PAUL SCHERRER INSTITUT

PSI Bericht Nr. 13-03
August 2013
ISSN 1019-0643

The Energy Departments

Global Multi-regional MARKAL (GMM) model update: Disaggregation to 15 regions and 2010 recalibration

Hal Turton, Vangelis Panos, Martin Densing, Kathrin Volkart

PAUL SCHERRER INSTITUT

PSI Bericht Nr. 13-03
August 2013
ISSN 1019-0643

Energy Economics Group (EEG)
Laboratory for Energy Systems Analysis (LEA)
The Energy Departments

Global Multi-regional MARKAL (GMM) model update: Disaggregation to 15 regions and 2010 recalibration

Hal Turton, Vangelis Panos, Martin Densing, Kathrin Volkart

Paul Scherrer Institut
5232 Villigen PSI
Switzerland
Tel. +41 56 310 23 61
Fax +41 56 310 44 11
www.psi.ch

Acknowledgement

Much of this work was conducted to support PSI's partnership with the World Energy Council, and was partly financed by the Swiss Energy Council and the Swiss Federal Office of Energy.

Table of Contents

List of Figures

List of Tables

1 Introduction

This report describes recent developments of the Global Multi-regional MARKAL (GMM) model of the Energy Economics Group (EEG) at PSI. Much of this work has been conducted to support PSI's partnership with the World Energy Council (WEC).

Specifically, this report describes the disaggregation of GMM from 6 world regions into 15 world regions in order to facilitate a richer analysis of future global energy trends and technology pathways for scenario quantification. Further, GMM has been recalibrated to 2010 statistics. This disaggregation and recalibration also afforded the opportunity to update estimates of energy resources used in the model.

The next section describes the rationale for disaggregating the regional representation of GMM, the criteria applied for defining new regions, and a comparison of these regions. Section 3 then presents the data used to recalibrate the model in terms of primary energy extraction and trade, electricity generation (including installed capacities, and planned retirements and additions), and end-use sectors. Section 4 outlines the update of resource assumptions based on recent statistical estimates in line with the new regional disaggregation.

GMM model

The global multi-regional MARKAL (GMM) model is a technologically detailed model of the global energy system developed over several years at PSI (e.g., Rafaj 2005, Gül et al. 2009).

GMM is a cost optimization model that determines the least-cost combination of technologies and fuels to satisfy demands and fulfil other constraints, from the perspective of a single social planner. The major input parameter set consists of technology specifications, including efficiencies, costs (investment, O&M costs etc), load factors etc. for current and future technologies. Resources and demand projections (generally derived from economic and population scenarios) comprise other key inputs. These are described in Gül *et al.* (2009), Rafaj (2005), and Barreto and Kypreos (2006). For each world region in the model, specific assumptions are applied for the dynamics of technology characteristics, resource availability, demands and policy.

The model has most recently been used to quantify energy scenarios developed with the World Energy Council, based on coherent storylines about global economic-social-technological development until the year 2050.

For transparency, GMM uses entirely publicly available data sources.

2 Definition of 15 regions

2.1 Introduction

The global multi-regional MARKAL (GMM) model has been developed over a number of years at PSI (e.g., Barreto and Kypreos 2004; Rafaj 2005; Gül 2008; Densing et al. 2012). Earlier versions of GMM included a regional disaggregation of the world into 5 regions (1. North America, 2. Other OECD, 3. Asia, 4. Eastern Europe and the Former Soviet Union (EEFSU), and 5. Latin America, Africa and the Middle East (LAFM)) (Rafaj 2005). In later work, the disaggregation was increased to six regions, by splitting Other OECD and EEFSU regions into three subregions: Western Europe closely matching EU27; Other OECD (comprising Pacific OECD plus Turkey); and a smaller EEFSU (comprising non-EU27 Europe and the Former Soviet Union) (Gül 2008). Figure 2.1 shows the regional disaggregation of the 6-region model version: The developed world is represented by the regions of North America, Western Europe, and other OECD countries, the transitional world is Eastern Europe with the Former Soviet Union, and the developing world is represented by the remaining countries in Asia and Latin America together with the Middle East and Africa.

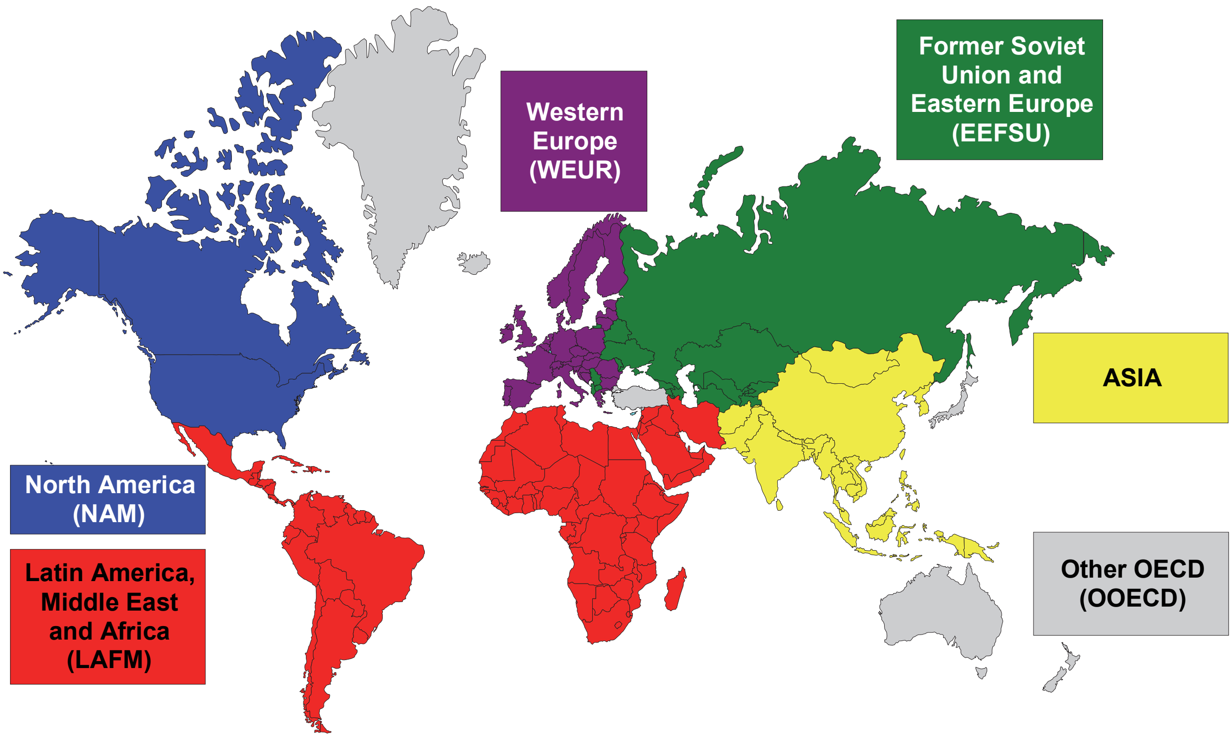


Figure 2.1 The six world regions in the previous version of GMM

While this 6-region disaggregation divides the world into regions of similar significance in terms of historical contributions and influence on the development of the global energy system, it aggregates into single regions a number of developing countries that are likely to have a large influence on the future development of the global energy system. For example, the region Asia aggregates India, China, Indonesia, and South Korea (along with numerous smaller countries). Moreover, the 6-region disaggregation groups together countries that are highly diverse in terms of economic development, geography, resource endowments, and policy. For example, the LAFM region aggregates countries from across 3 continents with highly diverse natural resources (e.g., Brazil, Saudi Arabia, South Africa), and at divergent stages of economic development (e.g. Mexico vs. Congo). For the modelling and quantification of future global scenarios, this has the potential to underestimate the influence of country- or region-specific factors on energy system development (by averaging the characteristics of all countries making up an aggregate region), potentially leading to less robust results for the deployment of particular technology or fuel options.

2.2 Definition of new 15 regions and aggregation criteria

To address the drawbacks of highly aggregated regions, the regional disaggregation in GMM has been revised around 15 world regions. This number of regions was selected to enable a substantial improvement in model resolution, while still ensuring that computational times would remain manageable and other future extensions (e.g., increased technological or temporal detail) would not be precluded. Several criteria[1] have been used to select and define these 15 regions, including:

1. economic size and influence on future energy system development (i.e., applying the principle that influentual large countries should be modelled as single-country regions)

2. level of economic development (i.e., including in the same region countries at similar level of economic development)

3. energy resource endowments (e.g., grouping countries with similar resource endowments; and avoiding grouping of resource-rich with resource-poor countries)

4. level of intra-regional economic/social/cultural integration (e.g., considering existing economic-political integration, e.g., EU, NAFTA, ASEAN)

5. geography (i.e., maintain geographical contiguity; avoid enclaves/exclaves)

6. policy and political situation (e.g., aggregating regions with similar policy environment and governance structure and similar climate policy goals)

Based on the first criterion, several countries were identified as major individual drivers of the global energy system based on their economic scale (both current and future). These comprise: **USA**, **China**, **India**, and **Brazil,** which were defined as single-country regions in GMM (see Table 2.1 for relative sizes).

[1] Note, the numbers used to list the criteria do not imply a particular ranking of criteria, but are included for ease of explanation for the basis of defining particular aggregations.

Table 2.1 Twenty largest economies (measured according to Market Exchange Rates) in 2010 and 2050 (estimated)

GDP (MER) rank - Countries							
2010				2050 (reference)			
Rank		%	Cumulative %	Rank		%	Cumulative %
1	**EU**	**25.9**	**25.9**	**1**	**EU**	**16.7**	**16.7**
2	**USA**	**22.9**	**48.8**	**2**	**USA**	**15.3**	**32.0**
3	**China**	**9.4**	**58.2**	**3**	**China**	**14.3**	**46.3**
4	**Japan**	**8.7**	**66.9**	**4**	**India**	**8.4**	**54.7**
5	*Germany*	*5.2*	*66.9*	**5**	**Brazil**	**4.1**	**58.8**
6	*France*	*4.1*	*66.9*	**6**	**Japan**	**3.7**	**62.5**
7	*United Kingdom*	*3.6*	*66.9*	**7**	**Indonesia**	**3.2**	**65.7**
8	**Brazil**	**3.4**	**70.3**	*8*	*Germany*	*3.0*	*65.7*
9	*Italy*	*3.3*	*70.3*	*9*	*France*	*2.5*	*65.7*
10	**India**	**2.6**	**72.9**	**10**	**Russian Federation**	**2.4**	**68.1**
11	**Canada**	**2.5**	**75.4**	**11**	**Mexico**	**2.3**	**70.4**
12	**Russian Federation**	**2.4**	**77.7**	*12*	*United Kingdom*	*2.2*	*70.4*
13	*Spain*	*2.2*	*77.7*	*13*	*Italy*	*2.0*	*70.4*
14	**Australia**	**2.0**	**79.7**	**14**	**Canada**	**1.7**	**72.1**
15	**Mexico**	**1.6**	**81.4**	**15**	**Nigeria**	**1.6**	**73.7**
16	**Republic of Korea**	**1.6**	**83.0**	*16*	*Spain*	*1.6*	*73.7*
17	*Netherlands*	*1.2*	*83.0*	**17**	**Australia**	**1.4**	**75.2**
18	**Turkey**	**1.2**	**84.1**	**18**	**Turkey**	**1.3**	**76.4**
19	**Indonesia**	**1.1**	**85.2**	**19**	**Republic of Korea**	**1.3**	**77.7**
20	**Switzerland**	**0.9**	**86.1**	**20**	**Pakistan**	**1.1**	**78.8**

Italicized countries are included in the European Union (EU).

Source: IMF 2012; *own scenario calculations*

Based on the 2nd and 4th criteria (level of development and integration, respectively) and size, the **European Union**[2] was also defined as a region for GMM. See Figure 2.2 for an indication of level of economic development (with darker colouring representing higher GDP per capita); see also Table 2.2. To avoid creating small enclaves, while being consistent with criteria 2-6, Iceland, Norway and Switzerland were included in the EU region.

Other countries with higher levels of economic development include Australia, Canada, Japan, Korea, New Zealand, and Taiwan. On the basis of geographical contiguity and energy resource endowments, several of these were grouped into two regions: **Australia and New Zealand** and **Japan, Korea and Taiwan.**[3] Similarly, the China region was expanded to include Mongolia, to avoid creating an enclave or creating an aggregate region that would violate criteria 2-6.

The level of resource endowments was used to define several other regions, including the single-country region **Russia** (which is also significant in terms of economic size), and a region covering the **Middle East and North Africa**, based also on criteria 4, 5 and 6 (despite some divergence in criteria 2 (economic development – see Table 2.2)). Figure 2.3 provides an indication of energy resource endowments by presenting dependence on

---

[2] Including Croatia, which became a full member on 1 July 2013.

[3] It should be noted that there were also arguments in favour of aggregating Taiwan with the People's Republic of China, but in terms of the 2nd, 3rd, 4th and 6th criteria it was decided to include Taiwan with Japan and Korea.

net energy imports (the darker colours indicate higher dependence on imports). The figure shows, for example, lighter colours for fossil fuel-rich regions such as Russia, MENA and Central Asia (see below).

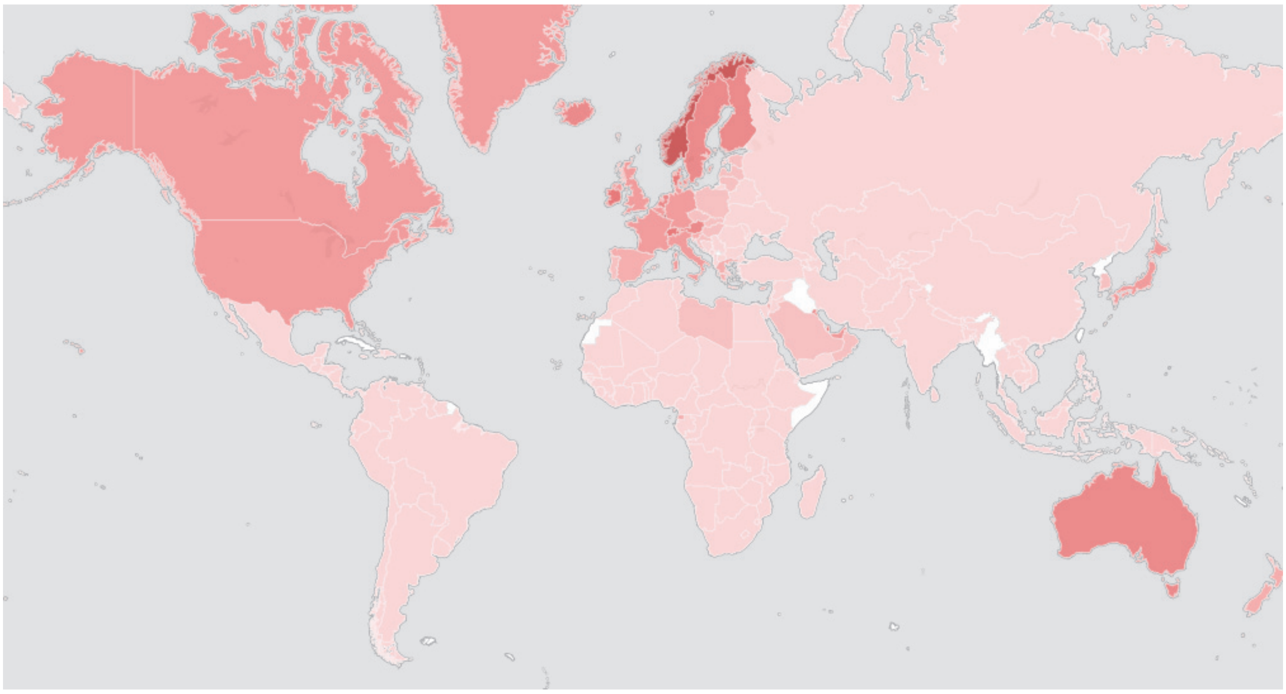


Figure 2.2 GDP per capita (MER), 2008-2012.

Source: World Bank 2012 (based on World Bank national accounts data, and OECD National Accounts data files)

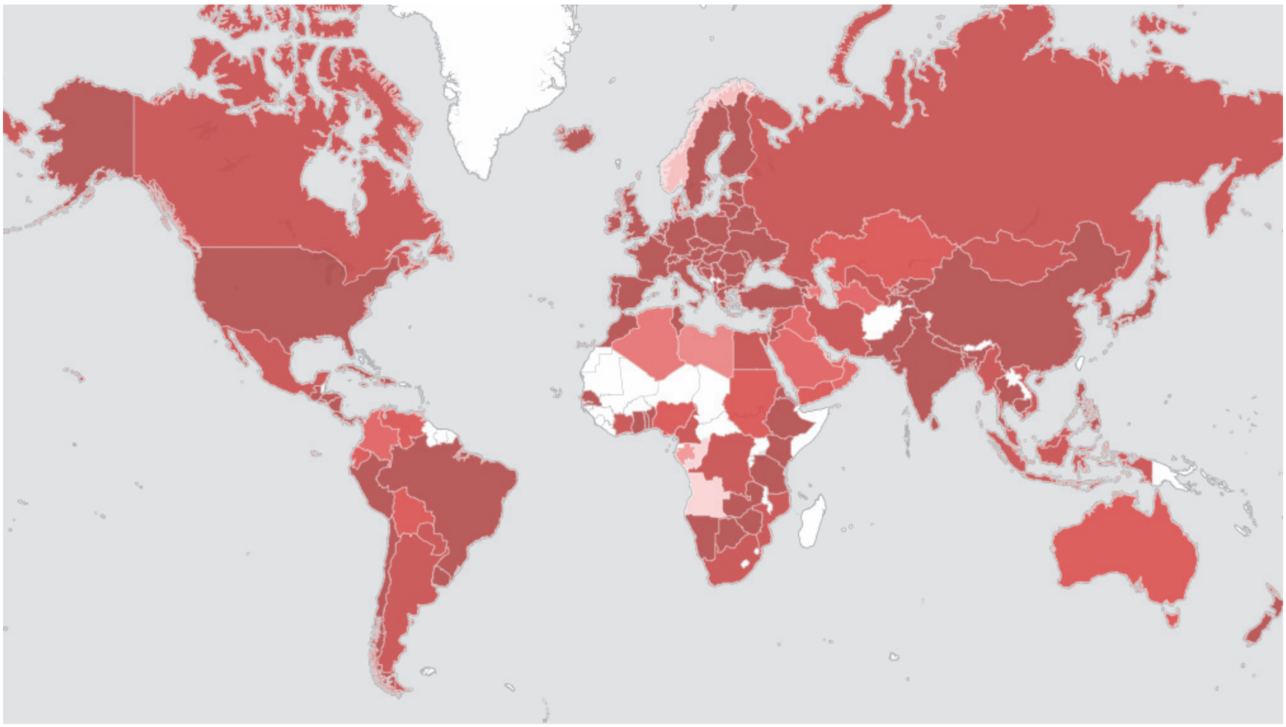


Figure 2.3 Share of net imports in total energy use, 2008-2012

Source: World Bank 2012 (based on IEA)

The remaining regions were defined based on economic development, geographical contiguity, resource endowments, and integration. On this basis, the regions **Latin America and the Carribbean** (excluding Brazil and Mexico); **Central and South Asia** (excluding India); and **Asia-Pacific** were defined. Based on geographical contiguity, resource endowments, and economic integration **Canada and Mexico** were grouped into a single region, despite some divergence in GDP per capita (although less so in PPP terms). Finally, **sub-Saharan Africa** was defined as a single region based primarily on economic development, and geographical contiguity; however, it must be noted that this remains a diverse region in terms of resource endowments, integration, policy and governance. This left a final region of **Eastern Europe** (comprising non-EU Balkan countries, Turkey, Belarus, Ukraine, Moldova, Georgia, and Armenia).

Table 2.3 summarizes the relevant criteria for each of the new 15 regions in GMM.

2.3 Indicators for 15 region disaggregation

Figure 2.4 shows visually the full regional breakdown, while Table 2.2 presents selected indicators for these 15 regions.

Table 2.2 Selected indicators for the 15 regions, 2010

	Size			Economic development		Global fossil resources share		Mobility	Energy and intensity			
	Population	GDP		GDP per capita	Divergence[a]	Oil and gas	Coal	Motorization	TFC[b]	TFC[b] per capita	TFC[b] per GDP	
	million (share)	USD2010 bn (share)	PPP2010 bn (share)	USD2010 (PPP2010)	90th:10th %-ile, MER (PPP)	%	%	cars/ 1000 pop.	EJ	GJ	MJ/USD2010 (MJ/PPP2010)	
ASIAPAC	604.2 (8.8%)	1,901 (3.0%)	3,175 (4.3%)	3,147 (5,254)	4.9 (3.9)	2.2	1.0	43	19.5	32	10.3 (6.1)	**ASIAPAC**
AUSNZL	26.6 (0.4%)	1,384 (2.2%)	997 (1.3%)	51,976 (37,420)	1.7 (1.4)	1.9	8.7	565	4.0	150	2.9 (4.0)	**AUSNZL**
BRAZIL	194.9 (2.8%)	2,143 (3.4%)	2,187 (2.9%)	10,992 (11,216)	na	2.0	0.1	177	9.3	48	4.3 (4.2)	**BRAZIL**
CANMEX	147.4 (2.1%)	2,613 (4.1%)	2,904 (3.9%)	17,719 (19,697)	5.1 (2.8)	7.2	1.3	280	13.2	90	5.1 (4.6)	**CANMEX**
CENASIA	475.2 (6.9%)	638 (1.0%)	1,336 (1.8%)	1,343 (2,811)	4.5 (4.2)	4.3	1.4	18	9.0	19	14.1 (6.8)	**CENASIA**
CHINAREG	1,351.1 (19.6%)	6,161 (9.8%)	10,467 (14.0%)	4,560 (7,747)	1.0 (1.0)	7.0	27.3	44	70.3	52	11.4 (6.7)	**CHINAREG**
EEUR	158.3 (2.3%)	1,034 (1.6%)	1,629 (2.2%)	6,531 (10,289)	3.3 (2.0)	0.5	0.6	135	8.8	56	8.5 (5.4)	**EEUR**
EU31	518.7 (7.5%)	17,343 (27.4%)	15,970 (21.4%)	33,434 (30,787)	3.7 (2.0)	3.8	3.3	477	57.5	111	3.3 (3.6)	**EU31**
INDIA	1,224.6 (17.8%)	1,630 (2.6%)	4,051 (5.4%)	1,331 (3,308)	na	0.6	1.3	11	19.6	16	12.0 (4.8)	**INDIA**
JPKRTW	222.3 (3.2%)	6,934 (11.0%)	6,677 (8.9%)	31,193 (30,040)	2.3 (1.2)	0.0	0.1	346	26.7	120	3.8 (4.0)	**JPKRTW**
LAC	277.6 (4.0%)	1,720 (2.7%)	2,684 (3.6%)	6,194 (9,666)	5.0 (3.3)	7.2	0.2	52	11.0	40	6.4 (4.1)	**LAC**
MENA	380.9 (5.5%)	2,532 (4.0%)	3,927 (5.3%)	6,649 (10,312)	6.3 (5.8)	30.3	0.2	76	23.4	61	9.2 (5.9)	**MENA**
RUSSIA	143.0 (2.1%)	1,487 (2.4%)	2,237 (3.0%)	10,404 (15,651)	na	19.0	17.0	232	19.8	139	13.3 (8.9)	**RUSSIA**
SSAFRICA	856.6 (12.4%)	1,160 (1.8%)	1,944 (2.6%)	1,355 (2,270)	5.2 (4.6)	5.3	0.6	19	17.2	20	14.9 (8.9)	**SSAFRICA**
USA	314.3 (4.6%)	14,499 (22.9%)	14,499 (19.4%)	46,132 (46,132)	na	8.6	36.9	686	65.2	207	4.5 (4.5)	**USA**
World	6,895.9 (100%)	63,180 (100%)	74,684 (100%)	9,162 (10,830)	54.3 (19.8)	100.0	100.0	124	374.6	54	5.9 (5.0)	**World**

a. ratio of 90th to 10th income percentiles (by population). Note, ignores intra-country divergence.
b. Total Final Consumption (plus blast furnaces, gas works and coke ovens)

= three largest/highest regions (where applicable, using averages of PPP and MER)
= two lowest regions (where applicable, using averages of PPP and MER)

Source: UN 2011; IMF 2012; BGR 2012; Rogner 1997; IEA 2012a; IRF 2012; Davis and Diegel 2012

Table 2.3 Criteria for region definitions and aggregation

Region	Criteria					
	Economic size (current & potential)	Economic development	Resources	Integration (economic social)	Geography	Policy and governance
Asia-Pacific		X		~	X	X/~
Australia & New Zealand		X	X	X	X	X
Brazil	X	na	na	na	na	na
Canada & Mexico		X/~	X	X	X	~
Central & South Asia		X	X	~	X	X
China (plus HK, Macau, Mongolia)	X	na	na	na	na	na
Eastern Europe		X			X	
EU (plus Iceland, Norway, and CH)	X	X		XX	X	X
India	X	na	na	na	na	na
Japan, Korea & Taiwan		X	X		X	X
Latin America & Caribbean		X	X	~	X	
Middle East & North Africa		~	X	X/~	X	X/~
Russia	~	na	X	na	na	na
Sub-Saharan Africa		X/~		~	X	~
USA	X	na	na	na	na	na

XX = criteria strongly favouring region specification
X = criteria favouring region specification
~ = criteria partly favouring region specification
[blank] = criteria not favouring regional aggregartion or not considered (or, in the case of 'Economic size' considered primarily for defining single-country regions)
na = not applicable for single-country regions

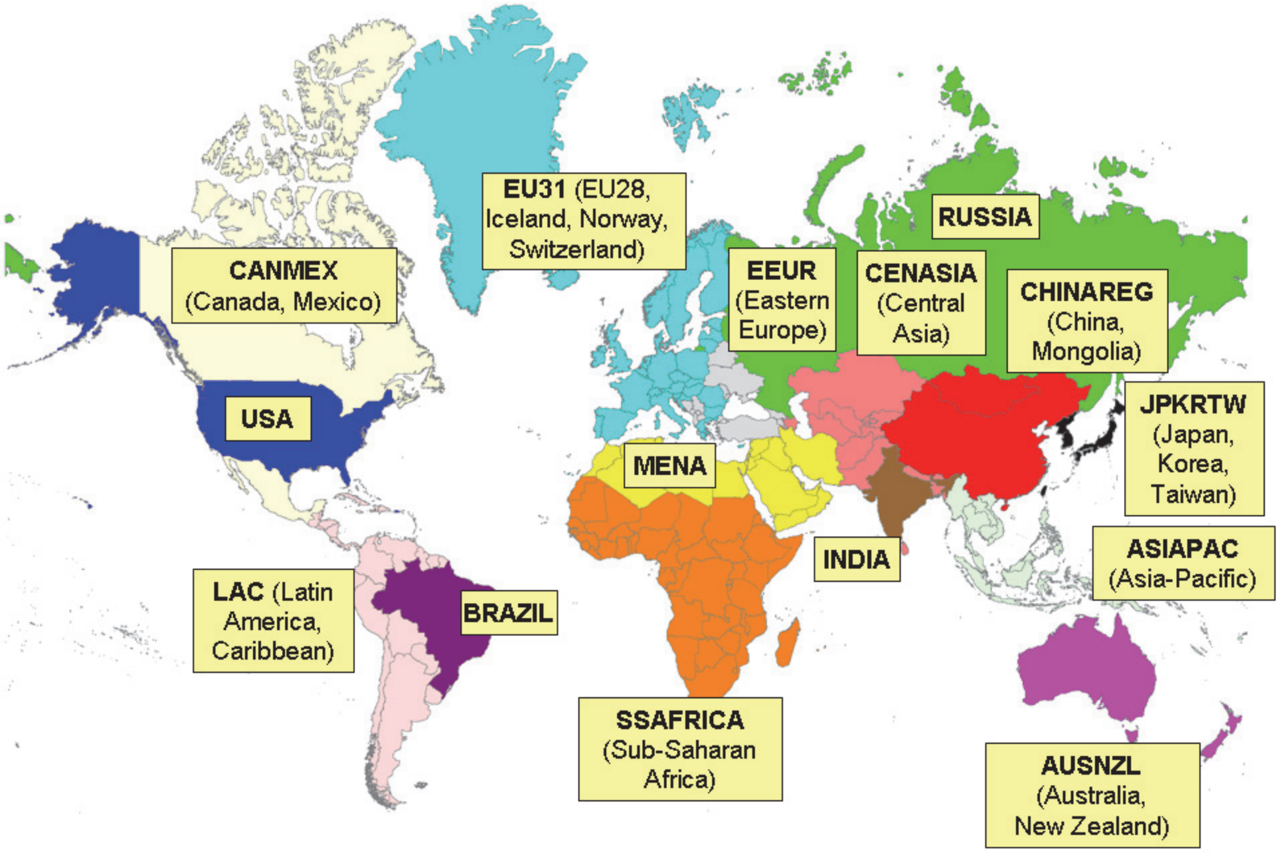


Figure 2.4 Map of 15-region disaggregation

3 Calibration of disaggregated regions to 2010 data

The calibration of GMM to historical statistics ensures that recent trends in energy supply and use are reflected in the starting point of the model. In addition, the calibration ensures an accurate representation of the existing capital stock, which is likely to influence future pathways given the long-lived nature of much energy equipment. The previous versions of the GMM model were calibrated to year 2000 statistics, although the model was updated to recent sources (2008/2009 data) in the course of other work. Given the 10-year timesteps of the model, the recent availability of global statistics for 2010 has enabled an extensive recalibration to 2010. As for all model data, the calibration relies entirely on publicly available data sources to support transparency and possible future open access.

3.1 Energy production and trade

Energy production and trade of energy carriers in 2010 have been calibrated in GMM based on data from the extended energy balances of the International Energy Agency; see IEA (2012b). Table 3.1 presents domestic energy production in each of the 15 regions in 2010. Note, the detailed energy carriers of the IEA statistics have been aggregated to match the more aggregate set of energy carriers in GMM; the aggregation is such that the combined energy carriers have similar characteristics (e.g. in terms of emissions and possible substitution in the energy system). See Appendix I for the complete correspondence table.

Figure 3.1 shows the shares of the different energy carriers presented in Table 3.1. The figure illustrates the diversity in energy production across the different world regions, which reflect to a large degree the resource endowments shown in Table 2.2. For instance, the share of coal in production is higher in relatively coal-rich regions such as China, India and Australia/NZ; the oil- and gas-rich regions of MENA, LAC, and RUSSIA exhibit high shares of these fuels in production. However, we also see similar levels in regions that do not account for major shares of global resources, but which nonetheless have significant resources relative to the size of their economies (CANMEX, CENASIA).

The trade of primary energy carriers is calibrated according to IEA statistics. The regional net trade is presented in Table 3.2, and the accompanying figure illustrates the relative dependence on imports of the different regions. The figure clearly identifies those regions that are relatively dependent on imports of all energy carriers (EU31, EEUR, INDIA, JPKRTW); those dependent primarily on oil imports (ASIAPAC, CHINAREG, USA); and those who are major exporters (AUSNZL, CANMEX, CENASIA, LAC, MENA, RUSSIA, SSAFRICA).

Table 3.1 Domestic Energy Production, 2010

(PJ)	Coal	Oil	Gas	Nuclear[a]	Bio	Hydro[b]	Wind[b]	Solar[b]	Geo-therm.[c]	Total Energy
ASIAPAC	9351	5559	7624	0	5062	303	0	1	694	28595
AUSNZL	10232	1232	1936	0	269	134	23	1	212	14039
BRAZIL	98	4624	523	157	3445	1452	8	0	0	10306
CANMEX	1635	13755	7560	1043	855	1399	39	1	238	26524
CENASIA	2125	6369	6994	37	2151	327	0	0	0	18003
CHINAREG	66105	8066	3322	798	8625	2600	161	3	6	89686
EEUR	2764	399	1120	990	423	395	11	0	24	6126
EU31	7195	8492	10943	10184	5392	1947	542	83	362	45140
INDIA	10092	1803	1776	284	7125	412	72	0	0	21564
JPKRTW	801	25	110	5167	542	373	21	17	95	7150
LAC	2146	12186	5366	77	1667	1046	4	0	118	22611
MENA	30	61392	22613	0	178	124	9	0	0	84346
RUSSIA	7765	21067	22328	1840	291	599	0	0	18	53909
SSAFRICA	6157	12695	1620	131	13595	319	1	0	53	34571
USA	22585	14498	20755	9060	3827	944	343	14	633	72660
World	149084	172161	114590	29768	53446	12375	1232	121	2453	535231

[a] assumed nuclear efficiency: 33% (IEA convention)
[b] actual energy production (IEA convention)
[c] assumed geothermal efficiency: 10% (IEA convention)

Source: IEA 2012b

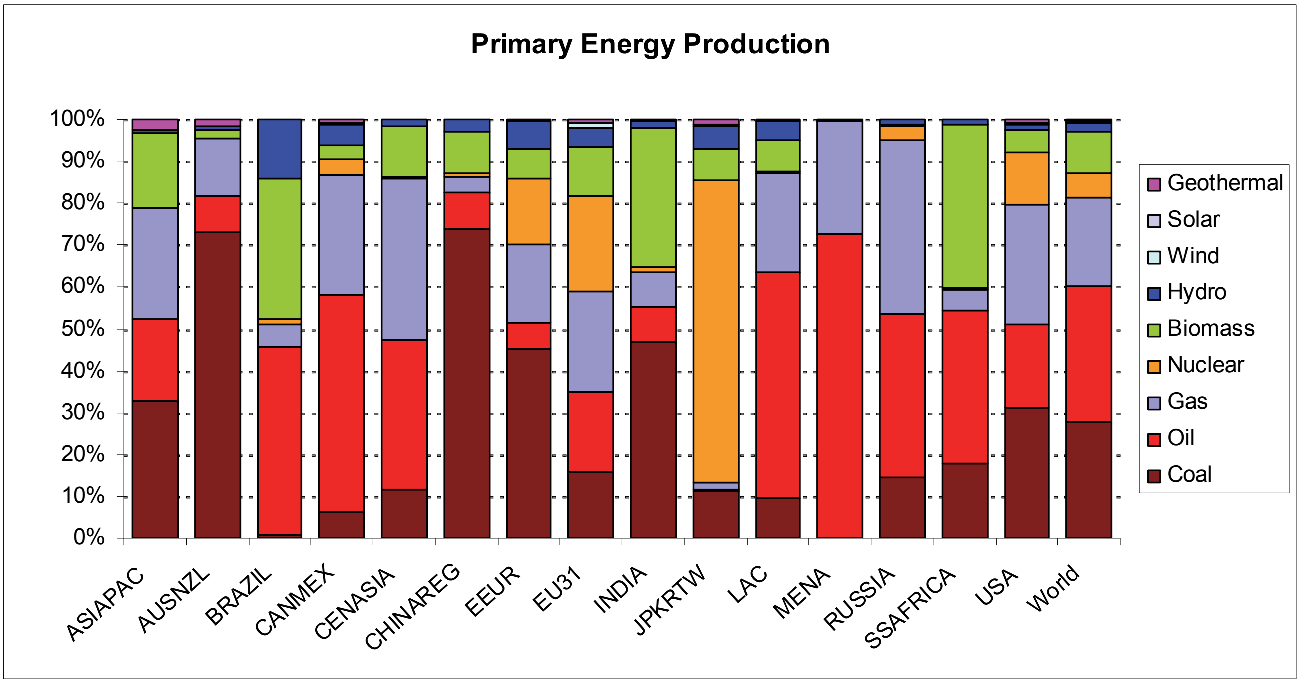


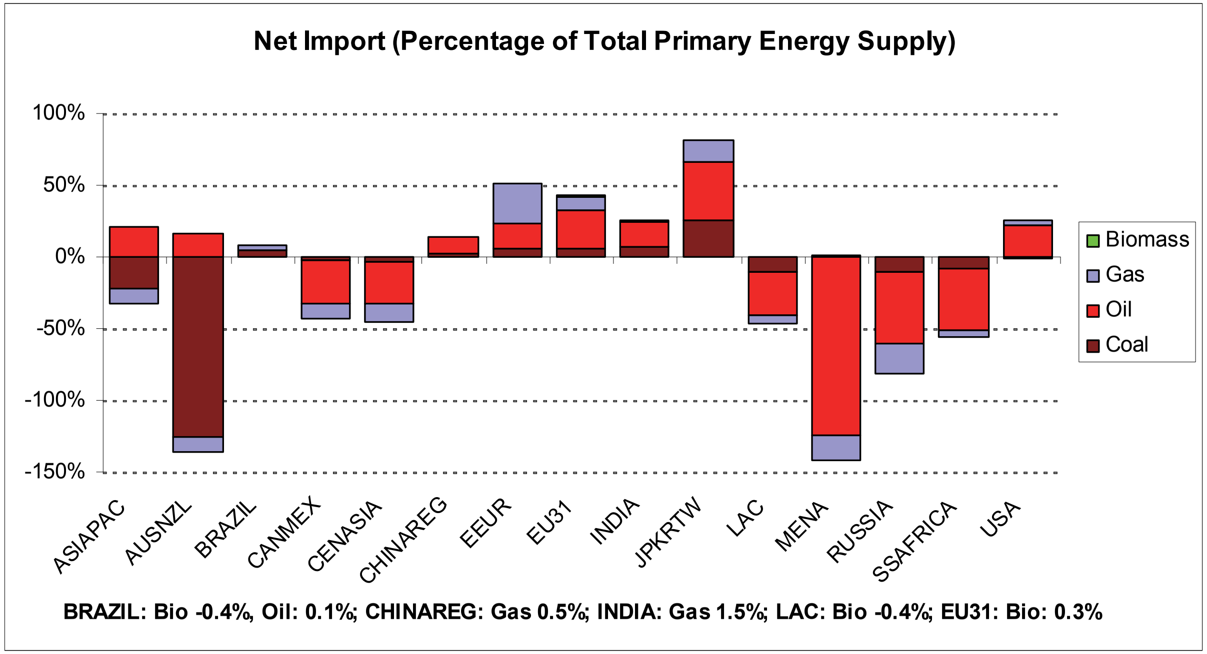
Figure 3.1 Domestic Primary Energy Production, 2010.

Source: IEA 2012b. Assumed conversion factors according to IEA: Nuclear efficiency = 33%; geothermal efficiency = 10%; solar, hydro and wind: actual energy production.

Table 3.2 Net Trade of Energy Carriers, 2010 (+ve = import)

(PJ)	Coal	Oil / Oil products	Gas	Biomass Biofuels	Total Energy
ASIAPAC	-5791	5363	-2495	-11	-2933
AUSNZL	-8027	1045	-671	0	-7653
BRAZIL	507	7	441	-40	915
CANMEX	-340	-5622	-2039	-1	-8002
CENASIA	-394	-3643	-1571	0	-5608
CHINAREG	2786	11509	517	0	14812
EEUR	771	2230	3517	0	6517
EU31	4638	20647	8029	221	33535
INDIA	1981	5165	431	0	7577
JPKRTW	9477	15372	5652	1	30502
LAC	-1691	-4535	-910	-56	-7192
MENA	544	-43594	-6212	1	-49261
RUSSIA	-2958	-14919	-6307	0	-24183
SSAFRICA	-1779	-9537	-1010	-11	-12337
USA	-1541	21285	2543	-42	22246

Source: IEA 2012b



3.2 Electricity and heat sector

The GMM model is a technology rich model including over 30 power and heat generation plant types (Appendix II). To calibrate the electricity and heat sector the following data were applied for each technology and for each region:

- Capacity in GW (electric or thermal, depending on the technology)
- Activity in PJ: electricity or heat production for electric only and heat plants, total production for CHP plants
- Average efficiency of the technology (derived from the activity and the fuel consumption)
- Average availability factor of the technology (derived from the capacity and activity)

In order to ensure a better representation of the stock of generation plant, additional information was applied in the calibration:

- Decommissioning plans of current installed capacity for each technology; this is implemented into the model as a “residual” capacity of current existing plants that is still available in future
- Planned investments of new installations for each technology; this is implemented into the model as a lower bound on the investment variables of the model

All the above imply that the calibration of the power and heat sector is an intensive data gathering task, with a large number of sources used (ADB 2008, BRA 2013, CBC 2013, China 2012, CNE 2013, COL 2012, DOM 2013, EAC 2013, EcoProg 2011, EIA 2012, EIA 2013, EIC 2013, EUR 2013, EuraCoal 2013, EWEA 2013, GEO 2012, HEP 2013, IEA 2012b, IEA 2012c, IEA 2012d, IEA 2012e, IHA 2013, IHS 2013, India 2013, JPTN 2013, NREL 2013a, PEIN 2013, PPAW 2012, REEEP 2013, RossStat 2013, SENER 2013, TRAN 2013, WindPower 2012, WNA 2012, Yang 2012).

Major challenges in this task included obtaining reliable, public-domain data and reconciling inconsistencies between the different data sources. To reconcile and consolidate different sources, a data reconciliation module was designed as a non-linear optimisation program, which minimises the logarithmic differences between the “hard” and otherwise published data and “soft” and otherwise incomplete information. In this way, the aggregated information was disaggregated to a level of detail corresponding to that in the model, in a way consistent with the available statistics that ensures the dataset’s overall integrity. Appendix III presents the general algebraic specification of the reconciliation module and illustrates graphically its use for producing the GMM model’s power and heat database.

3.2.1 Generation

Table 3.3 presents electricity generation by technology for each GMM region for 2010. Figure 3.2 shows graphically the electricity production mix. Fossil fuel based generation accounts for 67% of the world’s electricity production, with coal being the dominant source (40%), followed by gas (22%) and oil (5%). In China, India, Australia and Sub-Saharan

Africa coal accounts for more than 60% of electricity generation. In Russia and MENA, more than 50% of the electricity production is based on gas. In Latin America and MENA more than 20% of the electricity is generated from oil.

Hydropower electricity accounts for 16% of the world's electricity production. In Brazil, more than 78% of the domestic electricity is generated from hydropower. In Latin America and Canada the share of hydropower in the domestic electricity generation is slightly below 50%.

The global share of nuclear generation is around 13%. Major nuclear power producers are the European Union, USA and Japan, with nuclear shares in electricity generation higher than 20%, and Eastern Europe and Russia with nuclear power shares around 16-17%.

Finally, the share of non-hydro renewables in electricity production is still small at a global scale (less than 4%). However, in Europe the share of renewables is close to 10% (mainly wind turbines), and in Brazil is close to 7% (mainly biomass).

3.2.2 Capacity

Total installed electricity generation capacity at the global was 5162 GW in 2010, comprising: 1639 GW of coal based plants, 1351 GW of gas based plants, 1040 GW of hydroelectric turbines, 435 GW of oil plants, 381 GW of nuclear power, 194 GW of wind farms, 71 GW of biomass power plants, around 40 GW of solar power and 11 GW of geothermal energy—see Table 3.4.[4]

China accounts for around 40% of the world coal-based electricity generation capacity and 23% of the total hydropower capacity. USA accounts for around 30% of the gas-based capacity. Europe accounts for around 35% of the nuclear-based capacity. Regarding wind turbines, around 47% of the global capacity is installed in Europe.

In the next decade, substantial retirements of old capacity and additions of new capacity are planned (see Table 3.5 and Table 3.6). Of the approximately 800 GW of new capacity installations planned, around one quarter are expected to be in China. The new additions involve around 300 GW of coal (mostly supercritical and ultra-supercritical plants), around 175 GW of gas (mostly combined cycle), around 80 GW of nuclear, about 110 GW of new hydro, around 100 GW of wind turbines and close to 40 GW of solar PV (half in Europe). The new capacity additions are located mainly in China (nuclear, coal, hydro), India (coal), Europe (gas, wind, solar) and the USA (gas, wind).

Additional information on availability factors and efficiencies of electricity technologies is presented in Appendix IV. Installed capacities, production and efficiencies of heat technologies are also presented in Appendix IV.

---

[4] Note, dual-fired plants (gas, oil) are not represented separately in GMM and have been attributed proportionally to single-fuel units. This split was made using the reconciliation module (see Appendix III) in order to match the electricity generation and the fuel consumption.

Figure 3.2 Shares in electricity production in each region, 2010

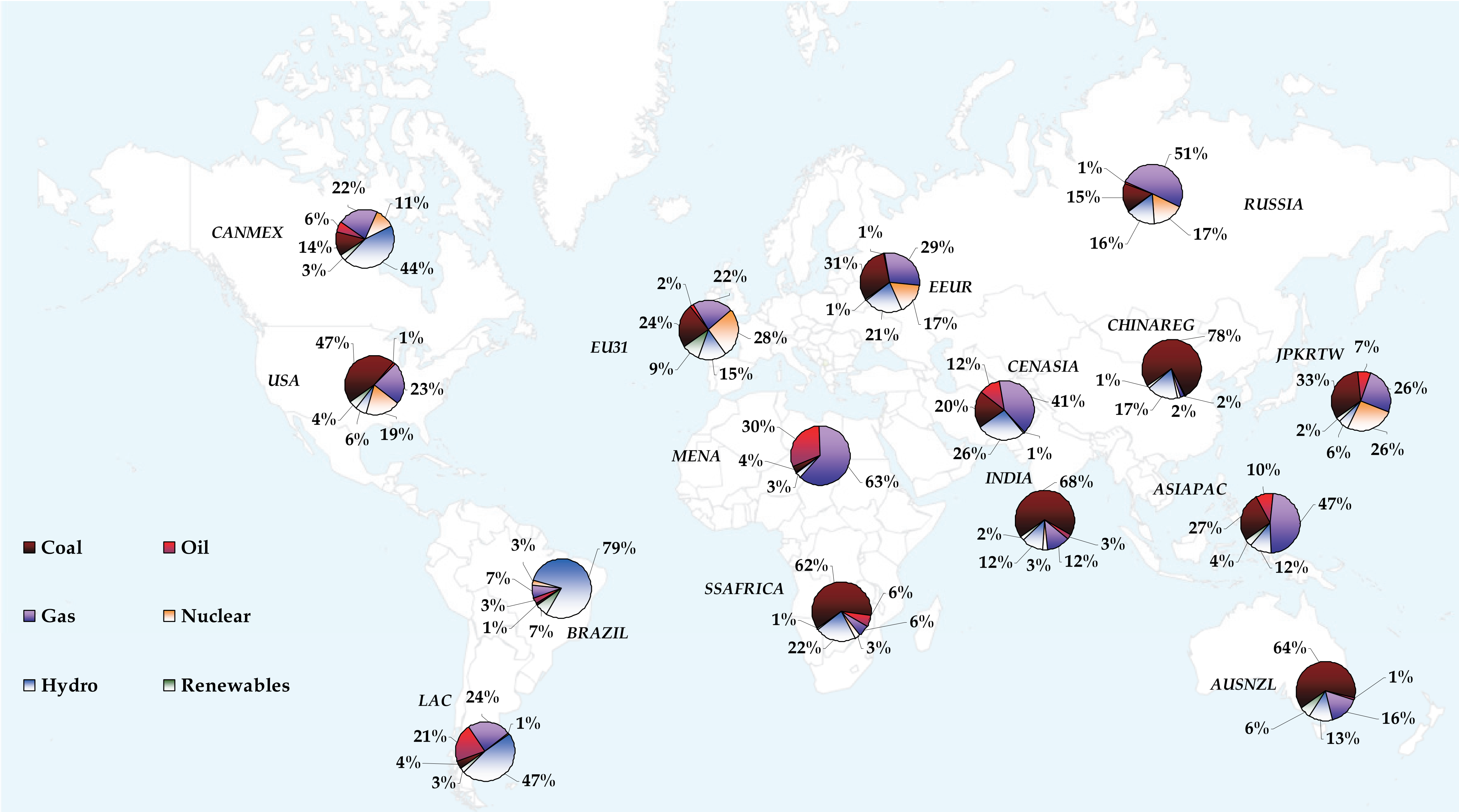


Table 3.3 Electricity production in each region by technology type in TWh in 2010

Electricity Generation in TWhe in 2010	Asia Pacific	Australia, New Zealand	Brazil	Canada, Mexico	Central Asia	China Region	Eastern Europe	EU31	India	Japan, Korea Peninsula, Chinese Taipei	Latin America	Middle East and North Africa	Russia	Sub-saharan Africa	United States	World
Region Total	**697.0**	**285.5**	**511.1**	**878.2**	**348.3**	**4190.3**	**529.1**	**3497.7**	**959.1**	**1813.2**	**612.4**	**1144.4**	**1028.9**	**401.8**	**4349.9**	**21246.9**
Nuclear	0.0	0.0	14.5	96.5	3.4	73.9	91.6	942.9	26.3	478.5	7.2	0.0	170.4	12.1	838.9	2756.3
Coal	185.0	182.0	7.0	119.9	69.8	3240.2	165.5	831.0	652.2	597.3	26.8	45.4	158.9	248.8	1990.6	8520.2
Subcritical coal	177.5	161.6	7.0	111.8	2.1	1746.1	137.3	530.6	652.2	245.6	26.8	45.4	0.0	248.8	1899.0	5991.9
Supercritical coal	7.5	14.0	0.0	8.1	0.0	1489.8	25.5	56.6	0.0	313.4	0.0	0.0	0.0	0.0	37.6	1952.4
Integrated Coal Gasification Combined Cycle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	2.5	0.0	0.0	0.0	0.0	2.3	12.8
Coal CHP Plants	0.0	6.3	0.0	0.0	67.6	4.3	2.7	235.8	0.0	35.8	0.0	0.0	158.9	0.0	51.8	563.1
Oil	66.6	3.2	16.1	51.3	41.7	13.5	3.9	87.1	26.4	127.8	127.6	340.9	9.3	25.7	48.1	989.3
Gas	335.5	46.1	36.5	192.9	142.5	83.4	153.7	766.7	117.8	465.0	144.7	720.9	520.5	24.0	1017.9	4768.1
Conventional	23.7	5.0	2.3	38.0	40.7	3.5	2.7	49.7	6.6	90.7	54.0	50.0	2.1	3.4	144.4	516.9
Gas turbines Combined Cycle	283.8	18.3	31.4	129.0	38.3	74.3	107.0	377.6	102.1	351.0	44.4	469.8	1.2	6.1	626.1	2660.3
Gas turbines Open Cycle	27.6	16.8	2.9	8.2	15.0	5.6	4.7	14.3	9.0	2.3	46.2	201.0	2.1	14.4	35.1	405.3
Gas CHP plants	0.4	6.0	0.0	17.6	48.6	0.0	39.3	325.1	0.0	21.0	0.1	0.0	515.2	0.0	212.3	1185.6
Hydro (incl. pump storage)	84.2	37.2	403.3	388.6	90.8	722.2	109.8	540.8	114.4	103.5	290.7	34.6	166.5	88.7	262.3	3437.5
Bio energy	6.0	4.5	31.5	11.4	0.0	11.4	0.9	145.3	2.1	28.2	11.2	0.1	2.8	0.8	75.4	331.7
Wind	0.1	6.4	2.2	10.8	0.0	44.6	3.0	150.7	19.9	5.8	1.0	2.5	0.0	0.2	95.1	342.3
Onshore	0.1	6.4	2.2	10.8	0.0	43.5	3.0	142.4	19.9	5.7	1.0	2.5	0.0	0.2	95.1	332.8
Offshore	0.0	0.0	0.0	0.0	0.0	1.1	0.0	8.3	0.0	0.1	0.0	0.0	0.0	0.0	0.0	9.5
Solar	0.2	0.3	0.0	0.2	0.0	0.9	0.0	23.2	0.0	4.6	0.0	0.1	0.0	0.0	3.9	33.5
Photovoltaics	0.2	0.3	0.0	0.2	0.0	0.9	0.0	22.5	0.0	4.6	0.0	0.1	0.0	0.0	3.1	31.9
Solar Thermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.6
Geothermal	19.3	5.9	0.0	6.6	0.0	0.2	0.7	10.1	0.0	2.6	3.3	0.0	0.5	1.5	17.6	68.1

Source: ADB 2008, BRA 2013, CBC 2013, China 2012, CNE 2013, COL 2012, DOM 2013, EAC 2013, EcoProg 2011, EIA 2012, EIA 2013, EIC 2013, EUR 2013, EuraCoal 2013, EWEA 2013, GEO 2012, HEP 2013, IEA 2012b, IEA 2012c, IEA 2012d, IEA 2012e, IHA 2013, IHS 2013, India 2013, JPTN 2013, NREL 2013a, PEIN 2013, PPAW 2012, REEEP 2013, RossStat 2013, SENER 2013, TRAN 2013, WindPower 2012, WNA 2012, Yang 2012

Table 3.4 Electricity generation capacity in GWe in 2010 by region and technology

Electricity Generation Capacity in GWe in 2010	Asia Pacific	Australia, New Zealand	Brazil	Canada, Mexico	Central Asia	China Region	Eastern Europe	EU31	India	Japan, Korea Peninsula, Chinese Taipei	Latin America	Middle East and North Africa	Russia	Sub-saharan Africa	United States	World
Region Total	**158.2**	**68.6**	**117.8**	**200.1**	**86.1**	**1029.3**	**153.8**	**936.6**	**211.1**	**425.5**	**143.8**	**261.2**	**231.6**	**91.6**	**1046.4**	**5161.7**
Nuclear	0.0	0.0	2.0	14.0	0.5	10.7	14.2	134.8	4.8	71.8	1.0	0.0	24.2	1.8	101.2	381.1
Coal	41.5	31.9	7.9	18.3	20.6	648.0	48.5	178.0	118.3	107.7	6.0	8.0	46.8	39.3	317.7	1638.5
Subcritical coal	40.1	28.7	7.9	17.0	2.5	340.5	41.6	124.3	118.2	46.8	6.0	8.0	3.5	38.4	301.8	1125.4
Supercritical coal	1.4	2.2	0.0	1.2	0.0	286.0	4.6	8.8	0.0	52.6	0.0	0.0	1.9	0.0	5.5	364.4
Integrated Coal Gasification Combined Cycle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.3	0.0	0.0	0.0	0.0	0.5	2.0
Coal CHP Plants	0.0	0.9	0.0	0.0	18.1	21.4	2.3	43.8	0.1	7.9	0.0	0.0	41.3	0.9	9.9	146.7
Oil	17.6	1.4	6.4	17.9	16.0	49.5	18.7	65.2	6.7	49.8	31.0	73.4	6.0	16.9	58.8	435.2
Gas	71.4	16.3	11.9	54.5	26.2	45.6	37.4	213.9	23.1	121.1	41.6	161.5	105.9	11.8	409.2	1351.4
Conventional	6.1	2.1	0.7	11.7	7.5	4.1	9.0	39.4	1.2	29.5	11.0	9.0	7.5	1.7	125.7	266.1
Gas turbines Combined Cycle	54.6	5.4	8.8	22.8	6.6	28.3	15.6	99.8	19.5	76.8	18.9	98.1	8.4	1.4	200.7	665.4
Gas turbines Open Cycle	7.5	7.8	1.1	10.4	2.7	5.6	4.2	14.3	1.8	9.5	8.3	41.4	1.5	8.7	16.3	141.2
Gas CHP plants	3.2	0.9	1.3	9.6	9.5	7.5	8.5	60.4	0.7	5.3	3.4	13.0	88.6	0.0	66.5	278.6
Hydro (incl. pump storage)	22.5	14.8	80.7	86.6	22.8	234.3	33.3	191.6	41.8	62.8	61.2	17.1	48.1	21.0	101.2	1039.8
Bio energy	1.8	0.8	7.8	3.2	0.0	6.4	0.2	29.8	2.7	4.3	1.8	0.0	0.5	0.6	11.4	71.3
Wind	0.1	2.4	1.0	4.5	0.0	33.9	1.5	91.5	13.6	3.2	0.7	1.2	0.0	0.1	40.2	193.7
Onshore	0.1	2.4	1.0	4.5	0.0	33.5	1.5	88.5	13.6	3.1	0.7	1.2	0.0	0.1	40.2	190.4
Offshore	0.0	0.0	0.0	0.0	0.0	0.4	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4
Solar	0.2	0.2	0.0	0.1	0.0	0.9	0.0	30.1	0.0	4.3	0.0	0.1	0.0	0.0	3.4	39.4
Photovoltaics	0.2	0.2	0.0	0.1	0.0	0.9	0.0	29.5	0.0	4.3	0.0	0.0	0.0	0.0	2.9	38.2
Solar Thermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.2
Geothermal	3.2	0.8	0.0	1.0	0.0	0.0	0.1	1.6	0.0	0.5	0.5	0.0	0.1	0.2	3.3	11.3

Source: ADB 2008, BRA 2013, CBC 2013, China 2012, CNE 2013, COL 2012, DOM 2013, EAC 2013, EcoProg 2011, EIA 2012, EIA 2013, EIC 2013, EUR 2013, EuraCoal 2013, EWEA 2013, GEO 2012, HEP 2013, IEA 2012b, IEA 2012c, IEA 2012d, IEA 2012e, IHA 2013, IHS 2013, India 2013, JPTN 2013, NREL 2013a, PEIN 2013, PPAW 2012, REEEP 2013, RossStat 2013, SENER 2013, TRAN 2013, WindPower 2012, WNA 2012, Yang 2012

Table 3.5 Capacity retirements in GWe by region and technology in 2010-2020

Capacity Retirements in GWe	Asia Pacific	Australia, New Zealand	Brazil	Canada, Mexico	Central Asia	China Region	Eastern Europe	EU31	India	Japan, Korea Peninsula, Chinese Taipei	Latin America	Middle East and North Africa	Russia	Sub-saharan Africa	United States	World
Region Total	**23.6**	**22.8**	**7.2**	**45.8**	**28.3**	**35.9**	**68.4**	**282.7**	**33.1**	**60.9**	**26.2**	**57.8**	**135.2**	**19.4**	**209.7**	**1056.9**
Nuclear	n.a.	n.a.	0.0	0.0	0.1	0.0	0.4	12.4	0.6	6.4	0.3	n.a.	6.5	0.0	0.6	**27.5**
Coal	2.2	16.6	1.8	11.1	11.4	11.7	36.1	131.7	22.4	14.7	4.5	2.1	40.2	12.1	88.3	**406.9**
Subcritical coal	2.2	16.6	1.8	11.1	1.4	8.3	31.6	95.7	22.4	13.1	4.5	2.1	3.1	12.1	81.9	**307.8**
Supercritical coal	0.0	0.0	n.a.	0.0	n.a.	0.0	2.3	1.7	0.0	0.0	n.a.	n.a.	0.0	n.a.	0.0	**4.0**
Integrated Coal Gasification Combined Cycle	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.0	n.a.	0.0	n.a.	n.a.	n.a.	n.a.	0.0	**0.0**
Coal CHP Plants	n.a.	0.0	n.a.	0.0	10.0	3.4	2.2	34.3	0.0	1.6	n.a.	n.a.	37.1	0.0	6.4	**95.0**
Oil	4.3	0.2	1.3	8.2	4.5	13.0	12.4	44.6	1.7	13.4	2.2	10.4	3.6	3.6	38.6	**162.2**
Gas	14.7	4.9	1.1	19.6	12.2	9.6	19.1	73.1	6.7	22.7	18.4	45.2	84.4	3.3	69.2	**404.3**
Conventional	1.6	2.1	0.0	7.8	5.3	0.0	7.4	29.4	1.2	11.1	9.9	3.6	6.6	1.7	46.2	**133.9**
Gas turbines Combined Cycle	7.2	0.7	1.1	1.3	2.4	0.8	3.6	8.0	3.9	4.6	1.1	15.5	0.0	0.0	17.7	**68.0**
Gas turbines Open Cycle	5.7	1.8	0.0	7.1	0.8	4.9	0.8	3.8	1.1	2.3	4.1	23.7	0.8	1.6	1.1	**59.7**
Gas CHP plants	0.1	0.2	0.0	3.4	3.7	3.9	7.3	31.9	0.4	4.7	3.3	2.3	77.0	0.0	4.2	**142.6**
Hydro (incl. pump storage)	0.0	0.4	0.2	4.5	0.0	0.0	0.2	1.7	0.1	0.0	0.1	0.0	0.3	0.0	2.3	**9.9**
Bio energy	0.6	0.4	2.8	1.5	0.0	1.3	0.1	8.5	0.5	1.8	0.3	0.0	0.1	0.2	4.6	**22.7**
Wind	0.0	0.0	0.0	0.1	0.0	0.2	0.0	7.9	1.0	0.1	0.0	0.1	0.0	0.0	1.5	**11.1**
Onshore	0.0	0.0	0.0	0.1	0.0	0.2	0.0	7.9	1.0	0.1	0.0	0.1	0.0	0.0	1.5	**11.1**
Offshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Solar	0.0	0.0	0.0	0.0	0.0	0.1	0.0	2.1	0.0	1.4	0.0	0.0	0.0	0.0	1.5	**5.2**
Photovoltaics	0.0	0.0	0.0	0.0	0.0	0.1	0.0	2.0	0.0	1.4	0.0	0.0	0.0	0.0	1.3	**4.9**
Solar Thermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	**0.2**
Geothermal	1.7	0.3	n.a.	0.8	n.a.	0.0	0.0	0.6	n.a.	0.3	0.2	n.a.	0.0	0.1	3.1	**7.3**

Source: ADB 2008, BRA 2013, CBC 2013, China 2012, CNE 2013, COL 2012, DOM 2013, EAC 2013, EcoProg 2011, EIA 2012, EIA 2013, EIC 2013, EUR 2013, EuraCoal 2013, EWEA 2013, GEO 2012, HEP 2013, IEA 2012b, IEA 2012c, IEA 2012d, IEA 2012e, IHA 2013, IHS 2013, India 2013, JPTN 2013, NREL 2013a, PEIN 2013, PPAW 2012, REEEP 2013, RossStat 2013, SENER 2013, TRAN 2013, WindPower 2012, WNA 2012, Yang 2012

Table 3.6 Capacity additions in GWe by region and technology in 2010-2020

Capacity Additions in GWe	Asia Pacific	Australia, New Zealand	Brazil	Canada, Mexico	Central Asia	China Region	Eastern Europe	EU31	India	Japan, Korea Peninsula, Chinese Taipei	Latin America	Middle East and North Africa	Russia	Sub-saharan Africa	United States	World
Region Total	**42.3**	**5.4**	**26.2**	**7.7**	**13.9**	**302.3**	**24.8**	**182.2**	**129.0**	**39.8**	**10.3**	**7.3**	**29.1**	**35.8**	**106.1**	**962.2**
Nuclear	n.a.	n.a.	n.a.	n.a.	0.9	36.6	1.0	4.7	5.3	13.4	0.7	2.4	11.5	n.a.	3.6	**80.1**
Coal	22.6	0.4	0.7	0.0	8.2	116.7	5.8	13.7	64.8	12.3	0.9	2.4	13.0	24.7	19.6	**305.8**
Subcritical coal	7.4	0.0	0.0	0.0	0.8	1.2	0.0	0.0	24.5	0.0	0.9	0.0	0.0	19.7	0.0	**54.6**
Supercritical coal	15.2	0.4	0.7	0.0	7.4	114.5	5.8	11.9	39.6	10.8	0.0	2.4	13.0	5.0	17.9	**244.6**
Integrated Coal Gasification Combined Cycle	0.0	0.0	0.0	0.0	0.0	0.9	0.0	1.8	0.7	1.5	0.0	0.0	0.0	0.0	1.7	**6.6**
Coal CHP Plants	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.0**
Oil	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.0**
Gas	1.2	0.0	0.6	0.0	0.0	30.0	11.1	54.9	35.5	4.6	0.0	0.5	0.9	0.3	36.6	**176.2**
Conventional	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.0**
Gas turbines Combined Cycle	1.2	n.a.	0.6	n.a.	n.a.	25.0	7.5	48.0	35.5	4.6	n.a.	0.5	0.9	0.3	35.5	**159.6**
Gas turbines Open Cycle	n.a.	n.a.	n.a.	n.a.	n.a.	5.0	3.7	6.9	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.1	**16.7**
Gas CHP plants	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.0**
Hydro (incl. pump storage)	17.2	n.a.	22.7	0.3	4.6	40.9	2.4	0.6	2.6	n.a.	7.0	n.a.	3.0	9.9	0.8	**112.0**
Bio energy	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.0**
Wind	0.1	1.4	2.2	6.2	0.1	63.8	4.0	56.7	17.9	2.8	1.6	1.2	0.0	0.2	33.6	**191.7**
Onshore	0.0	1.4	2.2	6.2	0.1	62.7	3.4	43.1	17.9	1.5	1.6	1.2	0.0	0.2	32.7	**174.3**
Offshore	0.0	0.0	0.0	0.0	0.0	1.1	0.5	13.6	0.0	1.3	0.0	0.0	0.0	0.0	0.9	**17.4**
Solar	1.1	3.6	0.0	1.3	0.1	14.3	0.5	51.6	3.0	6.7	0.1	0.9	0.7	0.5	11.9	**96.4**
Photovoltaics	1.0	3.6	0.0	1.3	0.1	14.2	0.5	49.9	2.5	6.7	0.1	0.6	0.7	0.4	10.4	**92.0**
Solar Thermal	0.1	0.1	n.a.	0.0	n.a.	0.1	n.a.	1.7	0.5	n.a.	n.a.	0.3	n.a.	0.2	1.5	**4.4**
Geothermal	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.0**

Source: ADB 2008, BRA 2013, CBC 2013, China 2012, CNE 2013, COL 2012, DOM 2013, EAC 2013, EcoProg 2011, EIA 2012, EIA 2013, EIC 2013, EUR 2013, EuraCoal 2013, EWEA 2013, GEO 2012, HEP 2013, IEA 2012b, IEA 2012c, IEA 2012d, IEA 2012e, IHA 2013, IHS 2013, India 2013, JPTN 2013, NREL 2013a, PEIN 2013, PPAW 2012, REEEP 2013, RossStat 2013, SENER 2013, TRAN 2013, WindPower 2012, WNA 2012, Yang 2012

3.3 Final demands

Final energy demands in 2010 have been calibrated in GMM based on data from the extended energy balances of the International Energy Agency; see IEA (2012a,b). The extended energy balances of the IEA use a classification of the energy consumption in approx. 30 end-use sectors. In GMM, these sectors are aggregated into 4 main sectors (industrial, other stationary uses (primarily residential and commercial), non-energy uses, and transport) – see Appendix V.

3.3.1 Industry and buildings

Final consumption of energy carriers in industry and buildings used to calibrate GMM is shown in Table 3.7 and Table 3.8, respectively. Figure 3.3 and Figure 3.4 present the shares of the different energy carriers in each sector.

Table 3.7 Final consumption of energy carriers in industry (year 2010, excluding non-energy uses)

(PJ)	Heat	Coal[a]	Oil Type[b]	Gas	Electricity	Bio, Alcohol[c]	Total Energy
ASIAPAC	0	1467	1083	843	924	775	5092
AUSNZL	0	255	164	357	321	111	1207
BRAZIL	0	517	496	367	732	1433	3546
CANMEX	17	251	547	1315	1013	312	3454
CENASIA	134	741	190	690	429	203	2386
CHINAREG	1703	22741	2023	691	8526	0	35685
EEUR	364	1243	147	648	638	12	3052
EU31	662	2549	1514	3613	4017	1052	13408
INDIA	0	2888	1080	311	1157	1223	6659
JPKRTW	98	4118	1367	656	2499	189	8926
LAC	0	160	1108	842	706	342	3158
MENA	0	141	1819	3046	762	37	5804
RUSSIA	1863	1488	465	1355	1177	15	6363
SSAFRICA	0	711	239	82	601	1148	2781
USA	220	1524	1262	4661	3166	1347	12180
World	5060	40794	13503	19478	26668	8199	113703

[a] includes coal for blast furnaces, gas works and coke ovens
[b] crude oils and oil products (e.g. gasoline, diesel, NGL)
[c] solid biomass, biofuels and waste

Source: IEA 2012b

Figure 3.3 illustrates the diversity of energy choices across different regions. For example, a large contribution of biomass (predominantly from non-commerical sources) is seen in several less-developed world regions, particularly sub-Saharan Africa, India and the Asia-Pacific. The role of natural gas varies widely depending on the availability of domestic resources and the level of infrastructure development, with particularly low shares in India, Japan/Korea/Taiwan, Brazil, China and sub-Saharan Africa. Electricity and oil play a role in all regions, with district heating of particular prominence in Russia and Eastern Europe.

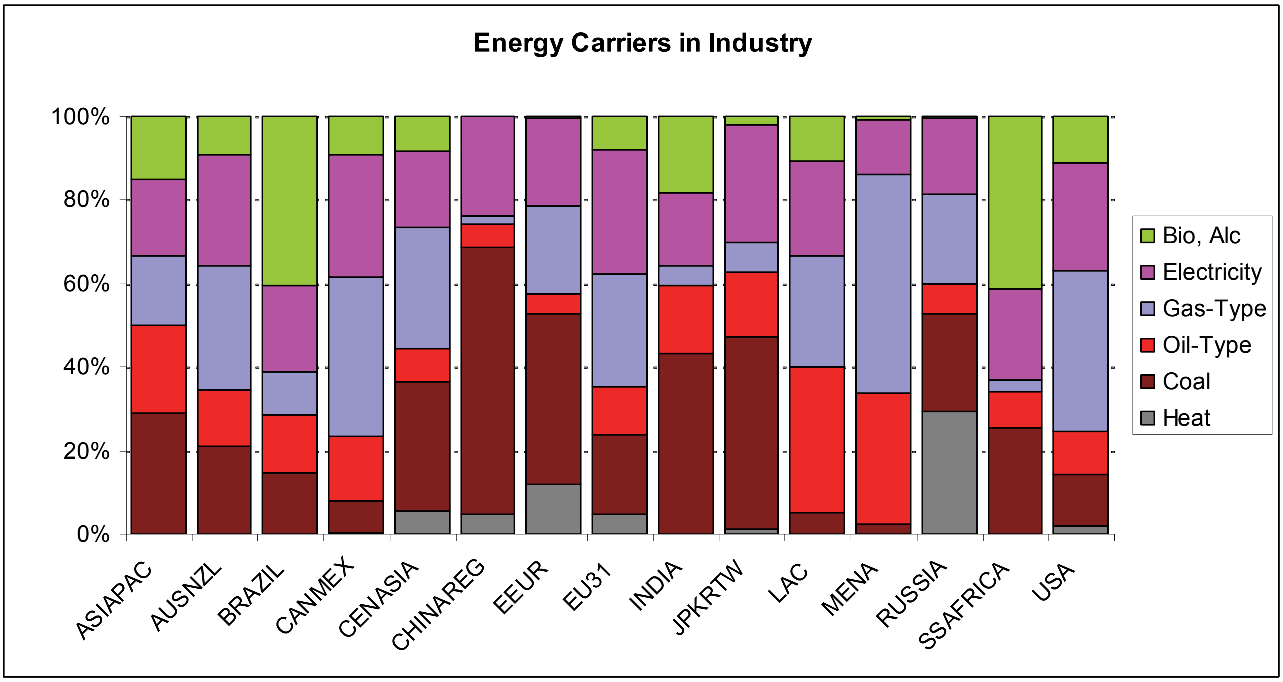


Figure 3.3 Shares of energy carriers in industry (2010, excluding non-energy uses).

Source: IEA 2012b

It should be noted that even though the IEA's categories are detailed, they lack some distinctions that are necessary for distinguishing energy service demands and technology types.[5] In GMM, energy service demands in industry and the residential/commercial sector are split into two main sub-demands based on technology and fuel substitution opportunities, as follows:

- The first main sub-demand is energy demand for thermal purposes (e.g., heating), which is distinguished from the energy demand for appliances and motors, because the thermal demand can be satisfied by more options of end-use device, and more fuels. For example, heating can be achieved by coal, oil, and gas heating devices, as well as electric resistance heating, heat pumps, solar thermal etc.
- The second main sub-demand category is for those energy service demands that in almost all cases are powered solely by electrical means and liquid motor fuels, such as motors and many household appliances (and most lighting).
- An additional demand category comprises non-commercial biomass (which is significant in the less-industrialized regions).

The IEA data used for calibration and presented in Table 3.7 and Table 3.8 are allocated to these categories based on a number of heuristics as outlined in Appendix II.

[5] That is, the IEA statistics provide no information to distinguish between different technologies using the same energy carrier.

Table 3.8 Energy carriers in residential/commercial sector (year 2010)

(PJ)	Heat	Coal	Oil-Type[a]	Gas	Electricity	Bio, Alcohol[b]	Total Energy
ASIAPAC	0	67	1051	20	1305	3645	6088
AUSNZL	0	5	144	186	531	64	931
BRAZIL	0	0	540	21	838	439	1839
CANMEX	0	0	791	1048	1410	364	3613
CENASIA	262	183	646	1397	528	1925	4941
CHINAREG	830	3161	2644	1300	3919	8361	20215
EEUR	492	355	492	1010	780	352	3481
EU31	1616	587	3511	7388	6681	1815	21598
INDIA	0	576	1082	8	1353	5845	8865
JPKRTW	108	188	1925	1669	3489	70	7449
LAC	0	3	712	510	996	995	3216
MENA	0	0	1900	1912	2559	124	6494
RUSSIA	2935	172	426	1842	1133	83	6592
SSAFRICA	0	154	465	11	609	10920	12159
USA	58	63	2193	7623	10495	528	20961
World	6301	5515	18522	25946	36627	35530	128442

[a] mainly oil products (e.g. gasoline, diesel, NGL)
[b] solid biomass, biofuels and waste

Source: IEA 2012b

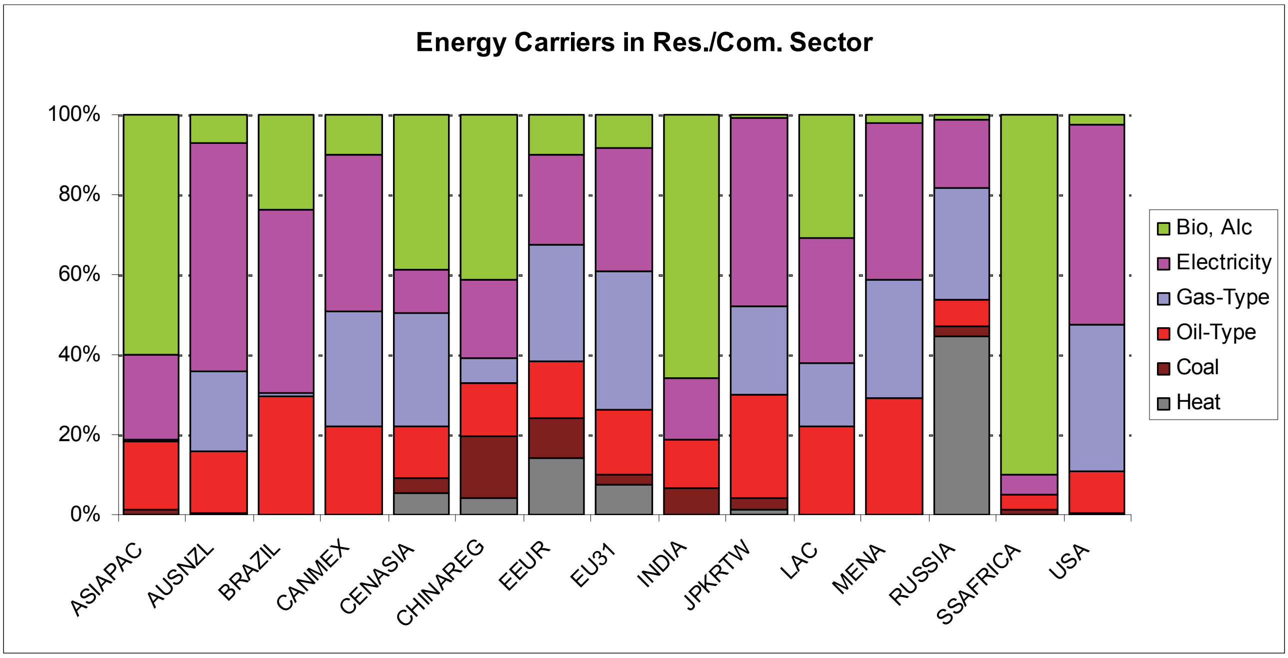


Figure 3.4 Shares of energy carriers in other sectors (primarily residential and commercial), 2010.

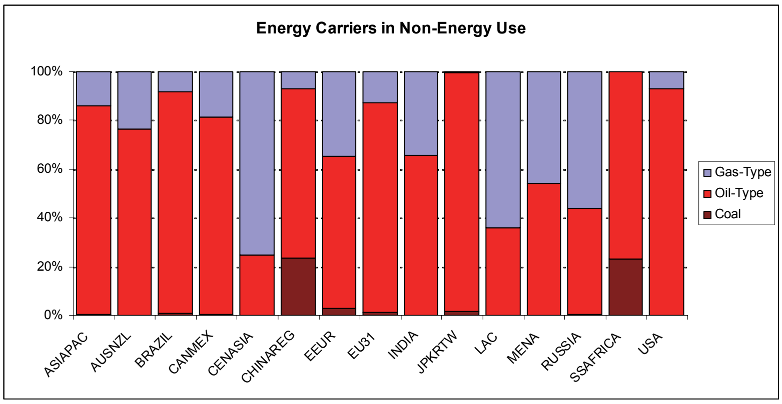
Source: IEA 2012b

3.3.2 Non-energy uses

Non-energy uses are also represented in GMM to ensure a full balancing of energy supply and demand. These non-energy uses are dominated by industrial feedstocks (e.g., for petrochemical production). The IEA data used to calibrated non-energy demands are presented in Table 3.9. The accompanying figure illustrates that these feedstocks comprise primarily oil products, and in some regions significant quantities of natural gas.

Table 3.9 Energy carriers for non-energy use (year 2010)

(PJ)	Coal	Oil-Type[a]	Gas	Total Energy
ASIAPAC	4	1695	278	1978
AUSNZL	0	191	58	249
BRAZIL	6	645	58	709
CANMEX	6	1035	240	1281
CENASIA	0	84	256	340
CHINAREG	1307	3901	387	5595
EEUR	21	441	244	707
EU31	54	3953	590	4597
INDIA	0	1041	544	1585
JPKRTW	71	4095	15	4180
LAC	0	294	528	821
MENA	0	1668	1420	3088
RUSSIA	11	1096	1423	2530
SSAFRICA	51	171	0	222
USA	0	5241	396	5637
World	1531	25551	6437	33519



[a] crude oils and oil products (e.g. additives, ethane, naphta)

Source: IEA 2012b

3.3.3 Transport

Calibration of final consumption of energy carriers in transport is based on the data shown in Table 3.10. Notably, the IEA statistics do not differentiate between energy used by different vehicles types in road transport. In contrast, GMM distinguishes between passenger cars and other road vehicles because there are important differences between technology options and fuel alternatives, along with different factors affecting future demands. To calibrate total passenger car numbers per region (see Table 3.11), the main data source is IRF (2012). Efficiencies are based on Fulton and Eads (2004), ICCT (2012), and Davis and Diegel (2012). The estimated shares of different car types are based on various sources (see table footnote).

Figure 3.5 shows that cars fuelled by gasoline dominate the global fleet, with significant shares of diesel vehicles in a small number of regions (particularly the EU, India and

Australia/NZ). Natural gas vehicles represent significant, but small shares in Latin America, India and Brazil.

Table 3.10 Energy carriers in the transport sector (year 2010)

(PJ)	Coal	Gasoline / Diesel / Kerosene	CNG	Electricity	Biofuels	Total Energy
ASIAPAC	0	6227	79	8	37	6350
AUSNZL	5	1561	18	14	12	1610
BRAZIL	0	2494	89	6	589	3178
CANMEX	0	4716	104	18	45	4883
CENASIA	0	1112	225	19	0	1356
CHINAREG	133	8432	17	144	51	8776
EEUR	2	1346	174	45	2	1568
EU31	0	17018	106	258	564	17946
INDIA	0	2337	96	48	8	2489
JPKRTW	0	5988	43	82	13	6125
LAC	0	3613	166	6	29	3814
MENA	0	7693	270	5	0	7968
RUSSIA	0	2683	1375	307	0	4365
SSAFRICA	0	2061	0	13	0	2074
USA	0	24660	679	28	1063	26430
World	141	91939	3440	1001	2410	98931

Source: IEA 2012b

Table 3.11 Personal cars by type, 2010

(million cars)	Gasoline	Diesel	Hybrid	CNG	EV	Total cars
ASIAPAC	26.1	0.0	0.0	0.0	0.00	26.1
AUSNZL	12.0	3.0	0.0	0.0	0.00	15.0
BRAZIL	32.3	0.3	0.0	1.8	0.00	34.4
CANMEX	40.7	0.6	0.0	0.0	0.00	41.3
CENASIA	8.3	0.4	0.0	0.0	0.00	8.7
CHINAREG	58.1	0.9	0.0	0.3	0.00	59.3
EEUR	20.4	0.9	0.0	0.0	0.00	21.3
EU31	161.9	84.6	0.4	0.4	0.00	247.2
INDIA	8.4	4.7	0.0	0.6	0.00	13.7
JPKRTW	63.3	3.1	10.5	0.0	0.00	77.0
LAC	12.3	0.4	0.0	1.7	0.00	14.4
MENA	27.0	2.0	0.0	0.1	0.00	29.1
RUSSIA	32.6	0.5	0.0	0.0	0.00	33.1
SSAFRICA	14.1	1.9	0.0	0.1	0.00	16.0
USA	214.2	1.0	0.4	0.1	0.03	215.6
World	731.7	104.3	11.3	5.1	0.03	852.4

CNG: fuelled by compressed gas
EV: battery electric vehicle

Source: IRF (2012); Davis and Diegel (2012); IGU (2009); IEA (2009, 2012f, 2013); data from car manufacturers

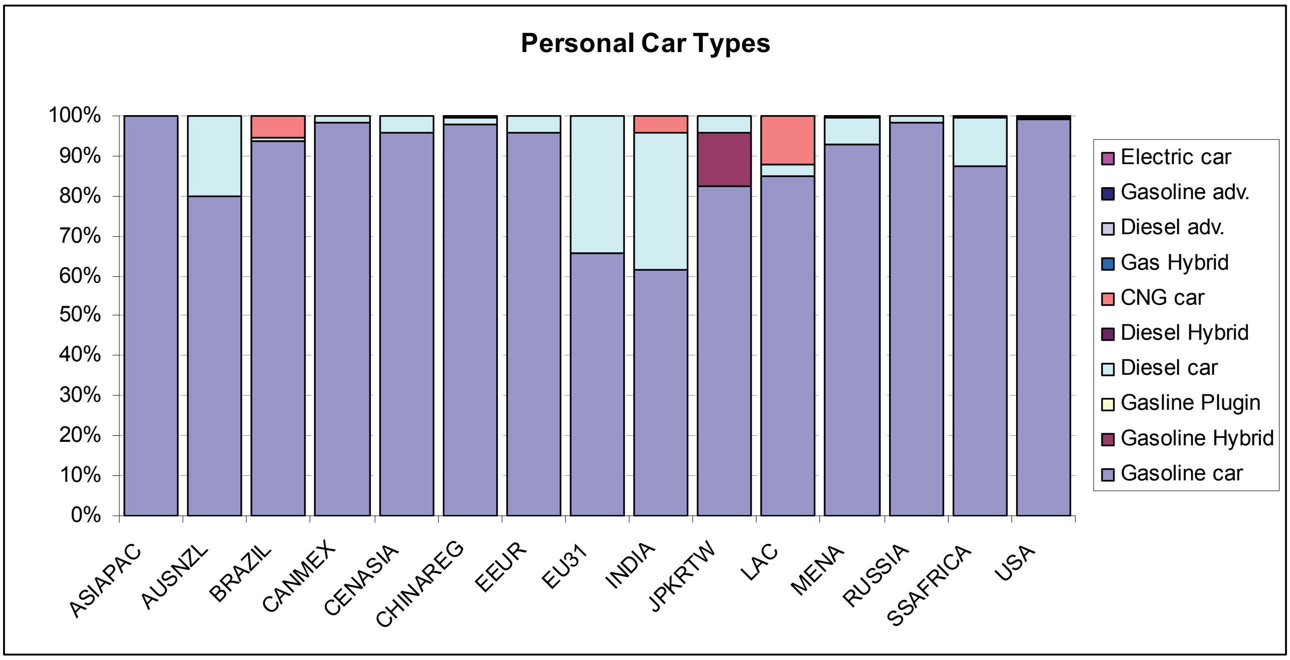


Figure 3.5 Estimated shares of passenger car by fuel type, 2010.

Source: IRF (2012); Davis and Diegel (2012); IGU (2009); IEA (2009, 2012f, 2013); data from car manufacturers

4 Disaggregation and update of resources and CCS

The availability of energy resources (fossil, nuclear, renewable) is likely to have a large influence on future options for the global energy system. As part of the disaggregation of the GMM model to 15 regions, the opportunity was taken to update the model to recent estimates of fossil and other energy resources.

4.1 Fossil fuel resources

Estimates of fossil energy carriers in the previous 6-region GMM model were based on estimates of reserves and resources of Rogner (1997). This 15-year-old dataset has been updated for the 15-region model according to the current estimates published by BGR (2012). BGR bases its estimates on the most recent national statistics and is thus considered to be the currently most complete and up-to-date source. It is frequently used as a primary source in studies such as the *World Energy Outlook* (IEA 2012g) and *Global Energy Assessment* GEA (2012). Nonetheless, a number of the resource category definitions used in Rogner (1997) are retained in the 15-region model (see Figure 4.1).

Crude oil and natural gas

	Conventional reserves and resources				Unconventional reserves and resources			
	Proved recoverable reserves	Estimated additional reserves	Additional speculative resources	Enhanced recovery[a]	Recoverable reserves	Resources	Additional occurrences	
Category	I	II	III	IV	V	VI	VII	VIII

Hard and brown coal

	Proved recoverable reserves	Additional recoverable resources	Additional identified reserves	Additional resources	
Grade	A	B	C	D	E

[a]From conventional reserves and resources, i.e. Categories I–III.

Figure 4.1 Fossil reserve and resource categories.

Source: Rogner (1997)

The estimates of BGR (2012) distinguish reserves and resources, and conventional and unconventional, and these estimates have been allocated to the Rogner (1997) categories and grades as indicated in Figure 4.2. The current BGR estimates do not distinguish between primary and secondary recovery (categories I, II and III) and enhanced recovery (category IV) as the exploitation of oil and gas fields is a continuous process the boundaries between conventional and enhanced categories are blurred. Thus enhanced recovery is now included in Categories I-III, and category IV is no longer considered.

The specific estimates for each energy carrier and category for the 15 regions are presented in the subsections below. A summary comparing the global totals for reserves and the resources in the 15-region and the 6-region GMM model is presented in Figure 4.3. In the figure, it is notable that estimates for hard coal are one order of magnitude higher than those for brown coal, oil and natural gas.

	BGR conventional gas		BGR unconventional gas	
	reserves	resources	reserves	resources
Rogner category	I	II, III	V	VI
	BGR conventional oil		**BGR unconventional oil**	
	reserves	resources	reserves	resources
Rogner category	I	II, III	V	VI
	BGR hard coal		**BGR brown coal**	
	reserves	resources	reserves	resources
Rogner grade	A	B, C, D, E	A	B, C, D, E

Figure 4.2 Allocation of the BGR (2012) reserve and resource estimates to the Rogner (1997) categories and grades.

The comparison of the estimates in the 6-region model and the new 15-region model in Figure 4.3 shows that coal reserves (grade A) are very similar, whereas the coal resources (grade B to E) are estimated to be considerably higher by BGR (2012) than in the Rogner (1997). For oil the reserves (category I and V) BGR (2012) gives lower estimates. The oil resources estimates are now higher than in old GMM model, partly because category VI is now included (see Figure 37 in Gül (2008)). The natural gas reserves (category I and V) are now estimated to be lower, whereas the resources (category II, III and VI) are approximately the same. Some of the reasons for these differences are outlined in the following subsections.

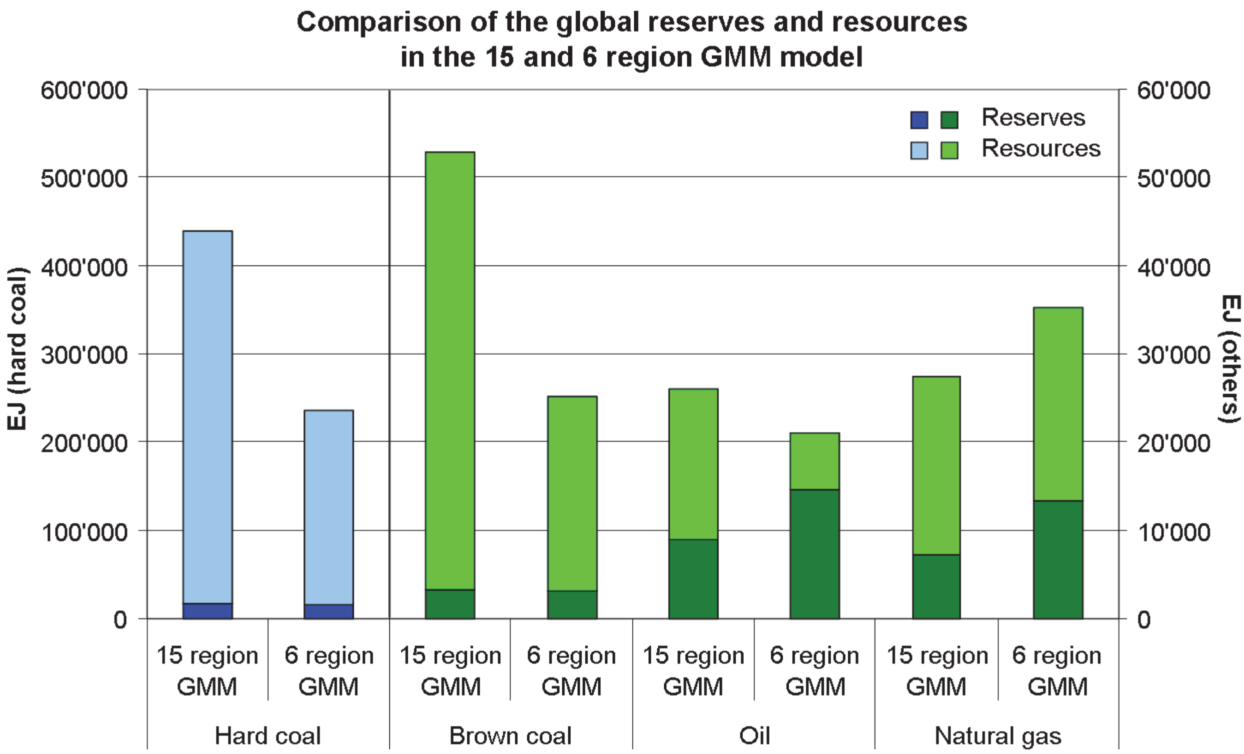


Figure 4.3 Comparison of the global reserves and resources in the 15-region and the 6-region GMM model.

Source: Rogner (1997); BGR (2012)

4.1.1 Oil

The oil reserves and resources are based on the country-level estimates in BGR (2012), aggregated to the 15 regions (Table 4.1). For those countries where BGR does not distinguish between conventional and unconventional reserves and resources, the total was split based on regional ratios between conventional and unconventional given by BGR (2012).

As discussed above, the allocation of the BGR (2012) estimates to the Rogner (1997) categories is carried out according to Figure 4.2. It should be noted that historically GMM has been used to analyze scenarios in which only the oil reserves and resources from categories I to V are available. In contrast, category VI is included in the new model.

The conventional resources are split into Cat. II and III according to the proportions reported in Rogner (1997) for each region. Regarding oil shale, BGR (2012) only reports the global resources (4658 EJ). This number is split into the 15 regions by using the regional shares reported for oil shale in GEA (2012) and then added to the other unconventional resoures from BGR (2012) in category VI.

Table 4.1 Oil reserves and resources per region, in EJ

	I	II	III	V	VI	Total
ASIAPAC	92	63	99	0	35	289
AUSNZL	24	16	32	0	68	139
BRAZIL	81	91	159	0	7	337
CANMEX	85	152	118	1119	3406	4881
CENASIA	276	99	198	0	309	881
CHINAREG	84	246	430	0	31	791
EEUR	7	3	8	0	8	25
EU31	90	113	193	0	17	413
INDIA	50	8	16	0	0	75
JPKRTW	0	0	0	0	1	2
LAC	471	57	99	927	2670	4225
MENA	4725	631	813	0	179	6348
RUSSIA	438	344	488	0	212	1482
SSAFRICA	378	237	341	0	29	984
USA	175	404	315	0	4312	5207
Total	6976	2464	3309	2047	11284	26078

Source: BGR (2012)

Comparing the estimates for conventional oil of the old 6 region and the new estimates in Table 4.1 (which are applied in the 15-region GMM model), we find Cat. I is around 5% higher, while Cat. II and III are lower (-15% and -6%, respectively). The regional distribution of the conventional oil is the same as in the old GMM model (see Figure 37 in Gül (2008)). The amounts of the unconventional reserves (Cat. V) are the same, but the regional shares are considerably different in Table 4.1 compared to the 6-region model. In the current estimates, only CANMEX (i.e. Canada) and LAC (i.e. Venezuela) contribute to this category due to their reserves of oil sands and heavy oil, respectively. The rest of the unconventional oil (also oil shale) is considered in Cat. VI (resources).

Figure 4.4 presents the oil extraction costs of the three largest regions with respect to the total reserve and resource numbers. Additionally, the global supply curve is given representing all regions and costs.

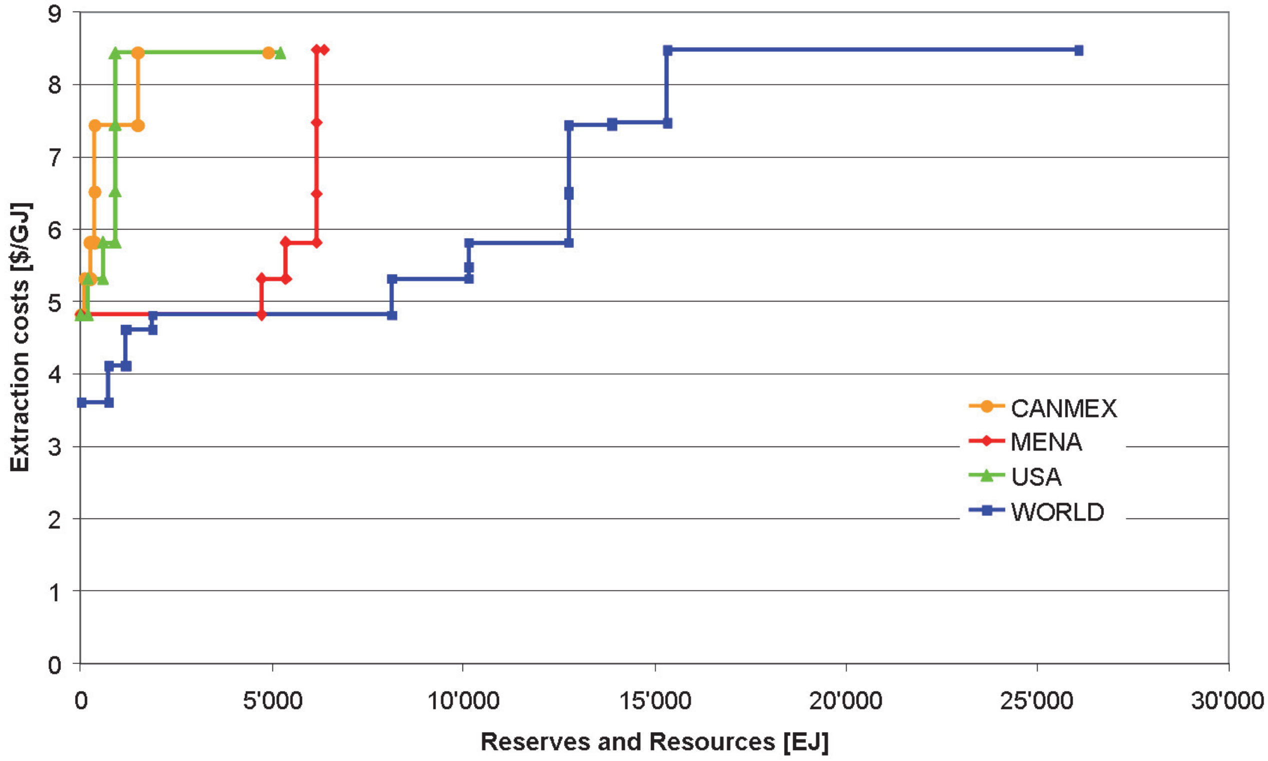


Figure 4.4 Oil supply curve.

Source: based on BGR (2012), Rogner (1997)

4.1.2 Gas

The natural gas reserves and resources are based on the estimates in BGR (2012), aggregated to the 15 regions (Table 4.2). As for oil, for those countries where BGR does not distinguish between conventional and unconventional reserves and resources, the total estimate was split based on regional ratios between conventional and unconventional given by BGR (2012).

The allocation of the BGR (2012) estimates to the Rogner (1997) categories is carried out according to Figure 4.2. The conventional resources are split into Cat. II and III according to the proportions reported in Rogner (1997) for each region.

The estimates in Table 4.2 for conventional reserves (Cat. I) are higher (+33%) then the number in the old GMM model (see Figure 37 in Gül (2008)). The figures for conventional resources in Cat. II and III are very similar to those in the 6-region model (+5% and +3%, respectively). In addition, the regional consistency between the new estimates of conventional gas and those used in the old GMM model is good. For unconventional reserves in Cat. V, the estimates are considerably lower (-98%), and the regional spread is very different (74% from NAM, i.e. USA in Table 4.2). For Cat. VI, the new estimates are around 20% lower, but distributed similarly as in the 6-region model.

Table 4.2 Natural gas reserves and resources per region, in EJ

	I	II	III	V	VI	Total
ASIAPAC	286	94	124	5	181	690
AUSNZL	86	39	62	26	597	810
BRAZIL	16	77	132	0	243	467
CANMEX	64	338	369	19	1004	1795
CENASIA	606	228	329	0	75	1237
CHINAREG	104	403	622	2	1066	2197
EEUR	38	56	97	0	31	222
EU31	185	74	109	0	850	1218
INDIA	52	27	39	3	80	202
JPKRTW	2	0	1	0	1	5
LAC	259	64	111	0	1198	1632
MENA	3194	961	1124	0	559	5837
RUSSIA	1805	1862	2690	0	836	7192
SSAFRICA	243	56	89	0	764	1152
USA	208	653	712	85	1095	2754
Total	7145	4933	6609	142	8581	27410

Source: BGR (2012)

One reason for the deviations in Cat. V and VI is that BGR (2012) only considers shale gas and coal bed methane in the unconventional categories, whereas Rogner (1997) considered also other types of gas reserves and resources[6]. In addition, Rogner (1997) notes the considerable uncertainties in his estimates of unconventional gas, some of which may have been reduced over the last 15 years. Additionally, BGR (2012) considers tight gas currently being developed/exploited to be conventional, which was considered to be unconventional in Rogner (1997).

Figure 4.5 displays the natural gas extraction costs of the three largest regions with respect to the total reserve and resource numbers. Additionally, the world's supply curve is given representing all regions and costs.

4.1.3 Coal

The coal (hard coal and brown coal) reserves and resources are based on the estimates in BGR (2012), aggregated to 15 regions (Table 4.3**,** Table 4.4). Coal with an energy content of >16,500 kJ/kg, and including sub-bituminous coal (hard brown coal), bituminous coal and anthracite is defined here as hard coal. Coal with an energy content of <16,500 kJ/kg is classified here as lignite.

6 Rogner (1997) reports on coalbed methane, gas from tight formations, geopressured gas, clathrates, and gas remaining in-situ after commercial production has ceased in the unconventional categories (V to VIII), whereby he doesn't specify which gas types occur in which category.

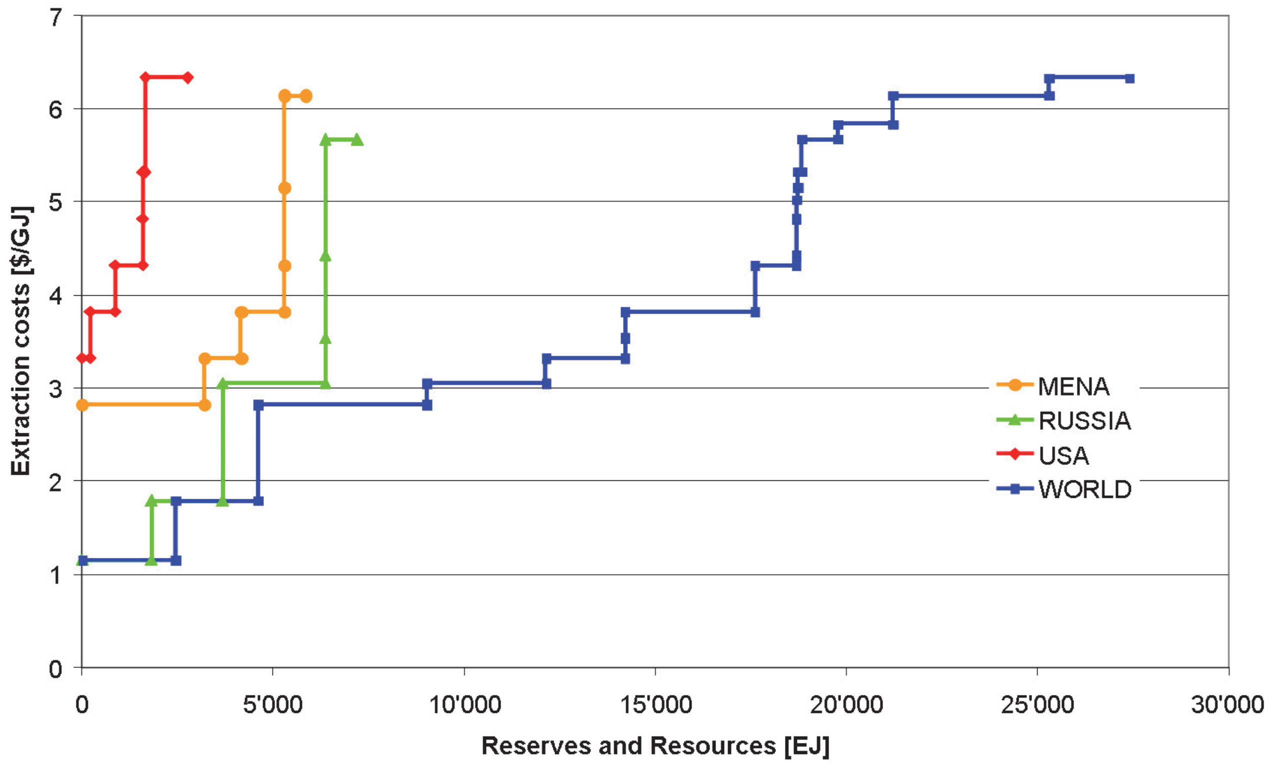


Figure 4.5 Natural gas supply curve.

Source: based on BGR (2012), Rogner (1997)

The allocation of the BGR (2012) estimates to the Rogner (1997) grades is carried out as described in Figure 4.2, separately for hard coal and lignite. The split into the four resource grades is carried out according to the proportions defined in Rogner (1997) for each region.

The hard coal grade A (reserves) reported in Table 4.3 are consistent with those in the 6-region GMM model (see Figure 37 in Gül (2008)), with some slight differences. The amount is 15% higher and ASIA has a higher share mainly at the expense of North America and Eastern Europe and the Former Soviet Union. The estimates for Grades B and C are regionally consistent with those in the 6-region GMM model, but the amounts are much higher (+121% and +204% respectively). For grade D and E, the estimates in Table 4.3 are around 75% higher, with North America gaining importance mainly at the expense of Eastern Europe and the Former Soviet Union.

Figure 4.6 displays the hard coal mining costs of the three largest regions with respect to the total reserve and resource numbers. Additionally, the world's supply curve is given representing all regions and costs.

For lignite, the size and distribution of grade A reserves is very similar in Table 4.4 as in the old 6-region GMM model, whereas for grade B, the new estimates are 62% higher (with more resources in Pacific OECD, and less in Asia). Grade C estimates are also higher (+138%) with relatively more in Western Europe compared to ASIA. For grade D and E the regional distribution of the estimates is similar but the total amount is higher by +138% and +140%, respectively.

Table 4.3 **Hard coal reserves and resources per region, in EJ**

	A	B	C	D	E	Total
ASIAPAC	316	0	953	0	953	2221
AUSNZL	1101	14290	1750	4569	18276	39985
BRAZIL	38	3	9	21	83	153
CANMEX	136	0	813	758	3025	4731
CENASIA	542	1477	1002	369	1477	4868
CHINAREG	4485	4375	29971	18049	72194	129074
EEUR	834	304	359	124	483	2104
EU31	414	141	657	2158	8'679	12048
INDIA	1841	1448	982	362	1448	6081
JPKRTW	31	227	28	72	290	648
LAC	187	15	45	105	419	770
MENA	32	0	0	199	798	1029
RUSSIA	1694	0	566	13018	52097	67374
SSAFRICA	745	0	634	274	1096	2750
USA	5572	0	28178	26281	104854	164884
Total	17968	22279	65946	66359	266169	438722

Source: BGR (2012)

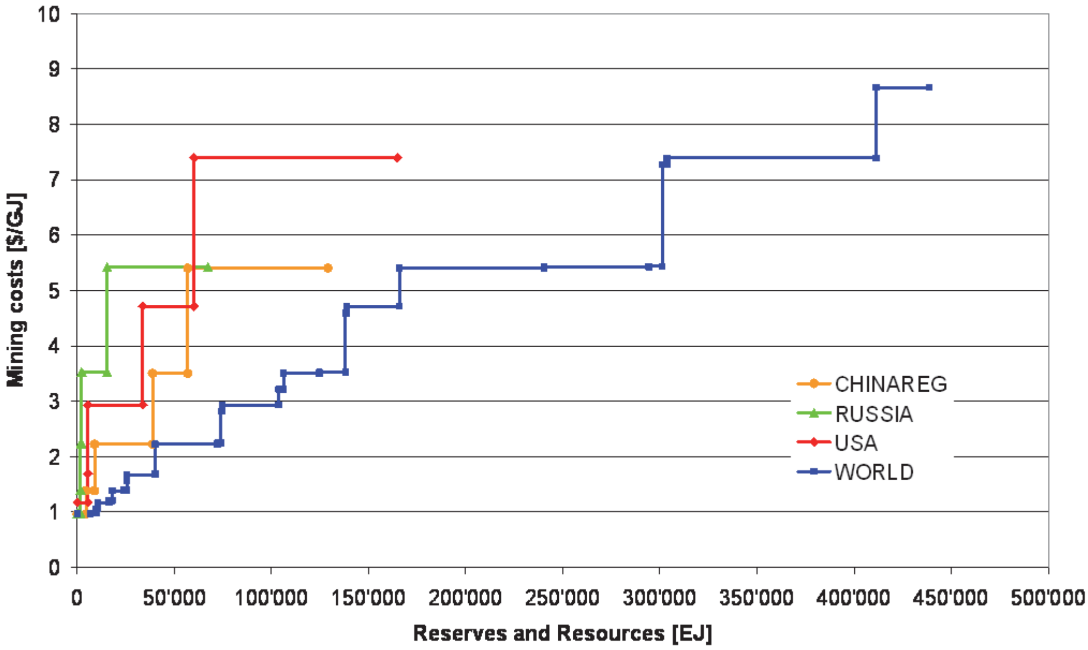


Figure 4.6 Hard coal supply curve.

Source: based on BGR (2012), Rogner (1997)

Figure 4.7 displays the lignite mining costs of the three largest regions with respect to the total reserve and resource numbers. Additionally, the world's supply curve is given representing all regions and costs.

Table 4.4 Brown coal reserves and resources per region, in EJ

	A	B	C	D	E	Total
ASIAPAC	117	0	0	641	1923	2681
AUSNZL	524	2045	89	0	0	2658
BRAZIL	60	0	0	0	150	211
CANMEX	27	0	30	279	1105	1441
CENASIA	34	0	20	430	1719	2203
CHINAREG	148	1309	1029	561	2197	5244
EEUR	192	250	125	0	125	692
EU31	672	247	1974	247	987	4126
INDIA	58	0	0	104	312	473
JPKRTW	0	12	1	0	0	12
LAC	0	0	0	0	90	90
MENA	0	0	0	0	0	0
RUSSIA	1092	0	138	3031	12124	16384
SSAFRICA	0	0	0	0	3	4
USA	368	0	345	3223	12775	16711
Total	3292	3863	3749	8514	33510	52929

Source: BGR (2012)

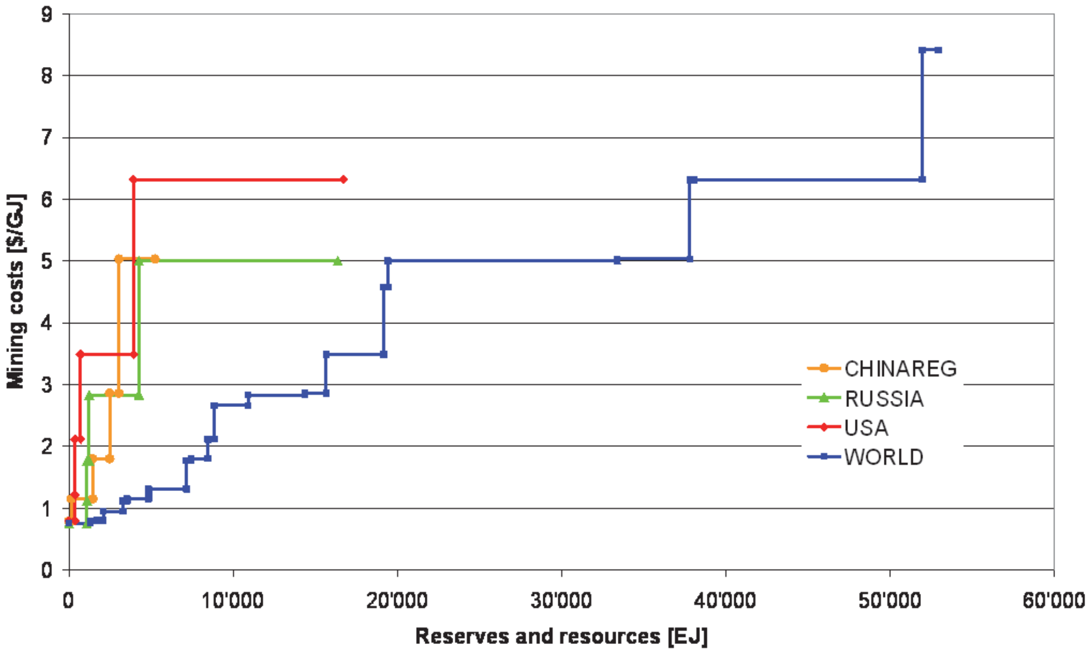


Figure 4.7 Brown coal supply curve.

Source: based on BGR (2012), Rogner (1997)

Overall, the coal reserve estimates of the old 6-region model are similar to those presented in Table 4.3 and Table 4.4 (and applied in the 15-region model), while there are much more coal resources available in the 15-region GMM compared to the 6-region GMM. One reason for this is the fact that additional resources in non-producing coal basins in Australia and in undeveloped regions of Alaska are newly taken into account in the most recent BGR (2012) reports. Generally, the reserves and resources of hard coal are much higher than those of lignite.

4.2 Uranium resources

Estimates of uranium resources have also been collected for future implementation into the GMM model, based on OECD/IAEA (2012) (Figure 4.8). The uranium categories are defined according to OECD/IAEA (2012) and based on the cost of extraction and their likelihood of discovery. The reasonably assured resources (RAR) amount to 2.2 ZJ. Inferred (possible), prognosticated and speculative resources add up to an additional 1.4 ZJ, 1.4 ZJ and 3.8 ZJ, respectively.

The majority of the cheapest resource category (<40 $/kg U) is reported for the regions CANMEX, BRAZIL and CENASIA. In the more expensive categories also AUNZ, SSAFRICA and USA hold considerable reasonably assured resources.

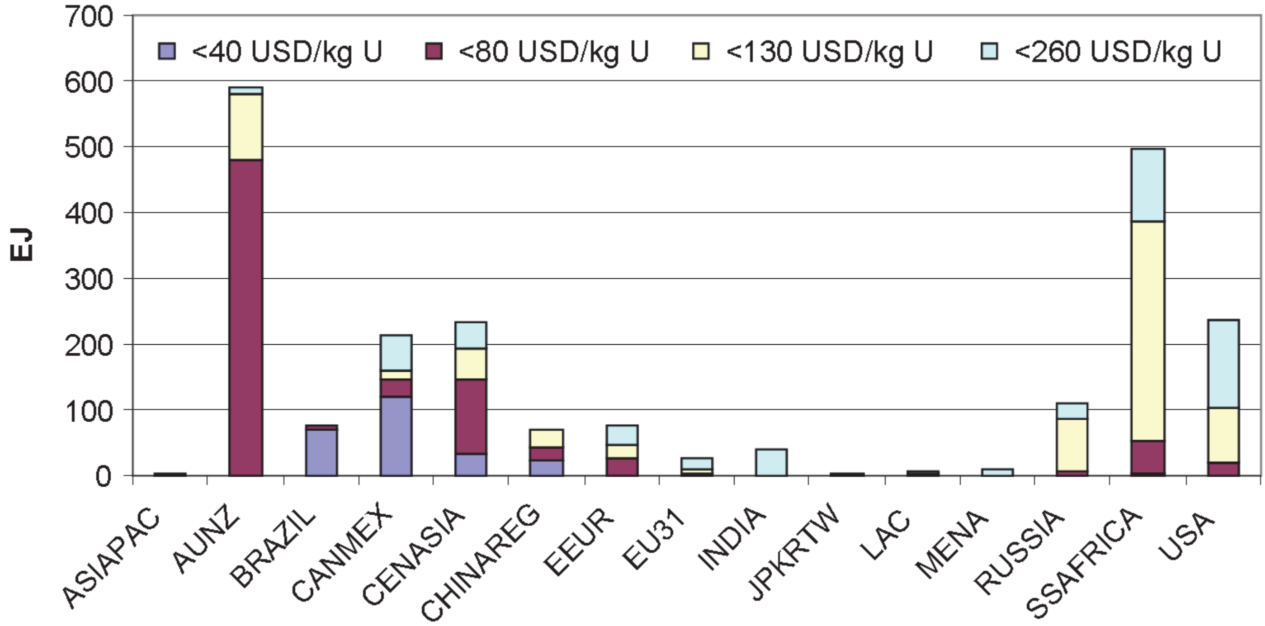


Figure 4.8 Reasonably assured Uranium resources (RAR), in EJ.

Source: OECD/IAEA (2012)

4.3 Renewable resource technical potentials

Renewable resource estimates in GMM have been updated based on recent literature estimates. In general, the resource estimates of interest correspond to the technical potentials. The technical potential represents the achievable energy output (primary energy in the case of biomass, electricity generation for most other renewables) of a particular technology given system performance, topographic limitations, environmental, and land-use constraints.[7]

The primary benefit of assessing technical potential is that it establishes an upper-boundary estimate of development potential of the technology, which is particularly useful for producing realistic forecasts. The figure below presents multiple types of potential – resource, technical, economic and market – with its key assumptions. For assessing the technical potential of each renewable energy source, assumptions and regional scope of relevant studies are compared. For some renewable energy sources the technical potential is based on a combination of the available sources.

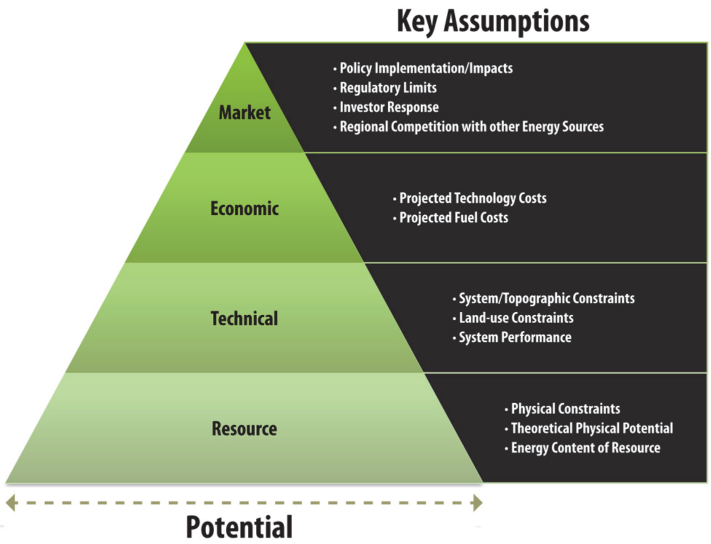


Figure 4.9 Different types of potential and associated assumptions.

Source: NREL 2013b

4.3.1 Biomass

The biomass potentials for corn grains, domestic waste, sugar cane/sugar beet, stover and wood residues is defined according to OECD/IEA (2005) (Figure 4.10). The potential of oil crops is set to the estimates of Ragettli (2007) which originally derive from Mattson *et al.* (2004). The allocation of all biomass estimates to the 15 regions in GMM was carried out according to each region's relative share of global surface land area.

The global potential is estimated to be 195 EJ/yr, mainly stemming from wood residues (>50%). Due to the similar approach used in estimating biomass resources, the regional shares and the total amounts of the feedstocks hardly differ between the 6- and the 15-region models.

---

[7] These are represented in the model either as upper bounds on the activity of the corresponding technology or as a cost-supply curve.

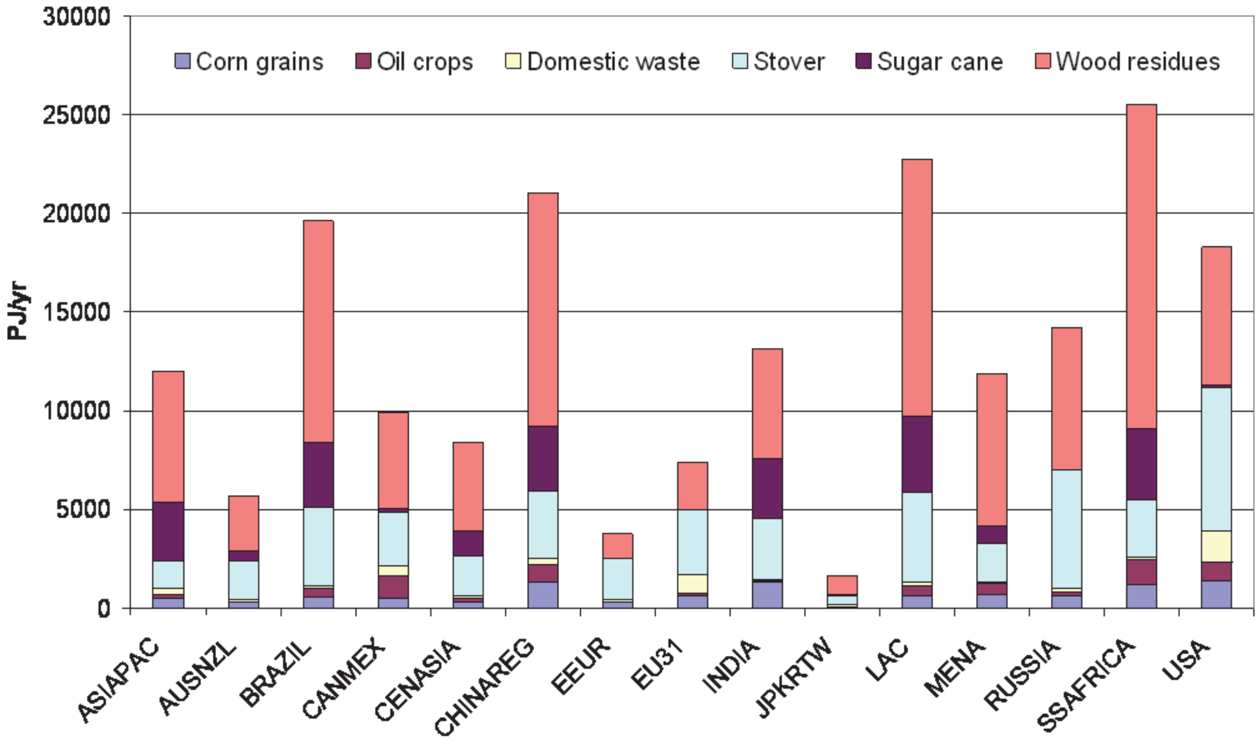


Figure 4.10 Biomass potential, in PJ/yr.

Source: OECD/IEA 2005, Mattson et al. (2004), Ragettli (2007)

4.3.2 Hydro

There is considerable debate regarding the quantification and classification of the world's hydropower resources. In order to define the technical potential from hydropower, several studies were compared (Ariel 2010, AUS 2010, GEA 2012, Hall 2011, Hoogwijk 2008, Hoogwijk 2004, IEA, 2012h, IJHD 2012, IPCC, 2011, Irving 2010, Krewitt 2009, Lopez 2012, NREL, 2012, RECIPES 2006, WEC, 2010). Estimates of worldwide technical potential are increasingly challenged as they tend to be based only on specific sites that have been studied at some point in the distant past, and thus tend to exclude other sites that could be developed. IHA (2013) estimates that, if the global level of deployment were to equate to the level already realised in Europe, only one-third of the realistic hydro potential has been developed to date.

Figure 4.11 below presents the technical potential for electricity production from hydropower (large and small hydro) in the 15 GMM regions. China, Russia, Latin America, Sub-Saharan Africa, and Brazil have the largest hydro potentials, where local and geographical factors such as the availability of water and the height difference for runoff water are highly favourable. In comparison, Australia, the Middle East and North Africa, and Eastern Europe have the lowest hydro potential. In Europe, Canada/Mexico, and Japan more than the half of the technical potential has already been exploited. On the other hand, Africa and the Asia Pacific are still underdeveloped. In Central Asia the percentage of development of hydro is small, but the remaining potential comes at a high cost since the low-cost hydropower has already been developed in this region.

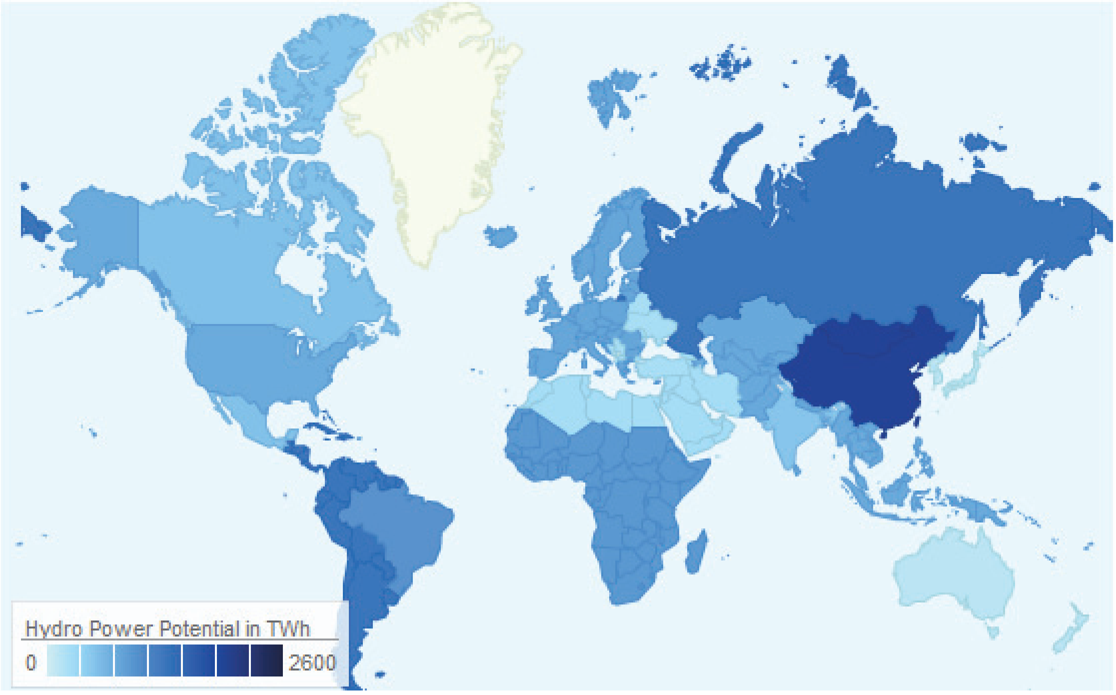


Figure 4.11 Hydro Power technical potential in TWh aggregated into GMM regions

Source: Ariel 2010, AUS 2010, GEA 2012, Hall 2011, Hoogwijk 2008, Hoogwijk 2004, IEA 2012h, IJHD 2012, IPCC, 2011, Irving 2010, Krewitt 2009, Lopez 2012, NREL, 2012, RECIPES 2006, WEC, 2010

4.3.3 Wind

The technical potential of onshore wind depends on wind resources, land available for the installation of wind turbines and the amount and rated power of wind turbines installed per unit of land area ("horizontal power density"). A typical wind turbine for onshore production is at present around 2 MW, and has a hub height of around 80 m. With increasing turbine sizes, costs per MW are reduced, and hub heights increase giving access to higher wind speeds. There are various studies that have assessed the technical potential of wind energy onshore on a global and regional scale (AUS 2010, EEA 2009, GEA 2012, GWEC 2011, Hoogwijk 2008, Hoogwijk 2004, IPCC 2011, Krewitt 2009, Kuick 2013, Lopez 2012, NREL 2012, RECIPES 2006, WEC 2010, Xiao 2009). All studies follow a similar approach but show some methodological minor differences.[8] The more recent studies tend to report higher estimates (approximately by a factor of 2).

North America has a significant potential, accounting for more than 40% of overall global potential. It is striking that China and India are projected to have low potentials in contrast to current developments in those markets. The main reasons for the low potentials are constraints on suitable area (exclusion of nature reserves, forests, urban area; average wind speeds) as well as the projections for demographic development in both regions.

---

[8] In general all studies use the internationally acknowledged dataset on environmental designations, compiled by the International Union for the Conservation of Nature (IUCN). Each land classification included in the dataset is assigned a suitability factor. High suitability factors are given to land-use and land-cover categories that facilitate dual use. Urban area, nature reserves and tropical forests are excluded entirely, whereas on avaregae 10% of other forest types are assumed to be available for installation of wind turbines. All studies use similar restrictions by altitude, land use functions, and wind regime, but the definition of land use suitability factors are slightly stricter in some compared to others (eg. Krewitt 2009 compared to Hoogwijk 2004).

Figure 4.12 below presents a graphical illustration of the technical potential for electricity production from onshore wind parks.

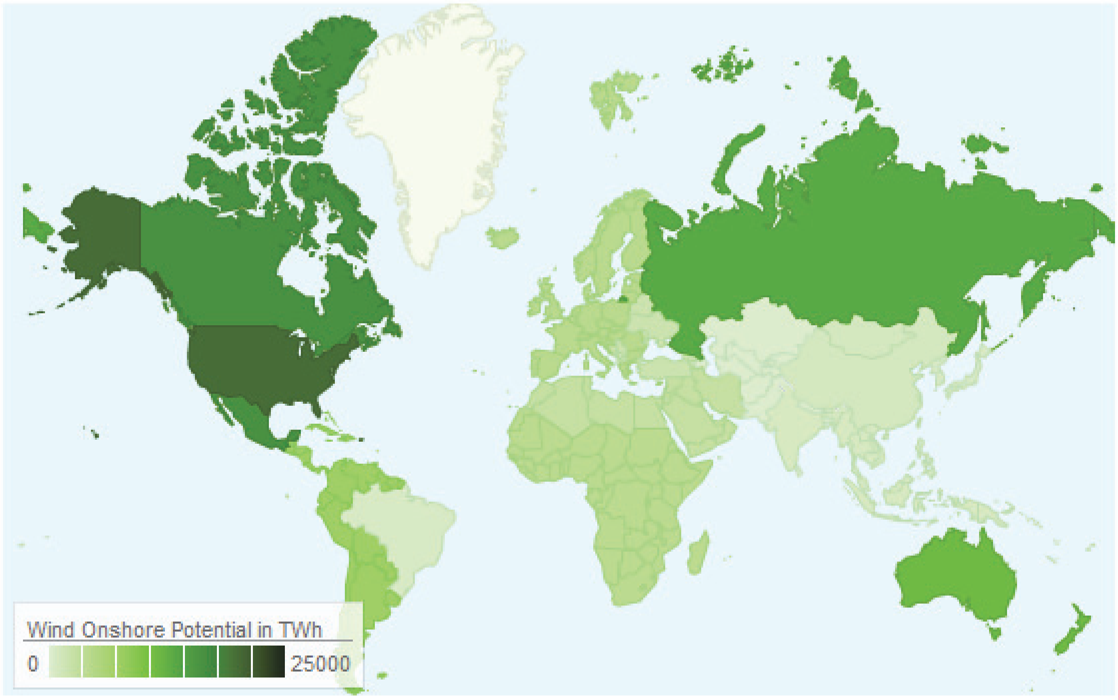


Figure 4.12 Wind Onshore Technical Potential in TWh aggregated into GMM regions

Source: AUS 2010, EEA 2009, GEA 2012, GWEC 2011, Hoogwijk 2008, Hoogwijk 2004, IPCC 2011, Krewitt 2009, Kuick 2013, Lopez 2012, NREL 2012, RECIPES 2006, WEC 2010, Xiao 2009

Offshore wind power is a less-mature renewable energy technology, with most of the large (over 1000 MW) plants located in OECD Europe. The technical potential of wind offshore depends on the wind resources offshore, the competition for other functions at sea (e.g. fisheries, oil and gas extraction, natural reserves) and the depth of the sea close to the shore.[9] Taking into consideration that the technology is still developing, it can be assumed that technology design will improve substantially with increased long-term practical experience which will extend the depth/distance to shore range of operation. In Norway, very recently a full-scale prototype of a floating wind turbine designed to operate at water depth of 100-200 m was realized.

Notwithstanding the above, it was assumed for the GMM model to focus on the technical potential of a distance no more than 50km and a depth less than 50m in order to be compatible with the economic characterisation of the wind offshore turbines, as it is represented in the model's database. Several studies were used and compared for assessing the technical potential at a global, as well as, regional scale (Arent 2012, AUS 2010, Dvorak 2010, EEA 2009, GEA 2012, GWEC 2011, Hoogwijk 2008, Hoogwijk 2004, IPCC 2011, Krewitt 2009, Kuick 2013, Lopez 2012, NREL 2012, RECIPES 2006, WEC 2010, Xiao 2009). The majority of the studies exclude conservation areas for wilderness

[9] The distance to the shore that is included in most potential assessments is around 40 km and a representative depth that is used as a maximum around 40 m. Currently, areas with a water depth of <20 m and a distance from the shore of <50 km are considered economically viable. The depth limit for current proven installation designs is 25 m. However, already today single installations have been realized in a water depth of 45 m.

protection, tourism and recreation, as well as maintenance of cultural and traditional attributes, according to the International Union for Conservation of Nature (IUCN).[10]

Figure 4.13 presents the offshore potential included in the GMM model. High potentials are found in OECD Europe, Latin America and Asia excluding India and China.

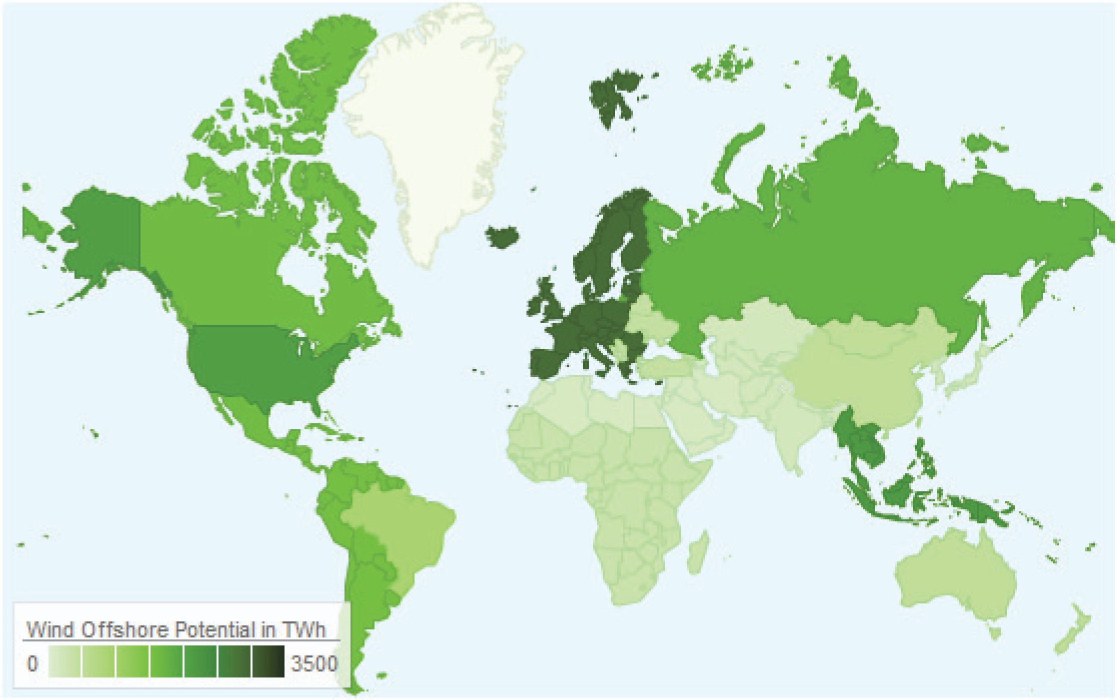


Figure 4.13 Wind Offshore Technical Potential in TWh aggregated into GMM regions

Source: AUS 2010, EEA 2009, GEA 2012, GWEC 2011, Hoogwijk 2008, Hoogwijk 2004, IPCC 2011, Krewitt 2009, Kuick 2013, Lopez 2012, NREL 2012, RECIPES 2006, WEC 2010, Xiao 2009

4.3.4 Solar

Several studies were compared for the assessment of the technical potential of solar PV systems[11] at a global and regional scale (AUS 2010, GEA 2012, Hoogwijk 2008, Hoogwijk 2004, IPCC 201, Krewitt 2009, Lopez 2012, NREL 2012, OEI 2012, RECIPES 2006, WEC 2010). The majority of the studies include geographical constraints by using an area suitability factor. The factor depends on competing land use options, such as agriculture, nature or farming for centralised systems and roof-tops and façade area for decentralised

---

[10] Typical area constraints range from 19% to 25 % of the near-shore area and 75 % of the sea bed between 5 to 40 km offshore and <40 m depth by homogeneous "thinning" to allow for unquantified technical and environmental constraints. The constraints were usually applied uniformly across the whole area as (in the majority of the cases) no information is available on a regional basis.

[11] Photovoltaic systems are semiconductor assemblies that directly convert solar energy into electricity. Two major types of PV systems exist; grid-connected systems and off-grid (stand-alone) systems, being especially viable for electricity production in remote areas. While off-grid systems are dependent on storage capacity, grid-connected systems do not need additional storage systems if the grid is able to cope with variations in electricity production. PV systems exist as ground-mounted systems (e.g.. in large centralised electricity generation facilities) or as rooftop systems, which represent the current dominant use. PV systems have been steadily improving over the last decades. At present, the majority of installed systems make use of single-crystalline and polycrystalline modules.

systems.[12] On average, the majority of the studies assume that the suitable area for centralised PV sums to on average 1.67% of total land area.

Figure 4.14 presents the technical potential for electricity production from solar PV. Africa is found to have by far the largest technical potential for solar PV, followed by the Middle East.

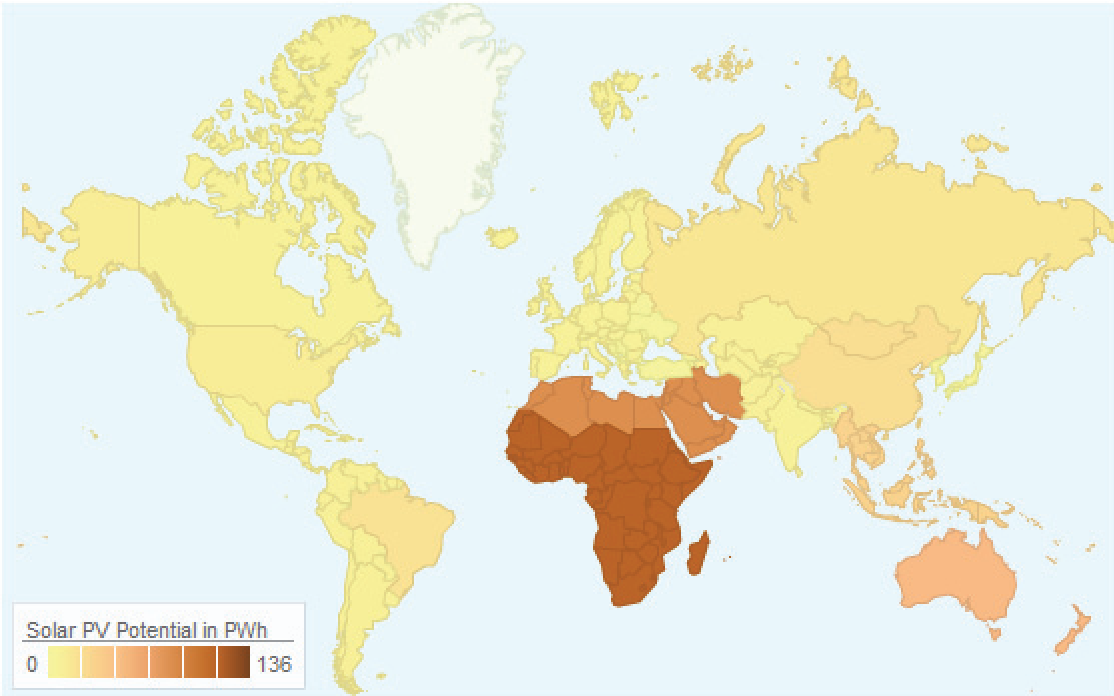


Figure 4.14 Solar PV technical potential in PWh aggregated into GMM regions

Source: AUS 2010, GEA 2012, Hoogwijk 2008, Hoogwijk 2004, IPCC 201, Krewitt 2009, Lopez 2012, NREL 2012, OEI 2012, RECIPES 2006, WEC 2010

In contrast to PV systems, solar thermal systems are based on the concentration of solar radiation and its conversion to heat.[13] According to the WEC Survey of Energy Resources (WEC 2010), the most promising areas are the Southwestern United States, Central and South America, Africa, the Middle East, the Mediterranean countries of Europe, South Asia, certain countries of the Former Soviet Union, China and Australia. In order to assess the technical potential of solar CSP several studies were used (AUS 2010, GEA 2012, Hoogwijk 2008, Hoogwijk 2004, IPCC 2011, Krewitt 2009, Lopez 2012, NREL 2012, OEI 2012, RECIPES 2006, Trieb 2009, WEC 2010). Most studies take into account

---

[12] For decentralised applications the suitability factor accounts for roof-top area per capita based on population density and GDP data. The available area for centralised PV-systems on crop land is restricted to small parts next to infrastructure or fallow areas. Extensive grassland is given a higher suitability factor than agricultural areas, as these areas are used less intensively and PV applications would interfere less with the original land use. Furthermore, installation of PV is excluded from land used for conservation of bio-reserves or landscapes of natural beauty (incl. protected areas and forest areas).

[13] Such plants are categorized according to whether the solar flux is concentrated by parabolic trough-shaped mirror reflectors, central tower receivers requiring numerous heliostats, or parabolic dish-shaped reflectors. The receivers transfer the solar heat to a working fluid, which in turn transfers it to a thermal power conversion system based on Rankine, Brayton, combined or Stirling cycles.

constraints related to surface slope, and competing uses (nature protection, water, and urban areas). Furthermore, they reserve room for alternative development opportunities. All areas recognized by the IUCN (International Union for the Conservation of Nature) are excluded.

Figure 4.15 present the technical potential for electricity production from concentrating solar thermal. The Middle East and North Africa is found to have by far the largest technical potential for solar CSP, followed by sub-Saharan Africa and Australia.

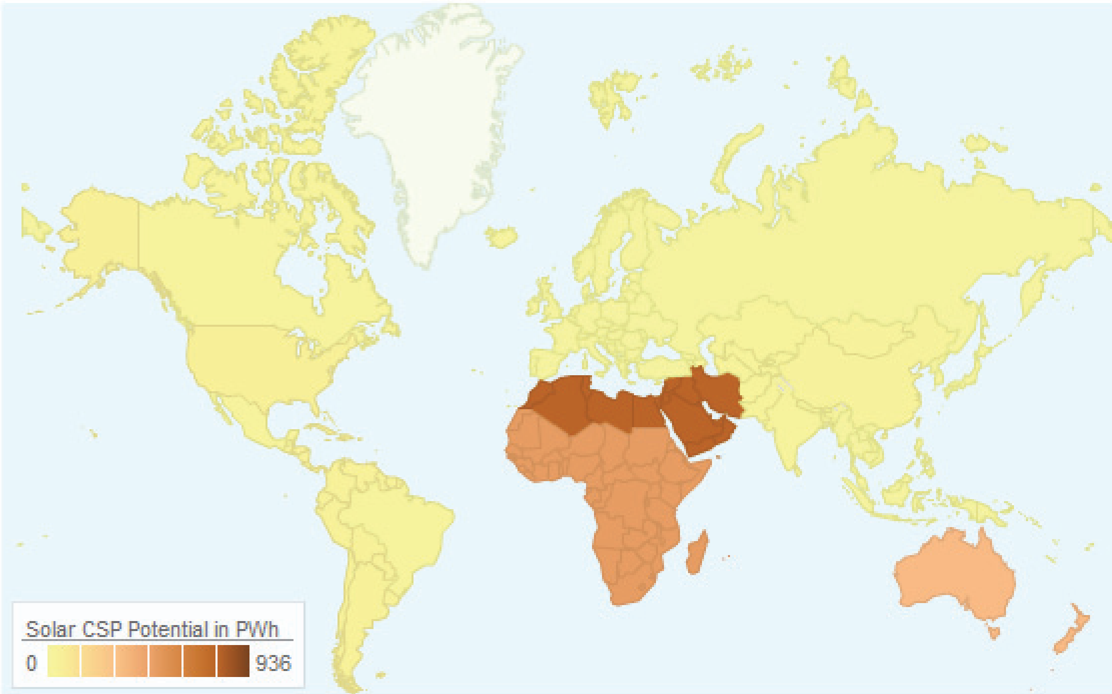


Figure 4.15 Solar Thermal technical potential in PWh aggregated into GMM regions

Source: AUS 2010, GEA 2012, Hoogwijk 2008, Hoogwijk 2004, IPCC 2011, Krewitt 2009, Lopez 2012, NREL 2012, OEI 2012, RECIPES 2006, Trieb 2009, WEC 2010

4.3.5 Geothermal

Geothermal energy utilization can be divided into two main sectors – direct use and electricity generation – depending on the temperature of the geothermal source. Low temperature resources, which are available in most countries and are easily accessible, are used for direct space or water heating applications. In contrast to direct use, high temperature sources (usually above 150 °C) are required for high-output power generation. These sources are less easily available and efficient use demands thorough geo-scientific investigations (multi-method approach) before designing a power plant. In the GMM model, only the high temperature geothermal resource potential was assessed.

Several sources and studies were compiled for the estimation of the technical potential at a global and regional level (AUS 2010, Bretani 2009, Gawell 1999, GEA 2012, Hoogwijk 2008, Hoogwijk 2004, IPCC 2011, Krewitt 2009, Lopez 2012, NREL 2012, RECIPES 2006, Stefansson 2005, WEC 2010). Some studies (Krewitt 2009, Stefansson 2005) derive the technical potential by creating an empirical relation between the number of active volcanoes and the technical potential of high temperature geothermal fields. These studies also, where needed, incorporated some additional assumptions based on land area according to IUCN.

According to the literature assessed, Africa, Asia and Latin America have the largest technical potential for electricity generation (Figure 4.16).

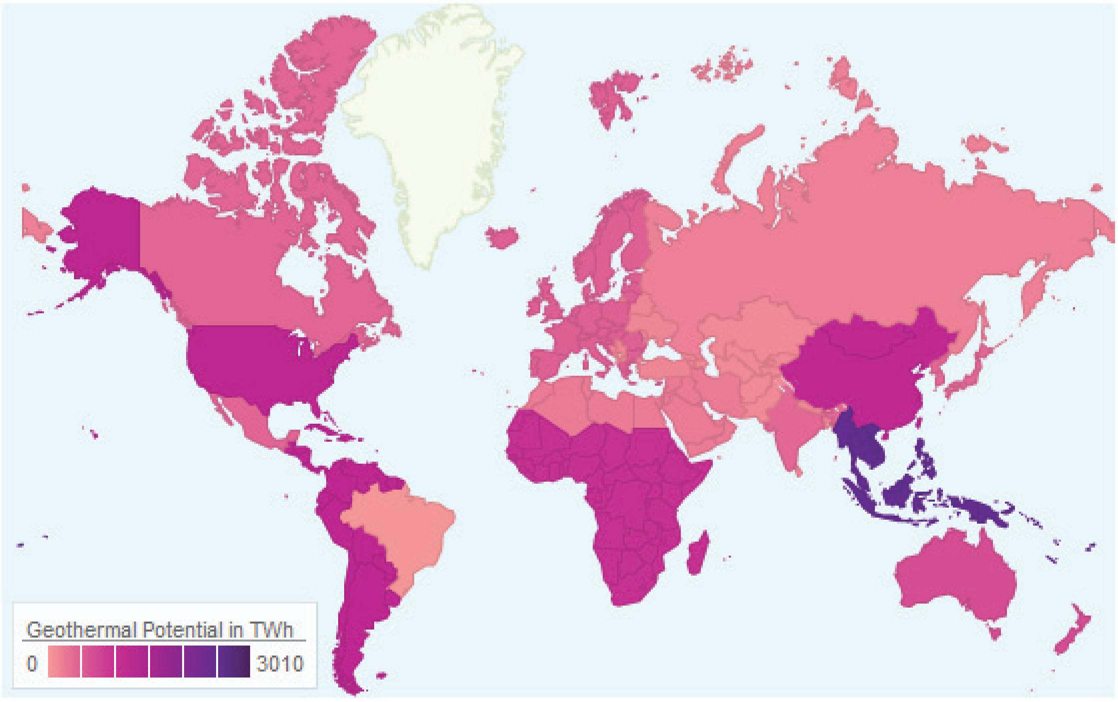


Figure 4.16 Geothermal technical potential for electricity production aggregated into GMM regions

Source: AUS 2010, Bretani 2009, Gawell 1999, GEA 2012, Hoogwijk 2008, Hoogwijk 2004, IPCC 2011, Krewitt 2009, Lopez 2012, NREL2012, RECIPES 2006, Stefansson 2005, WEC 2010

4.3.6 Summary of the technical potentials

On a global scale, the largest electricity generation potentials are estimated for the solar technologies, with the global technical potential for CSP about five times that of PV. The largest potentials for both solar technologies are in Africa and the Middle East, followed by the Asia Pacific.

Following the solar technologies, onshore wind is estimated to have the third-largest potential for electricity generation on a global scale. On a regional level, the technical potential for onshore wind is highest in North America.

Among the 15 regions in GMM, the European Union is estimated to have one of the smallest overall potentials for electricity generation from renewable energy sources (only India has a lower estimate). For the EU, the largest potentials are found for solar PV and wind offshore generation.

Table 4.5 below presents in detail the non-marketed renewables technical potential for electricity production in all GMM regions.

Table 4.5 Technical Potential of non-marketed renewables in TWh of electricity production

	Solar PV	*Solar Thermal*	*Wind onshore*	*Wind offshore*	*Geothermal*	*Hydro*	*% of Hydro Potential already exploited*
Asia Pacific	37,920	2,560	900	2,600	3,010	980	**8.6**
Australia/New Zealand	61,480	420,290	14,000	600	820	180	**21.0**
Brazil	22,810	24,900	800	1,100	20	1,250	**32.3**
Canada/Mexico	8,940	28,940	20,000	1,900	520	690	**56.2**
Central Asia	10,750	33,830	30	200	150	990	**9.1**
China Region	27,160	39,270	1,200	600	1,440	2,500	**28.9**
Eastern Europe	1,970	20	2,500	500	180	320	**34.6**
EU31	9,230	1,140	5,300	3,500	580	1,020	**53.3**
India	9,300	29,540	900	200	500	660	**17.3**
Japan/Korea Peninsula/Chinese Tai	1,110	0	600	200	490	160	**63.9**
Latin America	10,020	58,100	9,000	1,850	1,470	1,690	**17.2**
Middle East and North Africa	98,610	936,270	3,500	125	300	340	**10.3**
Russia	19,510	0	16,000	2,100	240	1,670	**10.0**
Sub-saharan Africa	135,920	591,850	5,000	400	1,210	1,170	**7.6**
United States	14,400	67,520	25,000	2,500	1,500	960	**27.2**
World Total	**469,130**	**2,234,230**	**104,730**	**18,375**	**12,430**	**14,580**	**23.6**

In 6-region GMM version the potentials of the non-marketed renewables can be characterised as economic rather than technical. For illustrative purposes, the table below presents the potentials of the previous model version.

Table 4.6 Potentials for the non-marketed renewables in the previous model version of 6 regions in TWh

	Solar PV	*Solar Thermal*	*Wind onshore*	*Wind offshore*	*Geothermal*	*Hydro*
Asia	9,680	n.a	993	324	660	3,564
Former Soviet Union	n.a	n.a	1,129	17	1,523	2,328
Latin America and Africa	3,192	n.a	998	31	893	2,982
North America	1,295	n.a	1,407	345	270	841
Other OECD	n.a	n.a	455	81	1,166	523
Western Europe	n.a	n.a	903	351	508	863
World Total	**n.a**	**n.a**	**5,885**	**1,151**	**5,019**	**11,101**

4.4 Carbon dioxide geological storage potentials

Estimates of carbon dioxide (CO_2) storage potential have been collected for the 15 regions for implementation into GMM. These estimates are defined according to the ECOFYS estimates in Hendriks et al. (2004). Where the ECOFYS regions did not match the 15 regions in GMM, the estimated potentials were – in a preliminary approach – allocated according to the surface area.

The storage potentials are differentiated according to onshore and offshore locations for each of the 15 regions. Further, the potentials are given for the different storage types, i.e. enhanced oil and gas recovery (EOR, EGR), depleted oil and gas fields (DOF, DGF), enhanced coal bed methane recovery (ECBM) and aquifers. Storage potentials by region are reported in Figure 4.17.

The largest potential is expected to be in the Middle East and Russia, mainly in onshore EOR, EGR and DGF as well as offshore EGR. For China, a significant potential for ECBM is estimated. Generally, there are still considerable uncertainties with respect to costs, technology availability, storage capacity, legal issues and public acceptance related to CCS.

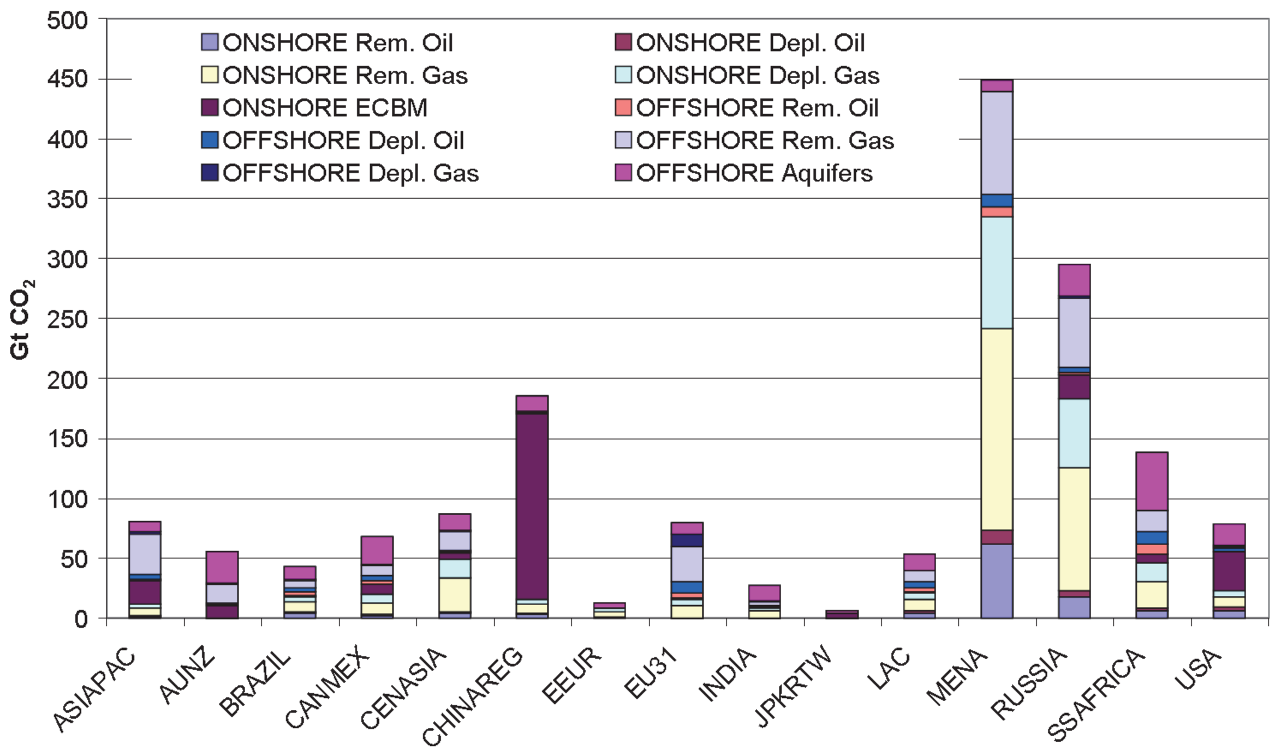


Figure 4.17 CO2 storage potential, in Gt CO2.

Source: Hendriks et al. 2004

5 Conclusions and Outlook

The developments of GMM presented in this report represent an important step in ensuring a richer representation of region-specific factors that may influence future global energy trends and technology pathways. The disaggregation of GMM from 6 world regions into 15 world regions ensures that different country-level economic, resource and policy factors are distinguished appropriately. In addition, the extensive recalibration of the model to 2010 statistics and energy resource estimates ensures that the impact of recent energy system developments are incorporated in future scenario analyses.

6 References

ADB, 2008: Asian Development Bank, “Bhutan Green Power Development Plan”, http://www.adb.org/search?keyword=37399&id=37399

Arent D. et al.,2012: “Improved Offshore Wind Resource Assessment in Global Stabilisation Scenarios”, NREL

Ariel et al., 2010: “Small hydro development in Mexico” , Energy Sector Management Assistance Program

AUS, 2010: “Australian Energy Resource Assessment “, Department of Resources, Energy and Tourism, Australian Government, 2010

Barreto, L., Kypreos, S. (2006): Extensions to the Energy-system GMM Model: An Overview. *PSI Bericht* No. 06-07. Energy Economics Group. Laboratory for Energy Systems Analysis. The Energy Departments. Paul Scherrer Institute. Villigen. Switzerland.

Barreto, L., Kypreos, S., (2004): The Energy-system GMM Model for Integrated Assessment. ETSAP 2004 Winter Semi Annual Workshop, 22-26 November 2004. Florence, Italy.

BGR, 2012. Reserves, Resources and Availability of Energy Resources 2011. Annual Report, Bundesanstalt für Geowissenschaften. Hannover, Germany. ISSN: 2193–5319.

BRA, 2013: Brazilian Government Portal Power Generation Statistics, http://www.brasil.gov.br/energia-en/power-sector/generation/br_model1?set_language=en

Bretani R., 2009: “Long-term projections of geothermal-electric development in the world”, GeoTHERM conference, Offenburg 2009

CBC, 2013: National Canada Statistics Agency,http://www.statcan.gc.ca/start-debut-eng.html

China, 2012: China Statistical Yearbook 2012, http://www.stats.gov.cn/english/publications/t20121011_402841708.htm

CNE, 2013: Chilean National Commission of Energy, Installed Capacity In Chile , http://www.centralenergia.cl/en/power-plants-chile/

COL, 2012: Ministry of Mines and Energy, http://www.minminas.gov.co/minminas/otroidioma.jsp

Davis, S., Diegel, S. (2012): Transport Energy Data Book. Ed. 31. Oak Ridge National Laboratory, Oak Ridge, US.

Densing M., Turton H., Bäuml G (2012). Conditions for the successful deployment of electric vehicles - a global energy system perspective, Energy 47 (2012), p. 137-149, http://dx.doi.org/10.1016/j.energy.2012.09.011

DOM, 2013: Electricity Superintendence Statistics, Dominican Republic, http://www.sie.gob.do/

Dvorak et al ., 2012: “US East Coast offshore wind energy resources”, Published online in Wiley Online Library

Dvorak et al., 2010: “California offshore wind energy potential”, Renewable Energy Vol. 35, 2010

EAC, 2013: Electricity Authority of Cyprus, Annual Report 2011, http://www.eac.com.cy/EN/Pages/Home.aspx

EcoProg, 2011: Market for Gas Power Plants in Europe, http://www.ecoprog.com/en/publications/energy-industry/gas-power-plants.htm

EEA, 2009: “Europe's onshore and offshore wind energy potential”

EIA, 2012: International Energy Statistics

EIA, 2013: Annual Energy Outlook 2013, DOE/EIA-0383(2013)

EIC, 2013: Quarterly Status Report on Global Gas Power Projects (1st quarter of 2013), http://www.the-eic.com/

EUR, 2013: EURELECTRIC, http://www.eurelectric.org/

EuraCoal, 2013: European Association for Coal and Lignite, http://www.euracoal.be/pages/home.php?idpage=1

EWEA, 2013: The European Wind Association, www.ewea.org

Fulton, L., Eads, G. (2004): IEA/SMP Model Documentation and Reference Case Projection, Internation Energy Agency.

Gawell K. et al, 1999: “Geothermal Energy, The Potential for Clean Power from Earth”, Geothermal Energy Association

GEA, 2012. Global Energy Assessment – Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. ISBN 9780 52118 2935.

GEO, 2012: Global Energy Observatory, http://globalenergyobservatory.org/

Gül, T., (2008): "An Energy-Economic Scenario Analysis of Alternative Fuels for Transport", Ph.D. Thesis, Nr. 17888, ETH Zürich, 2008.

Gül, T., Socrates, K., Turton, H. and Barreto, L. (2009): An energy-economic scenario analysis of alternative fuels for personal transport using the Global Multi-regional MARKAL model (GMM). *Energy*, 34 (10): 1423–1437. ISSN 0360-5442.

GWEC, 2011: “Global Wind Report Market Update 2011”, Global Wind Energy Council, http://www.gwec.net/

Hall et al, 2011: “Hydropower Resource Assessment of Brazilian Streams”, Idaho National

Laboratory USA

Hendriks et al., 2004. Global carbon dioxide storage potential and costs. By Ecofys in cooperation with TNO. Utrecht, The Netherlands. EEP-02001.

HEP, 2013: Hrvatska Elektroprivreda Croatia, http://www.hep.hr/hep/en/news/default.aspx

Hoogwijk M., Graus W., 2008: “Global Potential of Reneawable Energy Sources: A literature Assessment”, http://www.ecofys.com/en/publication/global-potential-of-renewable-energy-sources/

Hoogwijk M.,2004: “On the Global and Regional Potential of Renewable Energy Sources”, Phd Thesis, RIVM

ICCT, 2012: The International Council on Clean Transportation, Global Passenger Vehicles Standards, www.theicct.org,

IEA, 2005. PROSPECTS FOR HYDROGEN AND FUEL CELLS. Paris, France. ISBN 92-64-109-579 2005.

IEA 2009: Transport, Energy and CO_2: Moving towards Sustainability, OECD/IEA, Paris

IEA 2012a: IEA World Energy Statistics and Balances, International Energy Agency, France

IEA 2012b: Extended world energy balances, *IEA World Energy Statistics and Balances* (database). doi: 10.1787/data-00513-en

IEA, 2012c: IEA Electricity Information Statistics Database

IEA, 2012d: Global CHP/DHC data (The International CHP collaborative)

IEA, 2012e: IEA Electricity Information 2012 , ISBN 9789264174696

IEA, 2012f: Energy Technology Perspectives 2012, OECD/IEA, Paris.

IEA 2012g: World Energy Outlook, *IEA/OECD Press*. ISBN 978-92-64-18084-0.

IEA, 2012h: “Technology Road Map Hydropower”, http://www.iea.org/publications/freepublications/publication/name,32864,en.html

IEA, 2013: Hybrid & Electric Vehicle Implementation Agreement (IA-HEV), http://www.ieahev.org

IHA, 2013: International Hydropower Association, http://www.hydropower.org/

IHS, 2013: Solar PV market analysis, http://www.isuppli.com/photovoltaics/pages/headlines.aspx

IJHD, 20120 : Hydropower and Dams Atlas, 2010, http://www.hydropower-dams.com/#nogo

IMF (2012): World Economic Outlook Database, International Monetary Fund, October 2012

Inida, 2013: Central Electricity Authority of India, Ministry of Statistics and Programme

Implementation, http://www.cea.nic.in/welcome1.htm

IGU 2009: Report on NGV, nternational Gas Union, Report on Study Group 5.3, Natural Gas Vehicles (NGV), Final Report, IGU 24th World Gas Conference, WGC 2009

IPCC, 2000. EMISSIONS SCENARIOS. Cambridge University Press, UK. ISBN 0-521-80493-0.

IPCC, 2011: "IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation", Prepared by Working Group III of the Intergovernmental Panel on Climate Change [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, http://srren.ipcc-wg3.de/report

IRF (2012): International Road Federation – World Road Statistics 2012, Geneva, Switzerland. ISSN 2305-0365.

Irving J., 2010: "Hydropower in Canada", Canadian Hydropower Association Report, 2010

JPTN, 2013: The Japan Times News, http://www.japantimes.co.jp/news/

Krewitt et al., 2009: "Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply", Environmental Research of the German Federal Ministry and Nuclear Safety, ISSN 1862-4359, http://www.ecofys.com/en/publication/role-and-potential-of-renewable-energy-and-energy-efficiency-for-glo/

Kuick, 2013: "South Korea Wind Power Sector Analysis", Kuick Research

Lopez A. et al., 2012 "US Renewable Energy Technical Potential: a GIS based analysis", NREL

Mattson et al. (2004). Analysis of the World Oil Crops Market. Center for Agricultural Policy and Trade Studies, Department of Agribusiness and Applied Economics, North Dakota State University, Fargo, North Dakota. Agribusiness & Applied Economics Report No. 529.

NREL, 2012: "US Renewable Energy Technical Potentials: A GIS-Based Analysis"

NREL, 2013a: Concentrating Solar Power Projects database, http://www.nrel.gov/csp/solarpaces/

NREL, 2013b : http://www.nrel.gov/gis/re_potential.html

OECD/IAEA, 2012. Uranium 2011: Resources, Production and Demand. Paris, France. ISBN 978-92-64-17803-8.

OEI, 2012: Solar Resources By Class Per Country, online database at Open Energy Info, http://en.openei.org/datasets/node/498

PEIN, 2013: Power Engineering Industry News, http://www.power-eng.com/news.html

PPAW, 2012: Power Plants Around the World , http://www.industcards.com/

Rafaj P. (2005):"Analysis of Policies Contributing to Sustainability of the Global Energy System Using the Global Multi-regional MARKAL Model (GMM)", Ph.D. Thesis, Nr. 16122, ETH Zürich 2005.

Ragettli, 2007. Cost outlook for the production of biofuels – A cost comparison assessment of the future production of biofuels. Diploma thesis. Submitted to ETH Zurich, Switzerland.

RECIPES, 2006: “Renewable Energy Potential: Country Specific Reports”, RECIPES project, 2006

REEEP, 2013: Renewable Energy & Efficiency Projects, http://www.reeep.org/projects

Rogner, 1997. AN ASSESSMENT OF WORLD HYDROCARBON RESOURCES. Annu. Rev. Energy Environ. 1997. 22:217–62.

RossStat, 2013: Russian Federal State Statistics Service, http://www.gks.ru/

SENER, 2013: Secretaria de Energia, Mexico, http://www.sener.gob.mx/

Stefansson V, 2005: “World Geothermal Assessment”, Proceedings World Geothermal Congress, 2005

TRAN, 2013: Compania Natioanal de Transport al Energiei Electrica, Annual Report 2011, http://www.transelectrica.ro/EN/publicatii.php

Trieb F. et al., 2009: “Global Potential of Concentrating Solar Power, SolarPaces Conference Berlin”, September 2009

United Nations, Department of Economic and Social Affairs, Population Division (2011). World Population Prospects: The 2010 Revision, CD-ROM Edition.

WEC, 2010: “Survey of Energy Resources”, ISBN: 978 0 946121 02, http://www.worldenergy.org/publications/3040.asp

WindPower, 2012: The Wind Power Database (Onshore and Offshore wind farms), http://www.thewindpower.net/

WNA, 2012: World Nuclear Association, http://world-nuclear.org/

World Bank (2012): World Development Indicators, …

World Energy Council, IBM Corp. and PSI (2011): Global Transport Scenarios 2050, *WEC London*, ISBN 978-0-946121-14-4.

Xiao, Z., et al. , 2009: “China Wind Energy Resource Assessment”, China Meteorological Press

Yang A, Cui Y, 2012: Global Coal Risk Assessment, World Resources Institute, http://www.wri.org/publication/global-coal-risk-assessment

7 Appendix

7.1 Appendix I Classification of the energy carriers in GMM and IEA definitions.

Energy carriers (those for production and trade calibration)	Detailed energy carriers in IEA's data
Hard coal	Anthracite, coking coal, other bituminous coal (depending on country), sub-bituminous coal, patent fuel, coke oven coke, gas coke, coal tar
Brown coal	Lignite, sub-bituminous coal (depending on country), brown coal briquettes (BKB), peat briquettes, peat
Oil	Crude oil, NGL, refinery feedstock, additive/blending components, other hydrocarbons
Diesel type (long-chain hydrocarbons, e.g. for diesel-type engines and heating)	Gas/Diesel oil, fuel oil
Gasoline/kerosene type (all other lower-chain hydrocarbons)	IEA's oil products (secondary fuels) excluding the diesel type
Gas	Natural gas
Biomass	Industrial and municipal waste (renewable and non-renewable)[a], primary solid biofuels, biogases, biogasoline, biodiesels, other liquid biofuels, charcoal
Renewables: Wind, Solar PV, Solar Thermal, Geothermal	IEA's renewables categories
Nuclear	IEA's nuclear category

[a] Note that the GMM model treats waste similar to generic biomass; currently CO_2 emissions associated with this waste are ignored.

7.2 Appendix II GMM electricity and heat generation technologies classified by energy source

Nuclear
- *Light Water Reactor (LWR)*
- *Advanced New Nuclear Power Plant (NNU)*

Coal
- *Convential Subcritical Coal*
- *Convential Subcritical Coal with DeSOx/DeNOx filter*
- *Advanced Coal (supercritical, PFBC)*
- *Integrated Coal Gasification Combined Cycle*
- *Advanced Coal with post-combustion Carbon Capture and Storage*
- *Integrated Coal Gasification Combined Cycle with pre-combustion Carbon Capture and Storage*
- *Cogeneration Coal (CHP)*
- *Coal Heating Plant*

Oil
- *Oil Electric*
- *Oil Heating Plant*

Gas
- *Conventional Thermal*
- *Gas turbines Combined Cycle*
- *Gas turbines Open Cycle*
- *Gas Fuel Cell*
- *Gas turbines Combined Cycle with pre-combustion Carbon Capture and Storage*
- *Cogeneration Gas (CHP)*
- *Gas Heating Plant*

Hydropower
- *Hydro-electric plant*

Bioenergy
- *Biomass Thermal*
- *Biomass Integrated Gasification Combined Cycle*
- *Biomass Integrated Gasification Combined Cycle with pre-combustion Carbon Capture and Storage*
- *Biomass Heating Plant*

Wind
- *Onshore Wind Turbines*
- *Offshore Wind Turbines*

Solar
- *Solar Photovoltaics*
- *Solar Thermal electric*

Geothermal
- *Geothermal electric*

Hydrogen
- *Hydrogen Fuel Cell Cogeneration for the Industrial Sector*
- *Hydrogen Fuel Cell Cogeneration for the Residential and Commercial Sector*

7.3 Appendix III Reconciliation module

Reconciliation module: general algebraic specification

Central to the data generation process is the construction and use of a reconciliation module that uses the idealised but incomplete data set as input together with the published "hard" data and the identities that must hold (i.e. balances) to produce a complete and consistent data set.

The reconciliation module is a non-linear optimization program that minimises the square differences of the logarithms of the "idealised" and the required data set subject to a set of restrictions requiring the latter to satisfy the identities linking it to the "hard' and otherwise published data. The objective is set to represent proportional rather than absolute deviations in order to avoid problems of scaling. As some "soft" data maybe "harder" than others, the squared differences can be multiplied by weights following an *a priori* assessment.

The generic algebraic specification is as follows:

$$\min_{x_1 \ldots x_n} \sum_{i=1,,n} w_i \left[\ln \frac{x_i}{y_i} \right]^2$$

Subject to,

$$D_j(x_1 \ldots x_n) \equiv 0 \quad , \quad j = 1..m$$

$$F_k(x_1 \ldots x_n) = 0 \, , \quad k = 1..l$$

$$F_k(y_1 \ldots y_n) = 0 \, , \quad k = 1..l$$

$$l_i \le x_i \le u_i$$

Where,

y_i : are the "target" values, determined outside the reconciliation module

x_i : are the "unknown" missing data

D_j : are identities that will always hold (links to "hard" data, logical identities, i.e. balances)

F_k : are approximate behavioural or technical relations, which their parameters can be treated as x_i variables and figure in the objective (i.e. maximum utilization of a plant)

l_i, u_i : are optional bounds on x_i

w_i : are weights indicating the importance of approaching a target value

The use of reconciliation module implies expert involvement in the process. This involvement follows sequentially and repeatedly the following steps:

- Establish an *a priori* “order of merit” for different data items, by introducing constraints to reproduce exactly the idealised data and using weights on the objective for different targets (e.g. electricity production by source)

- Review results and obtain new ones by varying weights for targets in the objective function and/or introducing constraints and composite targets (e.g. total capacity)

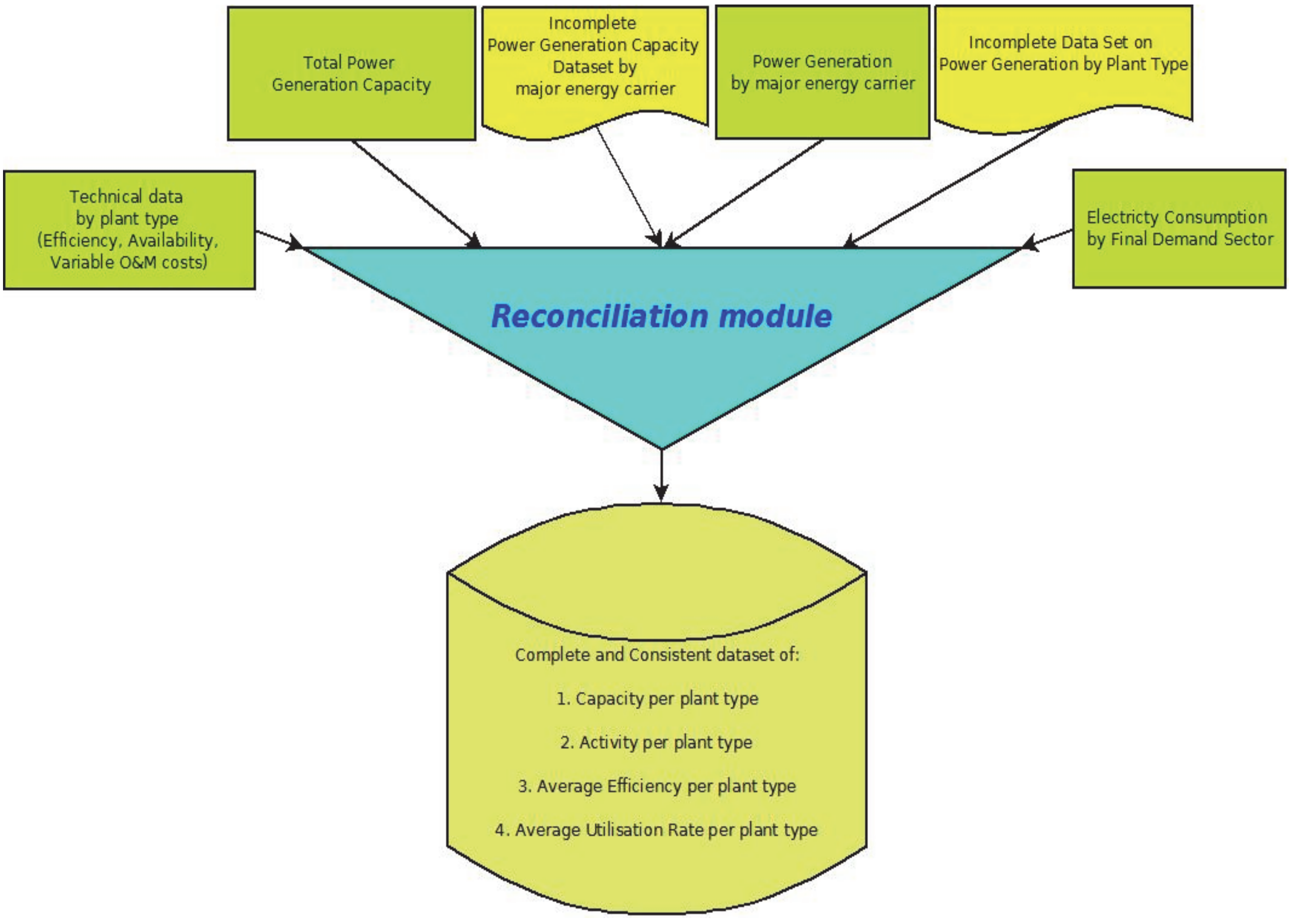
- Examine the final solution in view of assessing the deviations from the targets and the dual values of the constraints (a mathematical indication on how restrictive a given constraint is).

The outcome of the reconciliation module is a detailed set of capacities and production estimates by power plant type compatible with the GMM model’s requirements. This detailed set respects all “hard” data such as activity and capacity by major fuel.

Reconciliation module: Use

The figure below presents the use of the reconciliation module in order to split aggregated data on capacity and activity for power plants into the detailed plant categories required by the GMM model.

Figure A3.1: Schematic representation of reconciliation module usage for data splitting



Main inputs to the module were:

- “Hard” data (published): total power generation capacity, power and heat generation by major energy source, electricity consumption by final demand sector

- “Soft” data (published but not consistent between the different sources): power and heat generation capacity by major energy carrier, power and heat generation by plant type

- Additional data needed for the reconciliation: Technical data by plant type: mainly average efficiency, availability and variable O&M costs

Unknown variables for the reconciliation module were the capacity, the activity, the utilisation rate and the average efficiency for each GMM electricity generation technology.

The first step is the construction of the electricity load curve based on the final consumption of electricity by demand sector. Then, the module determines the share of each plant in the annual electricity load based on short-term costs (variable operating and maintenance costs, fuel costs). By applying the share of each technology to the annual load curve, the activity of each technology is determined based on cost-effectiveness. This implies that the “optimal” activity may not be consistent with the available statistics (in terms of fuel consumption, availability rates, etc.). To deal with this, and to produce a consistent dataset, the following constraints were introduced into the reconciliation module:

- Constraint on total generating capacity

- Constraint on fuel consumption by fuel

- Constraint on the technical availability of each plant type

- Constraint on activity per energy source (starting from the optimal activities of the reconciliation module)

- Other constraints, regional specific, taking into account for each region its individual characteristics (including data availability)

The objective function of the reconciliation module included weighted logarithmic differences of:

- Calculated capacity per plant type and “soft” capacity per plant type as reported in the incomplete data sources

- Calculated average efficiency and “hard” average efficiency as assumed in the technical characteristics of each plant type

- Calculated utilisation rate and “hard” availability of each plant type as included in the technical characteristics of each plant type.

- Calculated activity per plant type and “optimal” activity as determined from the short-term technology production costs of electricity.

The result of the reconciliation process is a complete and consistent (with the available statistics) dataset of capacity and activity per plant type. In addition, average efficiencies and utilisation rates were obtained respecting the published data in the energy balances.

It should be noted that the reconciliation module was used only for the electricity generating technologies (including CHP plants) and not for the heat plants. The aggregated information found in the energy balances about the activity and the fuel consumption of the heat plants is enough for the requirements of the model, thus no further data splitting was necessary.

7.4 Appendix IV Availability factors for power and heat generation

The table below presents the average availability factors for the power and heat generation technologies, used for the model calibration.

% Average Availability Factor in 2010	Asia Pacific	Australia, New Zealand	Brazil	Canada, Mexico	Central Asia	China Region	Eastern Europe	EU31	India	Japan, Korea Peninsula, Chinese Taipei	Latin America	Middle East and North Africa	Russia	Sub-saharan Africa	United States
Region Total	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nuclear	89%	82%	86%	90%	89%	89%	77%	83%	89%	89%	84%	82%	84%	82%	99%
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Subcritical coal	53%	67%	11%	78%	10%	61%	39%	51%	66%	62%	53%	68%	68%	77%	75%
Supercritical coal	63%	74%	65%	79%	65%	62%	66%	76%	65%	71%	65%	65%	75%	75%	81%
Integrated Coal Gasification Combined Cycle	75%	75%	75%	79%	75%	75%	75%	87%	75%	87%	75%	75%	75%	75%	81%
Oil	65%	65%	65%	65%	65%	65%	65%	65%	65%	65%	65%	65%	65%	65%	65%
Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Conventional	59%	49%	54%	55%	68%	40%	37%	43%	69%	54%	65%	69%	37%	47%	42%
Gas turbines Combined Cycle	70%	59%	60%	73%	74%	54%	83%	61%	70%	66%	53%	68%	39%	66%	57%
Gas turbines Open Cycle	57%	48%	50%	40%	69%	41%	42%	41%	66%	36%	69%	64%	44%	45%	48%
Hydro (incl. pump storage)	44%	30%	59%	53%	47%	37%	39%	34%	33%	20%	56%	26%	41%	50%	31%
Bio energy	75%	75%	75%	75%	75%	75%	75%	75%	75%	78%	75%	75%	75%	75%	79%
Wind	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Onshore	16%	32%	27%	28%	10%	16%	24%	20%	17%	22%	19%	24%	24%	25%	29%
Offshore	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%
Solar	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Photovoltaics	17%	18%	-	16%	6%	12%	9%	9%	8%	13%	18%	17%	6%	16%	13%
Solar Thermal	-	21%	-	-	-	-	-	13%	-	-	-	-	-	-	21%
Geothermal	75%	83%	75%	81%	75%	75%	84%	76%	75%	75%	76%	75%	75%	85%	75%

The table below presents the average efficiency for electricity production, used for the model calibration.

Average Thermal Efficiency per technology in 2010	Asia Pacific	Australia, New Zealand	Brazil	Canada, Mexico	Central Asia	China Region	Eastern Europe	EU31	India	Japan, Korea Peninsula, Chinese Taipei	Latin America	Middle East and North Africa	Russia	Sub-saharan Africa	United States
Region Total	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Subcritical coal	32%	34%	31%	36%	24%	32%	32%	37%	28%	37%	36%	38%	28%	34%	37%
Supercritical coal	40%	39%	43%	43%	43%	40%	43%	43%	43%	40%	43%	43%	43%	43%	42%
Integrated Coal Gasification Combined Cycle	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%
Oil	35%	32%	37%	37%	35%	28%	39%	44%	20%	46%	39%	30%	45%	33%	42%
Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Conventional	35%	40%	37%	37%	27%	15%	33%	40%	17%	40%	36%	26%	18%	37%	37%
Gas turbines Combined Cycle	46%	50%	50%	50%	50%	45%	50%	53%	47%	52%	49%	50%	50%	44%	52%
Gas turbines Open Cycle	34%	33%	35%	35%	35%	27%	35%	40%	20%	33%	35%	25%	18%	34%	35%

The table below presents heat plant capacities (in GWth), activities (in PJ) and average efficiencies by technology and region.

Heat Plants in 2010	Asia Pacific	Australia, New Zealand	Brazil	Canada, Mexico	Central Asia	China Region	Eastern Europe	EU31	India	Japan, Korea Peninsula, Chinese Taipei	Latin America	Middle East and North Africa	Russia	Sub-saharan Africa	United States	World
Coal Heating Plants																
Capacity (GWth)	0.0	0.0	0.0	0.0	0.0	218.7	3.1	14.4	0.0	0.0	0.0	0.0	39.6	0.0	0.0	**275.9**
Activity (PJ)	0.0	0.0	0.0	0.0	0.1	2508.2	35.7	165.5	0.0	0.0	0.0	0.0	454.6	0.0	0.0	**3164.1**
Average Efficiency (%)	-	-	-	-	0.9	0.8	0.8	0.8	-	-	-	-	0.8	-	-	-
Oil																
Capacity (GWth)	0.0	0.0	0.0	0.1	0.2	11.9	2.9	16.1	0.0	4.4	0.0	0.0	25.9	0.0	3.0	**64.6**
Activity (PJ)	0.0	0.0	0.0	1.1	2.3	143.8	34.5	193.8	0.0	53.4	0.0	0.0	312.0	0.0	36.4	**777.3**
Average Efficiency (%)	-	-	-	0.8	0.4	0.7	0.8	0.6	-	0.6	-	-	0.8	-	0.9	-
Gas																
Capacity (GWth)	0.0	0.0	0.0	0.0	3.6	7.6	41.0	26.0	0.0	1.6	0.0	0.0	187.2	0.0	0.0	**267.0**
Activity (PJ)	0.0	0.0	0.0	0.0	43.8	91.6	493.8	312.7	0.0	19.4	0.0	0.0	2146.3	0.0	0.0	**3107.6**
Average Efficiency (%)	-	-	-	-	0.6	0.9	0.9	0.8	-	0.9	-	-	0.8	-	-	-
Bio energy																
Capacity (GWth)	0.0	0.0	0.0	0.2	0.0	2.8	2.2	42.4	0.0	2.1	0.0	0.0	10.4	0.0	3.8	**64.0**
Activity (PJ)	0.0	0.0	0.0	2.2	0.0	33.9	26.6	510.5	0.0	25.2	0.0	0.0	119.5	0.0	44.0	**761.9**
Average Efficiency (%)	-	-	-	0.6	-	0.7	0.6	0.7	-	0.9	-	-	0.7	-	0.6	-
Geothermal																
Capacity (GWth)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.6**
Activity (PJ)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**13.2**
Average Efficiency (%)	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-	-

7.5 Appendix V Energy demand sectors in GMM and IEA definitions

Demand sector in GMM	Demand sectors in IEA statistics
Industrial sector	IEA Industry and IEA Non-Energy Use
Industry thermal demand	IEA’s Industrial sector • IEA's electricity in the iron/steel subsector • In the IEA statistics, coke ovens, gas works, and blast furnaces are in the energy conversion sector; for simplicity, in GMM, they are relocated to industrial end-use demand.
Industry specific demand (e.g. kinetic energy, that can be satisfied with motors; usually electric or combustion engines)	• Consumption of Gasoline, LPG and Gas/Diesel fuels • Consumption of electricity apart from iron/steel subsector
Non-Energy Use (mainly feedstock for industry)	Energy carriers for non-energy use
Residential/Commercial sector	IEA sectors: Residential, commercial, agriculture, fishing, military (“Other Sector”)
Thermal demand in res./comm. Sector	• Coal, gas and biomass and biofuel demand of IEA’s Other Sector • Assumption: 30% of electricity demand of IEA’s Other Sector is for thermal use
Demand for appliances in the res./comm. sector (e.g. air conditioning, household devices, lightning, and consumer electronics that can only be fuelled with electricity).	• LPG, Gas/Diesel, biomass and biofuel demand of IEA’s Other Sector • Assumption: 70% of electricity demand of IEA’s Other Sector is for appliances
Non-commercial biomass (burned for cooking and for heating)	In developing regions, most of the biomass is assumed to be non-commercial
Transport Sector	IEA’s transport sector
Personal cars includes: Sector for smaller, short-range cars	Part of IEA’s road transport
Other Surface Transport	Part of IEA’s road transport (bus, truck 2- and 3-wheelers), rail, ship (international and domestic)
Aviation	IEA’s aviaton (international and domestic)

PAUL SCHERRER INSTITUT

Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
Tel. +41 56 310 21 11, Fax +41 56 310 21 99
www.psi.ch