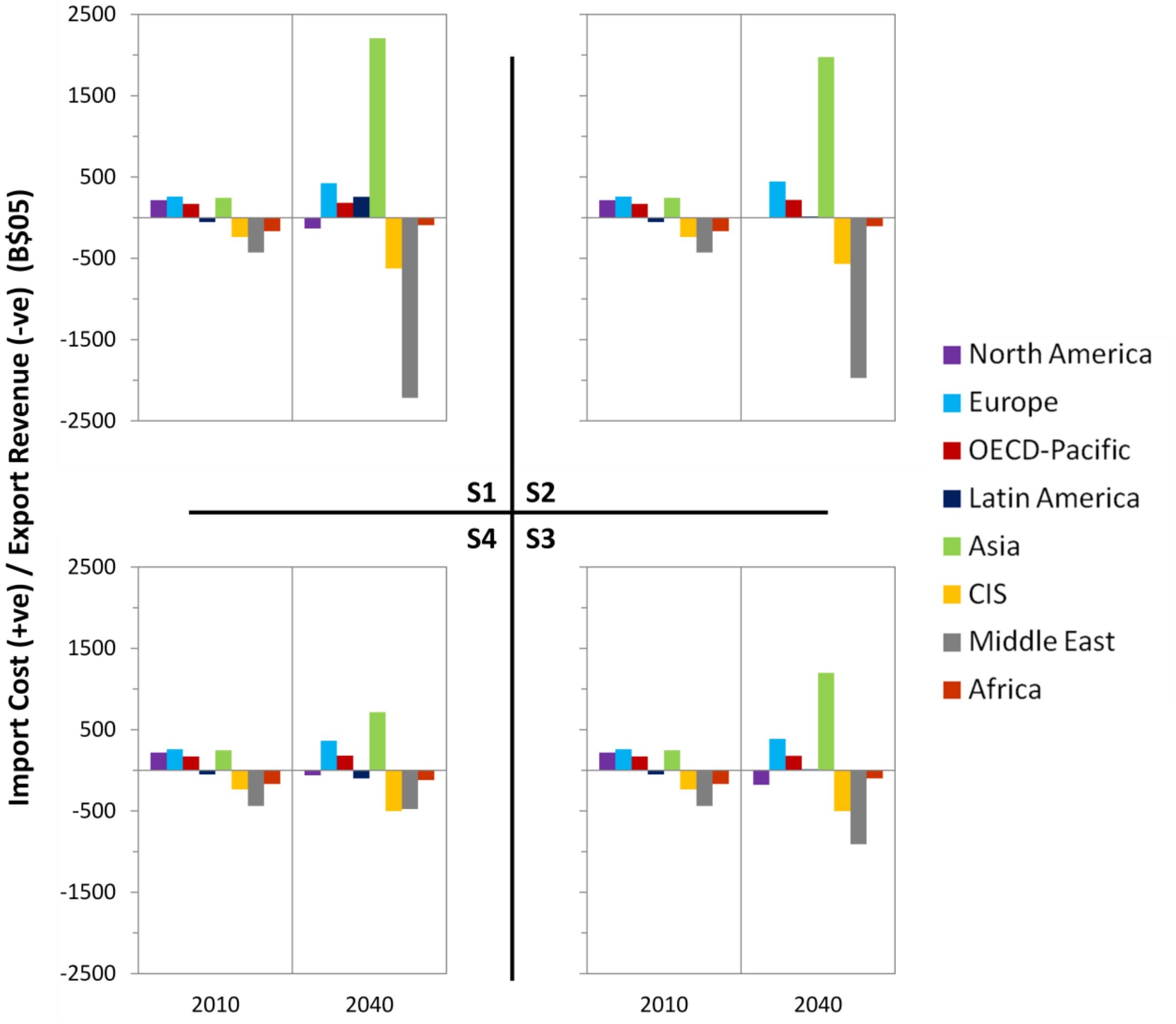


Figure 12: Oil Import Costs/Export Revenues

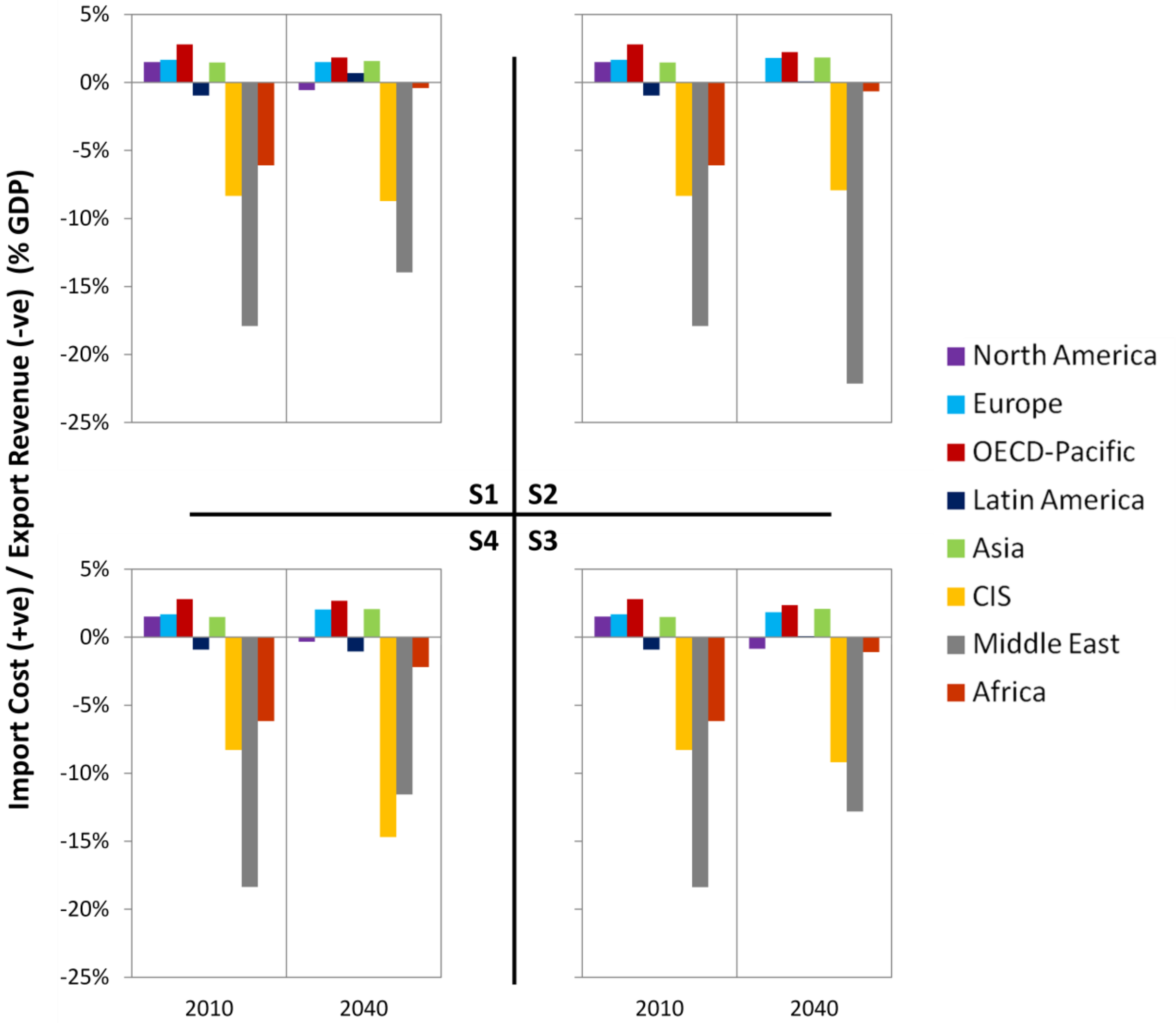


Figure 13: Oil Import Costs/Export Revenues as a Percentage of GDP

**Europe & OECD Pacific**: The rest of the OECD countries manage to decrease the volumes of oil and gas which they must import, either through efficiency improvements or demand reduction. However, despite importing less oil and gas, total import costs for Europe and OECD Pacific remain relatively stable over time, especially as a percentage of GDP. While these countries' reliance on foreign imports does not change much in economic terms, compared to the volumes being traded between other regions (e.g. from the Middle East to Asia) their influence on world markets is much reduced. Effectively, for both energy and non-energy areas of world negotiations, these OECD countries may lose their dominant position based partly on strong consumption relative to other regions.

**Developing Asia**: The complementary trend to Europe and OECD Pacific in oil and gas world trade is the rapid growth of Asian imports. Between 2010 and 2040, Asia increases their oil imports by a factor of 1.5 (S4) to 4 (S1), and gas imports by a factor of 25 (S4) to 70 (S1); although gas imports were not extensive in 2010. This expansion of imports places Asia far above other regions both in terms of volume and cost. Consequently, Asia emerges as the main consumer over time and should be able to influence fossil fuel prices more than any other region; but only if they manage to avoid becoming captive to the dictates of oil and gas producers. This major eastward shift of geopolitical power will have impacts in most sectors, including technology leaders, investment options, preferred climate policies, and government structure and diplomacy.

**CIS & Middle East**: In the cooperative scenarios, where economic growth is high, the main producing regions experience stable (CIS) or rising (Middle East) domestic demand for oil and gas. Despite this, oil and gas production increases in supplying countries so that they remain the principal exporters. Even in the conflict scenarios which have much lower domestic and world consumption, the CIS and Middle East produce sufficient amounts of oil and gas to maintain their current market shares. Increased revenues and a narrowing range of supplying regions (see Section 18.4.4.1) indicate that OPEC will continue to have considerable market influence, if they can maintain political cohesion.

**Latin America & Africa**: Due to relatively small traded volumes, these regions rely very little on revenues from oil and gas exports and do not need to pay much for imports. They are mostly self-sufficient for oil and gas, but cannot raise production enough to capitalize on rising market prices. Latin America and Africa will likely not gain much geopolitical influence based on fossil fuel trade in the coming decades. The exception to this is perhaps in an economically constrained scenario like S3 or S4, where Latin America and Africa contribute a somewhat more significant portion of global oil exports (5-15% compared to 1-5% in S1 or S2).

### 18.4.4. Energy dependence

For several decades, supplies of oil and gas have been concentrated in a few key regions around the world, and consuming nations have had few options: Persian Gulf countries and OPEC have exerted considerable influence over oil prices since the 1970s; Russia is by far the largest foreign supplier of natural gas to the European Union; the U.S. relies on foreign oil production for almost half of the oil consumed in its transport sector. In general, primary energy flows from developing regions such as the Gulf, CIS, Latin America, and North Africa, towards much wealthier OECD countries.

Consumption of fossil fuels, which dominate world energy trade, is slowly declining in OECD countries; however, a rapid rise in non-OECD consumption drives a global net increase under a wide range of possible economic conditions, more optimistic or more pessimistic. As increased production costs of oil and gas development are combined with rising demand, fossil fuel prices will climb. Consequently, concerns over the security of energy supply will likely be at the forefront of many government agendas in the coming decades.

#### 18.4.4.1. *Oil market concentration*

The number of countries producing oil will decline between 2010 and 2040.

There are several reasons for a likely concentration of oil supply regardless of which scenario is considered. Countries with relatively small resources, i.e. non-OPEC other than the U.S., Canada, or Russia, produce at the market price and can only marginally expand their production level; they remain price-takers throughout the forecasted period, while OPEC and the large producers of today still dominate the market in the future. In a high-consumption and economically prosperous world, considerable demand will ensure continued production from regions with abundant low-cost resources, such as the Gulf and Russia. If economic growth proves to be more difficult and areas prone to conflict cannot consistently produce oil and gas, prices should remain high enough to stimulate additional capacity in the few regions with sufficiently explored unconventional resources, such as Canada, the U.S., and Venezuela.

The concentration of producers is summarized by the Gini coefficient, which considers how evenly distributed oil production is across various regions (see Figure 14 to Figure 16).[11] Compared to 2000 (G=0.59), fewer regions produce a larger share of oil in 2010 (G=0.60), and this trend continues to 2040 (G=0.68). A very similar Gini coefficient is apparent in each of the scenarios by 2040, indicating that the number of oil producing regions will shrink regardless of economic conditions or governance structure.

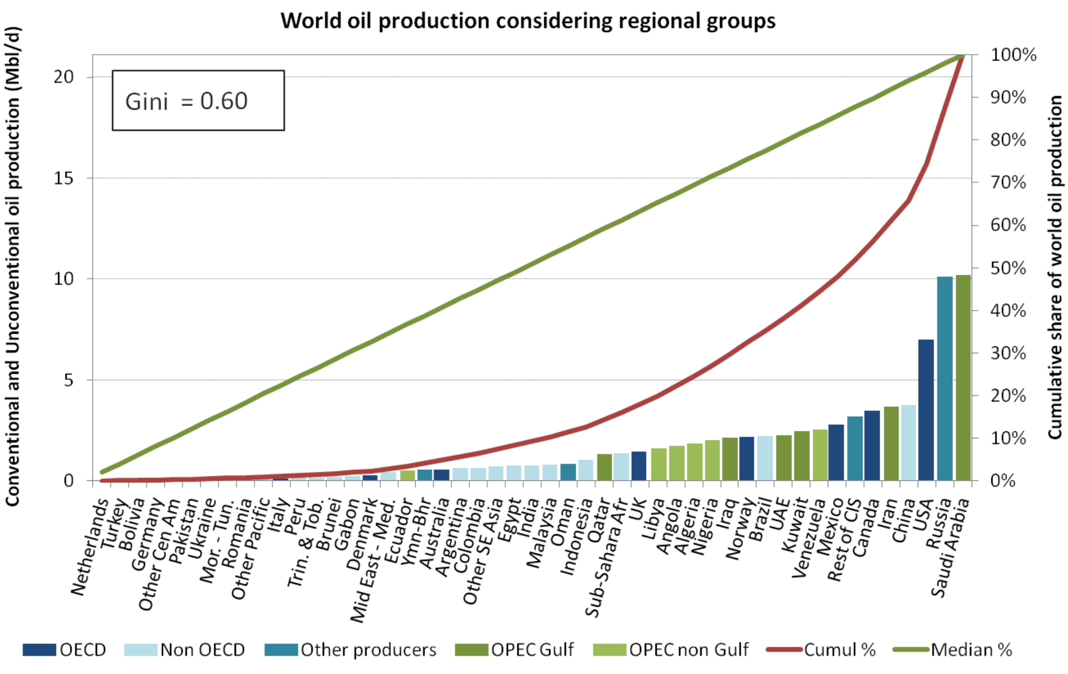


**Figure 14: Concentration of world oil suppliers in 2000**

While the production of oil resources will concentrate to a similar degree by scenario during the next several decades, the particular mix of producing areas will differ strongly depending on the economic and state conditions realized:

[11] For a Gini coefficient equal to 0, all regions produce equally; for a coefficient equal to 1, only one region produces a particular good.

- In 2000, of the top ten oil producers, OPEC accounted for 36% of production; of the top five it accounted for 43%.
- In S1 consumption is very high, adequate investment is made into replenishing production capacity, and the Gulf region remains stable; and by 2040 OPEC will make up 59% of the top ten and 50% of the top five.
- However, in S3 energy demand is much lower, but given the conflictual context of the scenario the Gulf and North Africa experience a lack of investment and do not manage to even maintain current capacity levels. Since, energy security is a stronger focus for consuming nations, by 2040 OPEC will make up "only" 43% of the top ten producers and 36% of the top five. In this situation, the share of OPEC nations in the top ten still grows to some extent, but overall OPEC slides down the list of top oil and gas producers.

Given strong economic growth, the market power of oil cartels (e.g. OPEC) and very large gas producers (e.g. Russia) will increase as nations with smaller endowments deplete their resources. However, maintaining political stability will be a key requirement for producers to sustain their prominence as providers of global oil and gas supplies.

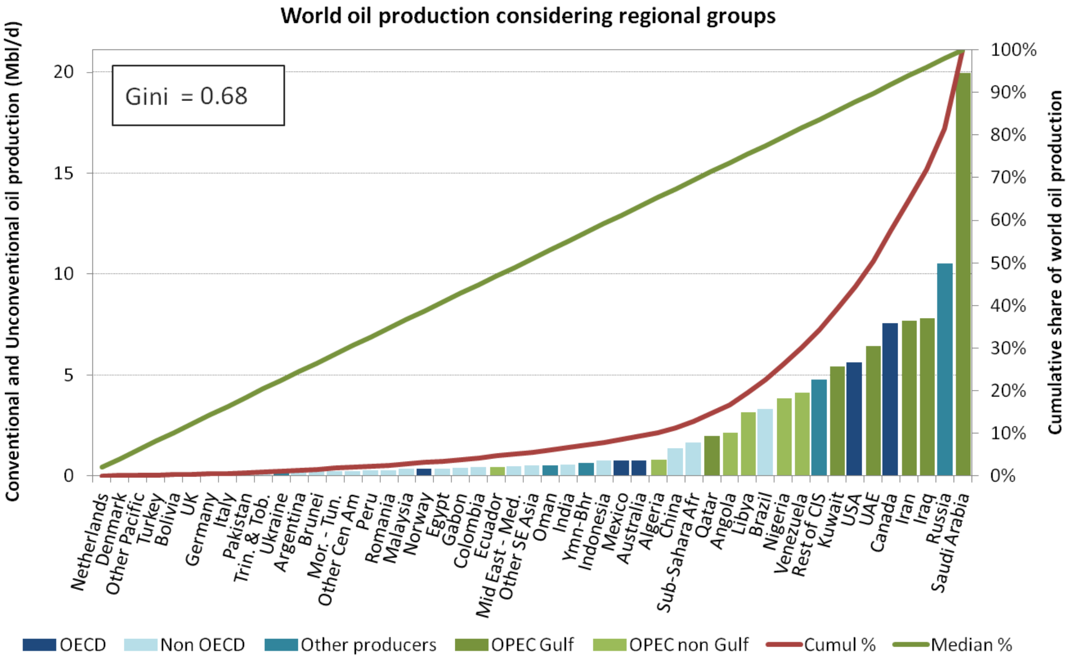


Figure 15: Concentration of world oil suppliers in 2040 (S1)

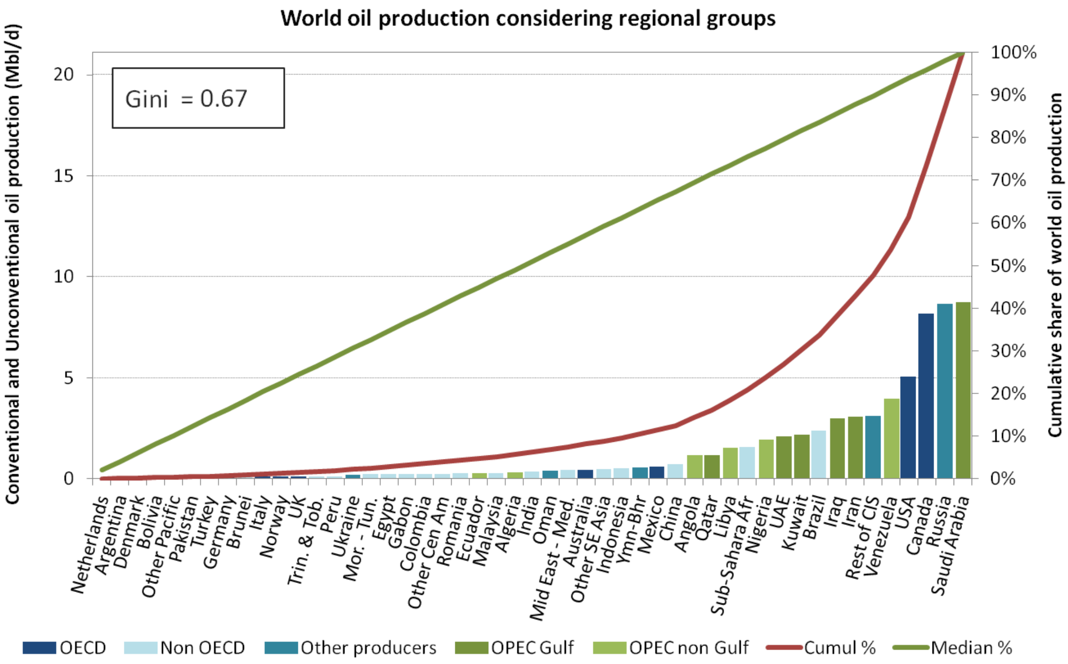


Figure 16: Concentration of world oil suppliers in 2040 (S3)

### 18.4.4.2. *Energy security and foreign dependence in S3*

As the number of nations and regions supplying energy resources declines, concerns over security of supply are likely to become more important for many countries. Of the four scenarios considered for this project, S3, where international conflict dominates political decisions and the economy is driven by states rather than a more market-based system, energy security considerations will have the greatest impact.

***Focus on China***

China will continue expanding its economy even under a slower growth scenario such as S3. Even when the increase in its consumption rate is slower, China will become more and more dependent on foreign sources of oil and gas; two resources which it does not possess in abundance (Figure 17).

In all scenarios, domestic oil production is set to decline by a factor of 3 to 7 compared to today, due to dwindling reserves (despite new discoveries in the future). The strong growth of the vehicle market in China will ensure that most of the imported oil is used for fuel consumption in the transport sector (two-thirds to three-quarters of the imported oil represents the transport sector use).

Gas production, on the other hand, is set to grow significantly by a factor of 2 to 3; but in the mid-term (2010-2030) does not grow fast enough to cover the whole rise in demand, and results in increased foreign dependence.

Despite the dependence ratio of gas being quite high (peaking at 55% in 2025), coal use represents a much larger portion of total energy use. Given China's vast coal reserves, it provides a cheaper and domestically-sourced fuel for electricity generation and heating purposes in industry.

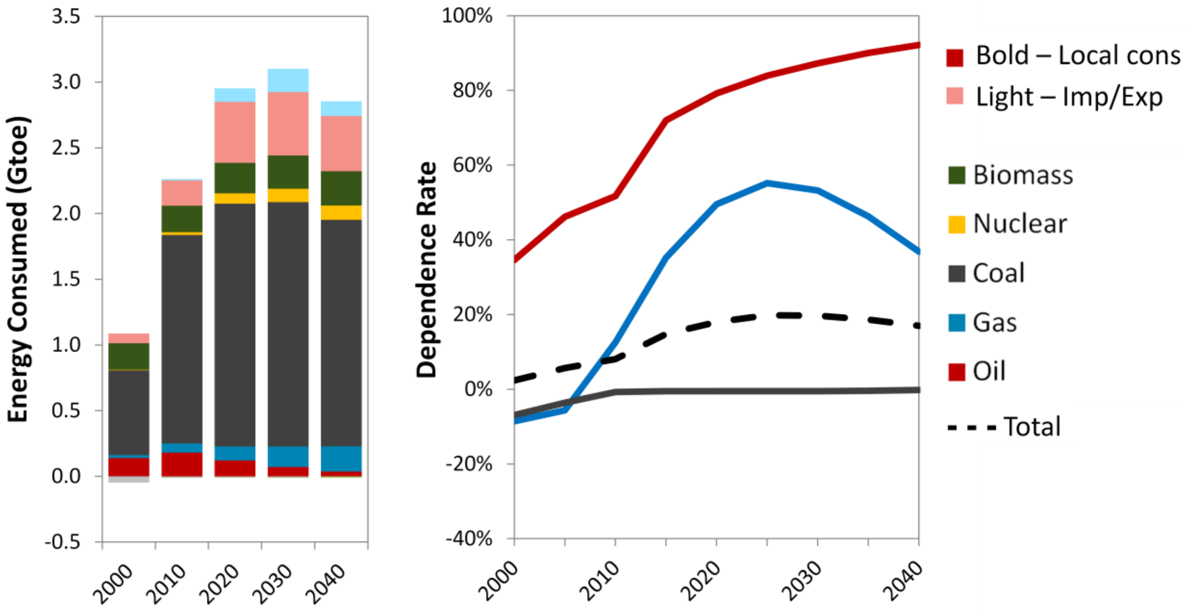


Figure 17: Dependency of China on Foreign Energy Sources (S3)

### *Focus on Europe*

Compared to China, Europe's total energy consumption is much lower; however, from an energy security perspective Europe is in an equally unfavourable position (Figure 18).

Europe's domestic production of most energy types is of a similar level to China despite its much lower total consumption; for oil, gas and biomass Europe produces approximately the same amount, but coal consumption is considerably lower. Imports are at about the same level as well, approximately 0.5 Gtoe, with a slightly larger proportion of gas to oil since oil demand in industry rapidly declines and the European vehicle market does not become as large as China's. Because the total amount of imported energy in Europe is approximately the same as China, but total consumption is much lower, imports represent some 40% of Europe's primary energy budget.

In S3, Europe makes much effort to reach low overall energy intensity by 2040 (Figure 8) even without putting a price on carbon which would provide additional energy savings stimuli, but it may not have enough flexibility to further reduce its dependence on foreign and potentially unstable energy sources. Without large domestic oil and gas resources to develop, border tax adjustments on the carbon content of fuels and the additional electrification of the transport and residential/service sectors may be the only options to further increase energy security.

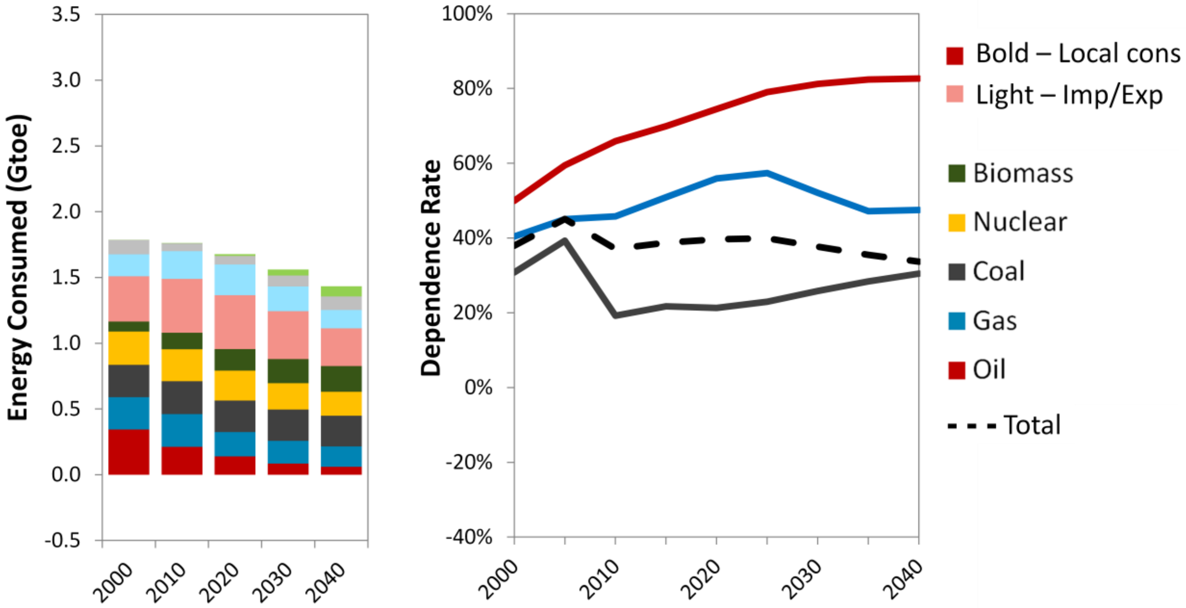


Figure 18: Dependency of Europe on Foreign Energy Sources (S3)

### *Focus on North America*

The U.S. and Canada are considered to still form a single geopolitical and energy bloc in the future given each country's complementary supply and demand balance. Like Europe, North America manages to decrease its energy needs over time in S3, mostly through efficiency improvements. Combined with additional production, North America's energy security position greatly improves (Figure 19).

North America moves from being a net importer of energy (mostly oil) to a net exporter of energy goods (oil and coal) by 2030. This change in North America's dependence on foreign oil is driven almost entirely by development of unconventional resources (Canadian tar sands and U.S. shale oil). When global conventional oil sources are interrupted due to political or economic strife, North America will fill the supply gap – aided by rising oil prices to cover the higher production costs of the unconventional resources. Throughout the 2000-2040 period, North America provides natural gas for its own needs which remain roughly stable; and neither needs to import nor export given gas prices that justify maintaining current levels of gas production.

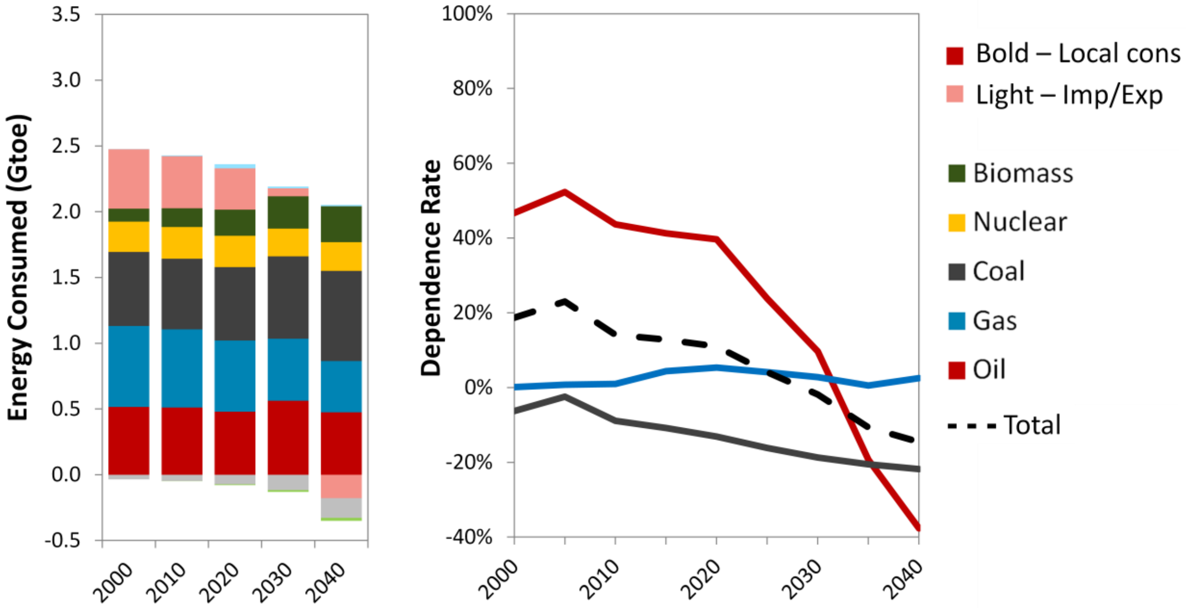


Figure 19: Dependency of North America on Foreign Energy Sources (S3)

### 18.4.5. CO2 emissions and Climate Change

#### 18.4.5.1. *Emissions in the 4 Future World Images*

In terms of carbon dioxide emissions, the lack of specific policies to modify the cost competitiveness of fossil fuels compared to low- or non-emitting sources results in fossil fuels making up a large part of the energy mix throughout 2040. Emissions are essentially directly linked to economic activity, with what little variation exists between scenarios coming from policies and investments not directly linked to carbon and climate, but to R&D and efficiency (high for S1, low for S4).

Thus, annual CO2-energy emissions increase significantly in the high growth scenarios (S1 & S2) and stabilize slightly higher than 2009 levels in the lower growth scenarios (S3 & S4). Even this stabilization is, however, far from sufficient compared to targets discussed in the UNFCCC for maintaining long-term global temperature increase to around 2-3°C at the end of this century: targets for 2050 that have been discussed are a 50% reduction of emissions at world level compared to 1990, decomposed into a 75% reduction for OECD compared to 1990 and a 50% reduction for non-OECD compared to 2005, which is the last column displayed in the figure below. Emissions in the POLINARES scenarios in 2040 are two to four times higher than these 2050 targets.

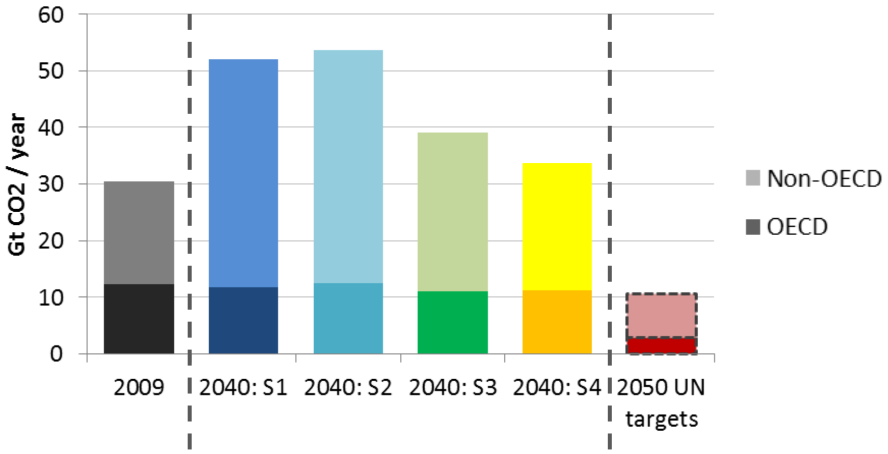


Figure 20: CO2-energy emissions in 2009 (historical), in 2040 for the 4 scenarios, and targets in 2050 to maintain temperature increase to 2-3°C

When factoring in CO2 emissions from other sources (e.g. land use) in the scenarios, we forecast an increase of atmospheric concentration of CO2 over time that would bring us to 480-560 ppmCO2 at 2040 and rising. This is already above the long-term stabilization figure of 450 ppm discussed in international negotiations (corresponding to a long-term 2-3°C increase) and far above the pre-industrial level of 280 ppm.

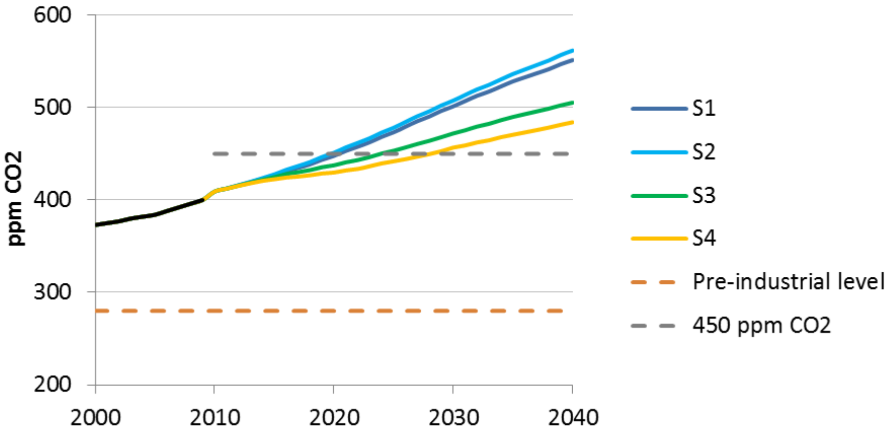


Figure 21: Atmospheric CO2 concentration in the 4 scenarios (ppm CO2)

Carbon emissions budgets that are allowed over 2000-2050 have been estimated in order to limit the long-term temperature increase to 2°C: they are 1440 GtCO2 (for a 50% probability not to exceed 2°C, widely used in literature) and 1000 GtCO2 (for a 75% probability not to exceed 2°C)[12][13]. With roughly 360-400 GtCO2 already emitted in the past decade, all four scenarios exceed the 2000-2050 budget before 2040.

[12] Meinshausen, L., et al. (2009), *Greenhouse-gas emission targets for limiting global warming to 2°C*, Nature, Vol. 458, No. 7242, pp. 1158-1162
[13] IEA (2011), World Energy Outlook 2011

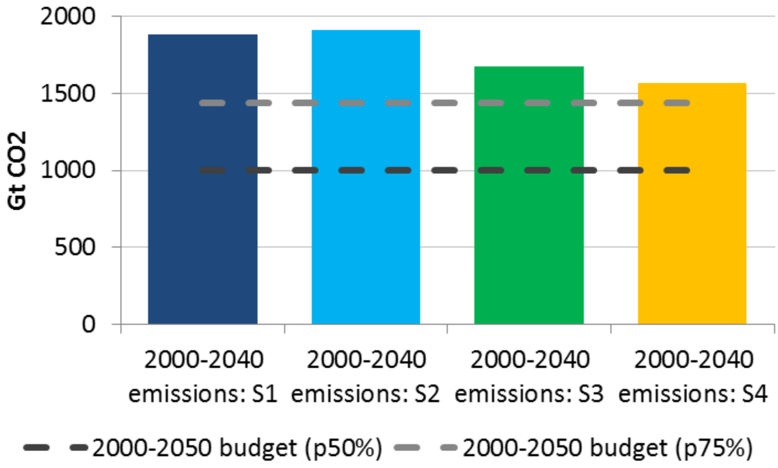


**Figure 22: Cumulated CO2 emissions (2000-2040) for the 4 scenarios and CO2 budget (2000-2050) not to exceed 2°C warming**

Thus, without discussing environmental effects such as particulate matter pollution from coal use or water scarcity and availability effects with regards to fossil fuel resources left after 2040, all four scenarios are engaged on a path that leads to a long-term temperature increase above 2°C, with severe impacts beyond the time frame of the POLINARES study.

#### 18.4.5.2. *Tackling climate change in the 4 Future World Images*

However, it is worth noting that not all scenarios are on the same footing in 2040 with regards to tackling climate-related issues.

High economic growth and technological diffusion across all world regions in S1 results in high technological development and higher efficiency (however this relative decoupling of economic activity and emissions does not translate into an absolute decoupling). S1 is the best-suited scenario to invest in low-carbon growth and curb its emissions beyond 2040. S2 is in a similar position.

Lower economic growth in S3 and S4 do result in a rough stabilization of emissions, however in these two scenarios the world is ill-equipped to transition to a lower carbon economy in terms of investment capability and a climate of stability that would allow climate-related issues to enter the policy agenda.

Additionally, with economic growth and international cooperation being predominant in S1, this scenario is the one best suited for implementing binding targets to reduce emissions within the time frame of POLINARES. We conducted a case study where an international carbon price is set across the globe, be it a carbon tax or a trading scheme inspired by the EU ETS and currently discussed internally in China, beginning with 2012 and progressively rising so as to stabilize long-term CO2 concentrations around 450 ppm.

In this case study, emissions peak within this decade and decrease to 17 GtCO2/year by 2040.

The energy mix and energy markets across the globe are greatly modified. As an example, we provide an illustration of the oil import costs and export revenues in this case study below.

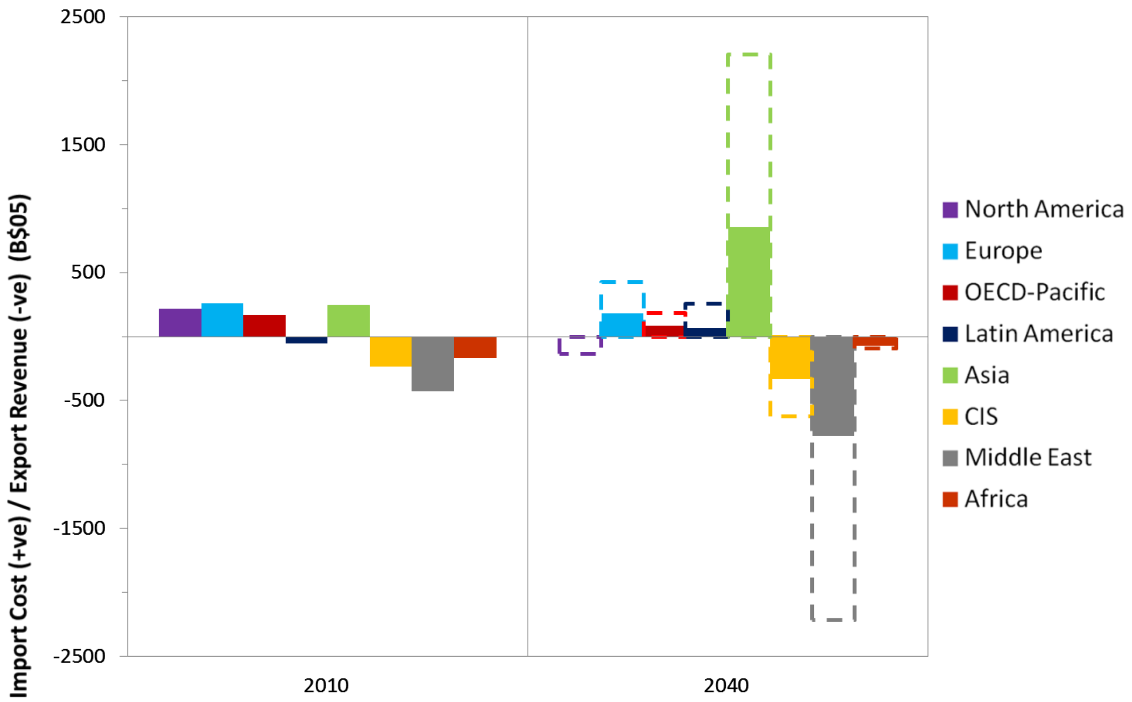


Figure 23: Oil Import Costs/Export Revenues in S1 (dashed) and in a case with a global climate policy (plain)

Oil demand decreases over time and oil prices are lower than in S1 as a result of a different equilibrium with fewer tensions on the market. Expenditure for oil provision by importing countries is close to the figures obtained for S4, despite the economic growth of S1 (see Figure 12). Export revenues in exporting countries are also greatly diminished compared to the same year in S1. However, for CIS and Middle Eastern countries in particular, there is still a net increase in revenue compared to today due to oil prices rising over time due to higher production costs.

## 18.5. Main findings: Minerals

A large part of the modelling of minerals demand as it was done in POLES for POLINARES is directly dependent on GDP growth and population: the GDP/capita ratio (i.e. average national income per capita) drives demand in the transport sector (via the car ownership ratio), in the buildings sector (via the growth of the number of dwellings with income), in the power sector (via the increase of power demand with income growth) and in the "residual" demand for minerals (which is directly dependent on GDP/capita, as explained above).

### 18.5.1. Iron & Steel

Demand for steel is expected to grow as high as 2700 Mt in the scenario with the highest growth (S1) by 2040, compared to 1200 Mt in 2010 and 465 Mt in 1980.

Table 7: World demand for steel, historical and in the 4 scenarios (Mt/year)

| Mt | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 |
|---|---|---|---|---|---|---|
| **S1** | 562 | 845 | 1240 | 1940 | 2320 | 2720 |
| **S2** | | | | 1830 | 2080 | 2300 |
| **S3** | | | | 1610 | 1910 | 1910 |
| **S4** | | | | 1330 | 1290 | 1300 |

This great increase is observed mostly in emerging economies, where steel demand grows by 148% during the 2010-2040 period, or by an annual average of 3.1% (S1). In developed economies, steel demand grows by 49% but decreases in importance compared to world demand from 30% in 2010 to 20% in 2040.

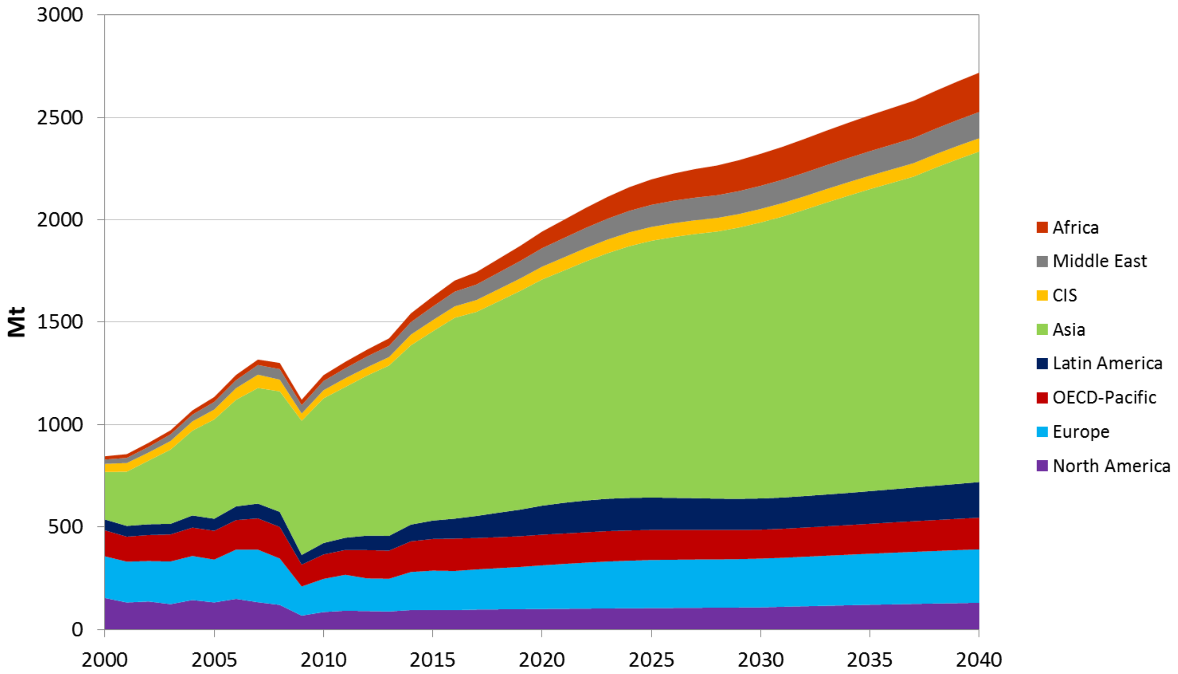


Figure 24: Demand for steel per world region in S1 (Mt)

Despite these large increases in demand, steel intensity per unit of GDP marks significant decreases across all regions. This is most obvious in Emerging Asian Economies, where income rises dramatically, and where large structural shifts in the economies occur: the weight of services in the overall GDP grows from 52% in 2010 to 75% in 2040 (S1). Increases in efficiency and the shift towards a service-based economy combine to decrease material intensity.

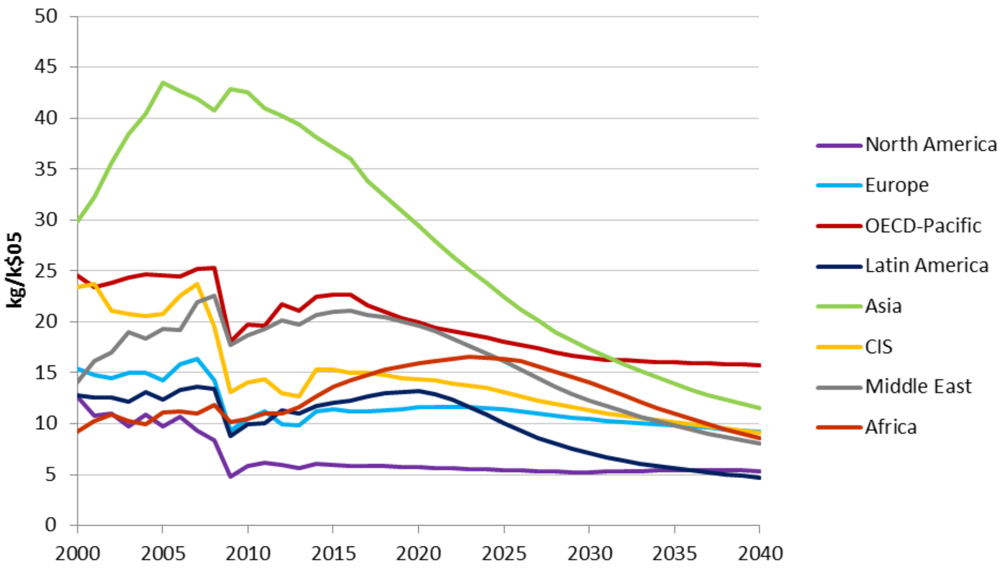


Figure 25: Demand for steel per unit of GDP in S1 (kg / k$05)

The situation is quite different in the competitive scenarios (S3 & S4), where two effects combine into a resulting lower demand for steel compared to the cooperative scenarios S1 & S2 (as explained in the methodology):

- a lower GDP decreases demand levels (for the detailed demand sectors: buildings, transport);
- a lower GDP growth means less progress is made to reduce the material intensity per unit of GDP (for the remaining "residual" demand).

This is reflected in the material demand per capita. In a high economic growth scenario, demand per capita continues to increase significantly in the long term, while it grows less and stabilizes in the long term in a situation where economic growth decelerates.

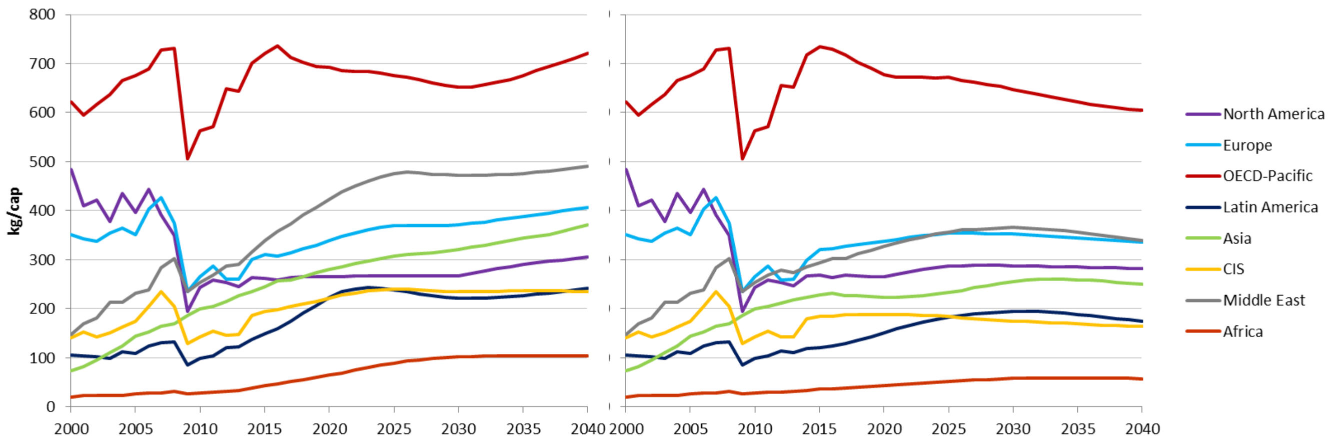


Figure 26: Demand for steel per capita per world region, in S1 and S3 (kg/cap)

These tendencies can be broken down in a number of explaining factors. Taking the examples of the EU-27 and China:

**Transport**: The growth of steel demand in the transport sector is approximated by the growth of annual sales of private cars. In the EU, growth is rather small and demand is essentially due to replacing old cars and maintaining the car park. In China, income growth and the associated increase of car ownership more than doubles steel demand for that sector between 2010 and 2040.

**Buildings**: The growth in consumption in buildings can be attributed to several factors: an increase in the number of dwellings (due to income growth and also changing family structures, with less people occupying a dwelling); a growing requirement of surface per dwelling on average (due to income growth); the dynamics of old buildings being abandoned and buildings being renovated. In the EU, the housing stock is renewed faster and more energy-efficient housing are constructed rapidly; as a result, demand for steel recovers and even exceeds its pre-2008 levels. In China, demand in buildings peaks around 2015, after which the growth rate of new and renovated surfaces begins decelerating and the construction industry stabilizes towards adding annually roughly constant surfaces to the stock; lower rates for renewal of the housing stock than in the EU helps dampen the growth of demand for steel.

**Rest**: The remaining demand for steel follows the skewed bell-shaped curve described in the methodology above; as GDP per capita grows, demand undergoes a peak and a progressive decrease beyond. For the EU, this means an average decrease of demand of about 10% in the 2030s compared to the 2000s. For China, demand continues to increase significantly in the upcoming decade, reaching a peak around 2020 at a level 50% higher than that of 2010; afterwards, demand declines towards a long-term alignment with EU values. Demand per capita in China first reaches a peak of nearly twice the value in the EU in 2020, before decreasing to 20% higher than the demand per capita in the EU in 2040.

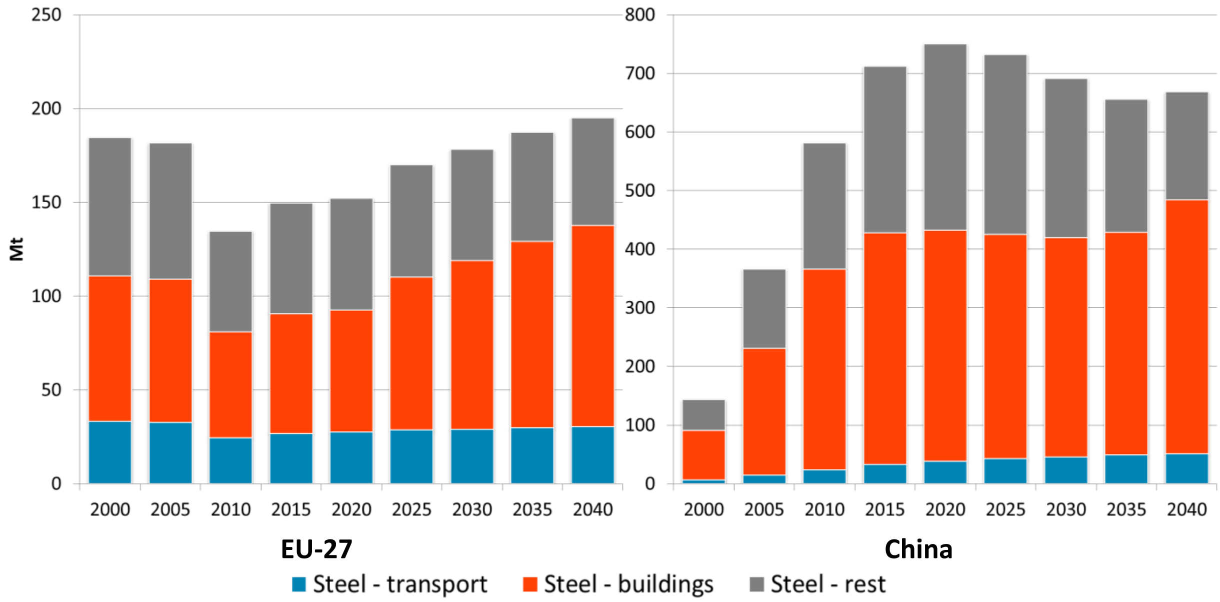


Figure 27: Demand for steel per sector for the EU-27 and China in S1 (Mt/year)

The aggregated demand from these three sectors results in the total demand per capita seen in Demand for steel per capita per world region, in S1 and S3 (kg/cap)Figure 26 above. Total steel demand per capita in China has been catching up rapidly the EU levels in the 2000s decade and largely exceeded it following the 2008 economic crisis. In our projections for S1, China demand per capita exceeds twice the EU figure around 2020 at its peak and decreases to a demand per capita 27% higher than in the EU by 2040. In S3, the lower economic growth has China's demand per capita being cut short earlier, around 2015, and decreasing more slowly as China has to make efforts to complete its development in all sectors for a longer time period; by 2040, demand per capita is still 40% higher than in the EU.

It is important to note that these figures include hypotheses on the material content of each of these sectors (kg of steel per new or renovated building surface; kg per private car; kg per unit of economic activity); for the building and transport sector, these unit consumption figures are stable through time. End figures will be different with a different set of hypotheses on all kinds of technological innovation that could shift unit consumption up (substituting the use other materials with steel; new uses emerge) or down (steel substituted by another material; efficiency measures).

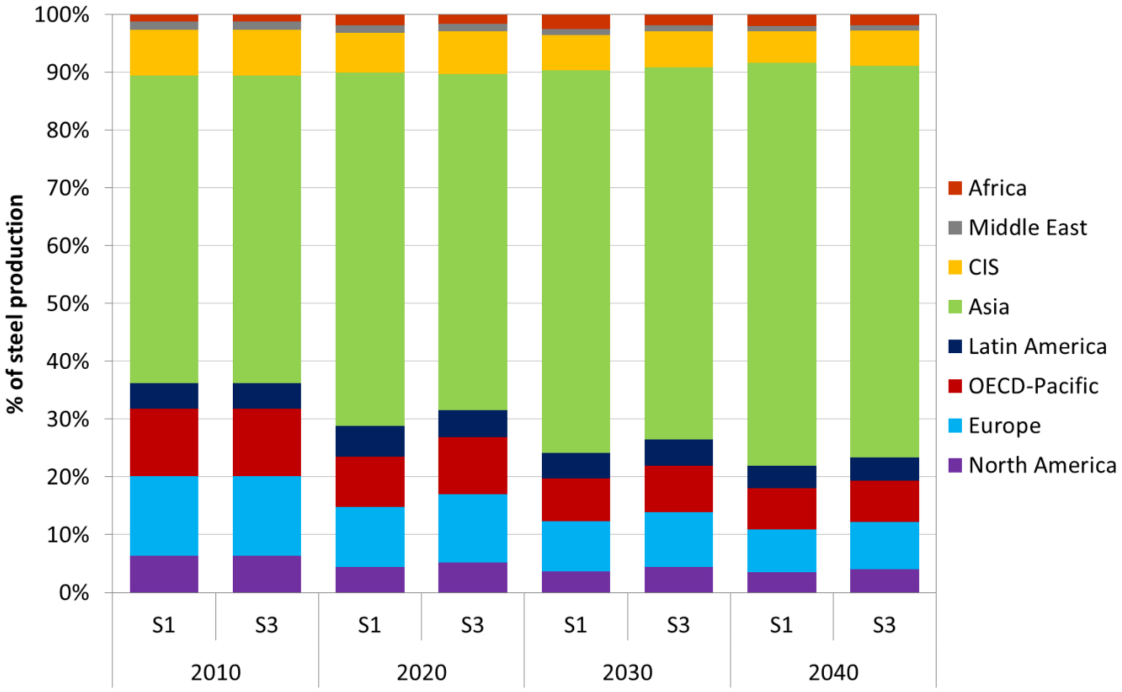


Figure 28: Steel production per world region, in S1 and S3

Production of steel from iron ore dynamically shifts between regions over time based on satisfying each region's domestic demand, but also due to the relative costs of steel refining and smelting in each region. Over time, steel production in non-OECD countries increases and comes to represent a larger share of world steel production; production in the OECD stays stable (S1) or even decreases (S3). From 32% in 2010, the OECD comes to represent about 20% or less of world production by 2040 (compared to 20% or more of steel demand).

This does not reflect the dynamics in the mining of the iron ore itself; production here refers to the provision of primary steel (refined ore) or secondary steel (recycled scrap).

Additionally, we expect the use of electricity in steel production to increase in all regions; electricity-based processes such as electric arc furnaces are preferentially chosen to replace fossil fuel-based equipment at the end of their lifetime. Electric processes increase from 28% in 2010 to 32% (S1) or 37% (S3) of total steel produced by 2040. The higher share in S3 is due to a smaller total amount of steel to produce; in S1, the growth in total demand is higher than the growth of electric processes. In OECD countries in particular, electric processes come to represent as much as two thirds of production by 2040 (S3).

Further research with these figures can be done on issues of pricing of scrap and the preference for recycling (i.e. electric processes) in strategies towards a closed material flows economy or an economy striving towards minerals independence. Also, the issues of steel availability for recycling can be further investigated, comparing the timing a certain volume of steel becomes available for recycling and how this volume relates to the total demand of steel at that time (i.e. will using the cities of today as the mines of tomorrow be sufficient to supply all of the steel demand of tomorrow?).

### 18.5.2. Copper

Demand for copper is driven by similar dynamics and follows largely similar patterns.

Demand is expected to exceed 60 Mt/year in the scenarios with the highest growth (S1 and S2), more than a doubling compared to 25.5 Mt in 2010, which itself was a doubling compared to the 12.5 Mt in 1980.

Table 8: World demand for copper, historical and in the 4 scenarios (Mt/year)

| Mt | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 |
|---|---|---|---|---|---|---|
| **S1** | 14.48 | 20.23 | 25.50 | 43.9 | 60.4 | 58.5 |
| **S2** | | | | 42.1 | 52.8 | 63.7 |
| **S3** | | | | 37.3 | 46.4 | 51.2 |
| **S4** | | | | 32.5 | 34.9 | 36.6 |

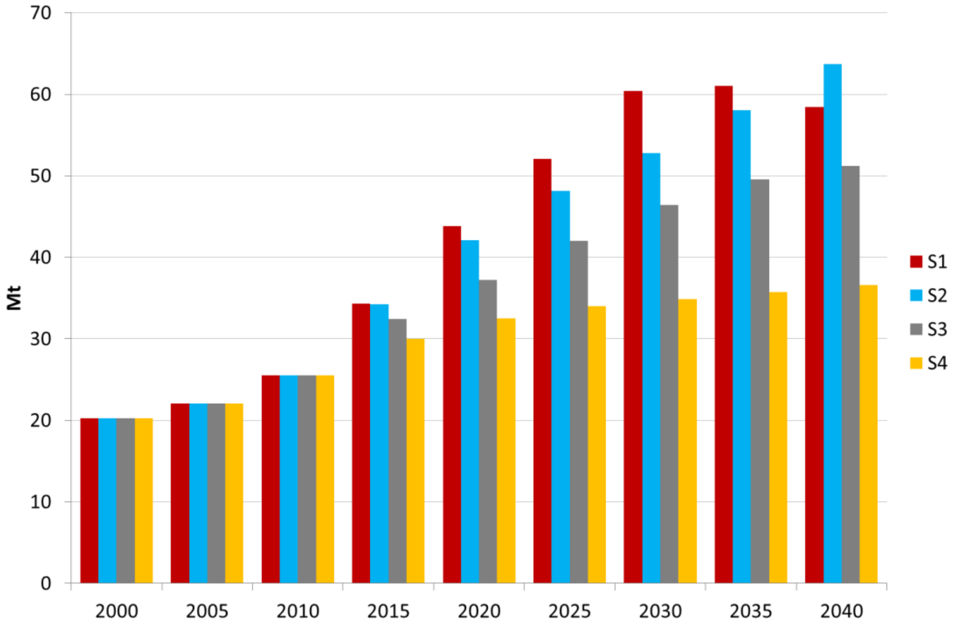


Figure 29: World demand for copper for the 4 scenarios (Mt/year)

Copper demand increases by an annual average of 1.2% to 3.1% depending on the scenario. The largest part of the increase is observed in Emerging Asian Economies, which make up for half of the increase by 2040 in S1. In developed economies, copper demand increases by a considerable 45% by 2040, however the importance of these regions compared to the rest of the world is greatly reduced: from 42% of the world's demand in 2010 to 26% in 2040 (S1).

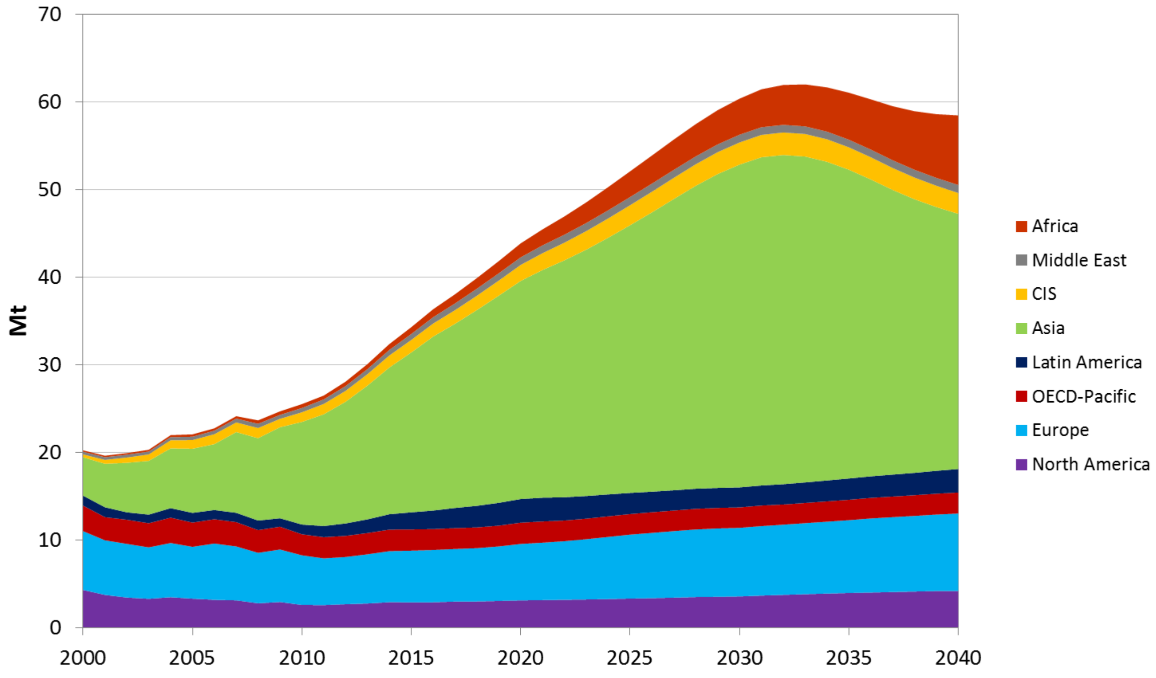


Figure 30: Demand for copper per world region in S1 (Mt)

As seen in Figure 29, copper demand increases throughout 2010-2040 in most scenarios, however we notice a peak in demand in S1 (Figure 30) due to Emerging Asian Economies – which does not correspond to an absolute world peak, as demand in other world regions is still growing fast beyond 2040. This can be explained by the differences in economic growth between scenarios that impact the "residual" demand:

- **Transport**: Copper demand follows the development of the car sector as the average income grows, with a different distance to saturation between regions.
- **Buildings**: Demand follows the dynamics of new and renovated surfaces between regions.
- **Power**: Similar to the transport sector, demand follows the development of the power sector and newly installed capacities as electrification increases, at different rates depending on the economic development of each region.
- **Rest**: Demand per unit of GDP intensifies then progressively decreases as the GDP per capita of a region grows. Due to largely different trends for economic development between scenarios, this maximum point in terms of demand per unit of GDP (i.e. a "peak") in "residual" demand occurs at different times for different countries. For China, this is around 2020 for both S1 and S2, however the growth in South-East Asia and India continues to drive demand up beyond that date up to a peak around 2030 in S1, and a peak beyond 2040 in S2. By 2040, nearly all countries have crossed that

peak point except sub-Saharan Africa and demand beyond 2040 is expected to grow but at a lesser rate in S1. In the other scenarios, many countries or even the largest part of the world have not crossed that point and are still under an "industrialization" or "increasing equipment" phase throughout 2040.

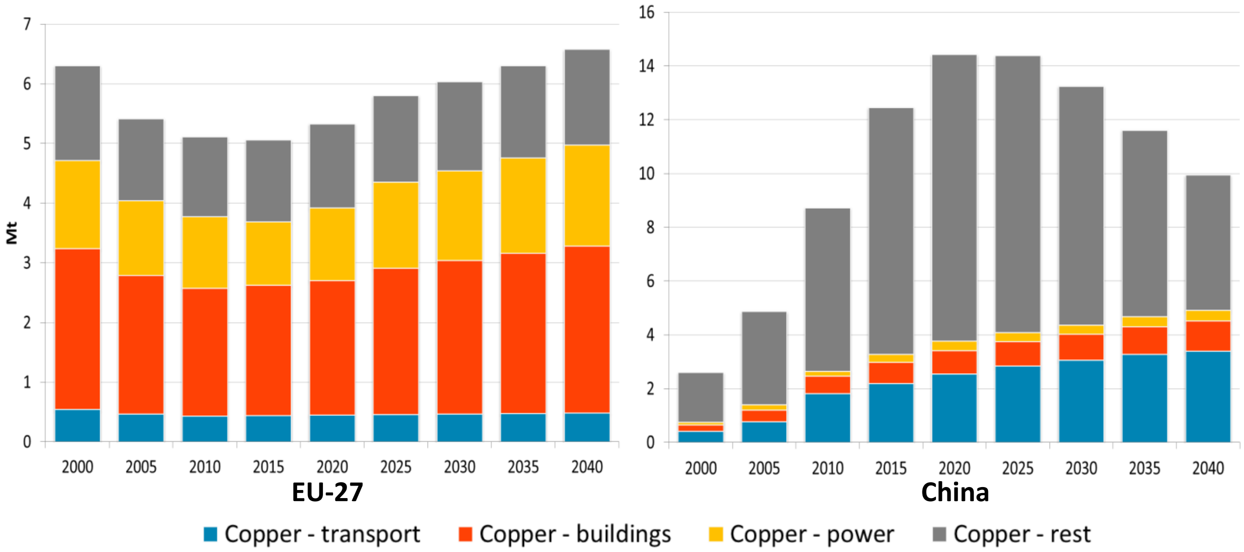


Figure 31: Demand for copper per sector for the EU-27 and China in S1 (Mt/year)

### 18.5.3. Other minerals

Many of the renewable energy generation technologies require significant quantities of minerals whose market in volume is small: neodymium and cobalt for magnets and electric motors in wind generation or electric vehicles; gallium and indium for solar panels; zirconium in nuclear reactors.

As a result, the cooperative scenarios, S1 and S2, will require much greater quantities of key minerals to be mined and processed to facilitate new electricity generation capacity (Figure 32). S1 installs over three times more nuclear, solar, and wind combined capacity than S4 between 2010 and 2040, and the year-on-year growth of mineral-intensive technologies is much faster in the cooperative scenarios.

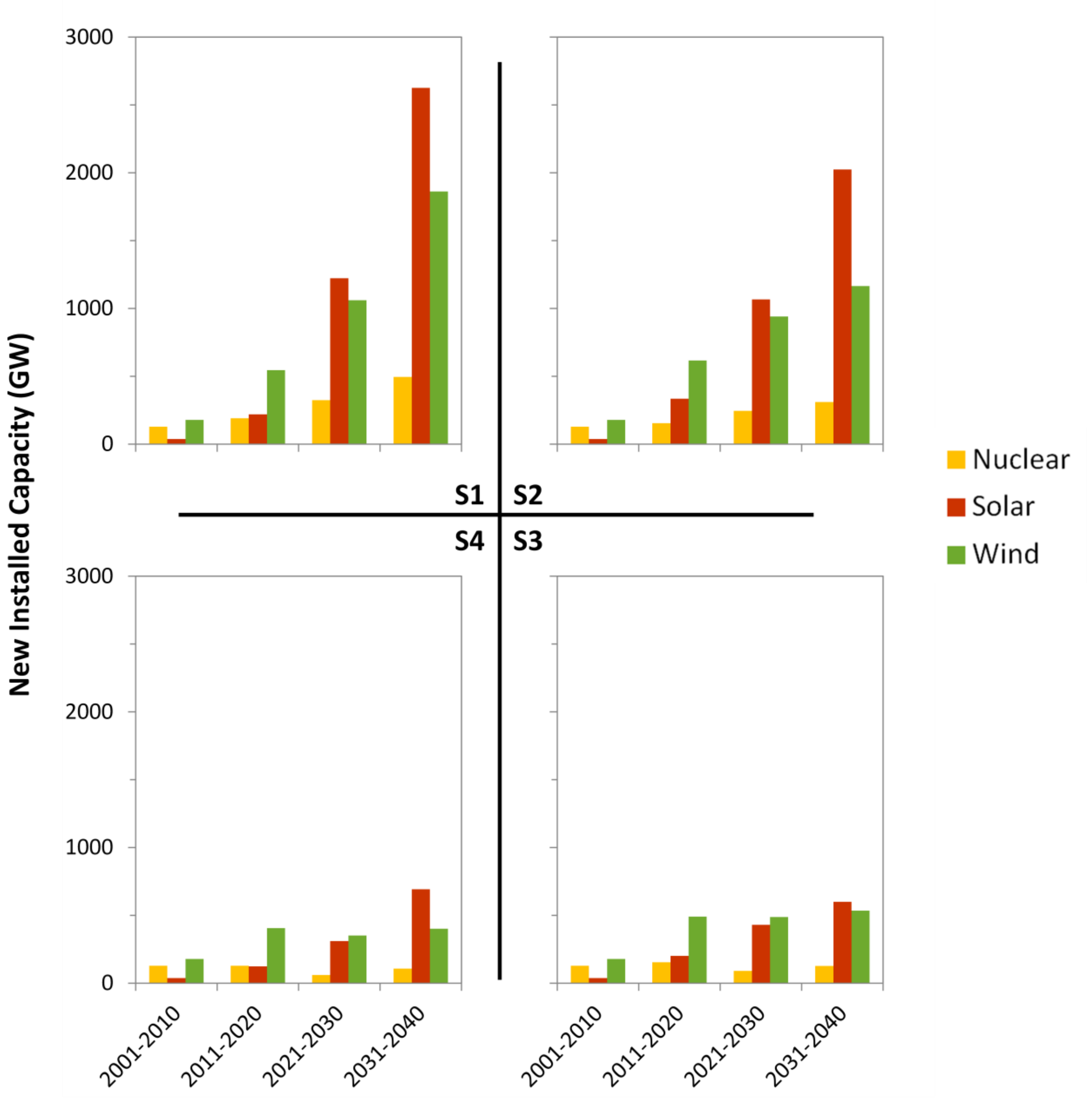


Figure 32: New Electricity Generation Capacity from Mineral Intensive Technologies

### *18.6. Possible future developments*

Possible future developments and issues to be investigated further identified thanks to research initiated with the POLINARES project include:

- **"Energy bill" vs "minerals bill"**: The Import expenditure and Export revenues graphs developed for oil and gas for this project can be further applied to the markets of minerals as well. This implies a good knowledge of minerals supply routes and future minerals prices. In particular, we can investigate the issue of energy and mineral dependency and what an increase in energy independence (decrease of fossil fuel imports) implies for expenditure in raw materials provision (development of energy savings infrastructure and renewables technologies). Initial estimates of market volumes in WP2 indicate that the net effect would be a financial gain, however a cross-sectoral quantified study has not been conducted.
- **Materials modelling**:
  - *Specific consumptions*: Better informed specific consumptions of technologies and how they evolve in the future. Different data sets could be incorporated, based on different learning curves or consumption patterns for particular technologies.
  - *Endogeneization*: For the materials with certain uses that are explicit in the model ("indirect approach"), it would be possible to make the conversion endogenous from the activity indicator already present in the model to the raw material demand for these uses (e.g. gallium in PV panels).
  - *Supply side*: The supply side of certain minerals can be developed to some extent by looking at the current and likely geographical locations of reserves and resources. It is possible that future discoveries might change the geographical distribution of the reserves; however, given investment lag times for mining facilities an initial mapping can provide useful information for the first 10-15 years of the forecast period.
  - *Recycling*: For each use of a material, it is possible to apply lifetimes to the equipment and a recycling availability rate, which would provide the potential for secondary supply of a material in the future. Such a materials flows study could shed insights in topics such as the circular economy, cities as the mines of tomorrow, etc.
  - *Other materials*: The demand of more materials can be included in the modelling, for example aluminium, glass, cement for materials with large markets.

## A.1 The POLES model

The modelling work conducted in the POLINARES project was made with the use of the POLES model.

POLES (Prospective Outlook on Long-term Energy Systems) was originally developed by LEPII-CNRS, also a partner of POLINARES, and is currently co-developed by LEPII-CNRS (also a POLINARES partner), Enerdata and the European Commission's JRC IPTS. It was initially developed under different EU research programmes (JOULE, FP5, FP6) in the 1990s; it has been used for policy analyses by EU-DG Research, DG Environment and DG TREN, by a number of European Ministries of energy, industry or ecology, and by several private actors in the oil, gas and power industries.

The POLES model was initially developed to provide a complete system for the simulation and economic analysis of the sectoral impacts of climate change mitigation strategies. The POLES model is a dynamic Partial Equilibrium Model, essentially designed for the energy sector but also including other GHG emitting activities, with the 6 GHG of the "Kyoto basket". The simulation process is dynamic, in a year by year recursive approach that allows describing full development pathways from 2005 to 2050.

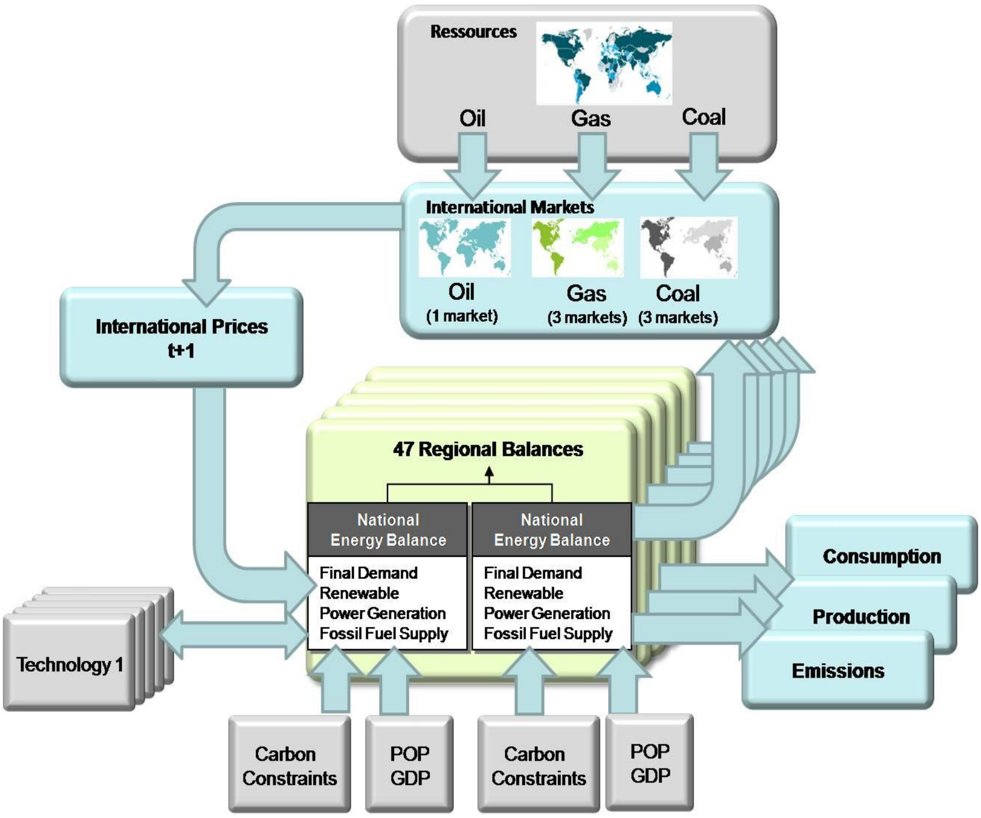


Figure 33: The global energy system of the POLES model

The use of the POLES model combines a high degree of detail on the key components of the energy systems and a strong economic consistency, as all changes in these key components are at least partly determined by relative price changes at sectoral level.

The model identifies 57 regions of the world, with 22 energy demand sectors and more than 40 energy technologies.

The model provides dynamic cumulative processes through the incorporation of Two Factor Learning Curves for technologies, which combine the impacts of "learning by doing" and "learning by searching" on the technologies' improvement dynamics. POLES relies on a framework of permanent inter-technology competition through prices, with dynamically changing attributes for each technology. In parallel, the expected cost and performance data for each key technology are gathered and examined in the TECHPOL database (developed at LEPII).

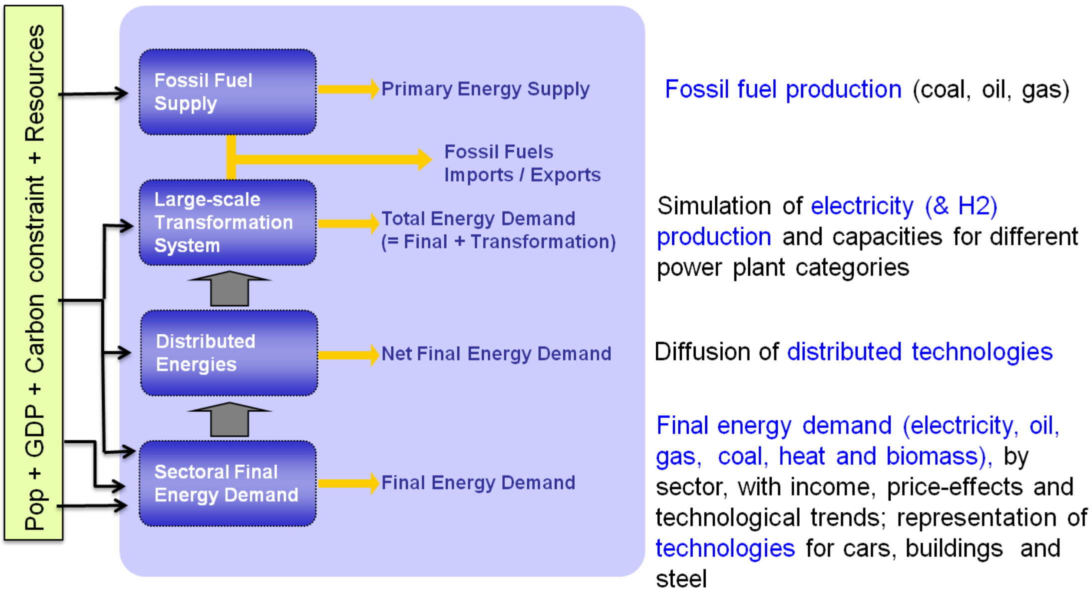


Figure 34: National/regional balances in the POLES model

Key issues addressed are:

- Long-term (2050) simulation of world energy scenarios / projections and international energy market, outlook for energy prices at international, national and sectoral level
- World energy supply scenarios by main producing country/region with consideration of reserves development and resource constraints.
- National/regional energy balances, integrating final energy demand, new and renewable energy technologies diffusion, electricity, Hydrogen and Carbon Capture and Sequestration systems, fossil fuel supply.
- Impacts of energy prices and tax policies on regional energy systems. National Greenhouse Gas emissions and abatement strategies.
- Costs of international GHG abatement scenarios with different regional targets/endowments and flexibility systems. Emission Quotas Trading Systems analysis at world or regional level.
- Technology diffusion under conditions of sectoral demand and inter-technology competition based on relative costs and merit orders

- Endogenous developments in energy technology, with impacts of public and private investment in R&D and cumulative experience with "learning by doing". Induced technological change of climate policies