Master's Thesis Energy Science

Modeling agricultural energy demand within the IMAGE 3.0 framework

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Abstract

Growing international consensus on the need to mitigate global climate change recently led UNFCCC parties to commit to an increase in global mean surface temperature (MST) well below 2°C compared to pre-industrial levels. In this context, integrated assessment models (IAMs) can provide valuable insights in the long-term impacts of human development on climate change. This thesis aims to model regional final energy demand (FED) for two main agricultural processes, irrigation and synthetic fertilizer production, within the IAM IMAGE 3.0. This is done in a new Agricultural Energy Demand (AED) module. The methodology for irrigation energy demand consists of two main components; water conveyance from a withdrawal source to the field; and subsequent distribution across the field by an application system. The former uses aquifer and groundwater table depths to determine specific energy consumption (SEC), the latter a region specific mix of three field application systems; surface irrigation, sprinkler and drip. These systems are characterized by zero, high and low SECs respectively. Since the production of ammonia dominates world synthetic fertilizer energy demands, it is modelled in more detail than other fertilizer types. At the heart of the ammonia energy demand methodology is a multinomial logit equation which assigns regional market shares to four ammonia plant types; natural gas, coal, heavy oil and solid biomass. SEC for each of these plant types is determined by a technological learning curve. Additionally, each plant type can be equipped with a carbon capture and storage (CCS) add-on, which reduces net CO_2 *emissions. Model runs are made for a new set of human development scenarios called the Shared Socioeconomic Pathways (SSPs). These include three plausible baseline scenarios and one that is constrained by the 2°C MST limit described earlier. Main results: projected global agricultural energy demand is dominated by ammonia production in all scenarios, and energy demand is higher for irrigation than for the production of all other fertilizer types combined. The SSP1 Sustainability scenario projects the lowest global AED, while the SSP3 Regional Rivalry and RCP2.6 2degree scenarios project the highest. These differences are mainly explained by the varying energy demands for ammonia production. The high ammonia energy demand in the 2°C MST limit scenario is explained by its high deployment of biomass plants, which have a high SEC but very low net* CO_2 *emissions. At the moment, the AED module covers an estimated 58.5% of world total AED and 2.0% of grand total final energy demand.*

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List of abbreviations

ACT	Activity
AED	Agricultural Energy Demand, including synthetic fertilizer production
AFOLU	Agriculture, Forestry and Other Land Use
AN	Ammonium Nitrate (fertilizer)
AP	Ammonium Phosphate (fertilizer)
BAU	Business As Usual
CAN	Calcium Ammonium Nitrate (fertilizer)
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
Ec	Irrigation conveyance water efficiency
Ef	Irrigation field application water efficiency
Ep	Irrigation overall / project water efficiency
FAO	Food and Agriculture Organization of the United Nations
FED	Final Energy Demand
GER	Gross Energy Requirement
GRACE	Gravity Recovery and Climate Experiment
Hmin	Minimal Operational Pressure
IAM	Integrated Assessment Model
IEA	International Energy Agency
IFA	International Fertilizer Association
IFT	Irrigation Functional Type
IMAGE	Integrated Model to Assess the Global Environment
IPCC	International Panel on Climate Change
LPJml	Lund-Potsdam-Jena Model with Managed Land
MAGNET	Agro-economic model
MF	Management Factor
MST	Mean Surface Temperature
N	Nitrogen (fertilizers)
NH_3	Ammonia (fertilizer)
NPK	Nitrogen Phosphate Potash (fertilizer)
O&M	Operation and Maintenance
P	Phosphate (fertilizers)
PBL	Netherlands Environmental Assessment Agency
PK	Phosphate Potash (fertilizer)
RAED	Remaining Agricultural Energy Demand
R&D	Research and development
RCP2.6	Two Degrees Mitigation Scenario
SEC	Specific Energy Consumption
SSP	Shared Socioeconomic Pathway or Single Super Phosphate (fertilizer)
STR	Structure
TIMER	IMAGE Energy Regional Model
TSP	Triple Super Phosphate (fertilizer)
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
WTD	Water Table Depth

1. Introduction

There is a growing international consensus on the need to mitigate global climate change. This was illustrated recently, when parties to the *United Nations Framework Convention on Climate Change* (UNFCCC) agreed to commit to an increase in mean surface temperature (MST) well below 2°C compared to pre-industrial levels. Moreover, the convention is 'urging efforts to limit the increase to 1.5°C' *(UNFCCC, 2015).* Environmental concerns that form the basis of this agreement are well founded scientifically. In their fifth assessment report, the *International Panel on Climate Change* (IPCC) estimates a MST increase of 3.7°C to 4.8°C in a business as usual (BAU) scenario. This overshoot of the 2°C limit would result in problems related to sea level rise, more extreme weather events, melting glaciers and ice caps, acidification of oceans and regional shifts of bio zones. Most of these aspects of climate change will persist for many centuries, and thus have an irreversible character *(IPCC, 2014).*

In order for national and international climate policies to be effective, they need to be based on sound science. Integrated assessment models (IAMs) can play an important role in this respect. IAMs describe the main processes in the interaction between human development and the natural environment. They provide insights in the long-term impacts of human activity on environmental aspects such as global climate change, air and water quality, water scarcity, biodiversity and the depletion of fossil resources (*Stehfest et al., 2014).* IAMs share the ability to compare plausible future scenarios and assess the effectivity of (packages of) policy measures. This makes them crucial tools in developing effective national and international policy.

In this line of thinking, the *Netherlands Environmental Assessment Agency* (PBL) developed the *IMAGE 3.0 framework*. This global IAM uses the energy system model *TIMER* to analyze long-term trends in region specific energy demand and supply. Final energy demand (FED) is already modeled in a technologically detailed way for many economic sectors. However, agriculture is still modeled using aggregated formulations *(Stehfest et al., 2014).* This generic way of modeling is prone to misinterpretation of historical trends; not fully able to grasp the role of structural changes (STR) and developments of specific energy consumption (SEC) in future projections *(van Vuuren et al., 2008).*

Modeling agricultural energy demand (AED) in a technologically detailed way allows for better interpretation, making more accurate energy demand projections possible. In addition, it enhances insight in the key drivers, variables and trends determining energy demand worldwide. Many of these insights are relevant to the so called 'water-energy-food nexus', which embodies the interrelationships between the use of water, the consumption of energy and the production of food. Increasing societal and scientific interest in the nexus makes modeling AED remarkably relevant.

As estimated in section (2.1), agricultural processes, including the production of synthetic fertilizers, currently account for 3.26% of grand total final energy demand worldwide. This translates to 2.1% of grand total CO_2 eq emissions and 8,6-10,4% of AFOLU (agriculture, forestry and land use) CO_2 eq emissions globally. This does not make the use of energy the most impactful agricultural activity regarding climate change. However, agricultural processes which are not related to energy use, including N_2O emissions from cultivated soil and NH_4 emission from rice field and livestock, are already modelled within the *IMAGE framework* in a technologically detailed way *(Stehfest et al., 2014)*. In contrast, agricultural energy demand is not. Moreover, no other institutes could be found which made detailed global AED projections that account for regional differences. A literature gap becomes apparent.

1.1 Goal and research questions

The main goal of this thesis is to gain insight in the long-term development of region specific agricultural energy demand (AED). The production of synthetic fertilizers is included in the AED, even though it is not accounted for by the agricultural sector in international statistics *(IEA Statistics, 2015)*. This inclusion allows for a more complete assessment of the energy that is consumed in the production of crops and livestock products. Consequently, in the wording of this report, wherever terms as 'AED' or 'agricultural processes' are used, synthetic fertilizers are included. When the term 'agricultural sector' is used specifically, only processes that are part of the *International Energy Agency* (IEA) agricultural sector are included. The focus is on two main agricultural processes; irrigation and synthetic fertilizer production. With an estimated 36,8% of current world AED, the production of synthetic fertilizers is a main energy demanding process (section 2.1). In addition, the global use of synthetic fertilizers is expected to grow significantly until 2050 due to population growth and shifts in cultivation methods *(Alexandratos and Bruinsma, 2012; IFA, 2009)*. The *IMAGE framework* provides suitable scenario dependent activity data in the form of regional consumption of nitrogen and phosphate fertilizers *(Stehfest et al., 2014)*. Considering the agricultural sector (thus excluding synthetic fertilizer production), irrigation and the use of mobile machinery (mainly tractors) are currently the most energy demanding processes *(Nan et al., 2012)*. Between these two, the *IMAGE framework* provides the most suitable activity data for irrigation in the form of regional water withdrawals, which are scenario dependent. This irrigation water use is specified per type of source withdrawn from. In addition, the framework determines irrigation water efficiency, which can be interpreted as the dominant type of irrigation system used in a region *(Stehfest et al., 2014)*. This is suited to be used as an energy intensity indicator for irrigation practices. For mobile machinery, the specific energy consumption is highly dependent on the type of crop cultivated. This crop specific energy consumption also differs significantly per region, due to varying methods of cultivation and access to machinery *(Sorensen et al., 2014; Spugnoli and Dainelli, 2012; Mileusnic et al., 2010; Williams et al., 2006)*. However, quantitative crop and region specific data is not abundant in literature for the current situation, let alone for future projections. This, together with the limited amount of time for this research project, is the reason energy demand for mobile machinery will not be modeled. Since the major share of final energy demand for livestock production is accounted for by the cultivation of feed crops, energy demands for the housing of cattle is not seen as a modeling priority. The processes irrigation and synthetic fertilizer production form the basis of a new *AED module,* which is incorporated in the *IMAGE framework*. During the development of this module, the following research question remains central:

What are the projected regional developments in direct final energy demand for the agricultural processes irrigation and synthetic fertilizer production during the 21st century?

This main research question is supported by three sub questions regarding the key aspects of final energy demand; the level of activity, the specific energy consumption of technological options able to provide this activity, and the structural mix of these options:

A. *What are the projected activity developments for agricultural irrigation and synthetic fertilizer production?*
B. *What are the projected developments in specific energy consumption for these processes?*
C. *What are the projected structural developments for these processes?*

Model runs are made for a new set of human development scenarios called the Shared Socioeconomic Pathways (SSPs). These include three plausible baseline scenarios and one that is constrained by a 2°C MST limit.

1.2 Research boundaries

The main boundaries are set by the IMAGE 3.0 umbrella framework. This implies a 1971-2100 timeframe, where the pre 2010 period is used for calibration with energy statistics. Geographically, all world countries are allocated to one of 26 world regions. Since the *AED module* is part of *TIMER's energy demand module*, final energy is considered rather than primary *(Stehfest et al., 2014).* Consequently, in the wording of this report, wherever terms such as 'energy demand' are used, they refer to final energy demand, unless stated otherwise. Only scope 1 'direct energy demand and emissions' are considered for both agricultural processes, as defined in the Greenhouse Gas Protocol *(WRI, 2011).*

1.3 Structure of the report

In section (2), the background to this research is set out. It consists of a brief exploration of current global AED, a description of relevant components within *IMAGE 3.0 framework*, and summaries of the four SSP narratives used for this research. Section (3) describes the methodological path the *AED module* follows to calculate regional and global final energy demand for irrigation, ammonia production and the production of other fertilizer types. Main module results for these agricultural processes are shown in section (4) and discussed in section (5). The latter section also examines whether or not the results correspond with the SSP narratives. In section (6), the main conclusions of this research are drawn and some policy recommendations are given. Finally, annex (6) provides an exploration on modeling the part of agricultural energy demand that is currently not covered by the *AED module*.

2. Background

2.1 Agricultural energy demand

Given the scope of this research, one cannot simply consult *IEA* statistics to determine current global AED. In these statistics, the agriculture sector covers direct energy demands for crop cultivation, livestock production and forestry. This includes main processes such as irrigation, use of mobile machinery and livestock management. However, the sector agriculture does not account for energy used in the production of synthetic fertilizers. Ammonia production is covered by the non-energy use sector, while other fertilizers are part of the chemical industry sector *(IEA statistics, 2015).* In the next two paragraphs, estimations are made for the 'current' situation using relevant percentages from multiple literature sources. Though these percentages refer to situations in various years between 2006 and 2010, they are all assumed to be applicable to the 'current' situation. This due to the lack of all relevant data for one specific year.

In 2008, world final energy demand (FED) of the agriculture sector was 7256 PJ *(IEA statistics, 2015).* Furthermore, an estimated 1,20% of grand total FED is accounted for by the fertilizer industry *(IFA, 2009). Of this,* 85% is used for the production of ammonia and the remainder for the production of other synthetic fertilizers *(IEA, 2007; IFA 2009 states similar percentages)*. Since world grand total FED was 351749 PJ in 2008, estimated FEDs in that year are 3588 PJ and 633 PJ for ammonia and other synthetic fertilizers respectively. Cumulated 2008 AED (thus including the sector agriculture and the synthetic fertilizer industry) is then 11477 PJ, covering 3.26% of grand total FED (also see figure 28).

This translates to 2.1% of world grand total CO_2 eq emissions, assuming that; a) AED also covered 3,26% of grand total FED in 2010; b) grand total CO_2 eq emissions were 49,0 Gt in 2010 *(IPCC, 2014)*; c) CO_2 eq emissions related to energy demand in were 31.2 Gt in 2010 *(EIA statistics, 2016);* and d) final AED is associated with the same direct and indirect emission factors as grand total FED. In perspective, AFOLU , which also includes agricultural and other land use emissions not related to energy, accounted for 20-24% of global CO_2 eq in 2010 *(IPCC, 2014)*. From this, one can estimate that 8,6 to 10,4% of global AFOLU emissions currently result from agricultural energy demands.

2.2 Place within the IMAGE 3.0 framework

Figure (2) shows the modular structure of *IMAGE 3.0*. The framework comprises several models that are connected through either hard links (direct data exchange) or soft links (indirect data exchange). The new *AED module* is basically a link between the existing models *IMAGE land* and *TIMER* (figure 1). The former provides all activity data for irrigation and synthetic fertilizers to the *AED module*. The module then determines the structural mix of available technological options to irrigate and produce fertilizers, as well as their specific energy consumptions, on the basis of literature finding and statistics. For this purpose also fuel price, carbon tax and electricity access data from the *TIMER* energy model is used. Subsequently, the *AED module* calculates demands for multiple final energy carriers and sends them to them to *TIMER,* which covers the supply dynamics of these carriers.

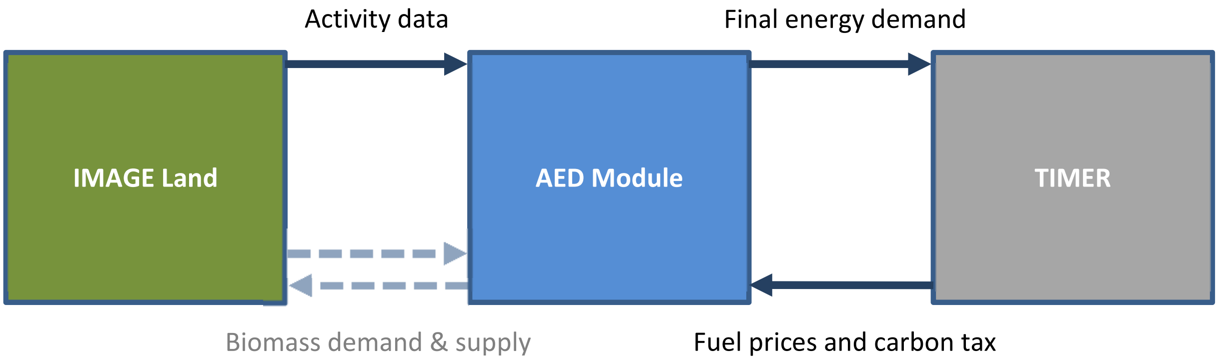

Figure 1: Interaction of variables between the new AED module and the existing models IMAGE land and TIMER. Dashed arrows indicate interactions that are expected to be incorporated in later stages of module development.

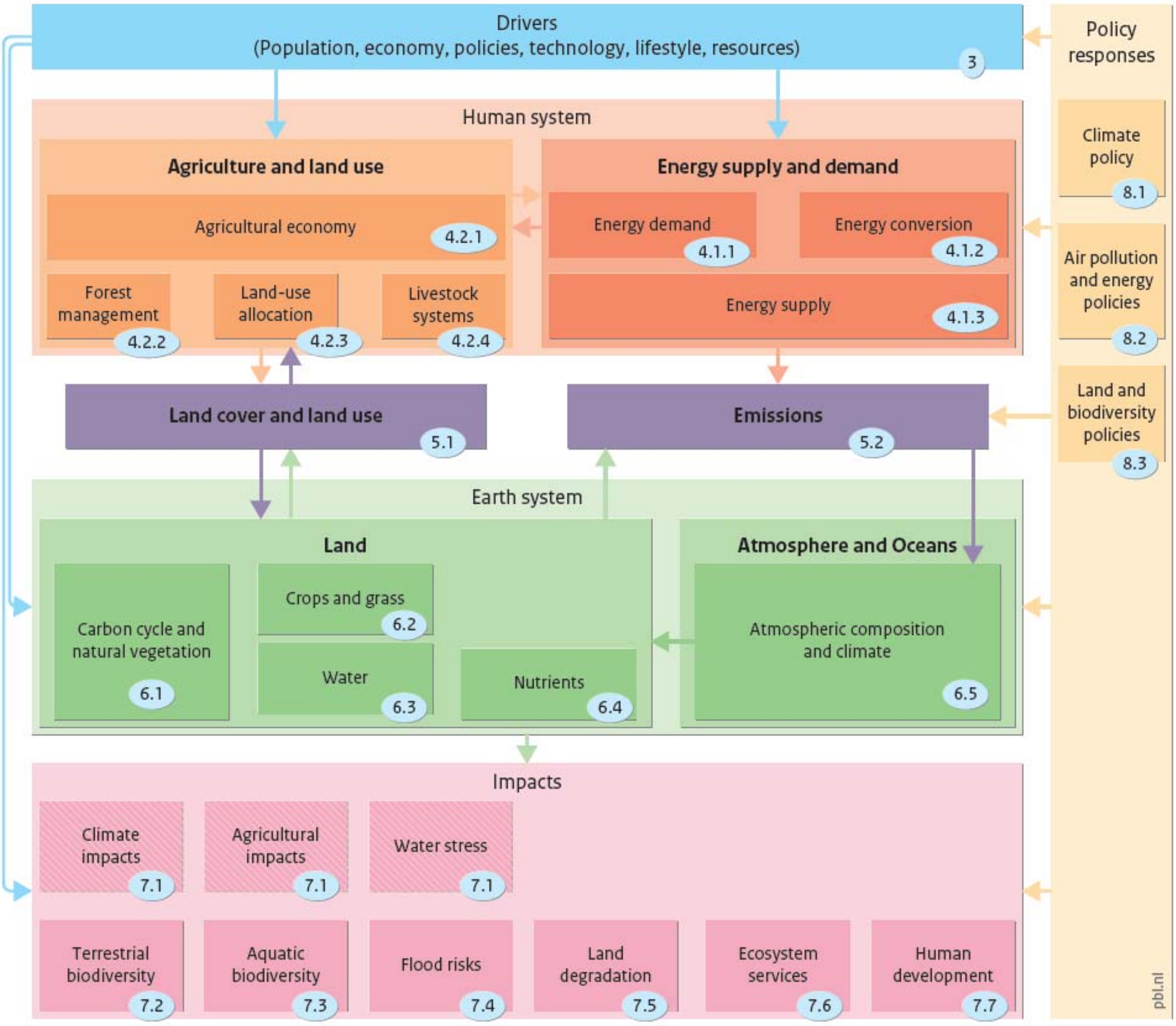

Figure 2: IMAGE 3.0 Framework (Stehfest et al., 2014).

2.2.1 IMAGE land

The *IMAGE land* model consists of the modules *MAGNET, Land Use* and *LPJml*. The agricultural economy module *MAGNET* determines regional demand for crops and livestock products on the basis of external drivers such as population, economy and lifestyle (figure 2, box 4.2.1). In order to meet these demands, the *Land Use module* assigns available land for agricultural production on a 0.5 degree resolution (boxes 4.2.3, 4.2.4 and 5.1). This strategic allocation considers grid specific potential crop yields and several sustainability factors. The *Land Use module* also determines regional fertilizer demands using statistics on nutrient efficiencies and their assumed scenario dependent developments. Agricultural irrigation water demands are calculated in the crop and vegetation module *LPJml* on a 0.5 degree resolution. This demand is based on crop water needs as well as grid variable precipitation, evaporation, runoff and availability of irrigation equipment *(Stehfest et al., 2014).* For the purpose of readability, the modules *MAGNET, Land Use* and *LPJml* are referred to as *IMAGE land* in the rest of this report.

2.2.2 TIMER

The *TIMER* energy model (figure 2, box 4.1) consists of three modules; *Energy Demand, Energy Conversion* and *Energy supply.* The *Energy Demand module* calculates final energy demand per economic sector, either in a technologically detailed way or using aggregated formulations (box 4.1.1). This is where the *AED module* is incorporated. Demands for eight types of energy carriers – including natural gas, coal, heavy oil, solid biomass and electricity – are then send to the *Energy conversion* (box 4.1.2) and *Energy supply* (box 4.1.3) modules. The former describes the way in which electricity is generated. The latter covers the production of the remaining energy carriers, as well as technological investment dynamics *(Stehfest et al., 2014)*. For readability purposes, the modules *Energy Demand, Energy Conversion* and *Energy supply* are referred to as *TIMER* in the rest of this report.

2.3 Shared Socioeconomic Pathways

The Shared Socioeconomic Pathways (SSP) are a set of future scenarios on global environmental change, combining the physical earth system and the socio-economic system. They are developed to provide insight in climate impacts and possible options for mitigation and adaption *(O' Neill et al., 2015).* In that respect, they enable an analysis of agriculture energy demand in the context of climate change and sustainable development. Note that the scenarios do not describe specific developments in agriculture. Rather, they provide more general narratives on population growth, equity within and between regions, (inter)national cooperation on sustainability issues, technological investments, preference for renewables and resulting challenges for climate mitigation and adaption. This makes them suitable for the analysis of a wide variety of human activities and subsequent social and environmental impacts. Several IAMs, including *IMAGE 3.0*, are currently used to form the backbone of this new generation of climate change research scenarios *(van Vuuren et al., 2014*).

The geographical scope and timeframe of the SSPs coincide with those of this research ; they cover the 21st century at the level of large world regions. This makes the interpretation of the narratives more straightforward. Since the scenarios together cover a wide range of plausible challenges regarding climate mitigation and adaption, it can help to determine the uncertainty of future AED developments. The SSPs are developed by an international collaboration of multidisciplinary researchers and experts. Therefore, they are expected to be widely used within the international climate research community. This makes comparison of projection from multiple IAMs possible, since there is no need to account for pathway differences. For example, when AED would be projected by another institute using the SSPs, outcomes deviating from the ones in this thesis are explained by the use of a different methodology, rather than the differences in scenario assumptions. Model runs for the *AED module* are made for the following SSP scenarios;

SSP1 Sustainability: This baseline scenario entails a global shift toward a more sustainable path, underlining societal development that respects environmental boundaries. Relatively low population growth and decreasing global iniquity result from educational and health investments. Increasingly effective cooperation between local, regional and international actors gradually improve the management of the world's commons. Investments in environmental technologies, together with tax structure changes, favor resource efficiency and the use of renewables. The economy is decreasingly focused on material growth. Relatively low energy demands lead to low challenges to mitigation. In addition, challenges to adaptation are low due to the increase in global equity and wealth *(O' Neill et al., 2015)*.

SSP2 Business as usual: In this baseline scenario, the world sees no notable shifts in socio-economic and technological trends from historical patterns. Moderate population growth and almost continuous global iniquity are explained by relatively low investments in education and health. Slow progress in local, regional and international cooperation leads to mediocre management of global commons. While technology improves gradually, no essential breakthroughs occur. Fossil fuels remain dominant, with no clear aversion towards unconventional sources. Together with unexceptional technological advances, the incapability to truly enhance global equity and social cohesion will lead to moderate challenges regarding mitigation and adaptation *(O' Neill et al., 2015).*

SSP3 Regional rivalry: Increasing nationalistic concerns about security and competiveness drive countries to focus on local issues, overlooking regional and global ones. Population growth is relatively high and iniquities are not resolved due to lack of international pursuit of sustainable development goals. Global institutions are feeble and small in number, reflecting low international priority to address environmental concerns. Investments in environmental technologies decline and consumption is material-intensive. The increasing reliance on fossil fuels will imply high challenges to mitigation. Challenges to adaption are also high due to restricted human development and low income growth *(O' Neill et al., 2015).*

RCP2.6 Two degrees: In terms of socio-economic developments, this mitigation target scenario follows the same pathway as SSP2 Business as usual. Therefore, it faces the same challenges regarding mitigation and adaption. However, the two degrees scenario imposes a pre-determined radiative forcing in 2100, namely 2.6 W/m^2. This corresponds with a mean surface temperature increase of no more than 2°C above preindustrial levels.

3. Methodology

Agricultural energy demand is modeled for each agricultural process (Pr), region (R) and year (Y) in accordance with the following equation:

$$FED_{Pr,R,Y} = ACT_{Pr,R,Y} * STR_{O,Pr,R,Y} * SEC_{O,Pr,R,Y} \quad (1)$$

Where 'FED' represents final energy demand, 'ACT' the total activity, 'STR' the shares in which this activity is covered by different available process options (subscript O), and 'SEC' the specific energy consumptions of these options.

In this chapter, each agricultural process (irrigation, ammonia production and other fertilizer production) is briefly introduced to get a feel for the important aspects involved and definitions used. Subsequently, the methodologies for ACT, STR, SEC and ED are elaborated upon in more detail.

Equation subscripts

AQ	Aquifer	P	Ammonia plant type
EC	Final energy carrier	Pr	Agricultural process
F	Fertilizer type	R	Region
GW	Groundwater	S	Irrigation withdrawal source
NG	Natural gas	Y	Year

3.1 Irrigation

Irrigated area roughly doubled in the past 50 years *(Jägermeyr et al., 2015; Siebert et al., 2015)* to 24% of world harvested cropland *(Portmann et al., 2010)*. Irrigation is the single largest user of freshwater, accounting for around 70% of global withdrawals *(Gleick at al., 2009).*

Systems that provide irrigation water are typically subdivided in two components; 'conveyance' and 'field application'. In the former, water is transported from a withdrawal source to the field. Subsequently, the water is distributed across the field in the latter. Main application systems are 'open canal surface', 'sprinkler' and 'drip', each with different irrigation water efficiencies (Ec) and energy demands *(Jägermeyr et al., 2015; Daccache et al., 2014; Rohwer et al., 2006)*. Regions that are currently dominated by surface systems are seen to gradually shift toward sprinkler systems (*AQUAstat; 2015; Fernández et al., 2014)*. Virtually all irrigation pumps are powered by either diesel or electric engines *(Xiaoxia, 2015; Daccache et al., 2014; Saddiqi et al., 2013; Shah et al, 2005)*.

3.1.1 Water withdrawals (ACT)

Irrigation water withdrawals are calculated by *IMAGE land* on a 0.5 degree resolution. Crop water needs are determined on the basis of crop characteristics, soil moisture and regional climate. Spread of the agricultural crop types are scenario dependent, as are climatic conditions. When soil moisture is insufficient to meet crop water needs and the given grid cell is fitted with irrigation equipment, irrigation takes place. Water is withdrawn from four possible sources with declining preference; local surface water; nearby reservoirs; renewable groundwater; and non-renewable aquifers *(Stehfest et al., 2014)*. Overall irrigation efficiency, which is the ratio between irrigation water plant uptake and water withdrawn, is based on so called Irrigation functional types (IFTs). For present day, each country is assigned one of four IFTs on the basis of *Food and Agriculture Organization of the United Nations* (FAO) irrigation system statistics *(Rohwer et al., 2006).*

Surface irrigation: This system has a relatively low field application water efficiency (Ef, 60.0%) due to high surface runoff, deep percolation and surface evaporation. It is assumed that surface irrigation systems are exclusively linked to gravity fed open canals for conveyance, which are characterized by a low conveyance water efficiency (Ec, 70.0%). Surface systems have the lowest overall water efficiency (Ep, 42.0%) *(Rohwer et al., 2006)*.

Sprinkler irrigation: The Ef of this system is intermediate (75.0%). Most losses occur through above-canopy sprinkling evaporations and crop interception losses. These systems are assumed to be connected to pressurized pipelines, having a high Ec (95.0%). The Ep is fairly high (71.3%) *(Rohwer et al., 2006).*

Drip irrigation: This system has a relatively high Ef (90%). Since water is applied directly at the root-zone of the crops, evaporation losses are kept at a minimum. Drip systems are also assumed to be linked to pressurized pipelines, sharing the high Ec (95%). These systems see the highest Ep (85.5%) *(Rohwer et al., 2006).*

Mixed irrigation: This is a 50/50 mixture of the above mentioned surface and sprinkler systems. Ef, Ec and Ep are 67.5%, 82.5% and 55.7% respectively *(Rohwer et al., 2006).*

Each scenario applies a different linear change of field, conveyance and overall efficiency for the period 2005-2030. Total water withdrawals are calculated as follows:

$$Withdrawal_{S,R,Y} = \frac{Crop\ water\ need\ _{R,Y} * Source\ share_{S}}{Ef_{R,Y} * Ec_{R,Y}} \quad (2)$$

3.1.2 Specific energy consumption (STR and SEC)

The *AED module* applies the following main equation, as used by *Daccache et al. (2014*) and *Pradeleix et al. (2015)*, to determine specific energy consumption for irrigation (SECirr):

$$SECirr = \frac{\mathrm{g}*(\mathrm{Lift}+\mathrm{Hmin}+\mathrm{f})}{\mu_{pump} * \mu_{engine}} \quad (3)$$

Where ‘g’ is the average gravitational field of earth (9,81m/s^2), ‘Lift’ the extraction depth of the well (m), ‘Hmin’ the minimal operational pressure of the field application system (m) and ‘f’ the frictional losses (m) associated within piped application systems.

Pump and engine efficiencies

Pump and electric and diesel engine efficiencies are assumed to be 80%, 90% and 40% respectively *(Daccache et al., 2014)*. In comparison, the *Food and Agricultural Organization of the United Nations* (FAO) state more pessimistic efficiency ranges for pumps (50-80%) and electrical engines (70-90%), while being more optimistic for diesel engines (50-75%) *(Phocaides, 2000).*

Share of electric and diesel engines

Literature on region specific ratios of diesel / electrical engines used to drive irrigation pumps are scarce and inadequate to construct a decent data set. However, several references state that when easy access to the electricity network is present, the use of electric engines is generally preferred by farmers. Main reasons for this are; reduced cost due to higher efficiencies; lower maintenance requirements; and more easily implemented pump controls *(NSW Farmers Association, 2013; Shah, 2008).* Building upon this finding, the *AED module* uses data on rural electricity access to determine the share of irrigation pumps driven by electric engines:

$$Share\ carrier_{Electricity,R,Y} = Rural\ electricity\ access_{R,Y} * Preference\ factor_{R,Y} \quad (4)$$

Where 'rural electricity access', originating from the *TIMER model*, indicates the region specific share of rural population which has access to electricity. At the moment this data is the same for all scenarios, but is expected to be made scenario specific in the nearby future. The 'preference factor' is adjusted so that shares for the period 2000-2015 match values given in literature as close as possible *(Xiaoxia et al., 2015, Shah et al., 2005)*. For SSP2, SSP3 and RCP2.6 the electricity preference factor is kept static, while it increases linearly during the period 2010-2050 in the SSP1 sustainability scenario. This reflects the higher preference for renewables, which are more easily implemented when electricity is demanded rather than diesel.

SEC Conveyance

Following *Daccache (2014),* the *AED module* assumes that the sources 'local' and 'reservoir' are, on average, on the same height as the agricultural field to which they supply water. Therefore, only water withdrawn from 'groundwater' and 'aquifers' require energy to be lifted to field level. As becomes clear from equation (3), the energy required for this vertical pumping is linearly proportional to the extraction depth.

For groundwater**,** this depth is based on a water table depth (WTD) map generated by *Fan et al. (2013 see figure 3)* and an irrigated area map produced by the in the *IMAGE land model.* For each region, an average groundwater extraction depth is determined for the irrigated area:

$$Extraction\ depth_{GW,R} = \frac{\sum_{irr\ cells,R} (Area\ cell * WTD\ cell)}{\sum_{irr\ cells,R} Area\ cell} \quad (5)$$

For aquifers, the extraction depth is based on aquifer depths found in literature *(Zekster and Everett, 2014; Steenbergen et al, 2014; Currel et al., 2012; Dhiman, 2012; UNESCO, 2009; Giordano and Villholth, 2007; Gehrels et al., 2001)* . The articles should clearly state that an aquifer is at least partly used for agricultural irrigation purposes. Aquifers which are solely used for drinking water or industrial purposes are not taken into account. When an article states a depth range for a certain aquifer, the lower end is used. This is based on the assumption that the piezometric surface is the same in the entire aquifer, so water will autonomously rise in the tube well to the lower end depth range. For regions with sufficient data availability, the extraction depth is the average of all aquifers in that region:

$$Extraction\ depth_{AQ,R} = \frac{\sum_{AQs,R} Depth_{AQ}}{N_{AQs,R}} \quad (6)$$

For regions with insufficient data availability, aquifer extraction depth is assumed to be the average of those of the data rich regions.

Due to time limitations, it is assumed that regional groundwater and aquifer depths are static for the entire modelling period. Combining equations (5 and 6) gives the specific energy consumption for vertical conveyance:

$$SECconv_{EC,S,R,Y} = \frac{g * Extraction\ depth_{S,R} * Share\ carrier_{C,R,Y}}{\mu\ pump * \mu\ engine_{EC}} \tag{7}$$

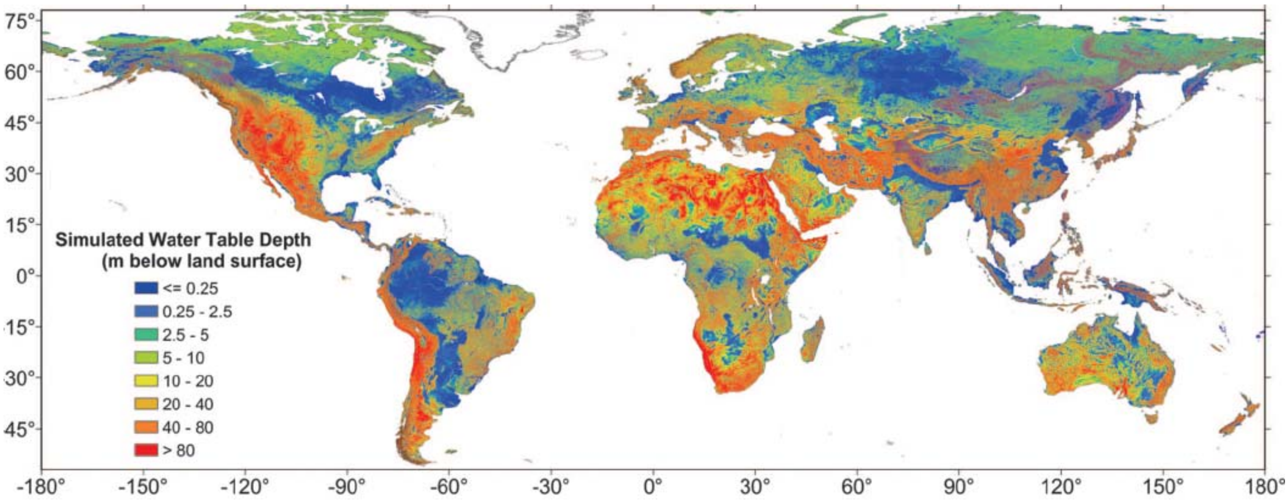

Figure 3. Simulated water table depth (Fan et al., 2013)

SEC Field application

Not only are irrigation systems characterized by specific water efficiencies, they also have typical field application SECs. As shown in equation (3), this specific energy consumption is linearly proportional to 'Hmin', the minimal operational pressure of a system. The *AED module* assumes a typical Hmin of 30.6m and 10.2m for sprinkler and drip systems respectively *(Daccache et al., 2014)*. In line with this, *FAO* reports respective values of 20.4-35,7m and 10.2m *(FAO, 2000)*. Furthermore, *Michael (2009)* states a range of 3.1-15.3m for drip systems. Surface water systems are assumed to demand no energy for field application, since they are gravity fed. Subsequently, plotting Ep for each irrigation system against their respective field application SECs produces figure (4) on the next page.

A parabolic relationship between Ep and field SEC becomes apparent; a shift from surface to sprinkler systems is accompanied by an increase in energy intensity, as shift from sprinkler to drip systems by a decrease. Inclusion of pump and engine efficiencies then yields the following SEC field application equation:

$$SECfield_{EC,R,Y} = \frac{\left(13897 * Ep_{R,Y}{}^{3} + 21565 * Ep_{R,Y}{}^{2} - 9702 * Ep_{R,Y} + 1338{,}8\right)}{\mu\ pump * \mu\ engine_{EC}} \tag{8}$$

Note that the driver for this energy intensity change is purely structural; it is only related to shifts in the irrigation systems mix since pump and engine efficiencies are kept static during the entire modelling period.

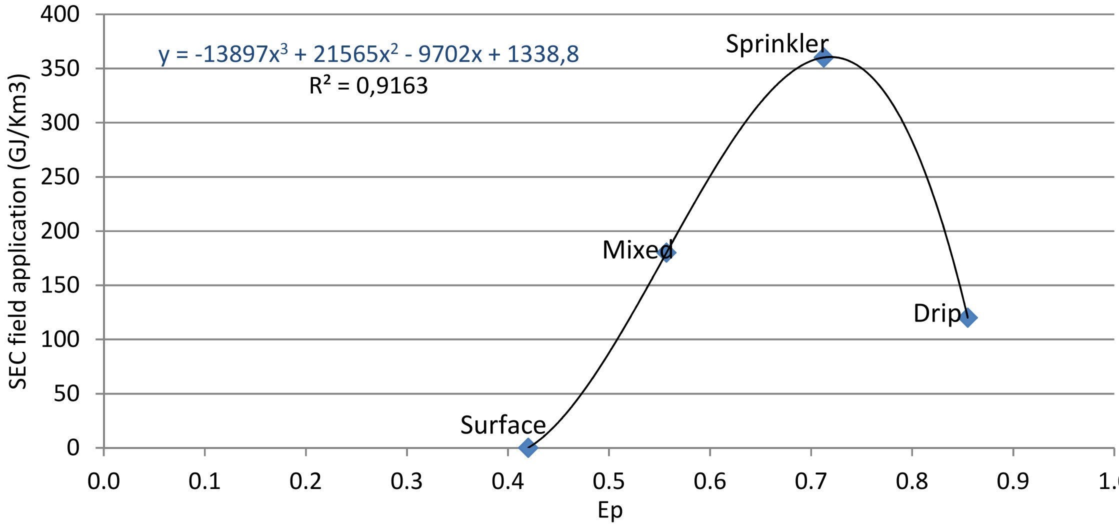

Figure 4: Ep versus SEC field application (GJ/km3), excluding pump and engine efficiencies.

3.1.3 Final energy demand (FED)

Equations (3, 7 and 8) are combined to determine regional final energy demand for irrigation:

$$Irrigation\ FED_{EC,S,R,Y} = \sum_{GW}^{AQ}(Withdrawal_{S,R,Y} * SECconv_{EC,S,R,Y}) + \sum_{S}(Withdrawal_{S,R,Y} * Ec_{R,Y} * SECfield_{EC,R,Y}) \quad (9)$$

Where the first part (green) accounts for groundwater and aquifer pumping, and the second (blue) for field application. Note the multiplication with Ec in the latter part, which reflects that not all withdrawn irrigation water reaches the field.

3.2 Ammonia production

Ammonia production dominates final energy demand in the fertilizer industry, as discussed in section (2.1). The production chains of virtually all nitrogen fertilizers start with the synthesis of ammonia *(IFA, 2009).* Due to the high production volumes and energy demands, ammonia is modeled separately and in more detail than the other fertilizer types.

Globally, ammonia is currently largely produced by *natural gas plants* (67%), for a significant part by *coal plants* (27%) and for a smaller part by light and heavy *oil plants* (5%) *(IFA, 2009)*. *Biomass plants* are seen as a viable option to achieve significant reduction in net CO_2 emissions *(IPCC, 2007)*.

Ammonia is produced in two succeeding steps; *hydrogen synthesis* and *ammonia synthesis*. In the first step a hydro-carbon feedstock is reduced to hydrogen, generating an almost pure stream of CO_2. In natural gas plants, methane is reduced by a steam reforming process. In other plant types coal, heavy oil or solid biomass is reduced by a partial oxidation process. The second step is basically the same for all plant types; hydrogen is reacted with nitrogen in a catalytic process known as the Haber-Bosch process. This process demands process energy rather than a hydro-carbon feedstock. Therefore, the generated CO_2 stream is not pure, rather comparable to that generated by fossil fueled power plants *(Kermeli et al, 2014)*.

The almost pure feedstock stream of CO_2 generated in the first production step is well suited for carbon capture and storage (CCS). In contrast to non-pure streams, no purification process is required, reducing the overall costs of CCS. Today, CCS is not yet used as a mitigation option in ammonia production. However, considering current research and development (R&D), the technology should be implemented before 2030 and wide-spread after that date *(IPCC, 2007; IPCC, 2005)*.

3.2.1 Production (ACT)

The *IMAGE land model* determines grand total nitrogen and phosphate fertilizer consumption on a 0.5 degree resolution. Use of synthetic fertilizers is based on historic nutrient efficiencies from *FAO*, indicating dry matter crop production per kg fertilizer applied. Fertilizer inputs exceed crop uptake in some regions, while growth is limited due to a deficit in others. Synthetic fertilizer consumption may be reduced due to application of manure, which is calculated from animal stocks and excretion rates *(Stehfest et al., 2014)*.

Since the *AED module* concerns fertilizer production rather than consumption, global trade matrices for grand total nitrogen and phosphate fertilizers are constructed using statistics from the *International fertilizer association (IFA statistics, 2015)*. First, country production and consumption values are summed per region, building on the assumption that trade within a region is preferred over trade with other regions. Secondly, fertilizer demand is met within a region as much as possible. This forms two types of regions; net exporters which have a production surplus after meeting their own demand; and net importers which are unable to fully meet their demand autonomously. The deficits of the net importers are produced by the net exporters linearly proportional to their respective production surpluses. This reflects the assumption that no economic or political preferences exist in choosing a global trade partner. For the historical period, trade matrices are produced with a 10 year interval until 2013. After 2013, they are kept constant.

Since the production chain of virtually all nitrogen fertilizers start with the synthesis of ammonia, the regional production of ammonia is calculated as follows:

$$Prod\ NH3_{R,Y} = Prod\ grand\ total\ Nfert_{R,Y} * \frac{Mass_{NH3}}{Mass_N} \quad (10)$$

3.2.2 Specific energy consumption (STR and SEC)

In the *AED module*, ammonia is produced by a mix of four main plant types; natural gas; coal; heavy oil; and solid biomass fed. Each is characterized by specific investment and O&M costs, SECs, emission factors and 'feedstock energy' to 'process energy' ratios. Additionally, each main plant type can be equipped with a CCS unit. This add-on significantly reduces net CO_2 emissions, yet involves CCS costs and slightly increased energy intensities.

Market shares

At the heart of the ammonia methodology is a multinomial logit equation, which assigns market shares to plant types on the basis of their relative expected costs:

$$MS_{P,R,Y} = \frac{e^{\lambda * Exp.LcoNH3_{P,R,Y} * Pref\ factor_{P,R,Y}}}{\sum_P e^{\lambda * Exp.LcoNH3_{P,R,Y} * Pref\ factor_{P,R,Y}}} \quad (11)$$

Where 'MS' is the assigned market share (%), 'Exp. $LcoNH_3$' the expected production cost of ammonia ($/$tNH_3$) and λ a logit parameter which determines the sensitivity of markets to price differences. A 'preference factor' is introduced to calibrate current market shares to values stated by the *International Fertilizer Association (IFA, 2009)*. It reflects region specific factors which are not directly related to $LcoNH_3$, such as preference for domestic energy supply, the state and extent of current carrier distribution systems and various political choices. For SSP2 and RCP2.6, preferences are kept static for the projection period. Biomass preference is linearly increased in SSP1 over the period 2010-2050, while SSP3 sees a decline. $LcoNH_3$ is determined using an adapted levelised cost equation from *Blok (2009):*

$$Exp.LcoNH3_{P,R,Y} = \frac{Inv_P * \alpha + O\&M_P + Fuel\ costs_{P,R,Y} + CO2\ tax_{P,R,Y} + CCS\ costs_{P,Y}}{Exp.NH3\ prod._P} \quad (12)$$

Where; 'Inv' is the investment costs ($); 'α' the capital recovery factor, 'O&M' the operation and maintenance costs ($/yr), 'Fuel costs' the costs associated with final energy carrier consumption ($/yr), '$CO_2$ tax' the costs arising from carbon taxes, and 'Exp.NH_3 prod' the expected ammonia production (tNH_3/yr). In the calculation, a typical capacity of 0.5475 MT/yr *(UNIDO, 1998; IPCC, 2007).* An average capacity factor of 0.90 *(Daioglou et al., 2013; Weiss et al., 2008)* and a lifetime of 30 years *(Ruijven et al., 2007; Bartels, 2008)* is assumed for all plant types. Plant specific investment costs are taken from *UNIDO (1998)*; namely 210, 420 and 336 m$ for natural gas, coal and heavy oil plants respectively. Other literature sources state relative investment costs by and large in line with these values *(IPPC, 2007; EFMA, 2000)*. Due to the lack of data, biomass plants are assumed to have the same investment costs as coal plants, since they entail very similar production processes. O&M is assumed to be 5% of investment costs per year, following *Mueller-Langer et al (2007)* who estimated this for hydrogen production plants. Specific percentages for ammonia plants where not found in literature. Discount rates are set to 0.05.

Expected fuel costs are the product of expected energy demand (GJ/yr) and expected fuel prices ($/GJ), which are in turn determined in the *TIMER model (Stehfest et al., 2014)*:

$$Fuel\ costs_{P,R,Y} = Exp.ED_{P,Y} * Exp.fuel\ price_{P,R,Y} \quad (13)$$

$$Exp.ED_{P,Y} = Cap_P * Cap.fact. * \frac{SEC_{dynP,Y}}{1 - \mu\ loss\ CCS_P} \quad (14)$$

Where; 'Cap' is the plant production capacity (tNH_3/yr) and 'Cap Fact' the expected capacity factor (%). 'μ loss CCS' covers the efficiency penalty associated with CCS add-ons; assumed 2%, 3%, 2% and 3% for natural gas, coal, heavy oil and biomass plants respectively *(Ruijven, 2007).* A learning curve describes the relationship between SEC natural gas (GJ/tNH_3) and global historical cumulative ammonia production volumes *(Ramirez Ramirez and Worrel, 2005):*

$$SECdyn_{NG,Y} = \left(23.3 + 317.12 * Hist.NH3\ prod_{world,Y}{}^{-0.3790}\right) * \frac{Mass_N}{Mass_{NH3}} \quad (15)$$

Production volumes of ammonia for non-fertilizer purposes also contribute to 'Hist.NH_3 prod'. These are assumed to be 20% of total volumes during the entire modelling period, based on *IFA (2009)* and *IPPC*

(2007). Furthermore, the assumption is made that plant type SECs relative to each other are constant during the whole modelling period:

$$SECdyn_{P,Y} = SECdyn_{NG,Y} * SEC\ relative_P \tag{16}$$

In this way all plant types learn, decreasing energy intensities with increased cumulative ammonia production. Relative SECs are assumed to be 1.00, 1.47, 1.21 and 1.50 for natural gas, coal, heavy oil and biomass plants respectively *(Neelis et al., 2005)*. Along these lines, *IFA* reports typical values of 1.00, 1.50 and 1.35 for natural gas, coal and heavy oil *(IFA, 2009)*.

Expected CCS costs are only determined for plants equipped with a CCS unit:

$$CCS\ costs_{P,Y} = Exp.ED_{P,Y} * EF\ gross_P * CO2pure_P * CCSunit_P * CCS\ price \tag{17}$$

Where *EF* gross is the energy carrier emission factor (tCO_2/GJ fuel) and 'CO_2 pure' the share of CO_2 that is emitted as an almost pure stream (see introduction of section 3.2). Shares for natural gas and coal plants are taken from *IFA (2009);* 67% and 75% respectively. Since they all entail a partial oxidation process for hydrogen synthesis, heavy oil and biomass plants are assumed to have the same share of CO_2 pure as coal plants. *CCS unit* takes value 1 if the plant is equipped with a CCS add-on and value 0 when it is not. In the *AED module*, a region can only build new CCS equipped plants when the share of CCS plants in its active standing capacity is lower than 50%. This restriction is based on the finding that, globally, an estimated 50% of the pure CO_2 stream from ammonia production is currently used for the production of Urea and other industrial processes *(IPPC, 2007)*.

Expected CO_2 tax (\$/yr) is proportional to the net CO_2emitted to the atmosphere and a scenario specific carbon tax:

$$CO2\ tax_{P,R,Y} = (Exp.\ ED_{P,Y} * EFnet_{P,R} - Exp.\ ED_{P,Y} * EFgross_{P,R} * CCSunit_P * CO2pure_P) * Exp.CO2\ tax_{R,Y} \tag{18}$$

Where the first part of the emission calculation (green) indicates net CO_2generated and the second (blue) the amount of CO_2that is captured and stored. Note that the first part uses a net emission factor. This differs from the gross factor only for biomass plants, where it is lower due to CO_2plant uptake during the production phase of the solid biomass. This region and scenario specific 'EF net' is determined in the *TIMER model.*

Plant construction & depreciation

Once the market shares are determined, the *AED module* builds a mix of ammonia plants types in each region. The total capacity constructed (tNH_3/yr) dependents on total needed capacity and the total standing plant capacity which is already present:

$$Cap\ construction\ tot_{R,Y} = MAX\ ((Cap\ needed\ tot._{R,Y} - Cap\ standing\ tot._{R,Y}),0) \tag{19}$$

Where an extra 10% back-up is assumed for the needed capacity:

$$Cap\ needed\ tot_{R,Y} = NH3\ prod._{R,Y} * \ (1 + Backup\ factor) \tag{20}$$

Total standing plant capacity is in turn obtained by summing the constructed capacity of the last 29 years, excluding the present one (since no construction has taken place yet):

$$Cap\ standing\ tot._{R,Y} = \sum_{Y-29}^{Y-1} Cap\ construction\ tot_{R,Y} \tag{21}$$

This implicates that constructed capacity is depreciated after 30 years, the assumed plant lifetime. The initial capacity, which the module constructs in 1971, is treated somewhat differently. Instead of being demolished all at once in 2000, it is linearly depreciated during the 1971-2000 period. This imitates that most of the initial capacity is constructed before 1971, implying earlier depreciation. Next, construction per plant type is the product of total constructed capacity and the market shares determined earlier:

$$Cap\ construction_{P,R,Y} = Cap.construction\ tot._{R,Y} * MS_{P,R,Y} \tag{22}$$

The capacity which is active after the construction and depreciation phase is then:

$$Cap\ active_{P,R,Y} = \sum_{Y-29}^{Y} Cap\ construction_{P,R,Y} \tag{23}$$

Average specific energy consumption
An average SEC per plant type is determined for the active capacity, assuming that capacity constructed in each year is dispatched equally (%):

$$SEC\ av_{P,R,Y} = \frac{\sum_{Y-29}^{Y}(Cap\ construction_{P,R,Y} * SECdyn_{P,Y})}{Cap.active_{P,R,Y}} \tag{24}$$

In this way, the average SEC for each plant type follows its respective dynamic SEC with a delay; the effect of current energy intensities improvements (SECdyn) are dampened by the higher intensities of the older but still active capacity.

3.2.3 Final energy demand (FED)

The dispatch (%) is the division of total ammonia production by the total active capacity:

$$Dispatch_{R,Y} = \frac{NH3\ prod\ tot_{R,Y}}{Cap\ active\ tot_{R,Y}} \tag{25}$$

Combining equations (23, 24 and 25) then yields final energy demand per plant type:

$$FED_{P,R,Y} = \ Cap\ active_{P,R,Y} * Dispatch_{R,Y} * SEC\ av_{P,R,Y} \tag{26}$$

The resulting net CO_2emissions are determined in a similar way as in equation (18):

$$CO2\ emm\ net_{P,R,Y} = ED_{P,R,Y} * EFnet_{P,R} - ED_{P,R,Y} * EFgross_P * CCSunit_P * CO2pure_P \quad (27)$$

Where again the former part (green) indicates net CO_2 generated and the latter (blue) the absolute amount of CO_2 that is captured and stored.

3.3 Production of other fertilizers

Part of the produced ammonia is applied directly to the soil. However, the largest part is processed further into other nitrogen and complex fertilizers. Most important are; ammonium Nitrate (AN), calcium ammonium nitrate (CAN), urea (urea) and nitrogen phosphate potash (NPK). Furthermore, significant energy is demanded for the production of several phosphate fertilizer types; phosphate potash (PK), ammonium phosphate (AP), single super phosphate (SSP) and triple super phosphate (TSP) *(IFA statistics, 2015)*. Because only an estimated 15% of global fertilizer industry energy demand is accounted for by non-ammonia fertilizers *(IEA, 2007)*, the *AED module* models them in less detail.

3.3.1 Other fertilizer production (ACT)

The *IMAGE land model* determines grand total nitrogen and phosphate fertilizer consumption, but does not distinguish between types. Therefore, the *AED module* uses fertilizer type consumption statics from the *International Fertilizer Association* (IFA) to determine shares per region *(IFA statistics, 2015)*. First, country statistics are aggregated to *TIMER* regional level*.* Then *IFA* fertilizer type consumption values are divided by their respective *IFA* grand total consumption values to obtain the consumption shares:

$$Consumption\ share_{F,R,Y} = \frac{IFA\ fert\ type\ consumption_{F,R,Y}}{IFA\ grand\ total\ consumption_{R,Y}} \quad (28)$$

This is done separately for nitrogen subtypes (which are divided by grand total nitrogen production) and phosphate types (which are divided by grand total phosphate production). The fertilizer type mix evolves during the historical period and is assumed to be static from 2013 onward. Once the shares are determined, absolute fertilizer type consumption (tN or tP2O5/yr) is calculated:

$$Fert\ type\ consumption_{F,R,Y} = Grand\ total\ consumption_{R,Y} * Consumption\ \ share_{F,R,Y} \quad (29)$$

Finally, fertilizer type consumption is converted to production via the same methodology as described in section (3.2.1.).

3.3.2 Specific energy consumption (SEC)

World average gross energy requirements (GER) for AN, CAN, urea, PK, AP, SSP, TSP and NPK are obtained from *Ramirez Ramirez and Worrel (2005)* for the period 1970-2003. Since the energy requirements for ammonia production are already accounted for in section (3.2), ammonia SEC is detracted from the GER of all *nitrogen* fertilizer types to obtain their respective SEC. In other words, the ammonia synthesis step is ‘removed’ from the nitrogen fertilizer production chains. Naturally, this is not done for the phosphate subtypes, since their production chains do not involve the synthesis of ammonia. Therefore their SEC equals their GER. From 2003 onward, SEC for all fertilizer types are kept constant. Due to time limitations and low data availability, the *AED module* assumes that the same regional mix of final energy carriers is used for other fertilizer types and ammonia production.

3.3.3 Final energy demand (FED)

The final energy demand for the production of each other fertilizer type is simply the product of their production volume and respective specific energy consumption:

$$FED\ fert\ type_{F,R,Y} = Production\ fert\ type_{F,R,Y} * SEC\ fert\ type_{F,Y} \tag{30}$$

The mix of final energy carriers used to meet this energy demand is assumed to be the same as the mix for ammonia production:

$$FED\ energy\ carrier_{EC,R,Y} = \sum_F (EDfert\ type_{F,R,Y}) * \frac{NH3\ ED_{EC,R,Y}}{NH3\ ED\ tot_{R,Y}} \tag{31}$$

This rough assumption, which might not entirely reflect reality, is made for two reasons; limited time; and the relatively low global energy demand for non-ammonia fertilizers.

4. Results

4.1 Irrigation

This section shows the main results for irrigation. First, irrigation water withdrawals are dealt with. Then, structural changes in final energy carrier mix are described. This is followed by developments in conveyance and field application specific energy consumption. The section ends with the main findings considering final energy demands. Each aspect is first treated globally, then regionally.

4.1.1 Withdrawals (ACT)

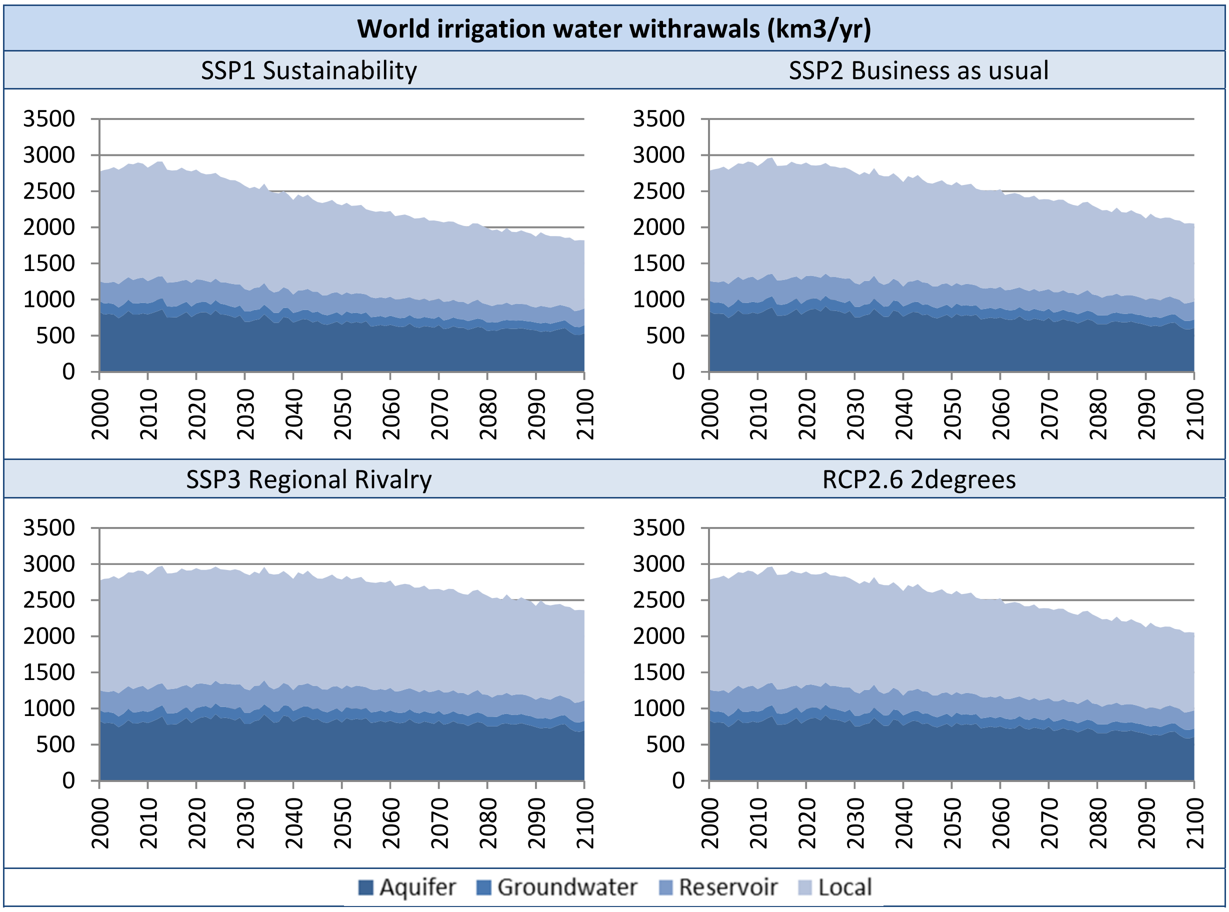

Figure 5: World Irrigation water withdrawals for SSP1, SSP2, SSP3 and RCP2.6 (km3/yr).

In all scenarios world withdrawals peak around 2010, then gradually decrease toward 2100 (figure 5). This decline is a result of only marginal irrigation area growth combined with water efficiency increases during the period 2005-2030. Withdrawals from local surface water are dominant, followed by aquifers, nearby reservoirs and renewable groundwater; local surface water is highly available, but reservoirs and groundwater are not. Therefore the *IMAGE land* model switches to the least favorable source, aquifers, in many cases. SSP1, which is assumed to have the highest increase in Ep, sees the highest decrease in withdrawals. In contrast, SSP3 sees only marginal decreases due to a lower assumed Ep increase.

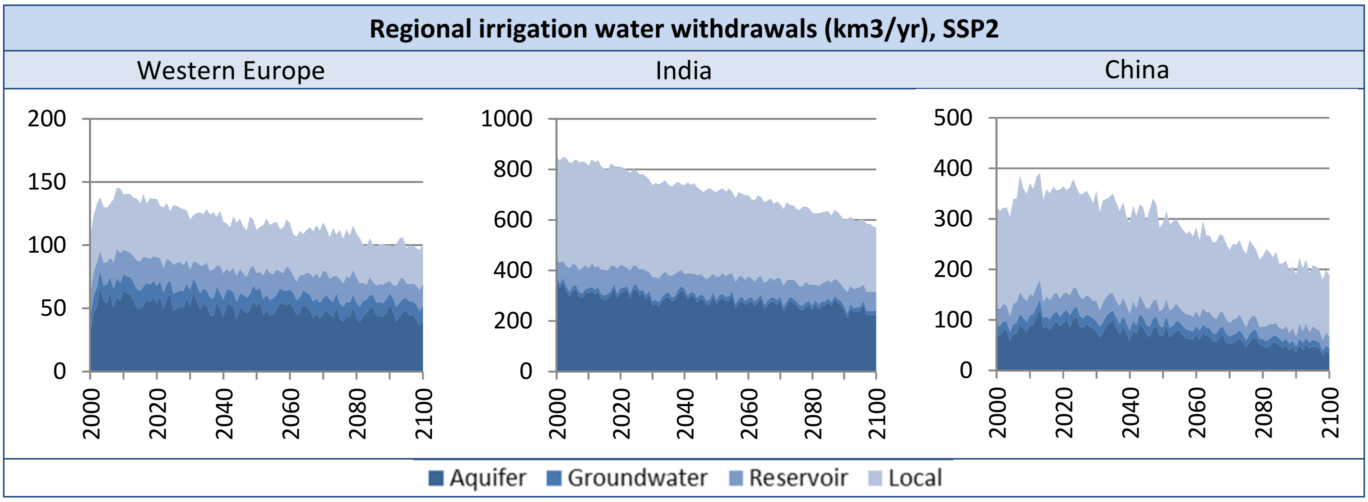

Figure 6: Regional irrigation water withdrawals for SSP2 (km3/yr). Mind the different axis settings.

India is the highest withdrawing region in the world (figure 6). This could be explained by a combination of large local food demand, high agricultural activity, seasonal droughts and relatively low water efficiency. In China, local withdrawals are very dominant, while they are roughly equal to local withdrawals in Western Europe. Apparently, China has high local surface water availability.

4.1.2 Diesel versus electricity (STR)

Since the *AED module* assumes an increasing electricity preference factor in SSP1, this scenario shows a larger increase in electric pump application than the others (figure 7). Nevertheless, the other scenarios also see an increase in electrical pumps because of global rural access to electricity growth, which is assumed the same in all scenarios.

Because present day electricity access already approaches 100% in OECD regions like Western Europe, they show only marginal increases in electric pump deployment (figure 6). In contrast, developing regions such as India see more drastic transitions since they have a sharp increase in rural electricity access.

4.1.3 Groundwater and aquifer extraction (SEC)

In all regions, aquifers are situated far below their respective groundwater tables (Table 1). The deepest groundwater tables are found in Southern Africa (10) and Pakistan (25), while the lowest are found in Russia (16) and Western Africa (8). Western Europe (11) and Western Africa (8) have the deepest aquifers, whereas India (18) and the USA (2) have the shallowest. Many regions share the global average aquifer depth of 90.8 meter since no specific data could be obtained. As is described in section (3.2.2), energy demand for vertical conveyance is directly proportional to the extraction depth; it costs 9.81 GJ/km3 to pump up water one meter, excluding pump and engine efficiencies.

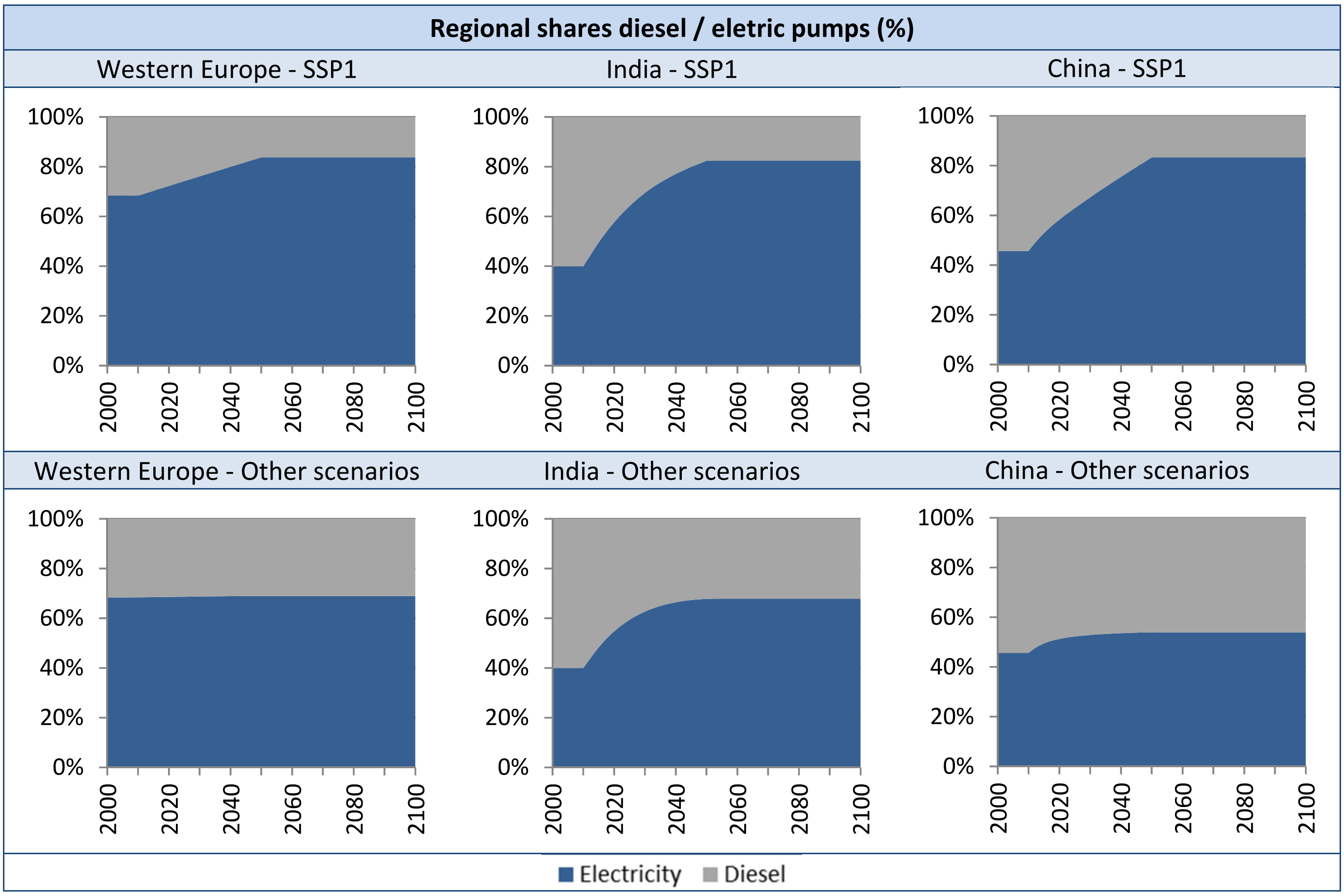

Figure 7: Regional shares of diesel and electric engines used to drive irrigation pumps (%).

Region	1	2	3	4	5	6	7	8	9
GW depth (m)	15.2	30.7	42.8	20.2	21.1	31.9	45.2	13.6	28.6
AQ depth (m)	75.0	56.7	60.0	100.0	85.0	88.3	90.8	146.7	90.8
Region	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
GW depth (m)	55.5	24.6	18.5	42.4	17.7	22.5	12.8	41.2	19.3
AQ depth (m)	90.8	210.0	90.8	90.8	90.8	90.8	90.8	90.8	68.9
Region	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	
GW depth (m)	31.6	30.1	23.6	15.1	25.0	27.9	43.5	24.7	
AQ depth (m)	90.8	73.5	90.8	90.8	90.8	90.8	90.8	90.8	

Table 1: Regional groundwater and aquifer extraction depths (m). Equal for all scenarios.

4.1.4 SEC field application (STR)

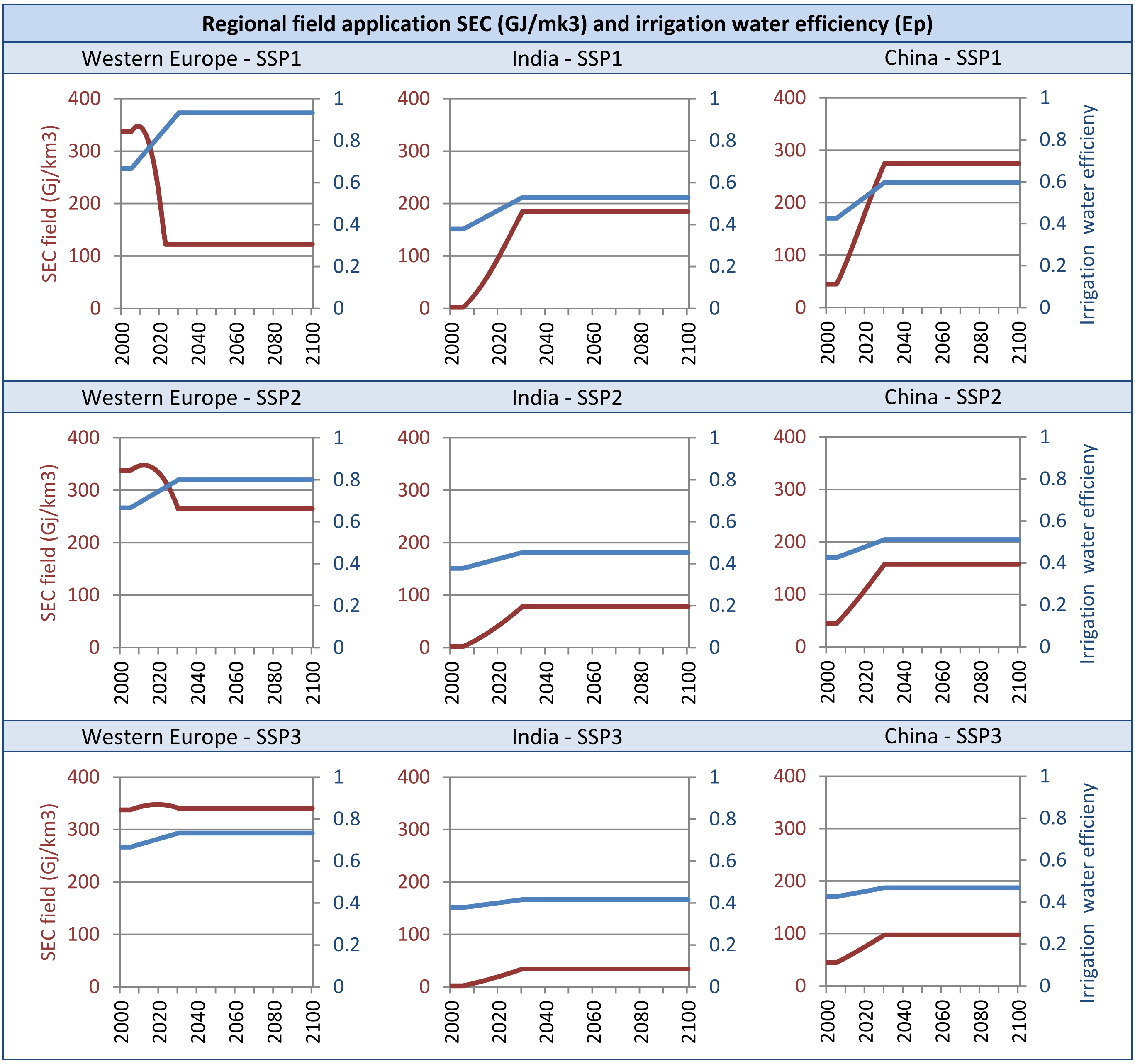

Figure 8: Regional SEC field application (red lines, GJ/km3) versus Ep: irrigation water efficiency (blue lines, %).

In all regions, irrigation project water efficiency (Ep) increases the most for SSP1, followed by SSP2 and SSP3 (figure 8). As explained in section (3.2.2), an Ep increase reflects a shift in irrigation system mix from open canal surface to sprinkler to drip respectively. Western Europe shifts from a sprinkler dominated mix to one where more drip systems are present, hence its field application SEC declines in all scenarios but SSP3. Both India and China shift from a surface dominated mix to one where sprinklers become more dominant. Therefore, their field application SECs increase, sometimes more sharply than others, in all scenarios. As a rule of thumb, developed countries ‘act’ more like Western Europe, and developing countries more like India or China. Globally, field application SECs increase for all scenarios, especially for SSP1 where project water efficiency increases most.

4.1.5 Final energy demand (FED)

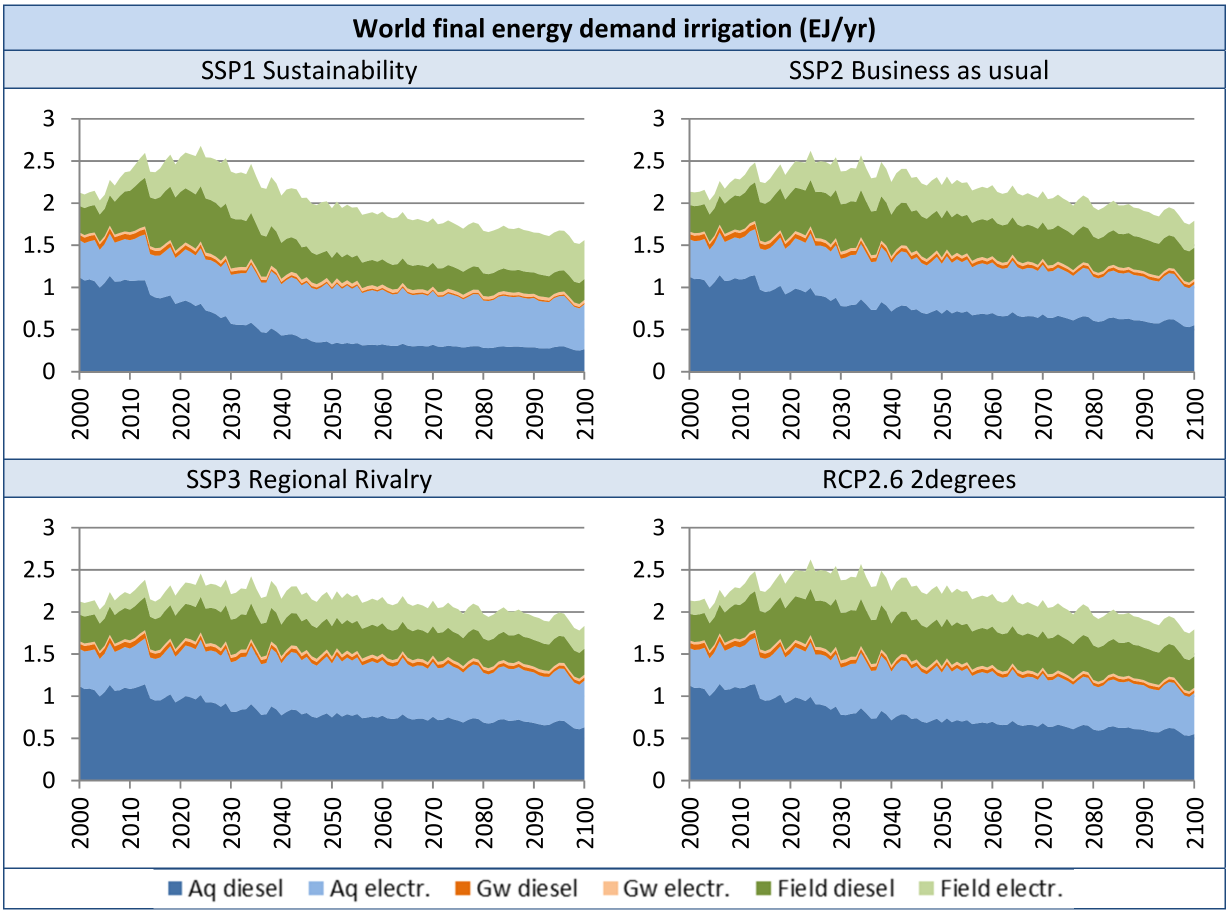

Figure 9: World final energy demand for irrigation for SSP1, SSP2, SSP3 and RCP2.6 (EJ/yr).

In all scenarios, irrigation energy demand peaks around 2025, then gradually decrease toward 2100 (figure 9). This more or less follows the decrease in water withdrawals. However, energy demand peaks later than withdrawals (peak around 2010), because field application SEC increases during the period 2005-2050. Final energy demand in 2050 is highest for SSP2 and RCP2.6, followed by SSP3 and SSP1 respectively. However, if not for the higher share of electric pumps in SSP1 compared to the other scenarios, this scenario would have seen the highest energy demand; electric engines have a much higher energy efficiencies than diesel engines. The fact that SSP3 has a lower field energy demand than SSP2 and RCP2.6 is explained by its lower increase in irrigation water efficiency. Energy demand for aquifer and groundwater pumping does not differ greatly between the scenarios except for SSP1. Again, the exception is due to the higher share of electrical pumps in this sustainable scenario. Groundwater energy demands are generally low because of low global groundwater withdrawals combined with the fact that groundwater tables are much shallower than aquifer tables.

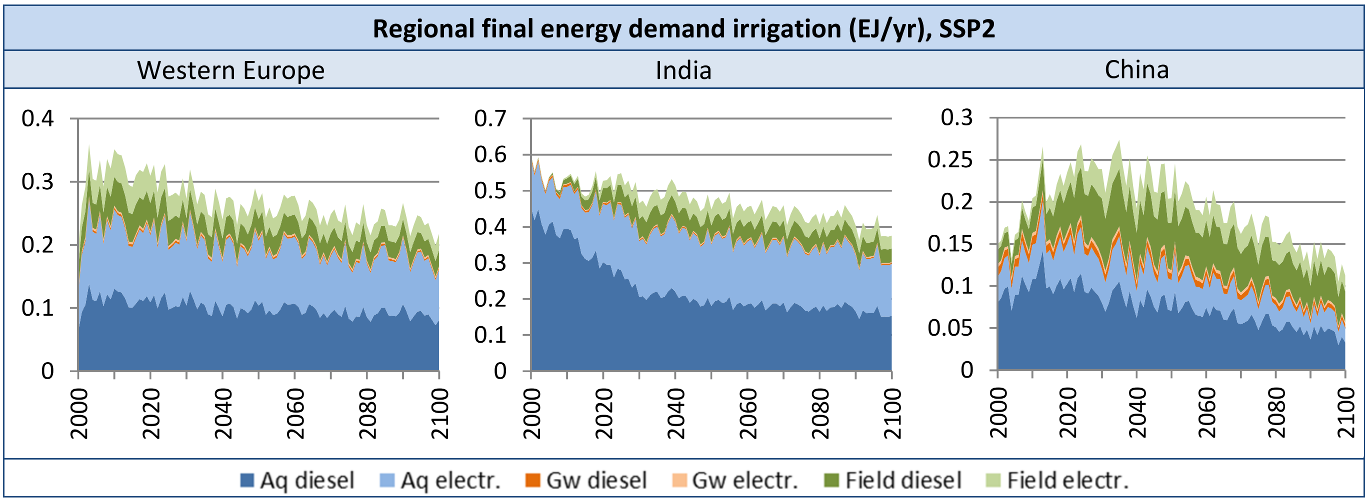

Figure 10: Regional final energy demand for irrigation for SSP2 (PJ/yr).Mind the different axis settings.

India's irrigation energy demand is much higher than those of Western Europe and China (figure 10). This is mostly the result of its high water withdrawals during the whole modeling period. Then again, the regional differences would have been much more extreme if not for India's relatively shallow aquifers and its rapid shift towards electric pumps. Energy used for groundwater pumping is marginal at best for all 26 regions. This results from low groundwater withdrawals combined with relatively low groundwater SECs. India and China, who shift from open canal to sprinkler irrigation systems, see a significant increase in field application energy demand. In contrast, Western Europe sees a decrease due to the shift from sprinkler to drip systems. Irrigation energy demand figures for other regions are found in annex 2.

4.2 Ammonia production

In this section, the main results for ammonia production are shown. First, ammonia production volumes are treated. Then, developments in plant specific energy consumption are covered. This is followed by expected costs for ammonia production which lead to region specific plant mixes in the active ammonia capacity. The end of the section deals with subsequent final energy demands and net emitted CO_2. Each aspect is first treated globally, then regionally.

4.2.1 Grand total fertilizer production (ACT)

Annex 1 shows the grand total n-fertilizer trade matrix for 2013 onwards. Cell values state the shares of fertilizer consumed by row regions that are produced by column regions. One notices a net export agglomerate on the Eurasia nexus; Central Europe (12), Ukraine (14) and Kazakhstan (15). Major exporters are the Middle East (17) and Russia (16) while Northern Africa (7), China (20), Canada (1) and Indonesia (22) play a relatively small role. Regions that are most import dependent are Eastern Africa (7), Western Africa (8), rest of Southern Africa (26) and Oceania (24). Western Europe (11) and India (18) are also net importers, though can be considered fairly independent. The grand total trade matrix for phosphate fertilizers is not discussed here because of the relatively small role of phosphate fertilizers in determining global final energy demand.

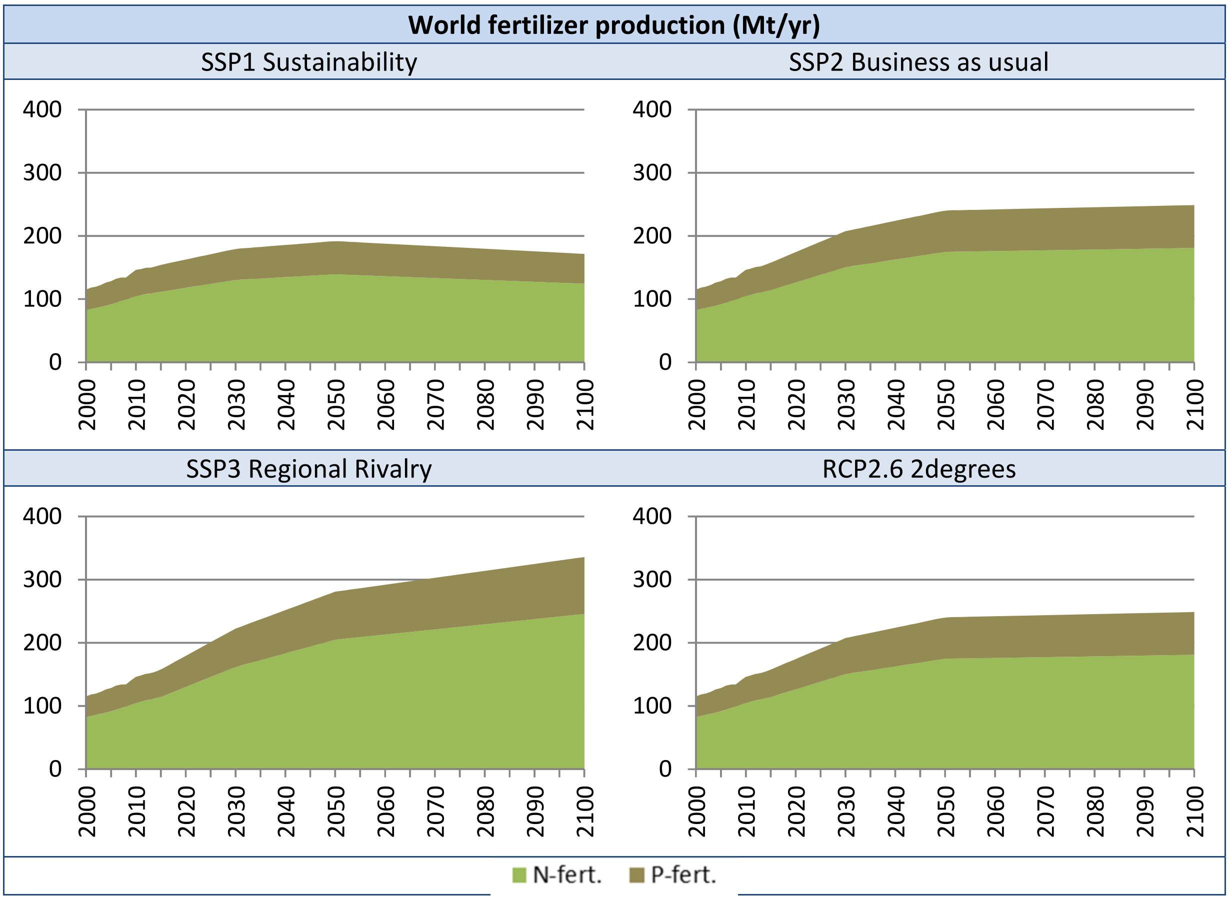

Figure 11: World grand total nitrogen and phosphate fertilizer production for SSP1, SSP2, SSP3 and RCP2.6 (Mt N or P2O5 /yr).

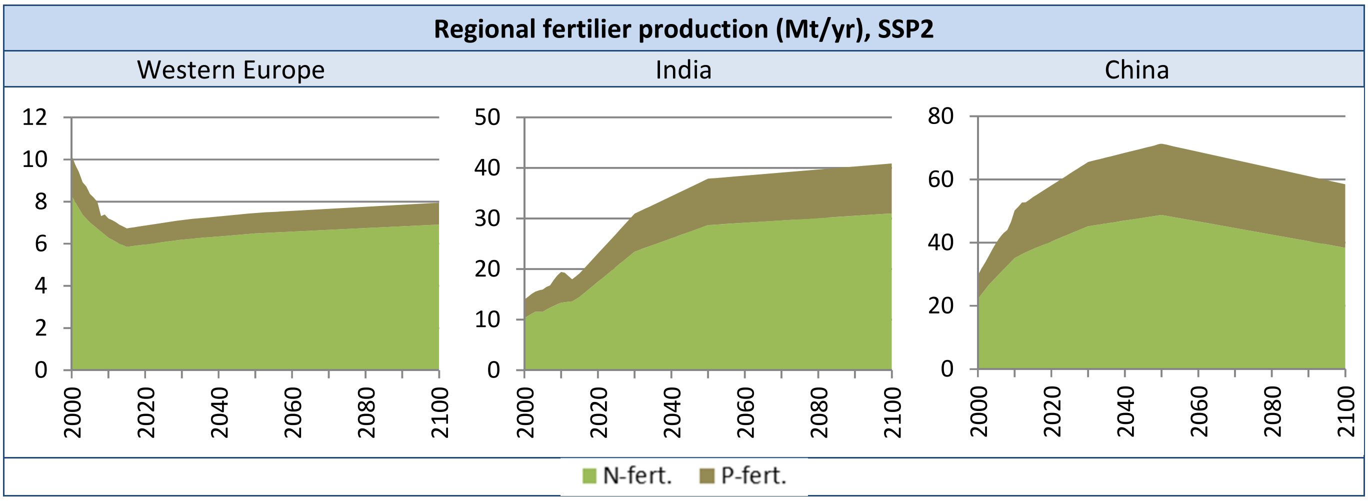

Figure 12: Regional grand total nitrogen and phosphate fertilizer production for SSP2 (Mt N or P2O5 /yr). Mind the different axis settings.

Total world production is dominated by nitrogen fertilizers in all scenarios (figure 11). This reflects that nitrogen is more often a limiting nutrient for crop growth than phosphate. While SSP2, SSP3 and RCP2.6 see a continuous growth in fertilizer production, SSP1 shows gradual decline from 2050 onwards. The decline is explained by lower global population and more sustainability measures in the latter scenario. The Regional rivalry scenario is the most production intensive, contrasting greatly with the Sustainability scenario.

China remains the biggest n-fertilizer producer throughout the projection period, though India is catching up (figure 12). Production in Western Europe, which only grows slowly, has a particularly low phosphate fertilizer share. In contrast, China shows a relatively high phosphate fertilizer share. As explained in section (3.2.1), ammonia production volumes equal's grand total production volumes (tN/yr).

4.2.2 SEC NH_3 plants (SEC)

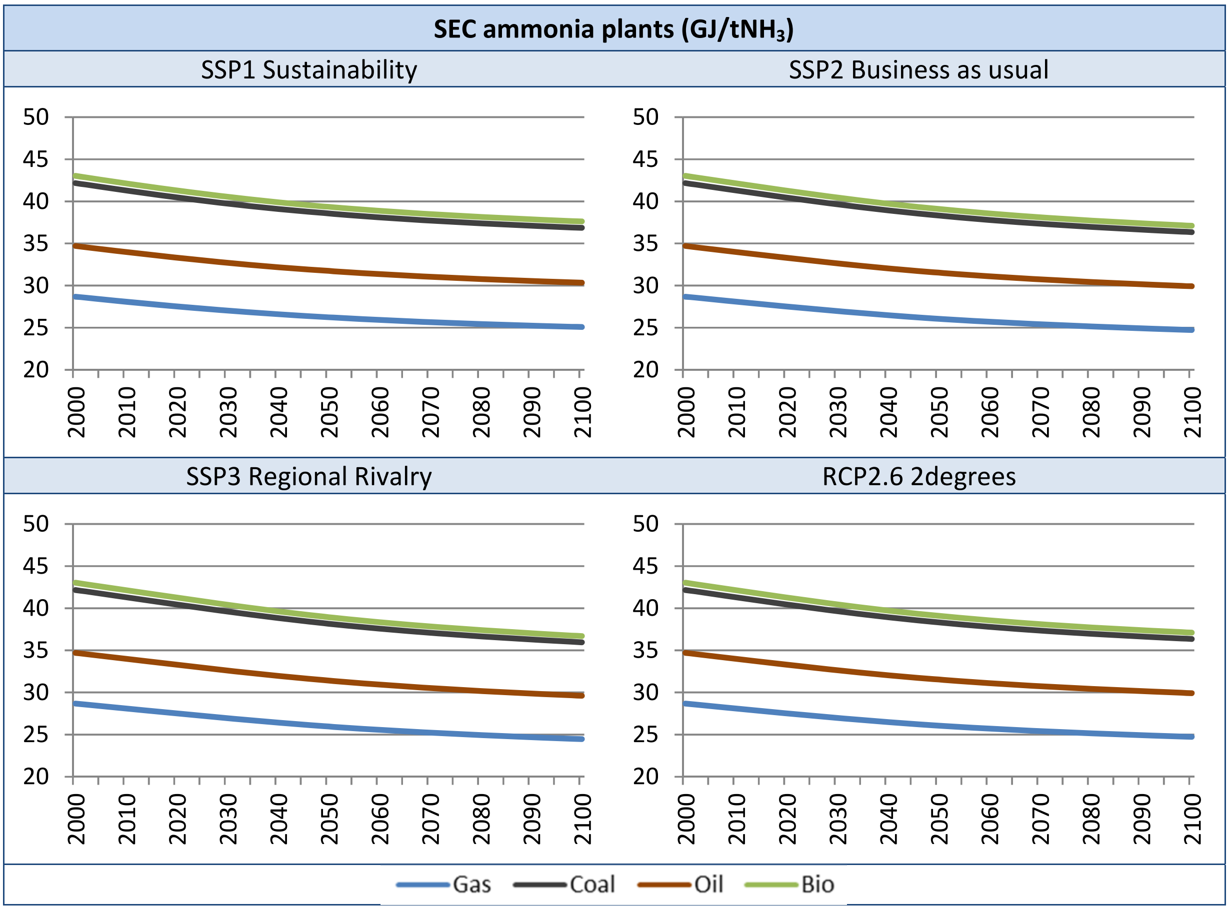

Figure 13: Specific energy consumption per main ammonia plant type for SSP1, SSP2, SSP3 and RCP2.6 (GJ/tNH_3). Small energy penalties apply to CCS variants. Same for all regions.

Specific energy consumption for all ammonia plant types decrease asymptotically toward 2100, following the natural gas learning curve explained in section (3.2.2) (figure 13). Since plant SECs are kept constant relative to that of natural gas, largest absolute reduction is seen for the highest demanding types, namely coal and solid biomass. The minor differences between the scenarios result from varying ammonia production volumes cumulated throughout the projection period.

4.2.3 Expected cost of ammonia production (STR)

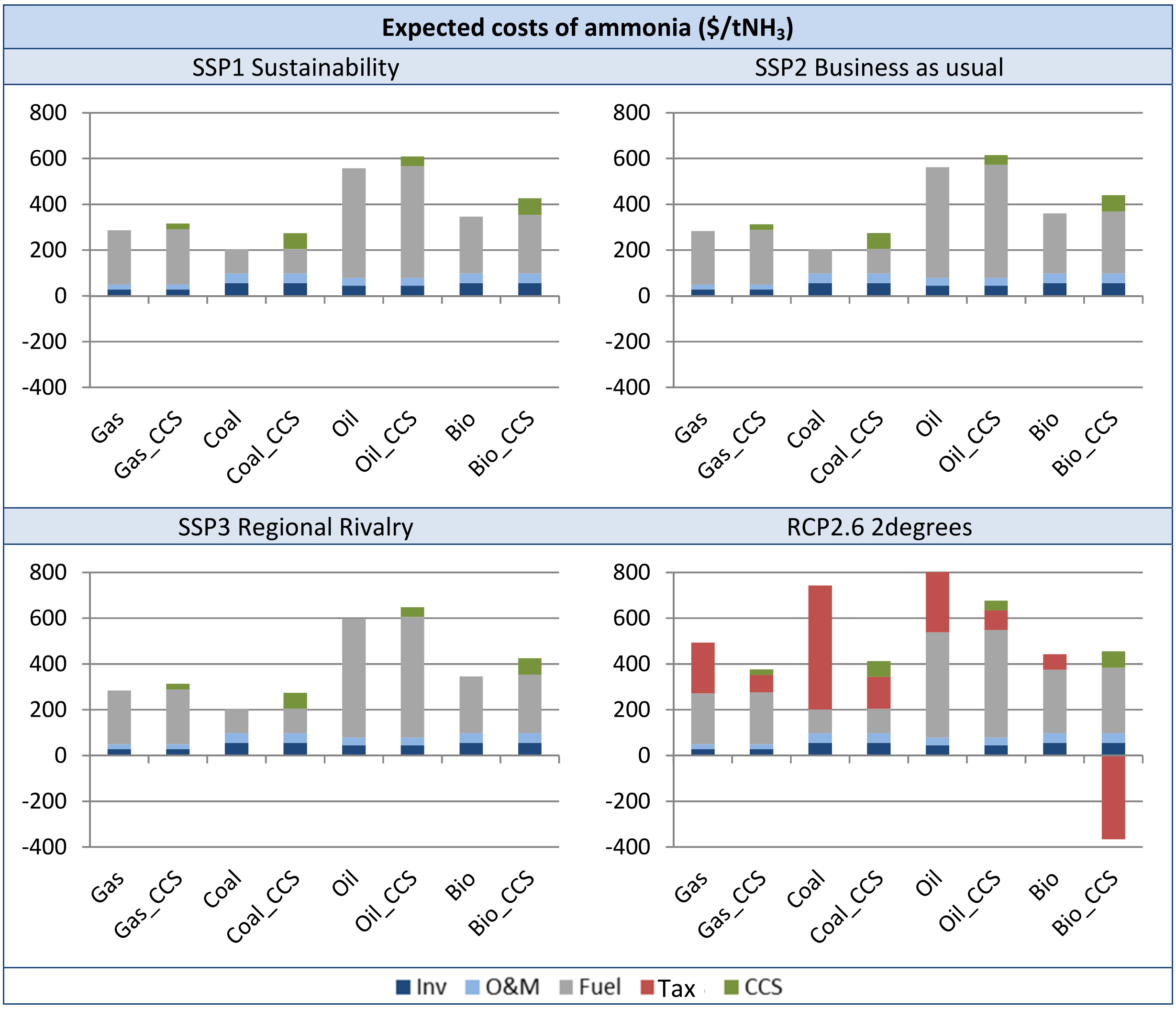

Figure 14: Breakdown of expected ammonia costs ($/tNH$_3$). Western Europe, 2030. Non-calibrated.

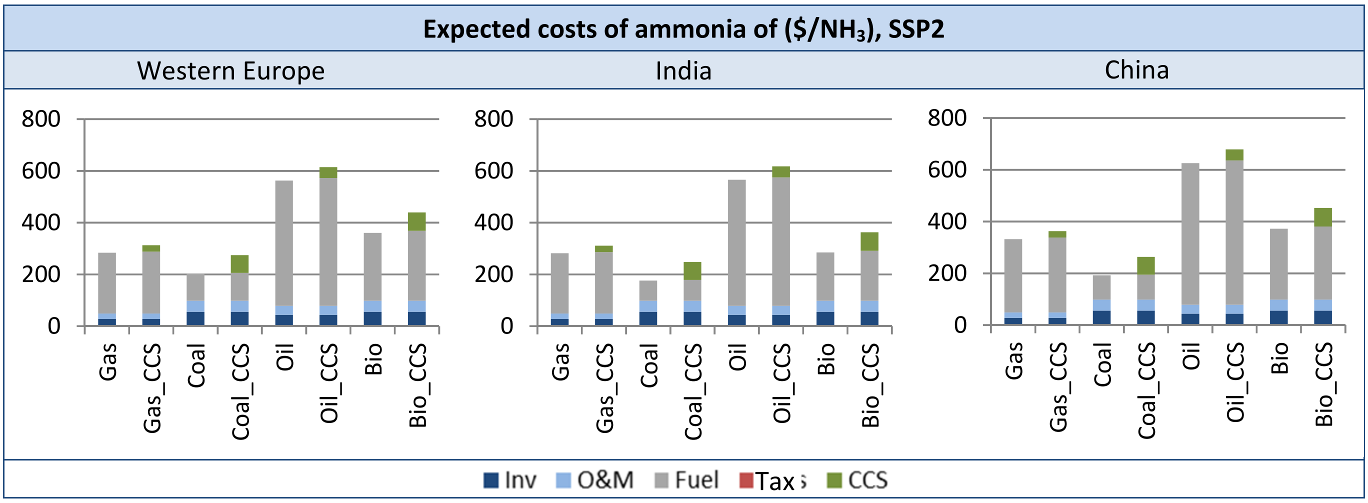

Figure 15: Regional breakdown of expected cost ammonia for SSP2 ($/tNH$_3$). Non-calibrated.

The expected costs of ammonia production shown in figures 14 and 15 do not include plant and regions specific preference factors as discussed in section (3.2.2). Therefore, they are determined only by costs arising from investments (Inv), operation and maintenance (O&M), final energy carrier use (Fuel), carbon taxes (Tax) and the potential CCS unit (investments, operation and maintenance).

Western Europe 2030 is taken as a reference for scenario comparison (figure 14). In all scenarios but RCP2.6 coal plants are cheapest, followed by natural gas, biomass and heavy oil respectively. Main drivers for this are expected fuel prices and plant SECs. Coal fuel prices are drastically lower than those of natural gas, overcompensating for the relatively high SEC of coal plants. This highlights the major role of energy demand (Fuel) in determining expected costs of ammonia. Investment and O&M costs influence total costs to a lesser extent. For these same scenarios, plant types with CCS add-ons have somewhat higher total costs than their respective main types. These extra costs arise from direct costs of the add-on and the small energy penalties it involves. The RCP2.6 two degrees scenario shows highly different results; biomass plants are cheapest, followed by natural gas, coal and heavy oil respectively. The difference with other scenarios is mainly due to the introduction of an increasingly higher carbon tax. Plants with a high net emission factor, coal and heavy oil, see the highest cost due to this carbon tax. In contrast, biomass plant have very low net emissions due to photosyntisis during the related production phase of the solid biomass. The carbon tax also causes CCS add-ons to decrease total costs; for all the CO_2 stored tax payments are avoided. As a result, biomass plants with a CCS-add on can even see negative taxes in the form of subsidies, causing them to be the cheapest option by far.

Zooming to regional level, expected cost differences are not very high (figure 15). Nevertheless, India shows lower costs for biomass and natural gas plants than Western Europe and China. Between the three regions, China has the highest costs for all plant types, most notably coal. Investment, O&M and CCS costs are the same for all regions.

4.2.4 Active capacity (STR)

Cumulative shares of active, still operating, capacity are shown in figures (16, global) and (17, regional). In contrast to the expected costs dealt with in section (4.2.3), these shares include influence from plant and region specific preference factors as discussed in section (3.2.2). Therefore, active plant shares might not always reflect their related expected costs of ammonia production. In the calibration process, especially coal is given a low preference factor in all regions except for China, the only one where coal plants are currently dominant *(IFA, 2009)*. Heavy oil plants are also assigned somewhat lower preference factors, less so for Western Europe, Eastern Europe, Ukraine and India than for other regions. For the historical period (1971-2009), regional preference for biomass are assumed to be the average of those of natural gas and coal. For SSP2 and RCP2.6 all preferences are kept constant during the projection period. In contrast, biomass preference gradually increases to that of natural gas in the Sustainability scenario, while it decreases to that of coal in the Regional rivalry scenario.

Global shares of biomass plants are largest in RCP2.6, followed by SSP1, SSP2 and SSP3 respectively (figure 16). The main RCP2.6 driver is the introduced carbon tax. Not only does this tax favor biomass plants (which generate very low net CO_2 emissions) but also the add-on of a CCS unit (which avoids generated CO_2 to be emitted to the atmosphere). The difference in biomass shares for SSP1,2 and 3 result mainly from the alternate preference settings explained above, and to a lesser extent from scenario specific fuel price developments. SSP1,2 and 3 show CCS equipped plants shares of no more than 35%; since no carbon tax is present, CCS variants are always more costly than their respective variants. For these same scenarios natural gas remains dominant, where scenario differences are mostly explained by the extent to which biomass is deployed.

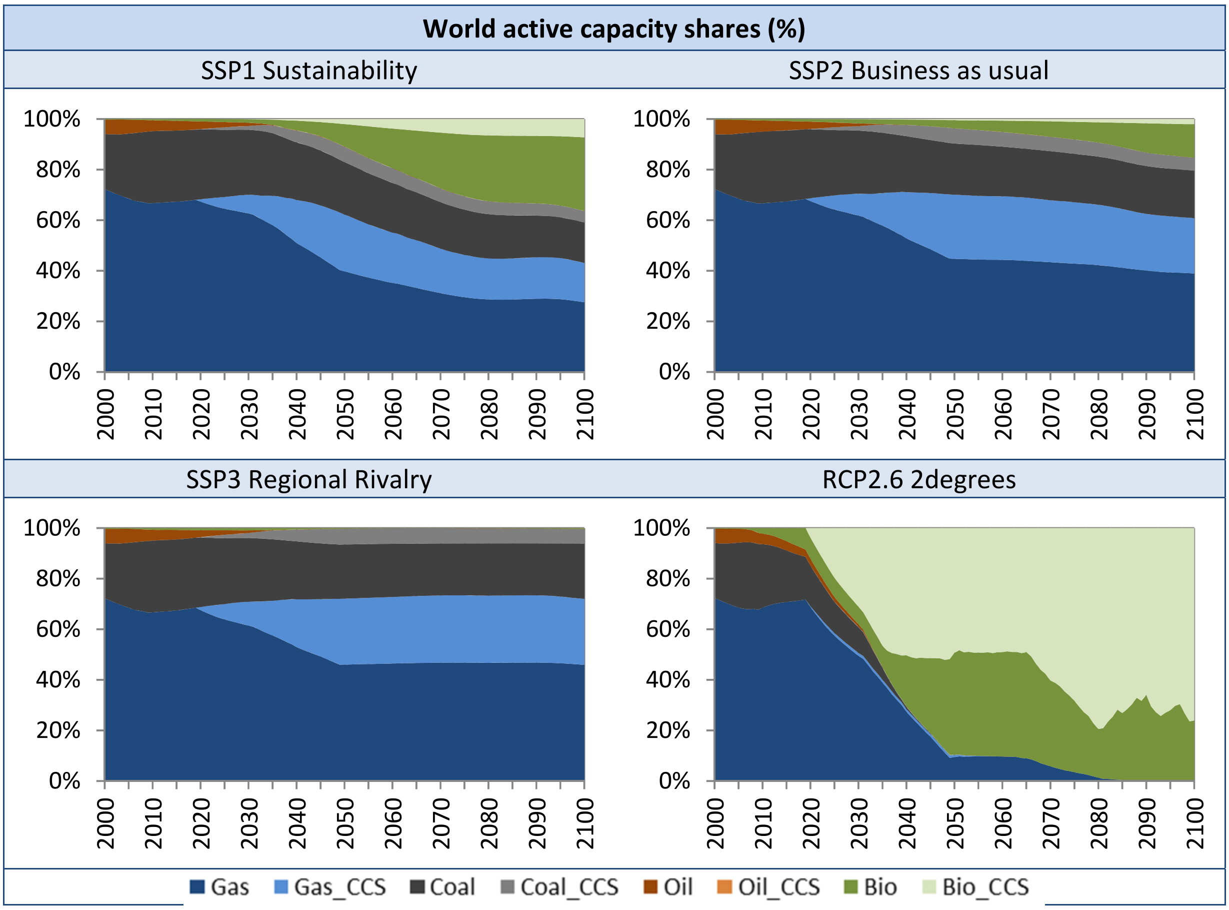

Figure 16: World active ammonia plant capacity shares for SSP1, SSP2, SSP3 and RCP2.6. Stacked to 100%.

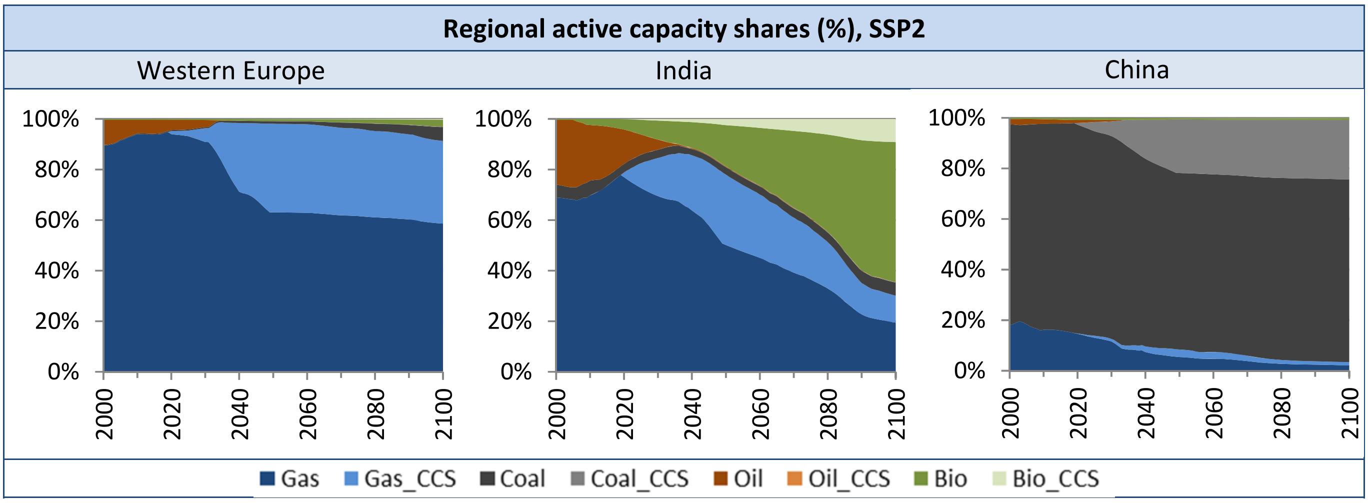

Figure 17: Regional active ammonia plant capacity shares for SSP2 (Mt NH_3/yr). Stacked to 100%.

4.2.5 Final energy demand (FED)

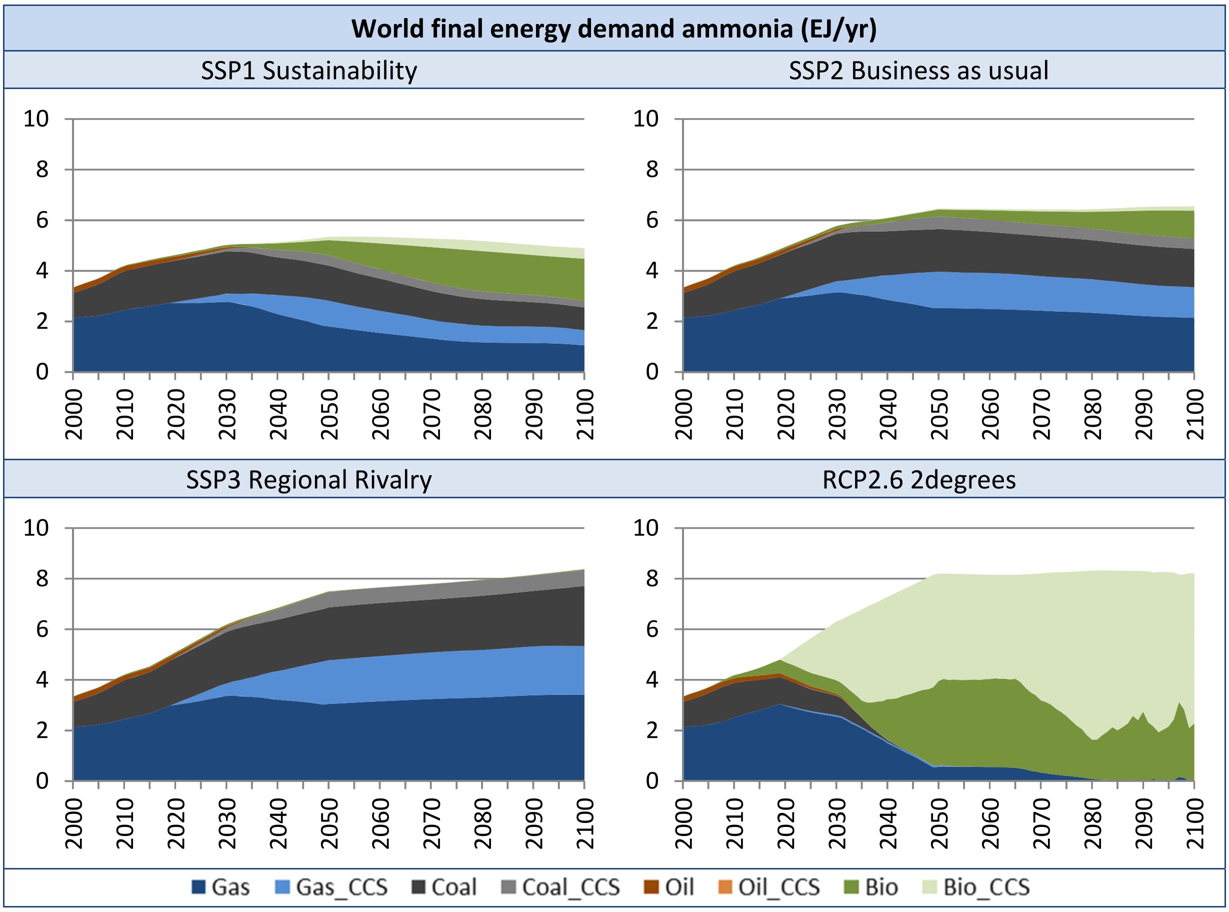

Figure 18: World final energy demand for ammonia production for SSP1, SSP2, SSP3 and RCP2.6 (EJ/yr).

As shown in equation (26) final energy demand results from an interplay of; total ammonia production volumes (4.2.1); structural changes in active plant mix (4.2.3); and plant specific energy consumption (4.2.2). Global total energy demand follows total ammonia production (4.2.1) for SSP1,2 and 3 (figure 18). This is not the case for RCP2.6 due to its high share of biomass plants, which have high specific energy consumptions. Corresponding with structural changes in active plant mix (4.2.4), biomass demand is highest in RCP2.6, followed by SSP1,2 and 3. For similar reasons, natural gas and coal demands are especially dominant in SSP3, and heavy oil use is diminished in all scenarios. In all scenarios, the share of coal in total energy demand is higher than its respective share in active capacity due to its relatively high specific energy consumption

During the projection period, China is by far the most energy intensive region considering ammonia production (figure 19); not only does the region have very high ammonia production volumes, it also produces it with energy intensive coal plants. India, which in 2000 consumed not much more energy than Western Europe, is continuously closing in on China towards 2100. The main drivers for this are the rapidly increasing production volumes and the extensive spread of energy intensive biomass plants from 2050 onward. Western Europe shows almost no structural changes energy use; natural gas is and remains the most demanded energy carrier.

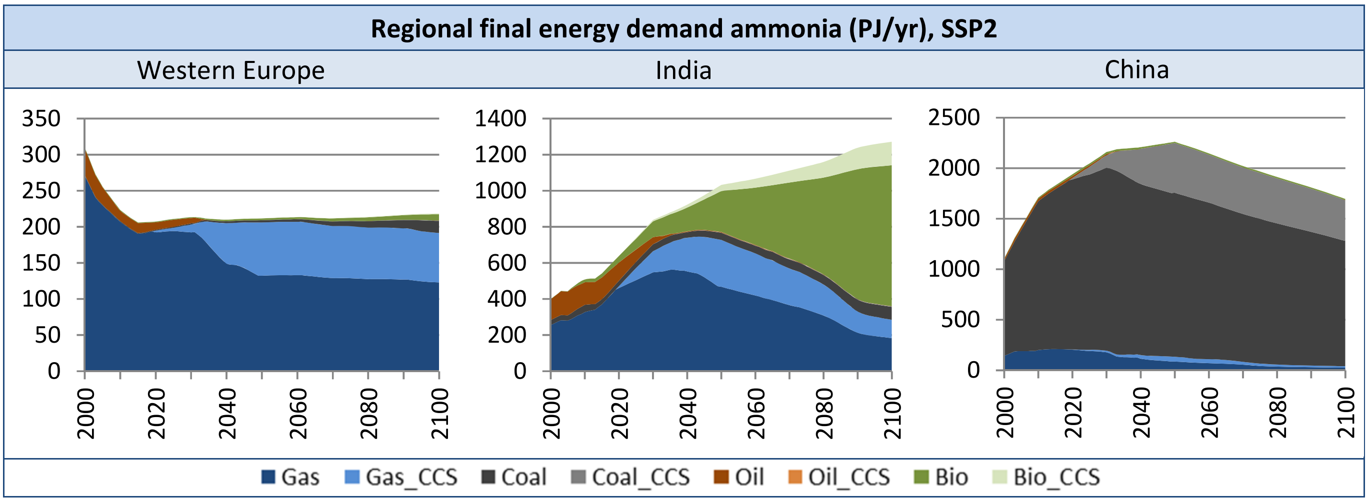

Figure 19: Regional final energy demand for ammonia production for SSP2 (PJ/yr). Mind the different axis settings.

4.2.6 CO_2 emission & storage

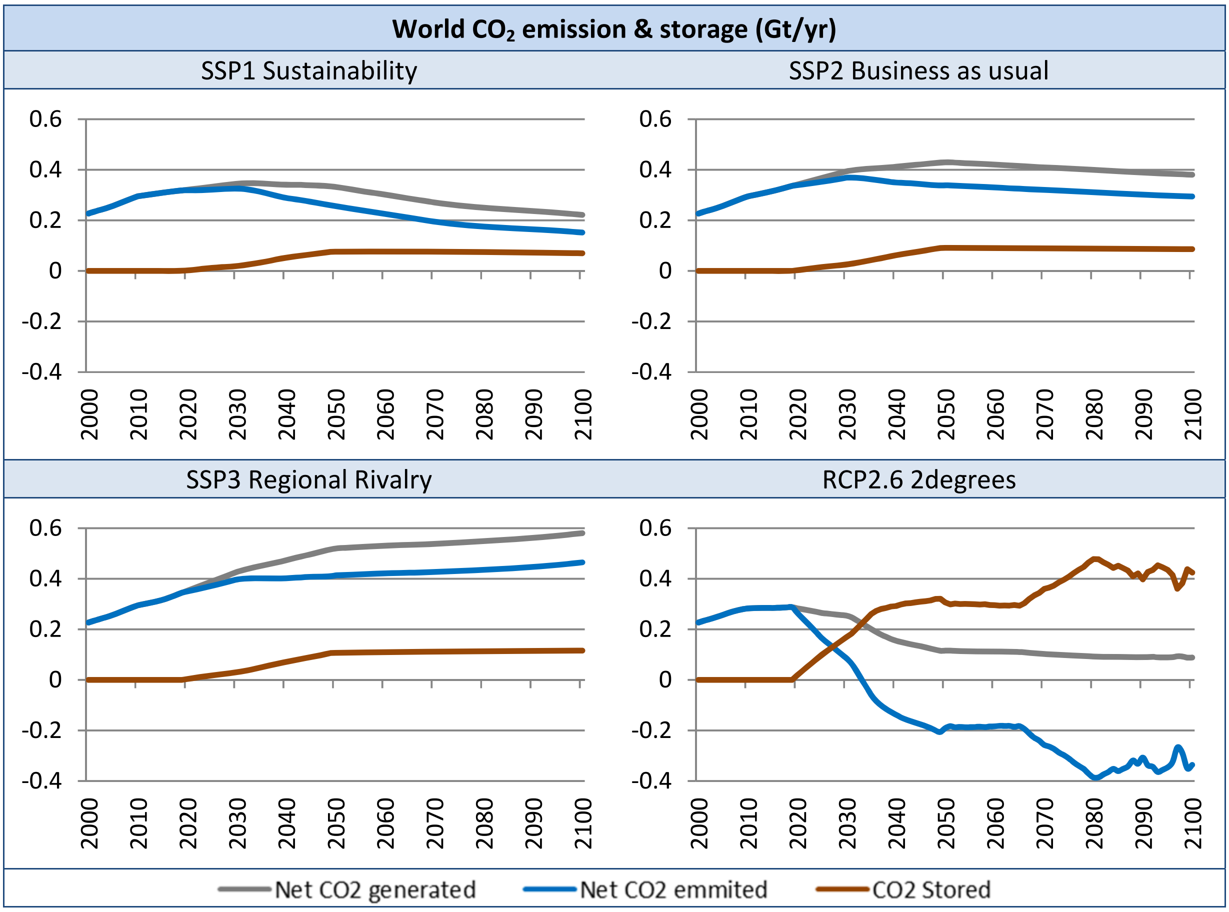

Figure 20: World net CO_2 generated, net CO_2 emitted and absolute CO_2 stored trough ammonia production for SSP1, SSP2, SSP3 and RCP2.6 (Gt/yr).

World net generated equals net emitted CO_2 in all scenarios until 2020, the assumed implementation year for carbon capture and storage (figure 20). Net generation is highest in SSP3 due to its very high demand for coal, which has a relatively high net emission factor. The main difference in net generation between SSP1 and SSP2 is explained by their varying demand for biomass, which has a very low net emission factor. The same mechanism explains why RCP2.6 has the lowest net generation. On top of that, this scenario sees the greatest spread of CCS add-ons, resulting in very high volumes of CO_2 being stored underground instead of being emitted to the atmosphere. Resulting net CO_2 emissions even becomes negative from 2033 onward; the ammonia system starts functioning as a carbon sink.

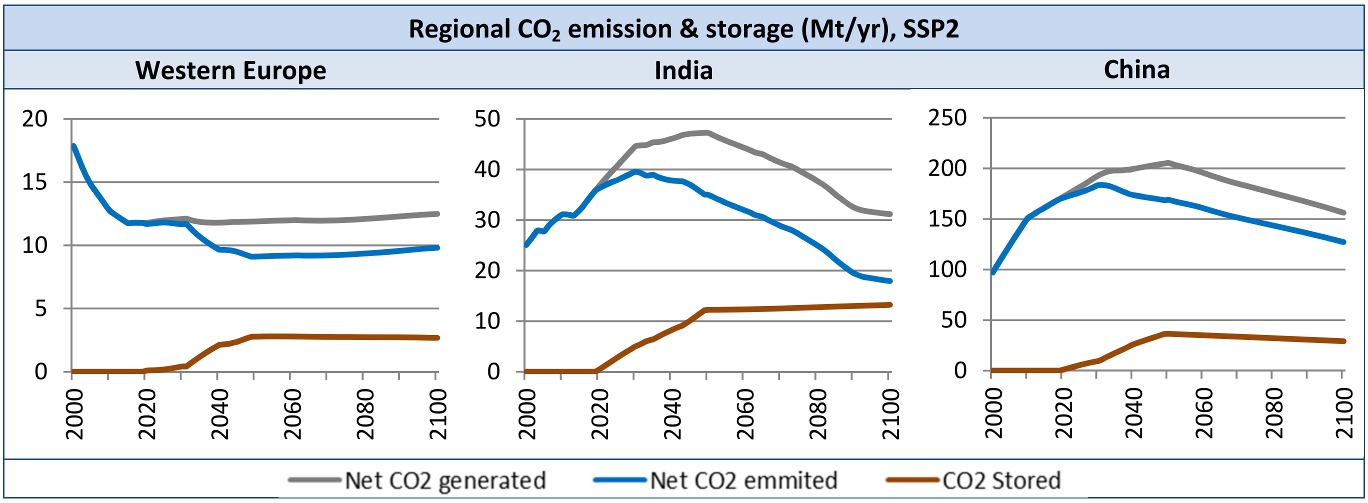

Figure 21: Regional CO_2 net generated, CO_2 net emitted and absolute CO_2 stored trough ammonia production for SSP2 (Mt/yr). Mind the different axis settings.

China's high demand for heavily emitting coal makes it the single most CO_2 emitting region in the world (figure 21). India's relatively high spread of CCS variants combined with increasing implementation of biomass plants causes its net emissions to decline after 2050. Western Europe's net emissions decreases between 2030 and 2050 due to the implementation of CCS plant variations.

4.3 Production of other fertilizer types

This section shows the main results for non-ammonia fertilizers. In the first part, fertilizer type production volumes are covered. Final energy demand is dealt with in the second part. Both aspect are first treated globally, then regionally.

4.3.1 Production (Act)

Global production volumes of non-ammonia fertilizers (figure 22) follow grand total volumes as shown in section (4.2.1). Urea clearly dominates in all scenarios, accounting for over half of total production. In addition, only AP and AN show notables shares.

Zooming in to regional level, Western Europe sees an a-typical production mix; the distribution is relatively even amongst the fertilizer types (figure 23). Most notable is the large share of CAN. In India urea dominates even more than in most other regions, while China shows a higher than usual AP share. No AN is produced in the latter two regions.

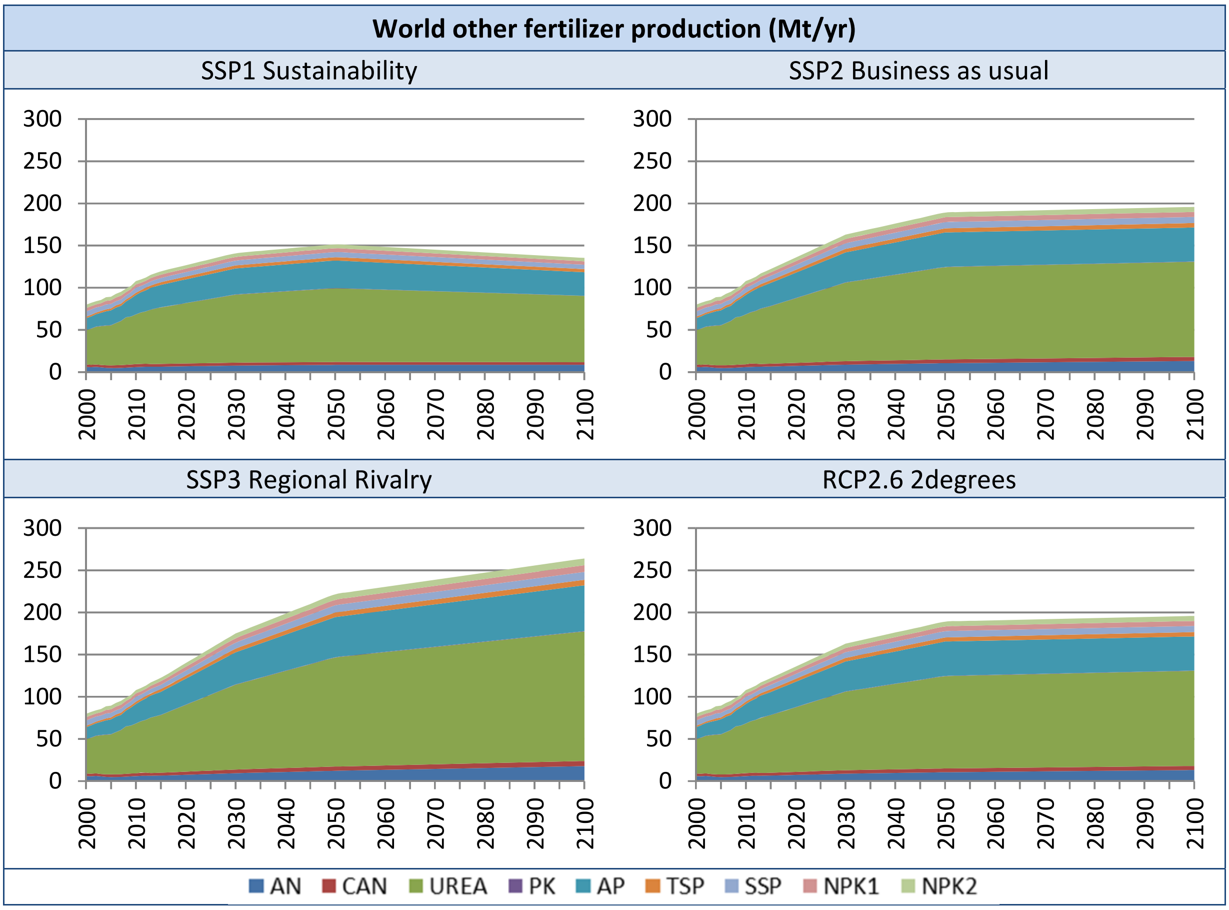

Figure 22: World production volumes of non-ammonia nitrogen (AN, CAN and Urea, Mt N/yr) phosphate (PK, AP, TSP and SSP, Mt P205/yr) and complex (NPK1 and NPK2, Mt N/yr) fertilizers. For SSP1, SSP2, SSP3 and RCP2.6

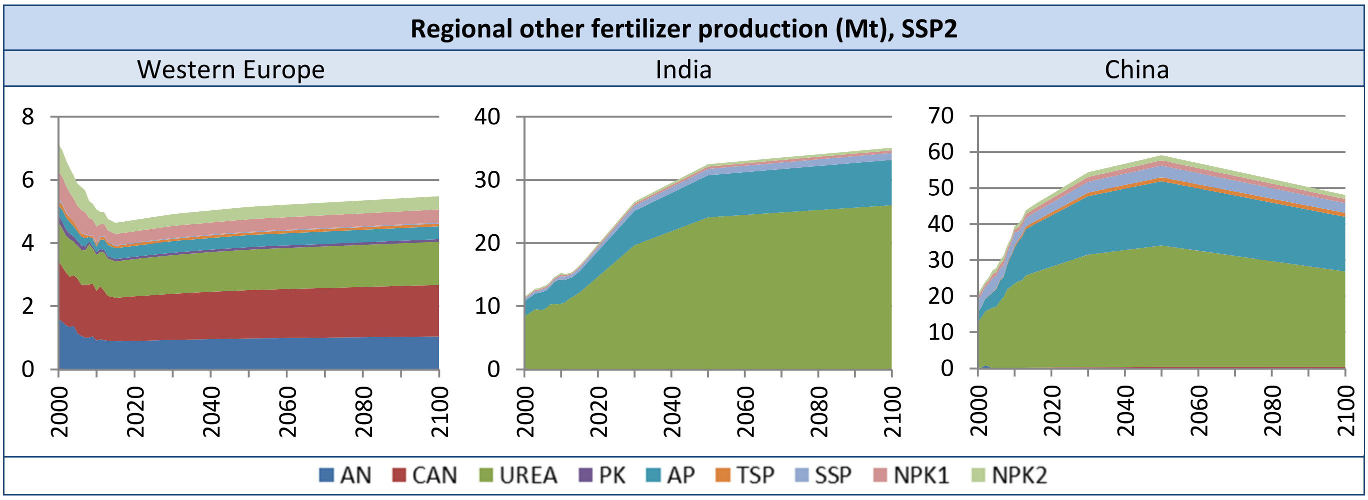

Figure 23: Regional production volumes of non-ammonia nitrogen (AN, CAN and Urea, Mt N/yr) phosphate (PK, AP, TSP and SSP, Mt P205/yr) and complex (NPK1 and NPK2, Mt N/yr) fertilizers. For SSP2. Mind the different axis settings.

4.3.2 Final energy demand (FED)

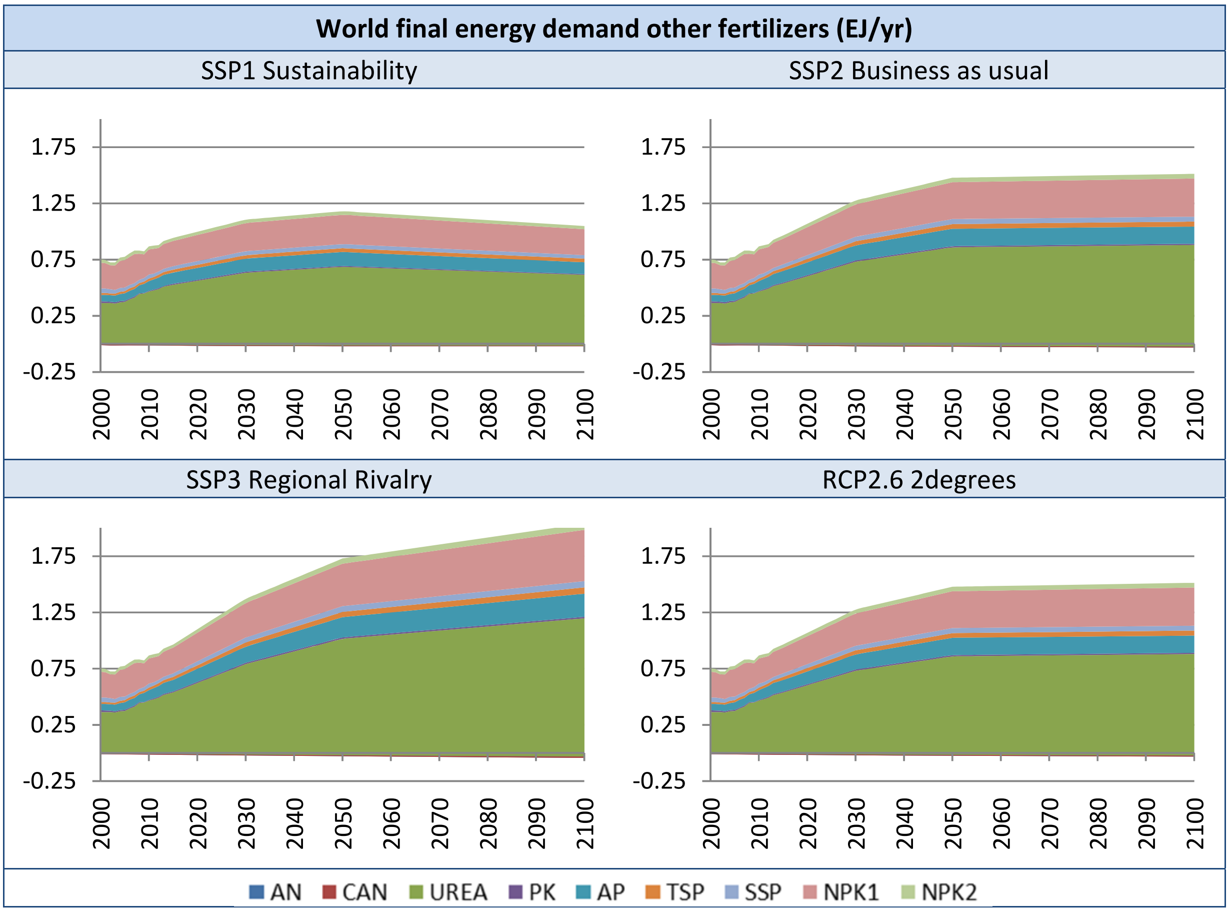

Figure 24: World final energy demand per fertilizer type for SSP1, SSP2, SSP3 and RCP2.6 (EJ/yr).

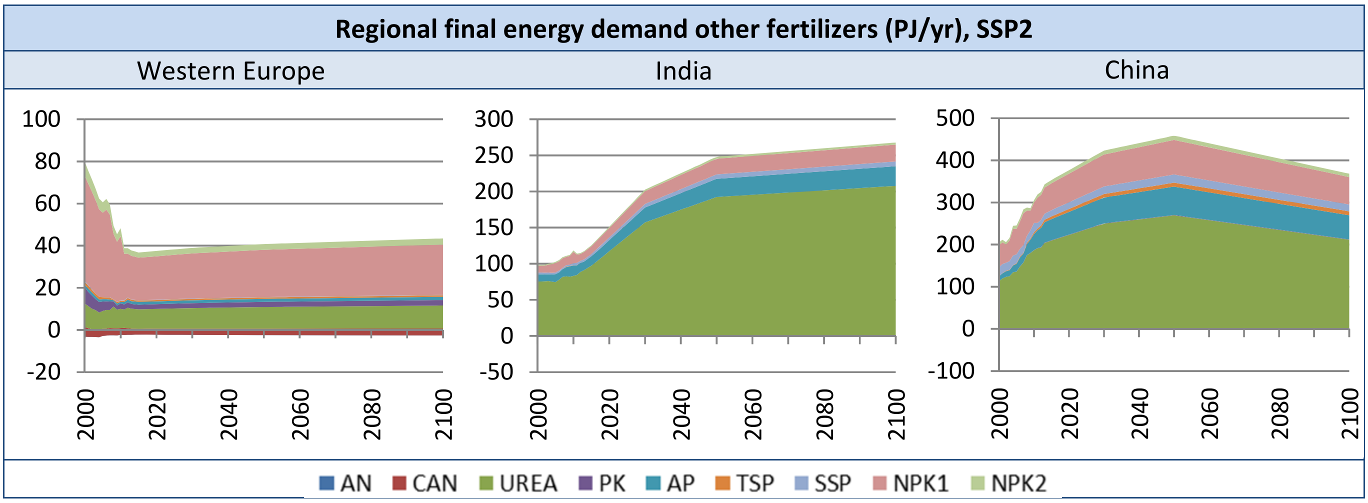

Figure 25: Regional final energy demand per fertilizer type for SSP2 (PJ/yr). Mind the different axis settings.

Global total energy demand (figure 24) roughly follows the production volume trends as shown in section (4.3.1). Not surprisingly, urea dominates in all scenarios. Notice NPK1; while it has only minor production volumes, its high SEC causes it to demand even more energy than AP. AN shows a negative energy demand; with ammonia synthesis excluded from the production chain, it generates net energy in the form of high temperature heat, which can be used in other industrial processes.

NPK1 dominates Western Europe's energy demand throughout the projection period (figure 25). This is a combined result of relatively high regional production volumes and NPK1s high SEC. India and China show energy demands mixes that are more similar to global ones.

4.4 The bigger picture

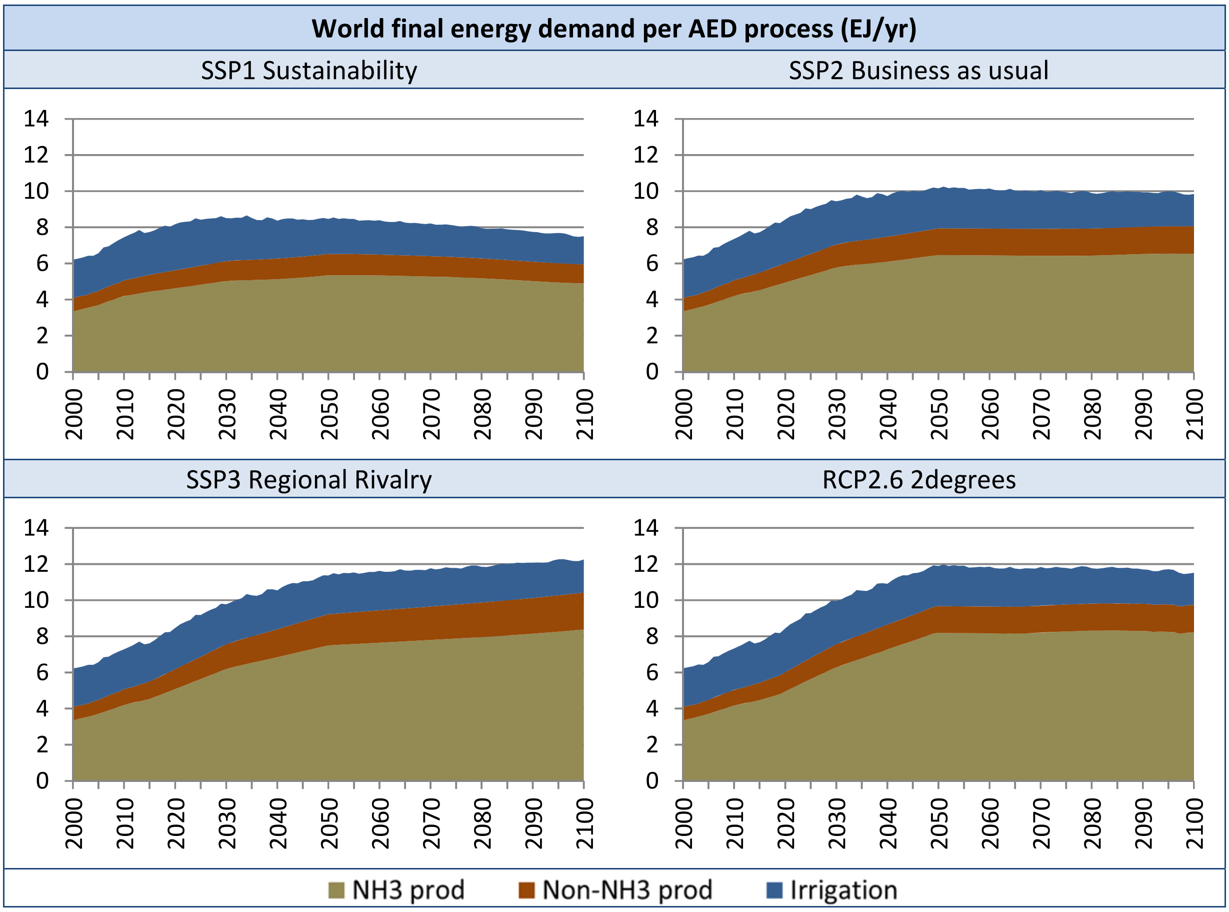

Figure 26: World final energy demand per AED process for SSP1, SSP2, SSP3 and RCP2.6 (EJ/yr).

The Sustainability scenario sees the lowest global energy demand, while SSP3 and RCP2.6 see highest (figure 26). Ammonia production dominates in all scenarios and energy demand for irrigation is higher than for non-ammonia fertilizers. Since the set of scenarios shows a wide range in AED projections, the uncertainty of future energy demand developments are regarded high. This uncertainty lays mainly in the future final energy demands for ammonia production, which differ greatly between the scenarios.

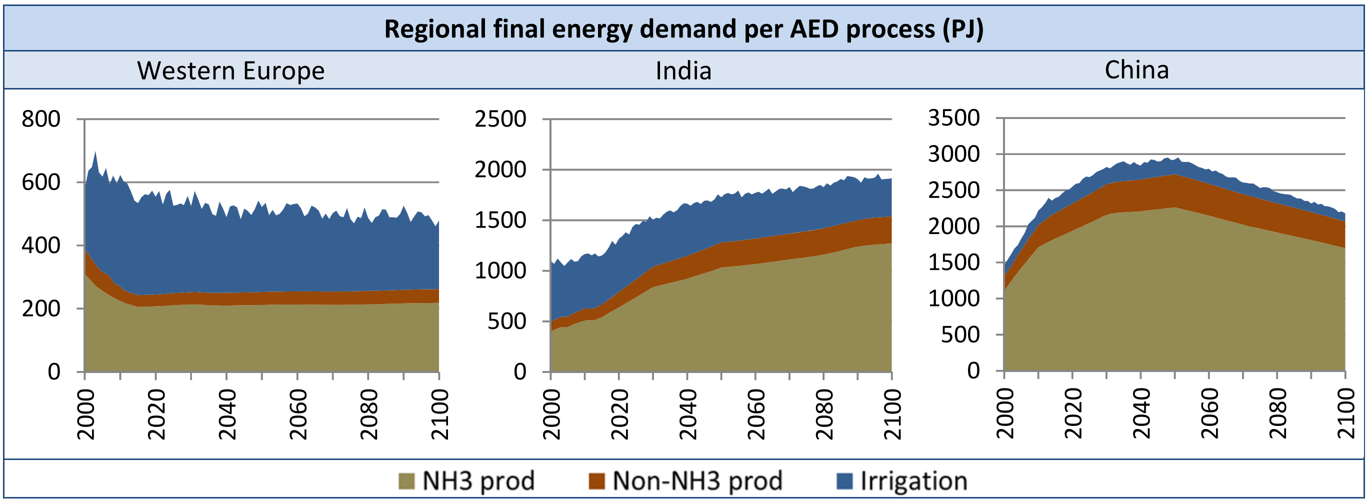

Figure 27: Regional final energy demand per AED process (PJ/yr). Mind the different axis settings.

Again, China shows the highest regional total final energy demand, while India sees world's highest energy demand for irrigation (figure 27). Western Europe has a relatively low total energy demand with a high share for irrigation throughout the projection period.

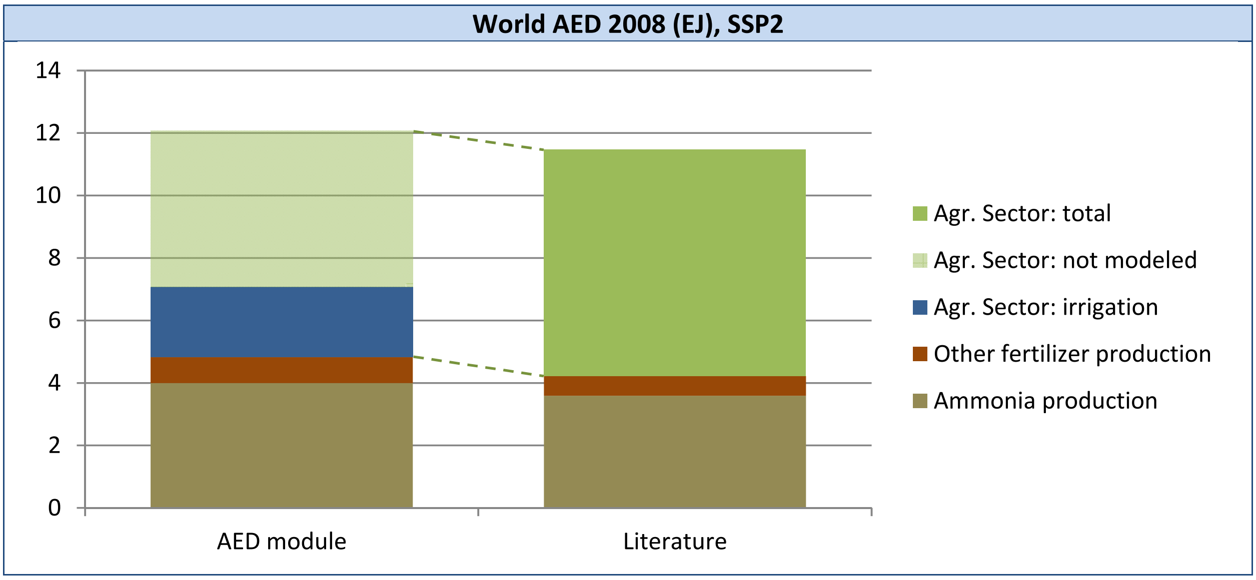

Figure 28: World AED 2008 (EJ) as calculated by the AED module for SSP2 (left bar) and as estimated in section 2.1 using energy statistics and literature (right bar). 'Agr.' stands for 'agriculture'. The 'not modeled' category represents all energy related processes part of the agricultural sector which are not modeled in the AED module at the moment. Together with the category 'irrigation', it equals the energy demand of the 'agriculture sector total'.

Compared to the literature estimations made in section (2.1), the *AED module* generates similar final energy demands for 2008 (Figure 28). Demands for production of both ammonia and other fertilizers are somewhat higher in the module, though. The 'not modeled' part is obtained by detracting the module's 'irrigation demand' from the literature estimate's 'total agriculture sector demand'. Subsequently, on finds that the module covers 58.5% of final AED and 2.0% of grand total final energy demand in 2008.

The residual part of AED, which covers processes such as mobile machinery use and livestock housing, has yet to be modeled. Annex 6 of this report suggests a methodology to do so. Note that this methodology entails modeling the total remaining AED in an aggregated manner, not accounting for process specific developments.

As a first order estimate, mobile machinery accounted for 17,5% of global AED in 2008. This percentage assumes that total 'transport fuel used in agriculture' was 4388 PJ in 2008, as stated by *FAOstat (2016)*. This covers fuel used for machinery and irrigation. Detracting 2008 values for irrigation, as calculated in the *AED module* (2242 PJ for SSP2), yields a final energy demand of 2112 PJ for mobile machinery. As a share of cumulative 2008 energy demands for ammonia (3993 PJ, *AED module*), other fertilizers (831 PJ, *AED module*) and the agricultural sector (7256 PJ, *IEA statistics, 2016*), this accounts for 17,5% of global AED in 2008.

5. Discussion

5.1 Irrigation

Scenario expectations

The SSP1 sustainability narrative tells a pathway of relatively low population growth and rapid transitions toward renewable systems. In contrast, SSP3 regional rivalry entails a high population growth and continuous dependency on fossil fuels.

Activity: Looking at the results, world projected water withdrawals are lowest for SSP1, tough not drastically. This corresponds with the narrative; lower population and rapid transition toward more sustainable irrigation systems are expected to lead to less water demand. In the *IMAGE land model*, the variation between the scenarios is mainly caused by the assumed quicker increase of irrigation water efficiency in SSP1. Meanwhile, the differences are not that drastic because the *IMAGE land* highly limits future expansion of agricultural land which is fitted with irrigation equipment.

Structure: Compared to the other scenarios, SSP1 sustainability shows an increasingly higher share of electricity driven pumps for irrigation. This also corresponds with its narrative; the higher electric share allows for more renewable options on the energy supply side (electricity can be generated by e.g. solar or wind power, while diesel cannot). In this line of thinking, one could argue that SSP3 regional rivalry should be assigned lower electricity preference factors than SSP2 since its narrative advocates higher fossil fuel dependency. However, this dependency is accounted for in *TIMER's* energy supply module , where less renewable techniques will be adopted compared to other scenarios.

Seemingly contradicting to the narratives, SSP1 shows the highest field application SEC when engine efficiencies are not taken into account; a big shift is made from low energy demanding surface systems toward high demanding pressurized sprinklers. This while one would expect lowest energy intensities in SSP1. A conflict of sustainability interests becomes apparent; while the irrigation system transition leads to lower water demand, it increases the demand for energy. Since agricultural irrigation accounts for only a small part of global final energy demand (see section 2.1), the increase in energy intensity results in only a low extra climate impact. Meanwhile, irrigation has a dominant share in total world water withdrawals *(Gleick at al., 2009)*, hence the considerable increase in water efficiency entails a large reduction in water scarcity. When one weighs both climate and water scarcity categories equally, the system transition is seen as a sustainable one. Consequently, SSP1 indeed shows the most sustainable developments.

Method and data

The method for determining regional groundwater depths is considered to be solid; it is based on data covering the entire world on a high spatial resolution. Furthermore, only land area fitted with agricultural irrigation equipment is taken into consideration, avoiding noise from non-irrigated areas. In contrast, literature support for aquifer depths is fairly poor; applicable data could only be found for 10 out of 26 regions. For some of these regions, the average depth is only based on one or two values. Consequently, depth variance in regions with no or low data availability is shaded, potentially leading to aquifer energy demands deviating from reality.

Currently, the *AED module* assumes extraction depths to be constant during the projection period. This while groundwater tables are generally lowered significantly when continuously exploited. Similarly, the *Gravity Recovery and Climate Experiment* (GRACE) project reports rapid decreases in world aquifer volumes, caused by over-exploitation *(Schmidt et al., 2015).* In both cases this would imply lower availability of source water and higher energy demands for extraction. Currently, the *IMAGE land model* imposes no limitation on aquifer withdrawals.

Currently, no bio-diesel option is implemented in the *AED module* for irrigation. Before this *is* done, it should be explored whether or not it can easily substitute regular diesel. If this is indeed the case, it is advisable to add this fuel option later on.

Lastly a suggestion for the *IMAGE land model*. At the moment, a global linear water efficiency improvement is imposed during the projection period. However, this doesn't directly describe the expected shifts between the various irrigation systems, it implies them. It is advisable to start by constructing regional narratives on these foreseen structural changes. In this way, resulting efficiency improvements are grounded more firmly and communicated more understandably to third parties. Moreover, the narratives would reveal regional differences regarding the ability to improve irrigation water efficiency. Regions currently dominated by surface systems are already reported to shift rapidly toward sprinkler systems (*AQUAstat; 2015; Fernández et al., 2014)*. In contrast, regions currently dominated by sprinkler systems have limited room for improvement due to the fact than only few crop types can be linked to drip systems. Consequently, the latter regions should show slower and limited water efficiency improvements. This would also lead to smaller decreases in field application SEC.

5.2 Ammonia production

Scenario expectations

Activity: Looking at the results, SSP1 Sustainability shows much lower ammonia production volumes than SSP3. This corresponds with its narrative; lower population combined with more sustainable application methods presume lower demand for and thus production of synthetic fertilizers. In the *IMAGE Land model*, this is reflected by the assumed reduction of over-application and the higher application of organic fertilizers.

Specific energy consumption: Plant specific energy consumptions develop virtually the same in all scenarios. This seems to be contradicting with the narratives, which presume higher technological advances for SSP1 and lower ones for SSP3. However, history has shown than specific energy consumption is mostly related to historical cumulative production volumes of ammonia *(Ramirez Ramirez and Worrel, 2005)*

Structure: Between the 3 baseline scenarios, SSP1 shows the highest penetration of biomass plants and relatively low use of coal. This corresponds with its story on higher renewable technique deployment and low dependency on fossil fuels. Only RCP2.6 shows (much) higher use of biomass due to the ever increasing carbon tax imposed. Resulting net emissions stroke with the two degrees narrative, which entails drastic reduction.

Final energy demand: SSP1 shows the lowest total final energy demand for ammonia production between the 3 baseline scenarios. Remarkable is the energy demand in RCP2.6; it is even higher than that of SSP3. However, this is predominantly biomass energy demand, whose very low net emission factor finally results in a small climate impact.

Method and data

In the AED module, plant specific energy consumptions are kept constant relative to that of natural gas plants. This might not always reflect reality. For example, biomass energy intensity might drop faster than those of other plants, considering that it is still an infant technology and could 'learn' faster during its earlier deployments. However, learning curves for non-natural gas plants could not be found in literature. Assuming static SEC for all plants during the projection period would result in an over-estimation of total final energy demand. Only applying learning to natural gas plants and not to the others would create an un-leveled playing field. Moreover, assuming co-learning might not be that unrealistic; all ammonia plants share a common production step, namely the conversion from hydrogen to ammonia.

The costs for carbon capture and storage are kept static at mid-range values reported in literature. One could argue that initial CCS add-on installations will occur on sites near suitable storage points. This would reduce the costs to values in the lower range due to the lesser pipeline investments needed. Subsequent add-ons could then only be placed in less optimal sites, causing investment costs to increase, and so forth *(IPCC, 2005)*. On the other hand, it is reasonable to assume that wider implementation of CCS reduces associated costs through technological learning and factors of scale.

The investment costs of biomass plants are assumed to be the same as those of coal plants. One could argue that during the first deployments of biomass plants, investments are higher since it is still an infant technique. This would be followed by a (rapid) drop relative to coal during widespread deployment due to technological learning. However, no comparable investment data or cost learning curves were found for biomass. Moreover, biomass and coal plants share similar techniques; gasification of solid fuels followed by hydrogen conversion to ammonia. Therefore, it might not be valid to name biomass an infant technique, since it has already 'learned' trough the more widespread historical deployment of coal plants. This makes the assumption made in the *AED module* more plausible.

It is currently assumed that preference for biomass plants goes up in SSP1, and down in SSP3. This is consistent with the narratives; SSP1 entails a pathway with higher implementation of renewables; and SSP3 a pathway which is continuously dependent on fossil fuels. However, these assumption might dilute the importance of expected costs of ammonia production in determining market shares.

Finally, increase of solid biomass supply is currently not limited in the AED module. This is due to the fact that the module is not fully integrated in the TIMER framework yet. When this *is* done, the high biomass plant expansion seen in the RCP2.6 two degrees scenario is expected to be restrained significantly.

5.3 Other fertilizer production

Scenario expectations

Activity: Total production volumes for other fertilizers are lowest for SSP1 and highest for SSP3. This corresponds with their respective narratives and is explained by the same mechanisms as for ammonia production volumes.

Specific energy consumption: Between the scenarios, the *AED module* shows no difference in fertilizer type SEC development. This is because they are assumed to be static during the projection period. Looking at the narratives, one could expect to see somewhat higher advances in energy efficiency for

SSP1 compared to the other scenarios. On the other hand, this argument appeared not to be entirely valid for ammonia production specific energy consumptions.

Structure: As for specific energy consumption, the scenarios see no variation in the composition of the fertilizer type mix. This while the SSP1 scenario presumes preference for substitutable fertilizers with the lowest specific energy consumption.

Method and data

The scenario expectations suggest a dynamic and scenario dependent mix of non-ammonia fertilizer types. However, this would be based on some large assumptions. Moreover, current global final energy demand of all non-ammonia fertilizers combined is around four times lower than that of ammonia alone. Therefore, the current somewhat simplified approach is considered to be sufficient.

5.4 The bigger picture

Scenario expectations

Corresponding with the narratives, Sustainability shows the lowest baseline AED and Regional Rivalry the highest. Seemingly contradictive is the sharply increasing AED in RCP2.6, since this scenario includes a two degree MST target. However, the increase is dominantly in final energy consumption for ammonia production. As explained earlier, this is high for RCP2.6 because ammonia is largely produced by energy intensive biomass plants. These plants, however, have low net emission factors and are therefore in line with the 2 degree MST target.

Comparison with literature

For 2008, the *AED module* generates a current world AED comparable to the literature estimate. The somewhat higher energy demand for fertilizer production in the module could be explained by the share used in the literature estimate to determine fertilizer industry energy demand. This share, which indicates world fertilizer energy demand relative to grand total energy demand, is given for 2003 and assumed to be the same for 2008. This share might have changed somewhat in the intermediate 5 years. Due to lack of more recent share estimates this cannot be verified, though.

6. Conclusions

This chapter aims to answer the main research question:

What are the projected regional developments in direct final energy demand for the agricultural processes irrigation and synthetic fertilizer production during the 21st century?

First, the three sub questions are answered. These entail the main aspects of final energy demand; the level of activity, the specific energy consumption of technological options able to provide this activity, and the structural mix of these options. Subsequently, the main research question on final energy demand is answered. Finally, some recommendations are given on sustainable policies.

6.1 Answers to the sub questions

A. What are the projected activity developments for agricultural irrigation and synthetic fertilizer production?

Irrigation water withdrawals peak around 2010, then decline gradually toward 2100 in all scenarios. This decrease is most prominent in the Sustainability scenario, and lowest in the Region Rivalry scenario. Withdrawals are dominated by local surface water, followed by aquifers, reservoirs and groundwater sources respectively. **Ammonia** is by far the most produced fertilizer type globally. While the Sustainability scenario shows a weak peak in ammonia production around 2050, the others see a continuous growth toward 2100; the Business As Usual scenario more so than the Regional Rivalry scenario. Global production volumes of **Other fertilizer** show similar scenario developments as those for ammonia, since they share a major driver; grand total nitrogen production. Urea production volumes dominate in all scenarios. Furthermore, AP and AN see notable volumes.

B. What are the projected developments in specific energy consumption for these processes?

Considering **irrigation**, extraction SEC is continuously higher for aquifers compared to groundwater in all regions. Field application SEC is highest for sprinkler systems, significantly lower for drip systems, and assumed zero for gravity fed surface systems. For all **ammonia** production plant types modeled in the *AED module*, SEC declines asymptotically toward 2100. For all **other fertilizers**, the module assumes static SEC during the projection period. NPK1 is by far the most the most energy intensive other fertilizer type, followed by PK.

C. What are the projected structural developments for these processes?

All scenarios see regional **irrigation** system shifts following open canal surface, sprinkler and drip systems subsequently. These shifts are strongest in the Sustainability scenario and weakest in the Regional Rivalry scenario. Considering energy carrier choices, the use of electric pumps increases fastest in developing countries. This is especially true in the Sustainability scenario. Considering **ammonia**, the Two Degrees scenario shows by far the largest expansion of biomass fed ammonia plants, followed by the Sustainability, Business As Usual and Regional Rivalry scenarios respectively. This biomass plant expansion mainly substitutes natural gas plants and to a lesser extent coal plants. Heavy oil plants, which are currently marginally deployed, are completely phased out by 2040 in all scenarios. **Other fertilizers** show no structural changes, since regional production shares are assumed to be static during the projection period.

6.2 Answers to the main research question

World final energy demand for **irrigation** peaks around 2025, then gradually declines toward 2100. The decline is most prominent in the Sustainability scenario. In all scenarios, world irrigation energy demand is dominated by aquifer extraction, closely followed by field application. Energy demands for groundwater extraction play only a small role. Total final energy demand for **ammonia** production peaks around 2050 in the Sustainability scenario, while it grows continuously in the others. This is especially true for the Regional Rivalry and Two Degrees scenarios. In the former, this is due to the large total production volumes and somewhat higher shares of coal plants. In the latter, it is explained by the high share of energy intensive biomass plants. Global final energy demand for **other fertilizers** show similar scenario developments as that of ammonia production. **Overall**, projected world AED is dominated by ammonia production in all scenarios, and energy demand is higher for irrigation than for the production of other fertilizer types. Scenario differences in AED are mainly explained by varying energy demands for ammonia production. At the moment, the *AED module* covers an estimated 58.5% of current world AED and 2.0% of grand total final energy demand.

6.3 Policy recommendations

Policies favoring a specific type of irrigation system should take into account two sustainability aspects; water use and energy consumption. As argued in section (5.1), a shift from gravity fed surface systems to sprinkler systems is generally associated by advances in reducing water scarcity greater than its increase in energy related impact. However, the choice should be made on a per region or country basis, taking into account the local availability of water and energy. In this way, situations where one type of environmental impact is replaced by another (of greater magnitude) can be avoided. Regarding both sustainability aspects, drip systems perform the best. However, they are associated by high costs and can not be applied to many crop types.

Considering pump types for irrigation, policies are recommended to focus on a wider deployment of electrical pumps. This can be facilitated by increasing rural access to electricity, especially in many developing regions. As argued in section (3.2.1), renewable energy supply is assumed to be more easily implemented when electricity is demanded rather than diesel. Furthermore, advantages for farmers, such as lower maintenance requirements and more easily implemented pump controls, are apparent.

Regarding technological support, policies that favor the development of biomass fed ammonia production plants and carbon capture and storage add-ons are recommended. These technologies are two of only few options to drastically reduce specific emissions of ammonia production. Projected decreases in SEC for fossil fuel fed plants are significant, but assumed insufficient to coincide with ambitious mean surface temperature targets.

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Annex 1 - Nitrogen fertilizer trade matrix

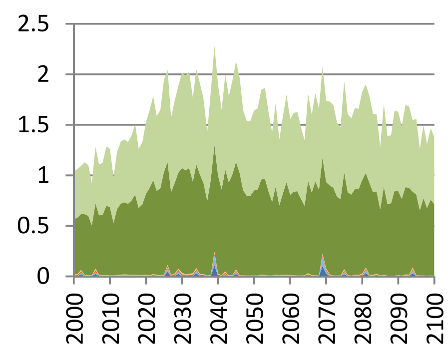
N-FERTILIZER CONSUMING REGION (2013)	N-FERTILIZER PRODUCING REGION (2013)																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.89	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.03	0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
3	0.02	0.00	0.37	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.03	0.00	0.04	0.05	0.16	0.21	0.00	0.00	0.05	0.00	0.01	0.00	0.00	0.00	0.00
4	0.01	0.00	0.00	0.81	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.05	0.06	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
5	0.03	0.00	0.00	0.00	0.21	0.00	0.07	0.00	0.00	0.00	0.00	0.04	0.00	0.05	0.06	0.20	0.27	0.00	0.00	0.06	0.00	0.01	0.00	0.00	0.00	0.00
6	0.02	0.00	0.00	0.00	0.00	0.54	0.04	0.00	0.00	0.00	0.00	0.02	0.00	0.03	0.03	0.12	0.16	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.03	0.00	0.00	0.00	0.00	0.00	0.07	0.21	0.00	0.00	0.00	0.04	0.00	0.05	0.06	0.21	0.27	0.00	0.00	0.06	0.00	0.01	0.00	0.00	0.00	0.00
9	0.04	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.03	0.00	0.00	0.05	0.00	0.06	0.07	0.25	0.33	0.00	0.00	0.07	0.00	0.02	0.00	0.00	0.00	0.00
10	0.02	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.45	0.00	0.03	0.00	0.04	0.04	0.14	0.19	0.00	0.00	0.04	0.00	0.01	0.00	0.00	0.00	0.00
11	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.81	0.01	0.00	0.01	0.01	0.05	0.06	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.02	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.02	0.55	0.03	0.03	0.12	0.15	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.02	0.07	0.09	0.74	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
19	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.02	0.00	0.03	0.03	0.10	0.13	0.00	0.61	0.03	0.00	0.01	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.02	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.03	0.00	0.04	0.04	0.14	0.18	0.00	0.00	0.04	0.46	0.01	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.03	0.03	0.00	0.00	0.01	0.00	0.00	0.90	0.00	0.00	0.00
24	0.03	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.04	0.00	0.05	0.05	0.20	0.25	0.00	0.00	0.06	0.00	0.01	0.00	0.25	0.00	0.00
25	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.02	0.08	0.10	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.69	0.00
26	0.03	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.04	0.00	0.05	0.06	0.21	0.28	0.00	0.00	0.06	0.00	0.01	0.00	0.00	0.00	0.17

Table 2: Nitrogen fertilizer trade matrix for 2013. Indicates share of fertilizers consumed in region on vertical axis produced by region on horizontal axis. Regions in green font are net producers, regions in red font net consumers.

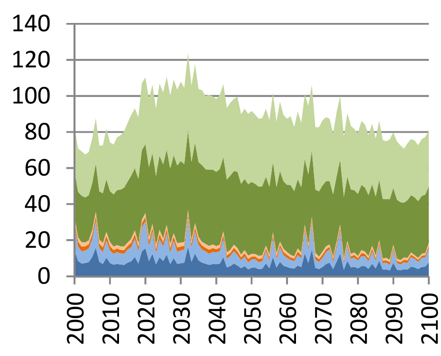
Annex 2 - Regional final energy demand irrigation

Regional FED irrigation (PJ), SSP2

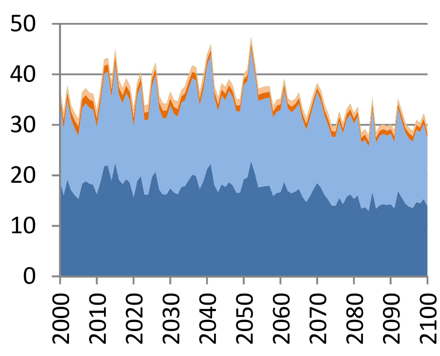
1. Canada



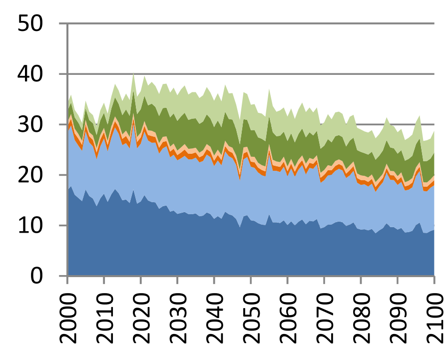
2. USA



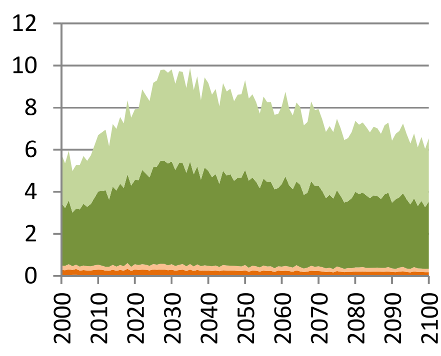
3. Mexico



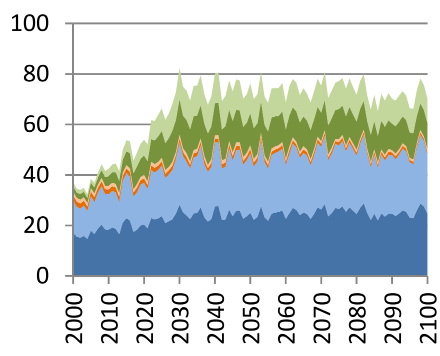
4. Central America



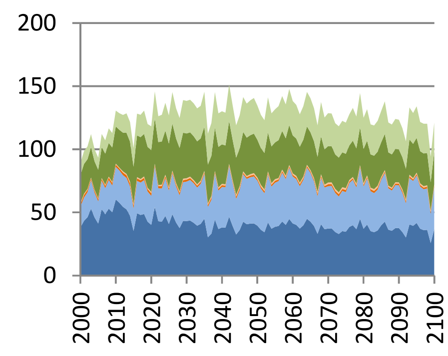
5. Brazil



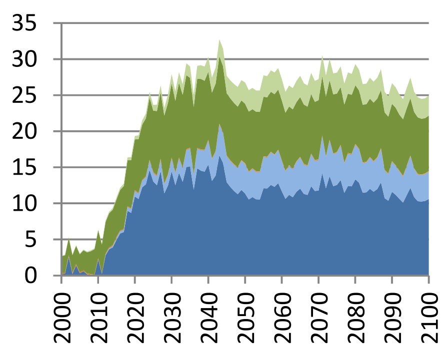
6. Rest South America



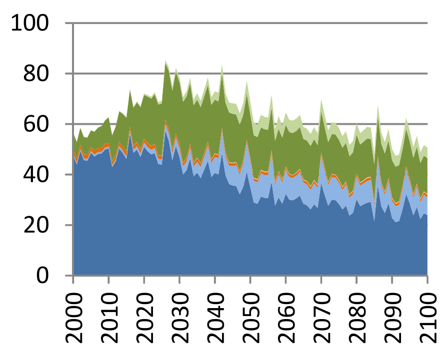
7. Northern Africa



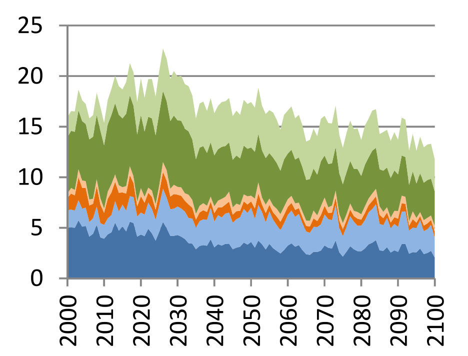
8. Western Africa



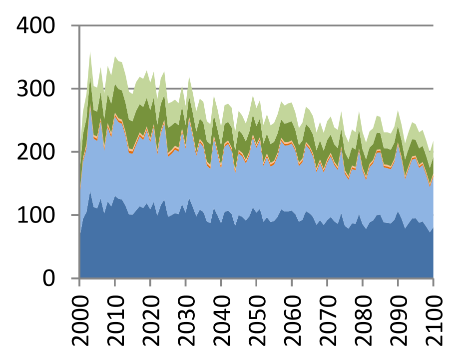
9. Eastern Africa



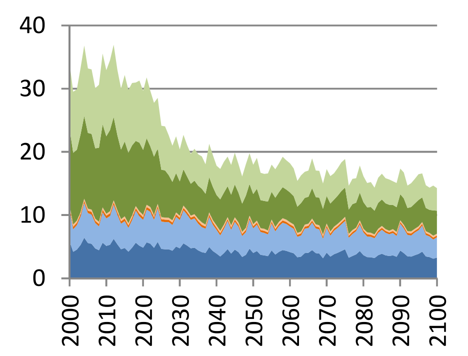
10. South Africa



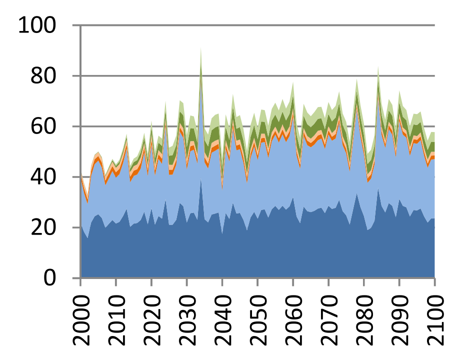
11. Western Europe



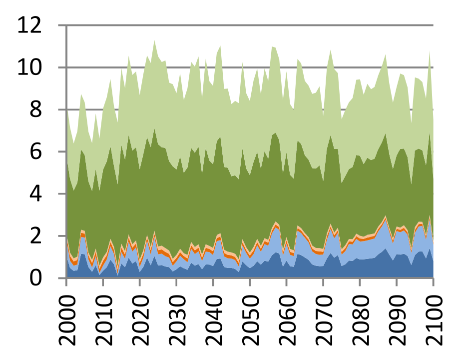
12. Central Europe



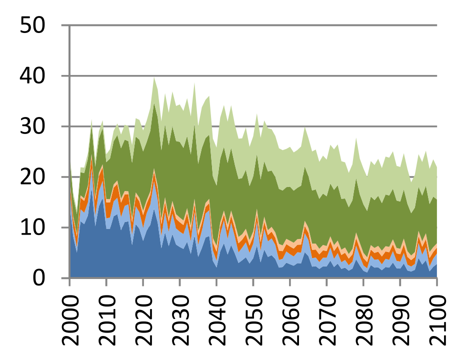
13. Turkey



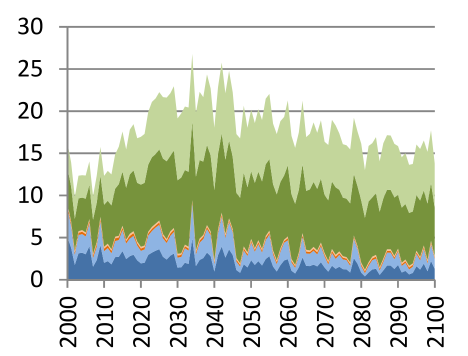
14. Ukraine region



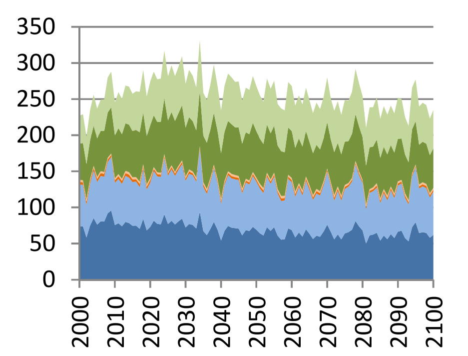
15. Kazakhstan region



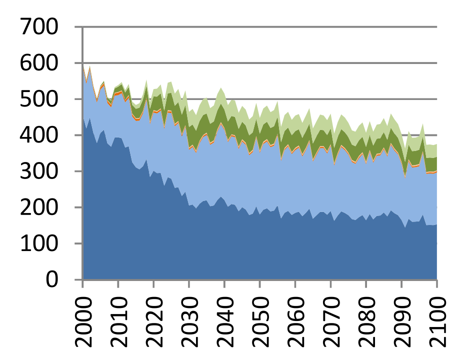
16. Russia region



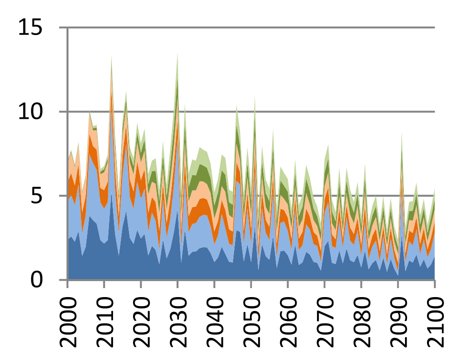
17. Middle East



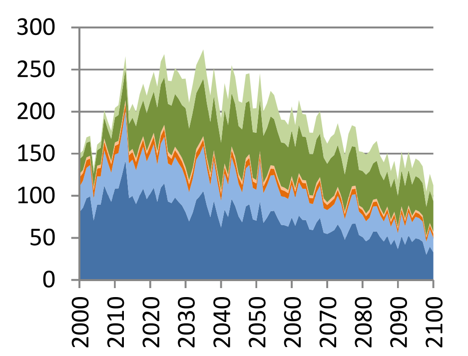
18. India region



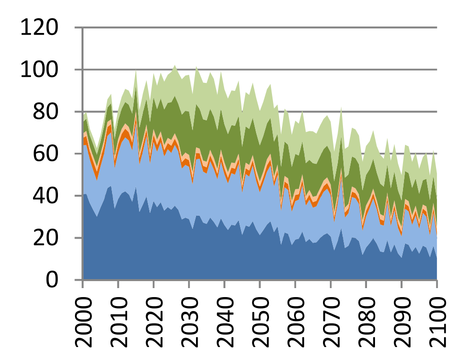
19. Korea region



20. China region



21. Southeast Asia



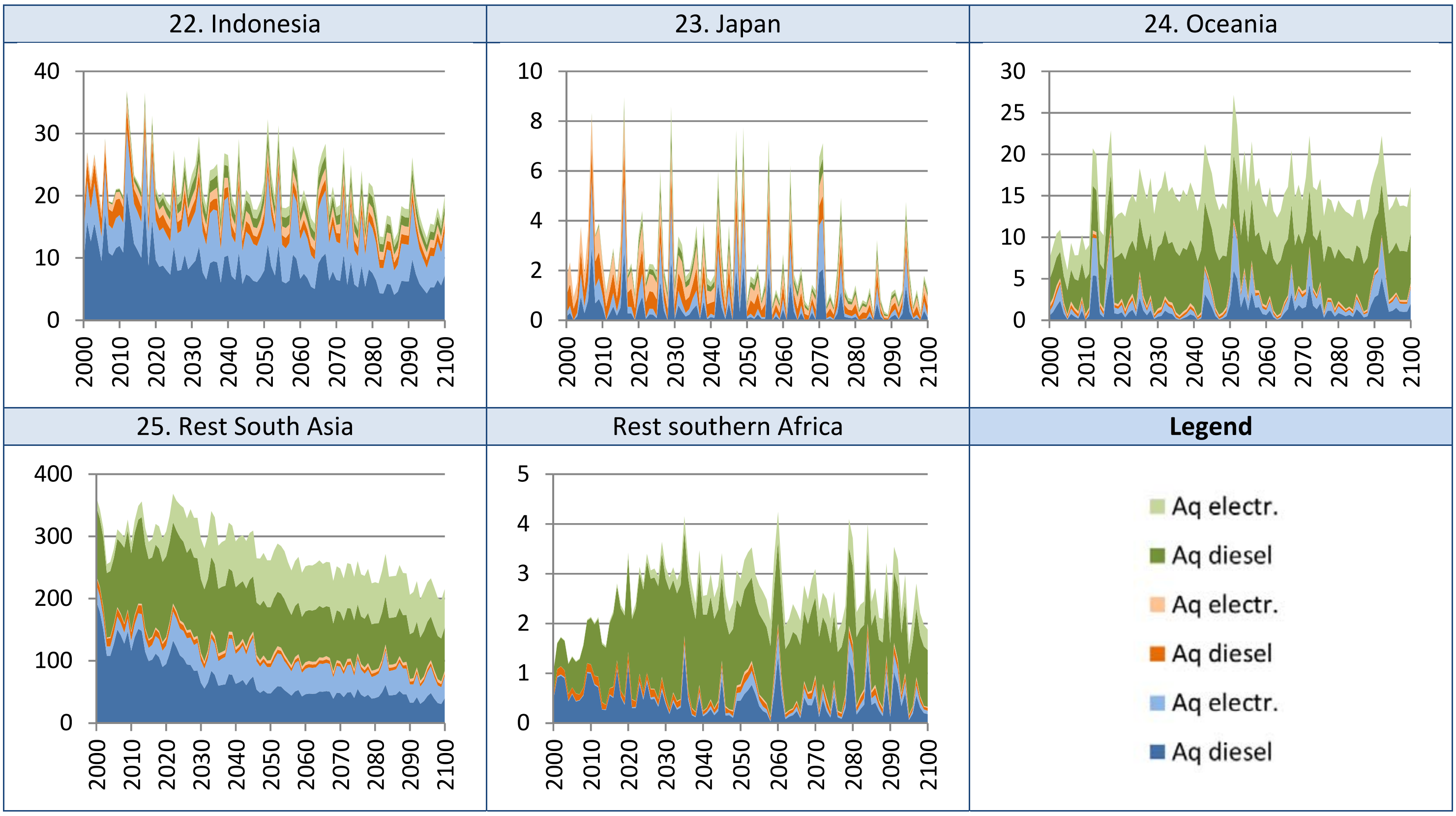
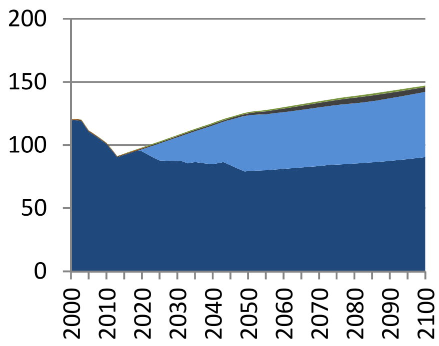


Figure 29: Regional final energy demand for irrigation for SSP2 (PJ/yr). Mind the different axis settings.

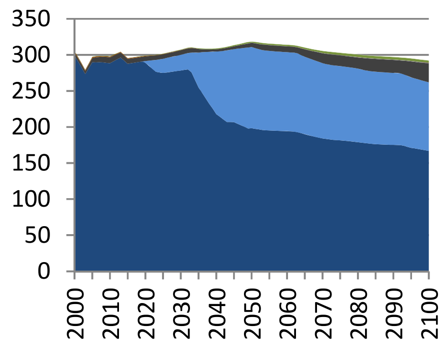
Annex 3 - Regional final energy demand ammonia

Regional FED ammonia fertilizer (PJ) SSP2

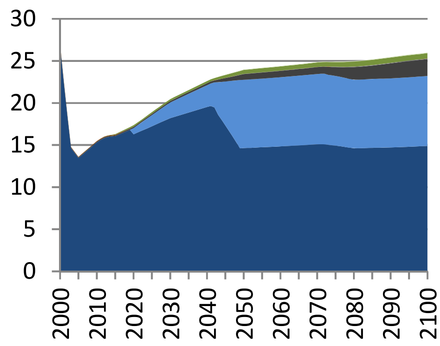
1. Canada



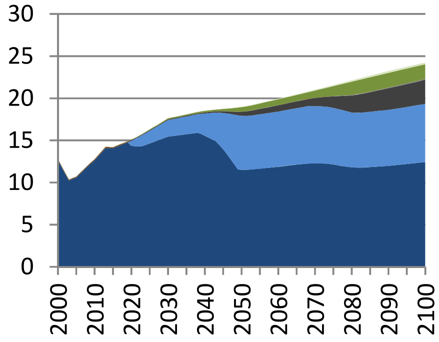
2. USA



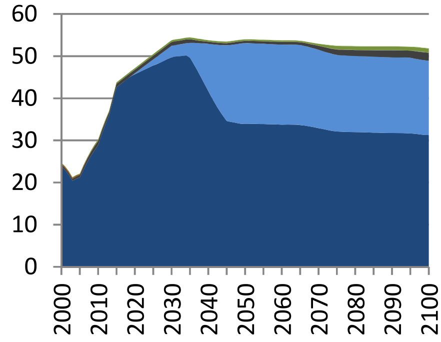
3. Mexico



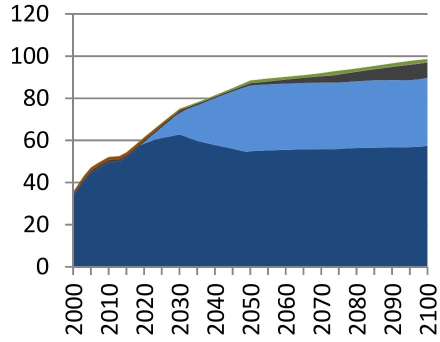
4. Central America



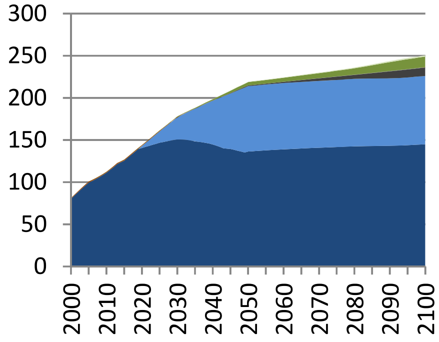
5. Brazil



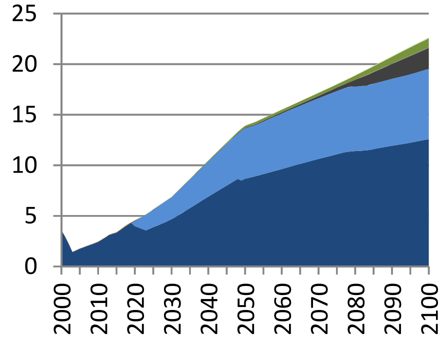
6. Rest South America



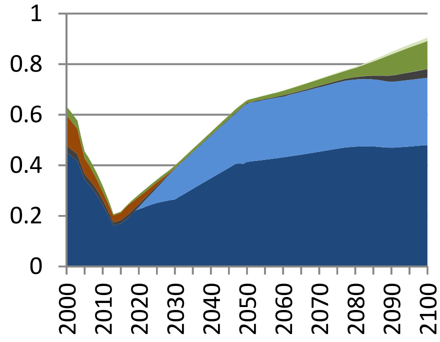
7. Northern Africa



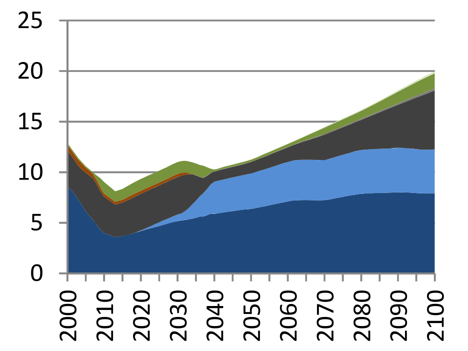
8. Western Africa



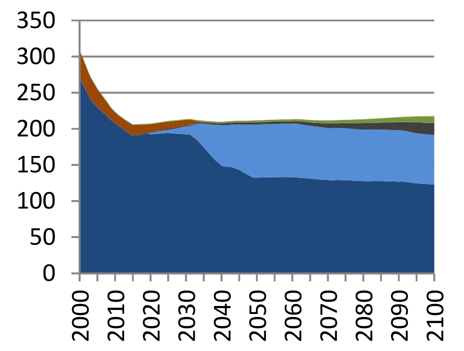
9. Eastern Africa



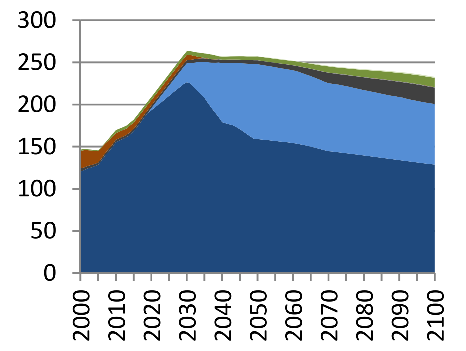
10. South Africa



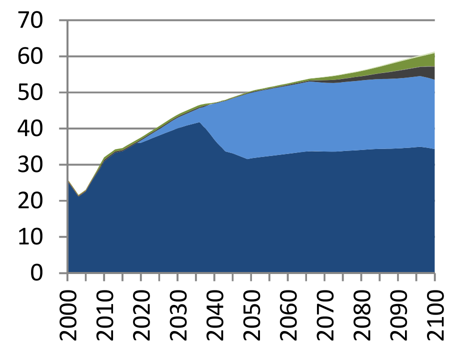
11. Western Europe



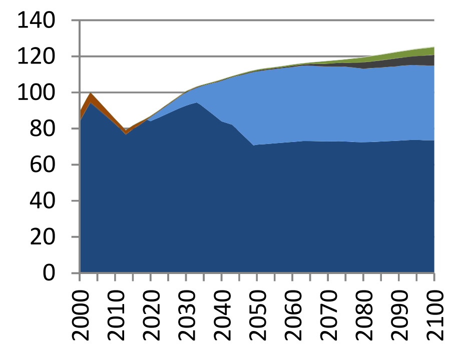
12. Central Europe



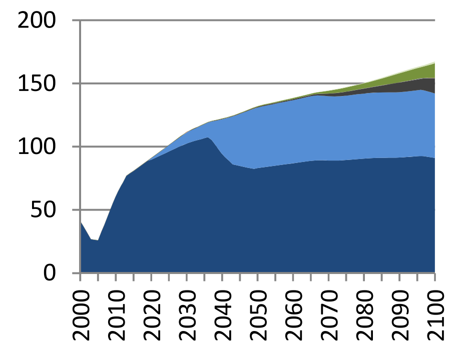
13. Turkey



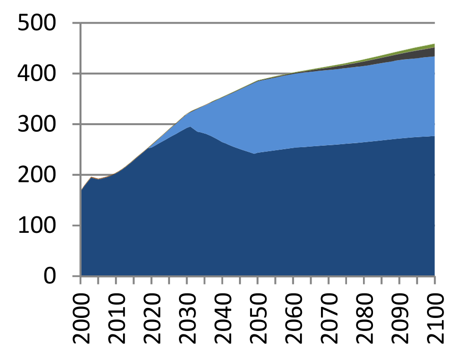
14. Ukraine region



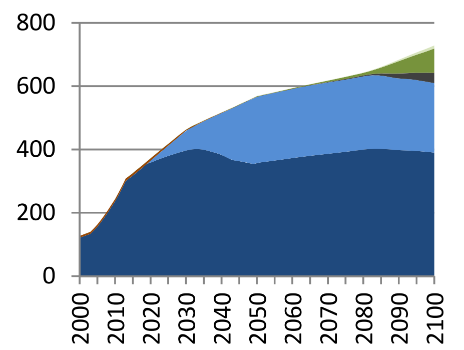
15. Kazakhstan region



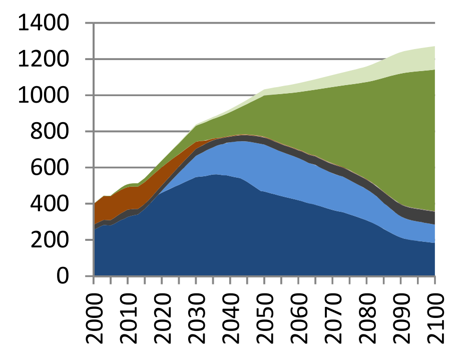
16. Russia region



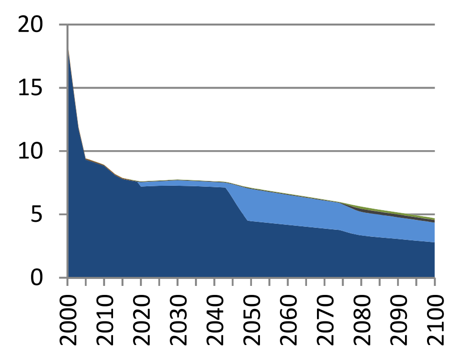
17. Middle East



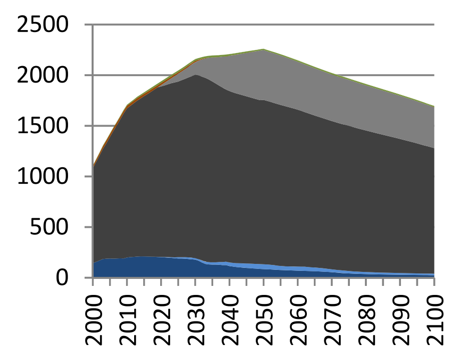
18. India region



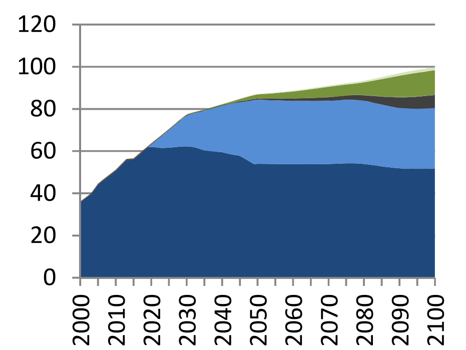
19. Korea region



20. China region



21. Southeast Asia



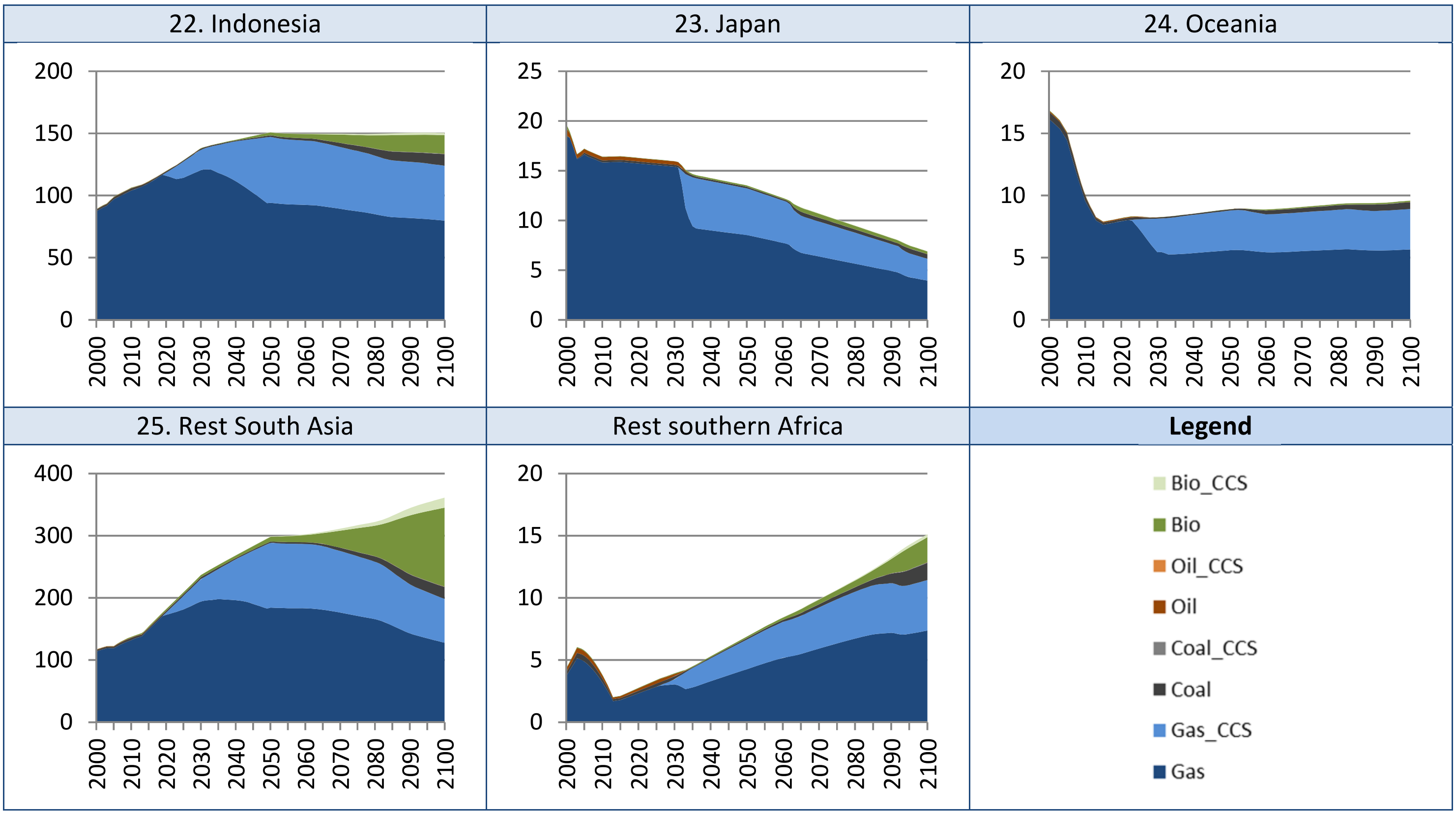
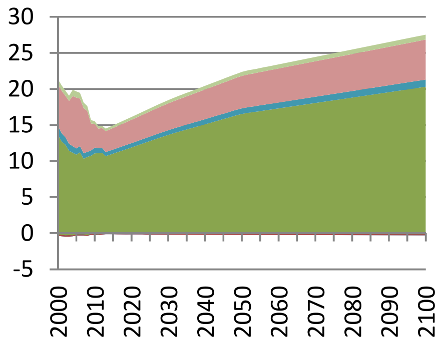


Figure 30: Regional final energy demand for ammonia production for SSP2 (PJ/yr). Mind the different axis settings.

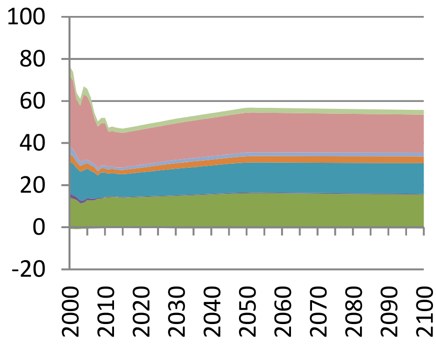
Annex 4 - Regional final energy demand other fertilizers

Regional FED other fertilizers (PJ), SSP2

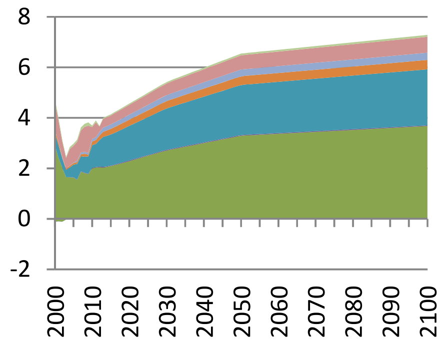
1. Canada



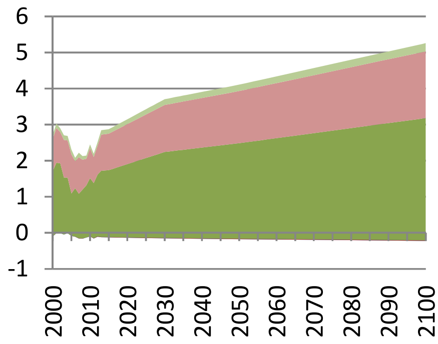
2. USA



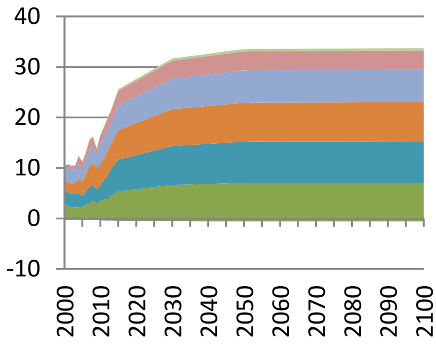
3. Mexico



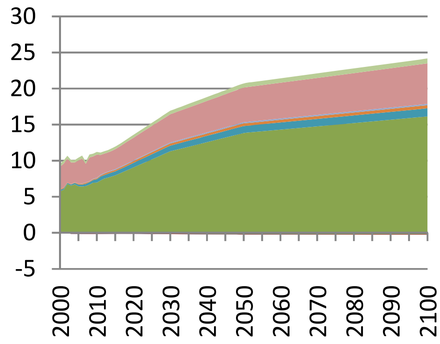
4. Central America



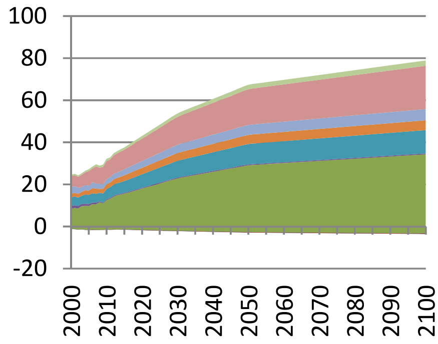
5. Brazil



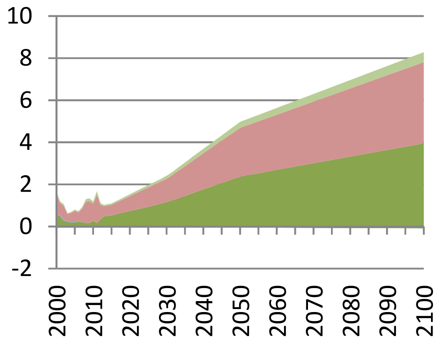
6. Rest South America



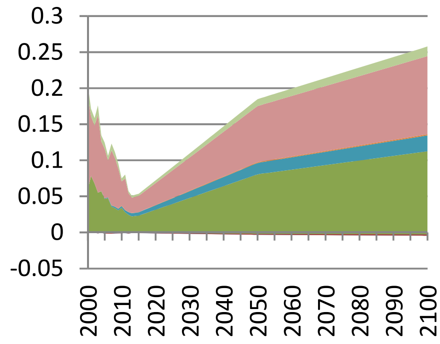
7. Northern Africa

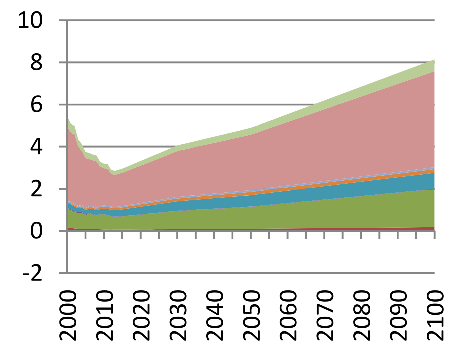
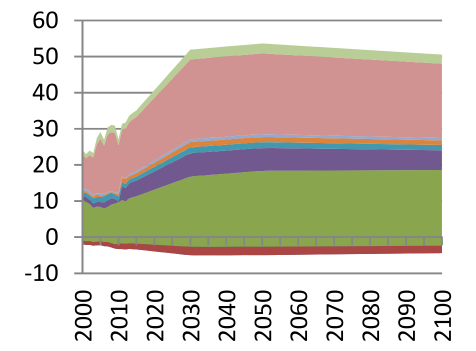
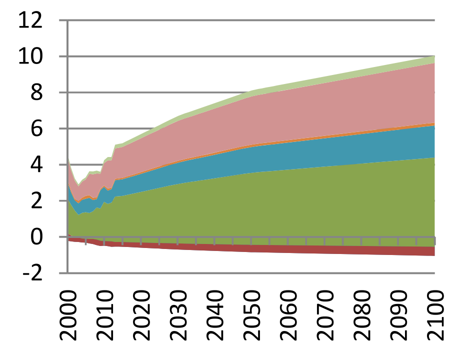
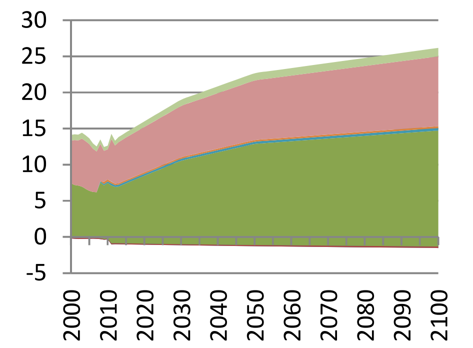
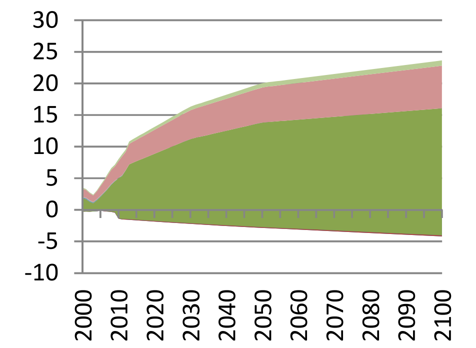
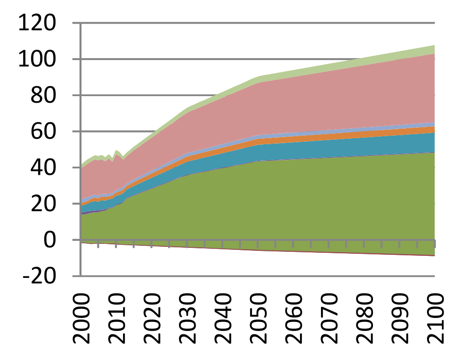
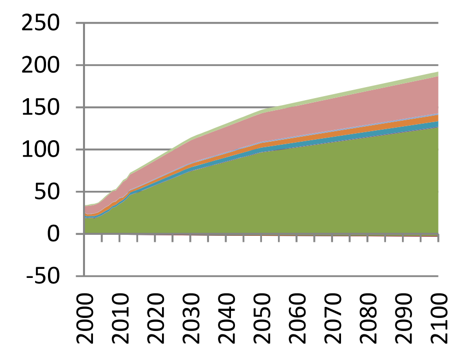
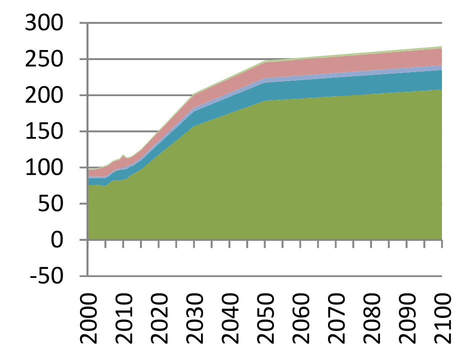
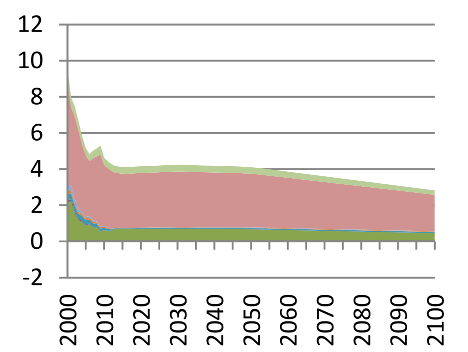
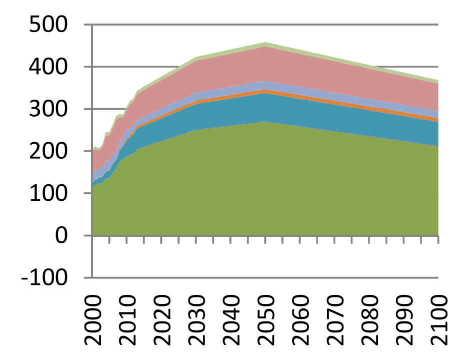
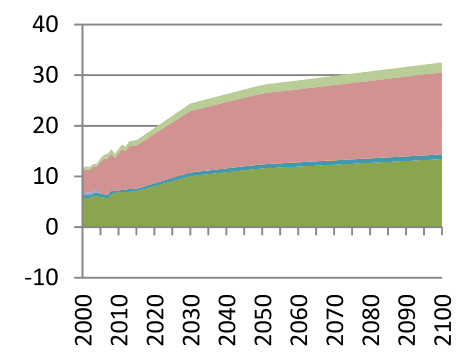


8. Western Africa



9. Eastern Africa



10. South Africa	11. Western Europe	12. Central Europe
		
13. Turkey	**14. Ukraine region**	**15. Kazakhstan region**
		
16. Russia region	**17. Middle East**	**18. India region**
		
19. Korea region	**20. China region**	**21. Southeast Asia**
		

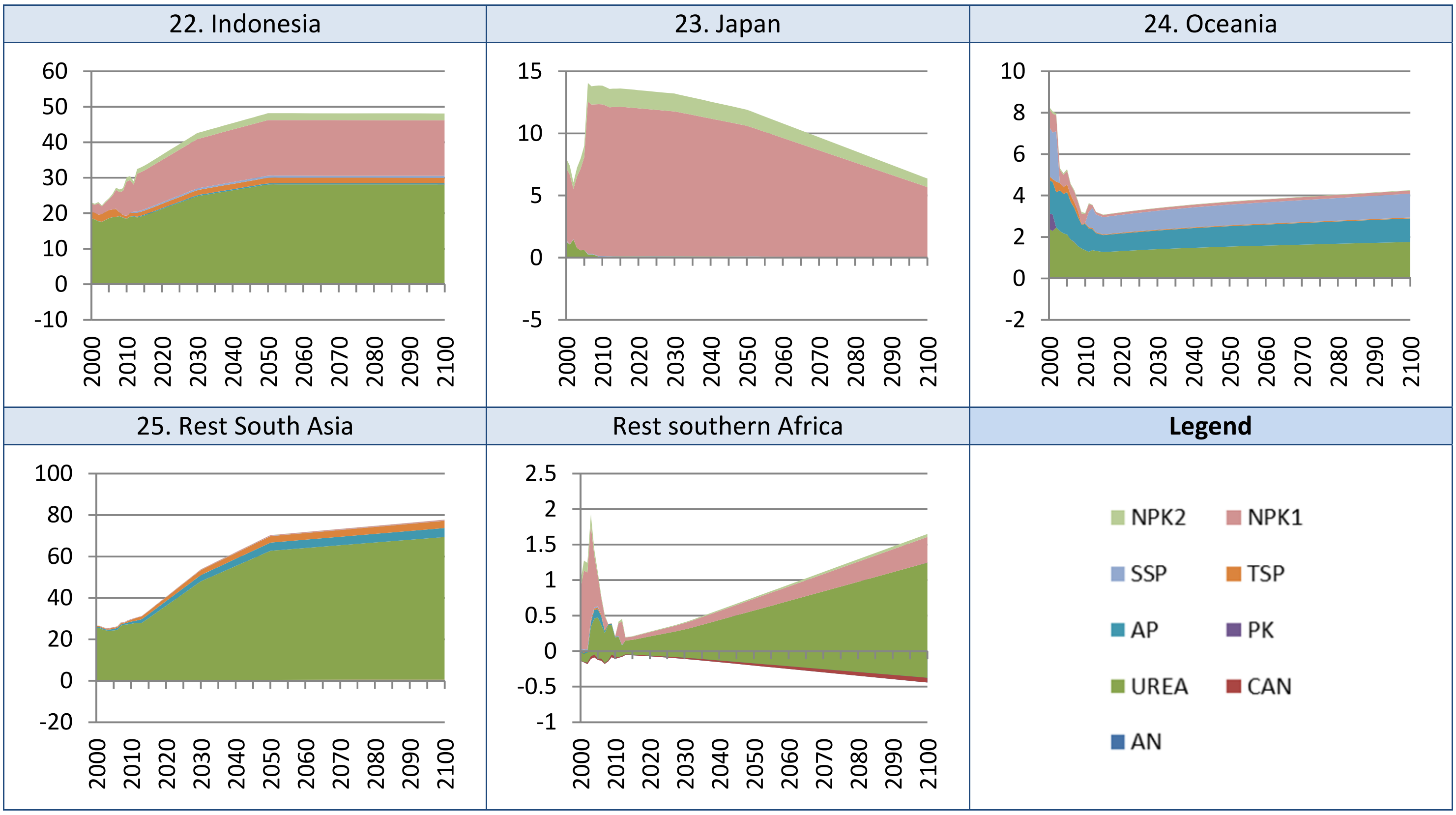
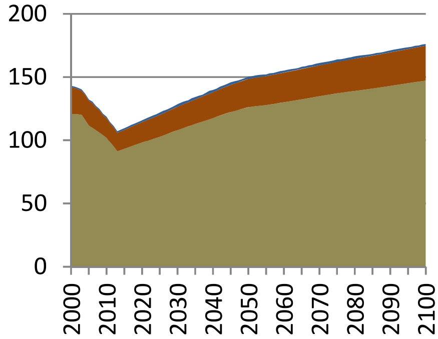


Figure 31: Regional final energy demand for non-ammonia fertilizers for SSP2 (PJ/yr). Mind the different axis settings.

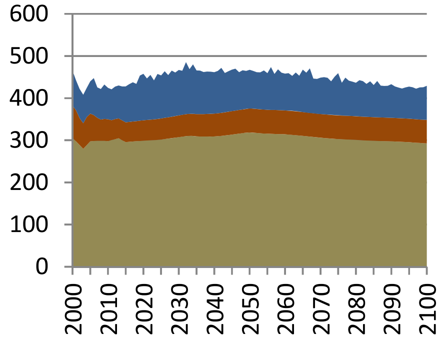
Annex 5 - Regional final energy demand per AED process

Regional FED per modeled process (PJ)

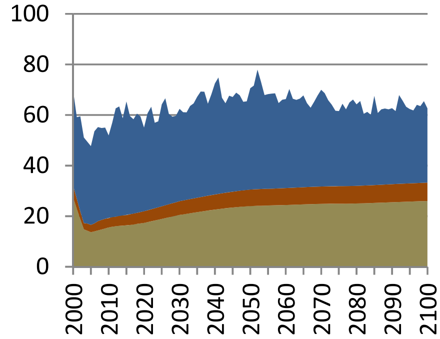
1. Canada



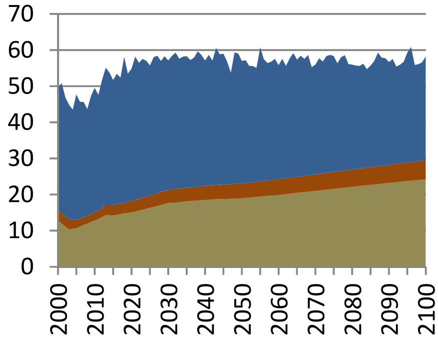
2. USA



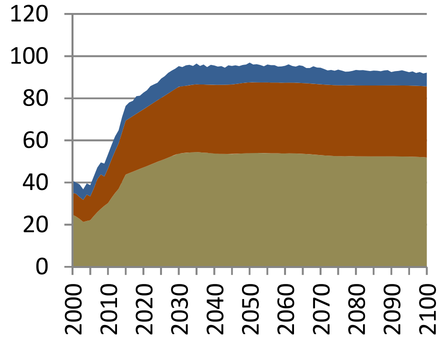
3. Mexico



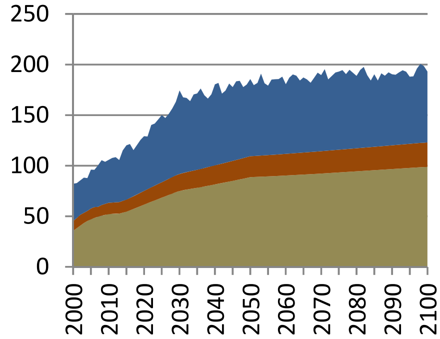
4. Central America



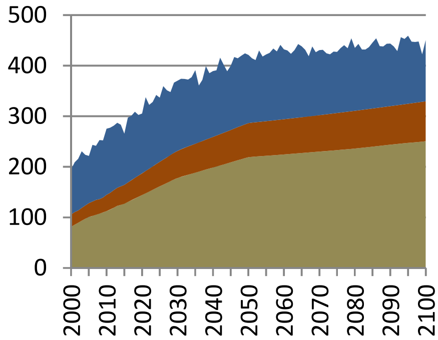
5. Brazil



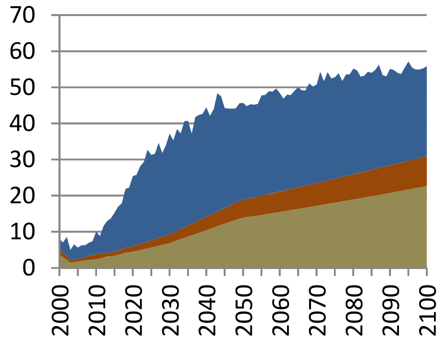
6. Rest South America



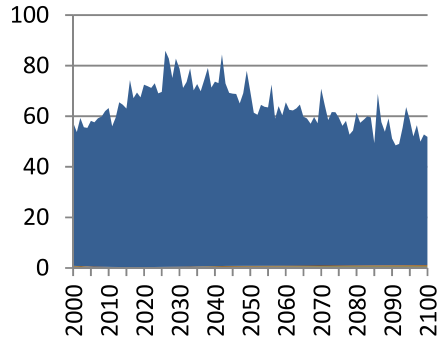
7. Northern Africa



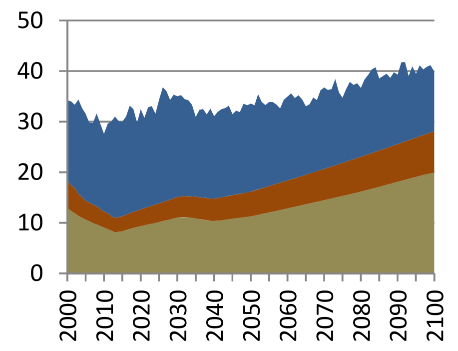
8. Western Africa



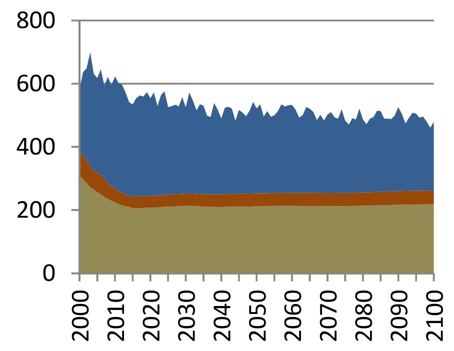
9. Eastern Africa



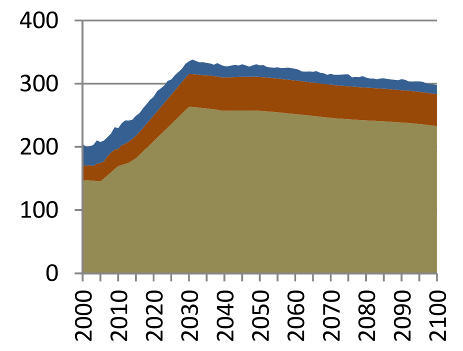
10. South Africa



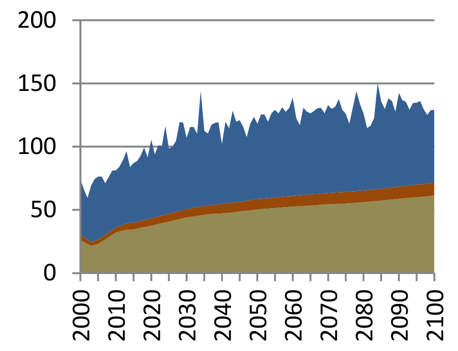
11. Western Europe



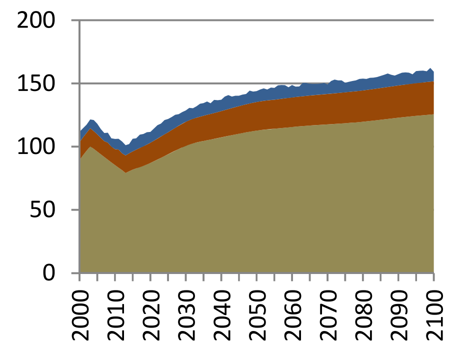
12. Central Europe



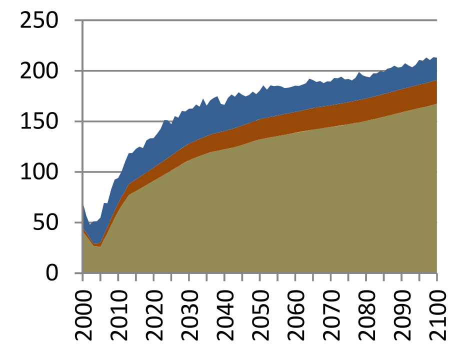
13. Turkey



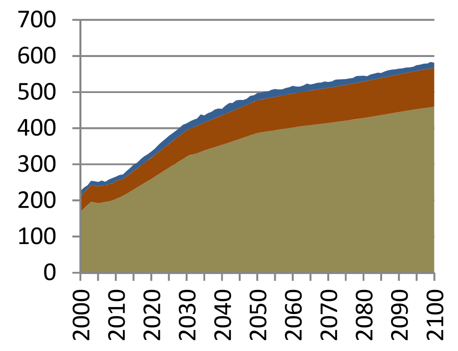
14. Ukraine region



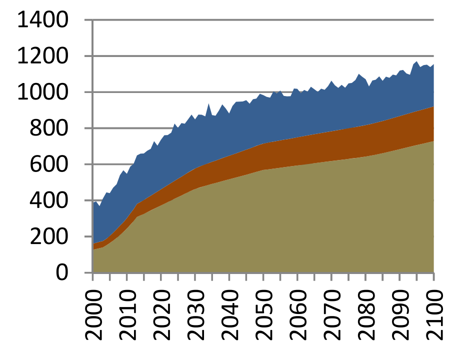
15. Kazakhstan region



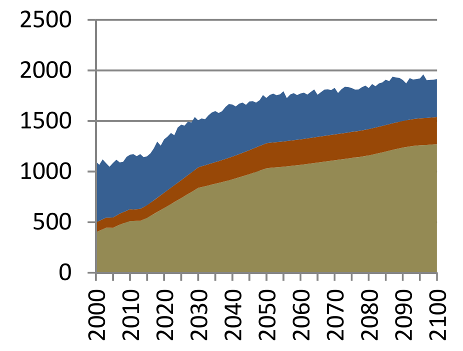
16. Russia region



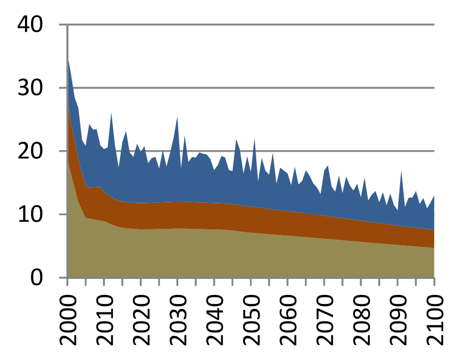
17. Middle East



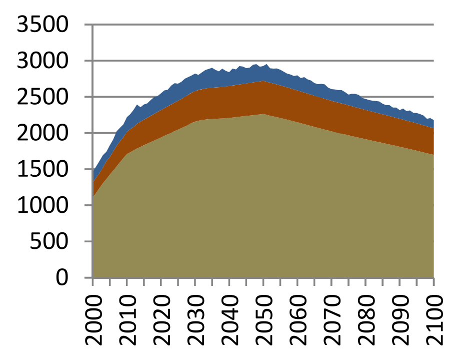
18. India region



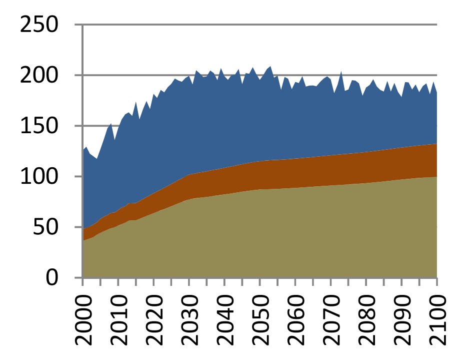
19. Korea region



20. China region



21. Southeast Asia



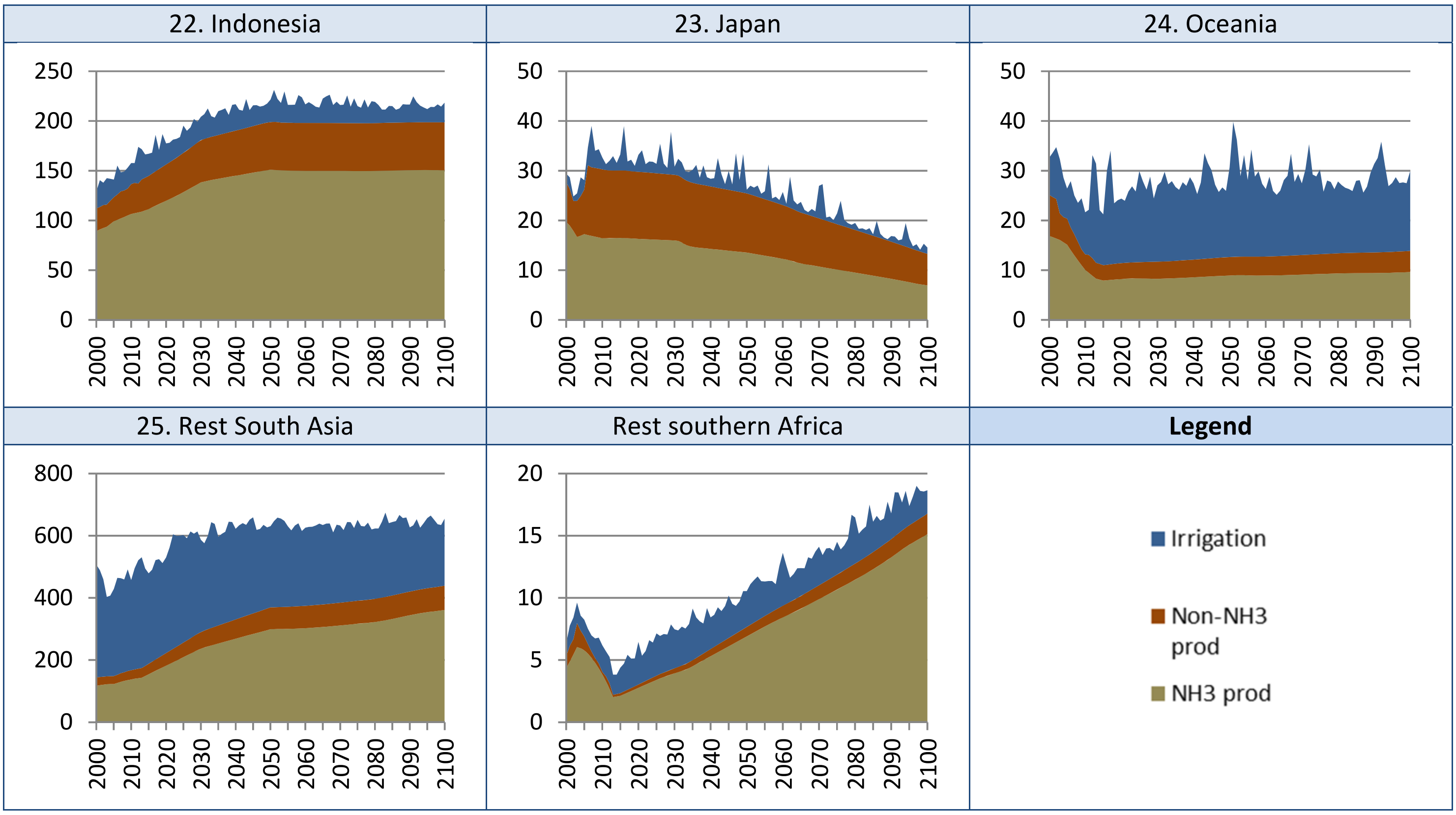


Figure 32: Regional final energy demand for the agricultural processes irrigation, ammonia production and non-ammonia fertilizer production for SSP2 (PJ/yr). Mind the different axis settings.

Annex 6 – modeling the remaining agricultural energy demand

As is shown in figure (28), the *AED module* currently accounts for an estimated 58,5% of global agricultural energy demand. The remaining 41,5% is accounted for by agricultural processes such as the use of machinery , livestock housing and forestry. In international statistics, these remaining processes are covered by the sector agriculture *(IEA, 2015)*. This annex explores options for modeling remaining agricultural energy demand (RAED) in a simple way. The main objective is to link READ to activity indicators from within the *IMAGE framework*. In this way RAED will develop scenario dependent, accounting for narrative differences. Furthermore, average SEC is potentially determined using energy intensity indicators from within the framework. Below, two sets of *IMAGE* variables are tested on their current (2010) correlation with regional RAED and specific energy consumption.

Production volumes (set 1)

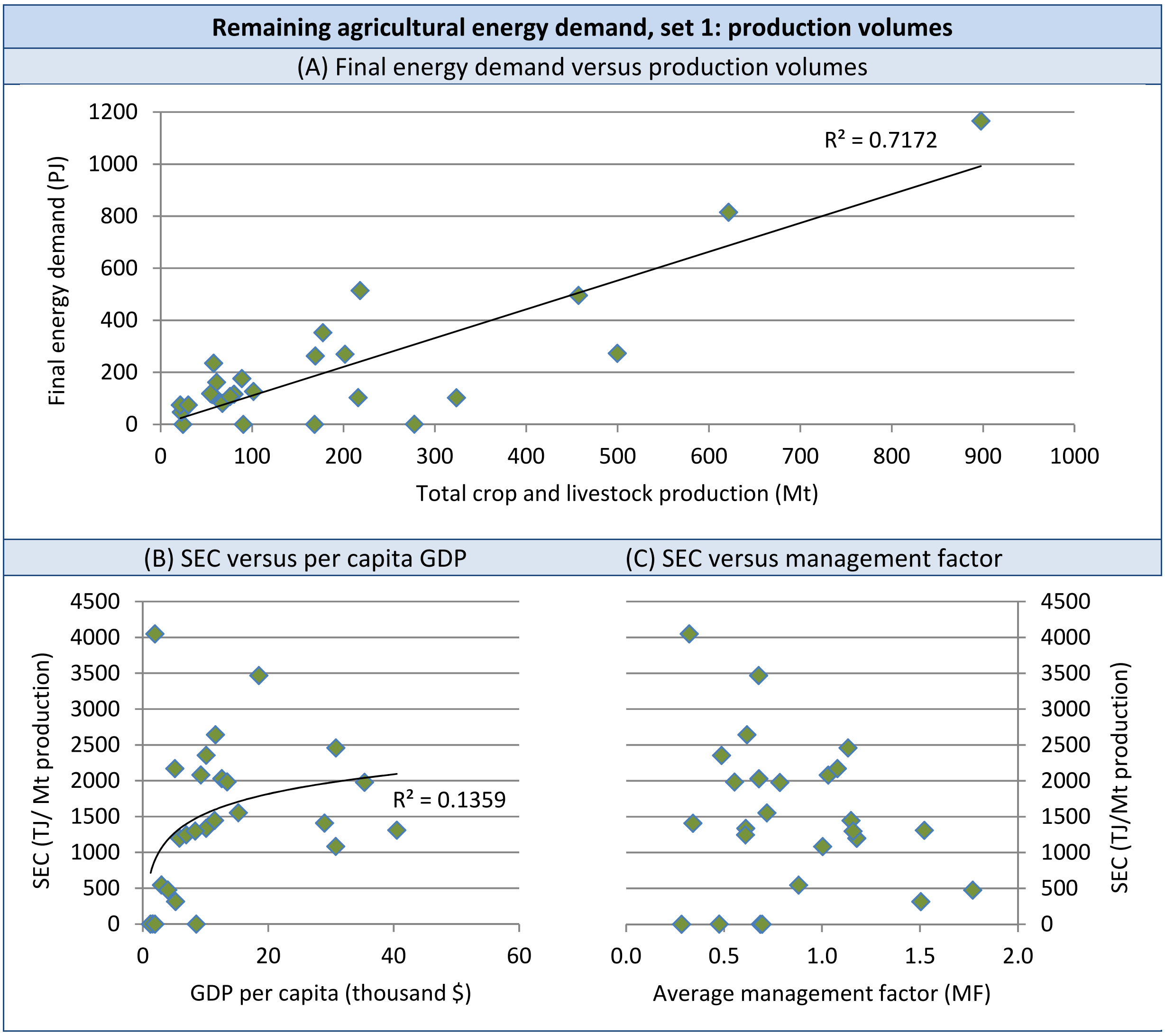


Figure 33: potential SSP2 activity (A) and energy intensity (B and C) indicators for determining future RAED, related to total crop and livestock production volumes. Each diamond represents one of 26 IMAGE regions (2010).

Production volumes for crops and livestock are determined in *MAGNET* on the basis of population growth, changes in income and dietary changes *(Stehfest et al., 2014)*. Figure (33A) plots total the production volume for crops *and* livestock (activity indicator) for each region against their respective READ. A fairly strong linear correlation becomes apparent between the two variables (R^2=0.72). When performing the same analysis with only crop or only livestock production volumes, this correlation is lower (R^2= 0,67 and 0,62 respectively). Therefore, total production volumes for crop *and* livestock are considered in the rest of this annex. Regarding regional SEC (TJ/Mt), one can presume a relationship with GDP; higher income grants access to machinery and intensive livestock stables. Remarkably, figure (33B) shows a very weak correlation between the SEC and GDP (R^2=0.14). A second potential energy intensity indicator is the management factor (MF), which represents 'actual crop yield'/ 'potential crop yield'. A regional MF for each crop type is determined in the *IMAGE land model*. One can expect a relationship with SEC; actual yields closer to their potential suggest the use of more intensified methods for cultivation. However, figure (33C) shows virtually no correlation between average crop management factor (which is weighted on the basis of crop production volumes) and specific energy consumption.

Harvested area (set 2)

Harvested area is calculated in the *IMAGE land model* on the basis of regional demands for crops and grid specific crop yields *(Stehfest et al., 2014)*. Compared to the activity indicator 'production volumes', 'total harvested area' shows a much lower linear correlation with regional RAED (R^2=0.33, figure 34A). Considering harvest SEC (TJ/thousand km2), a weak correlation with GDP is shown (R^2=0.34, figure 34B). Again, virtually no correlation is found between SEC and the weighted MF (figure 34C).

Discussion

Between the two potential activity indicators, 'total production volume' is considered to be more suited for determining RAED than 'total harvested area'. Not only do regional production volumes have a much higher correlation with RAED, they also indicate both crop and livestock activity. Harvested area only indicates crop cultivation activity, since pasture is not included. Considering potential energy intensity indicators, both GDP and management factor show insufficient correlation with production SEC (TJ/Mt) to firmly base energy intensity on. Alternatively, one can converge current regional production SEC to that of a typical developed region (e.g. Western Europe or USA) during the period 2010-2050. This would follow the assumption that, in the future, developing regions are going to act more like developed regions. The downside of this SEC methodology is that it is not product specific or technologically detailed; the SEC of all crop and livestock types basically converge to the same level and no set of technological options for the production is introduced. Therefore, this generic SEC methodology is still prone to misinterpretation of structural changes. However, the main objective mentioned in the first paragraph of this annex is satisfied; RAED is linked to an activity indicator from within the *IMAGE* framework.

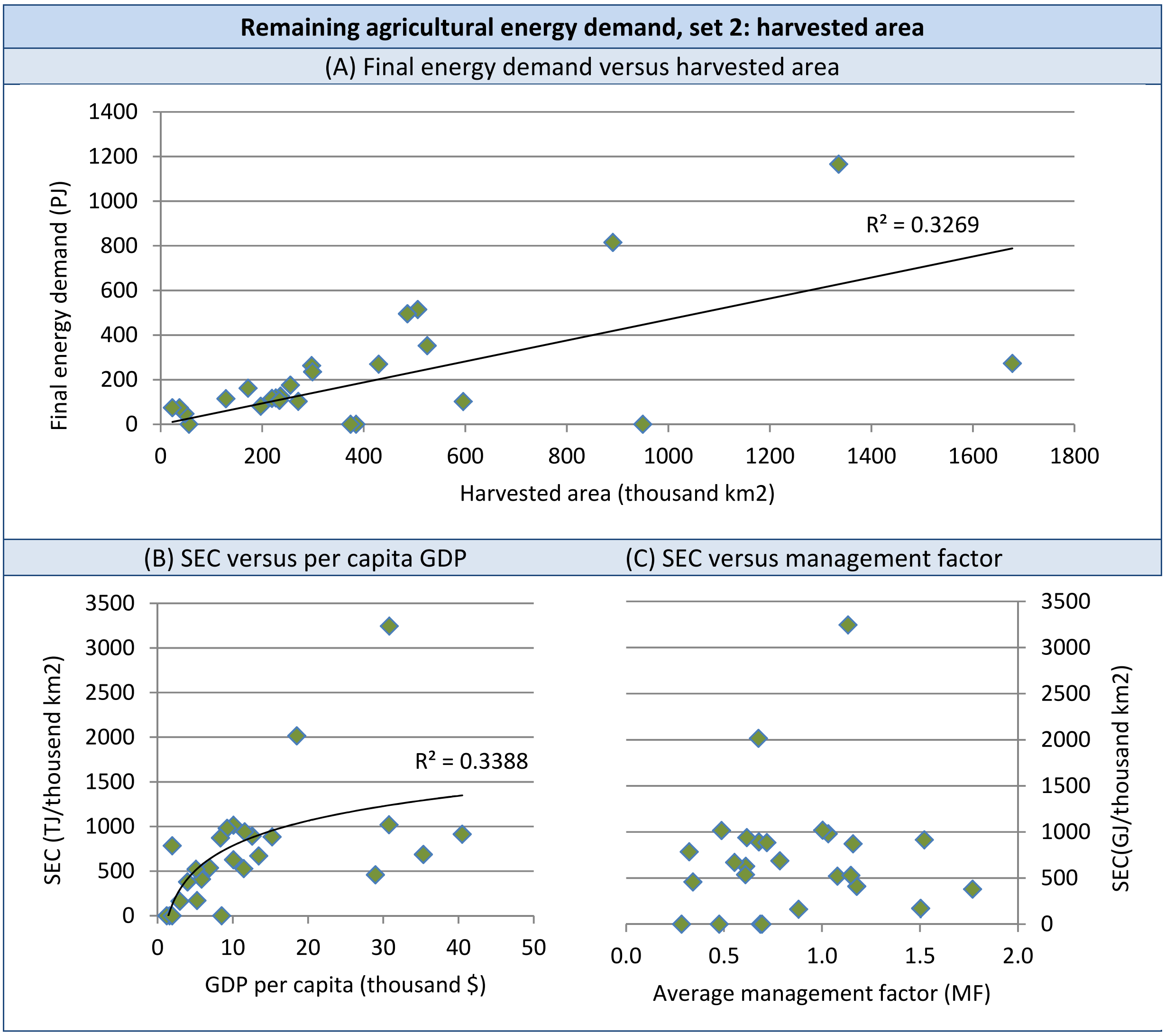


Figure 34: potential SSP2 activity (A) and energy intensity (B and C) indicators for determining RAED, related to total crop harvested area. *Each diamond represents one of 26 IMAGE regions (2010).*