

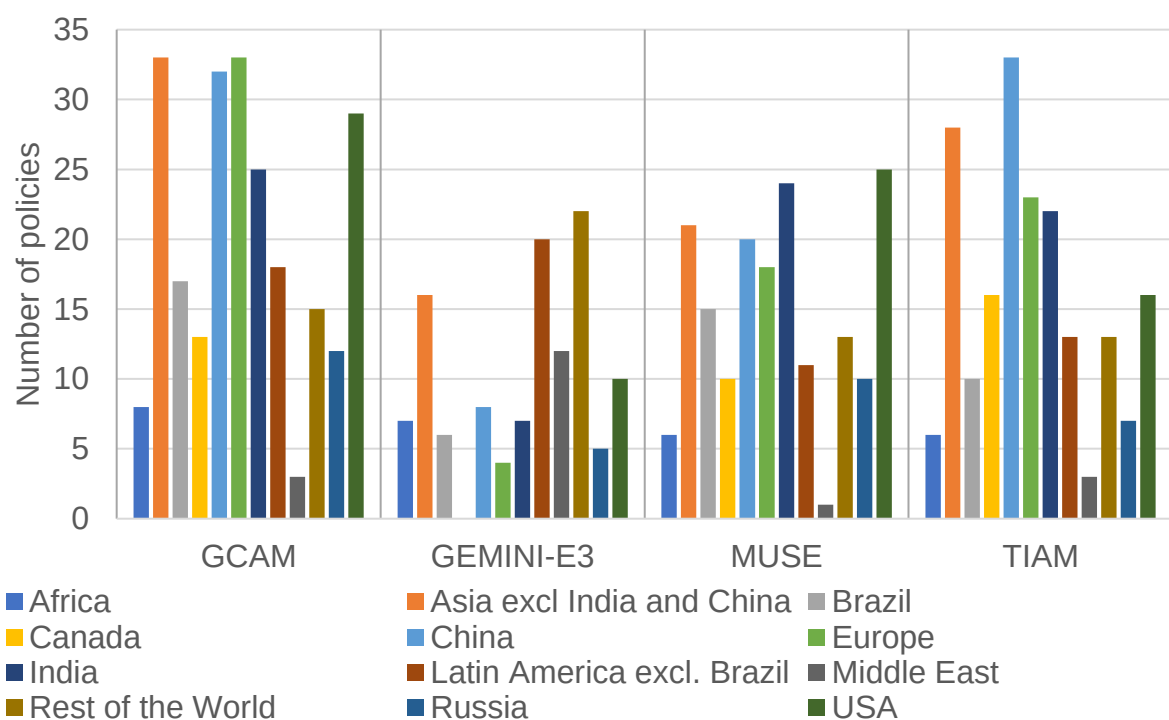
A multimodel analysis of post-Glasgow climate targets and feasibility challenges

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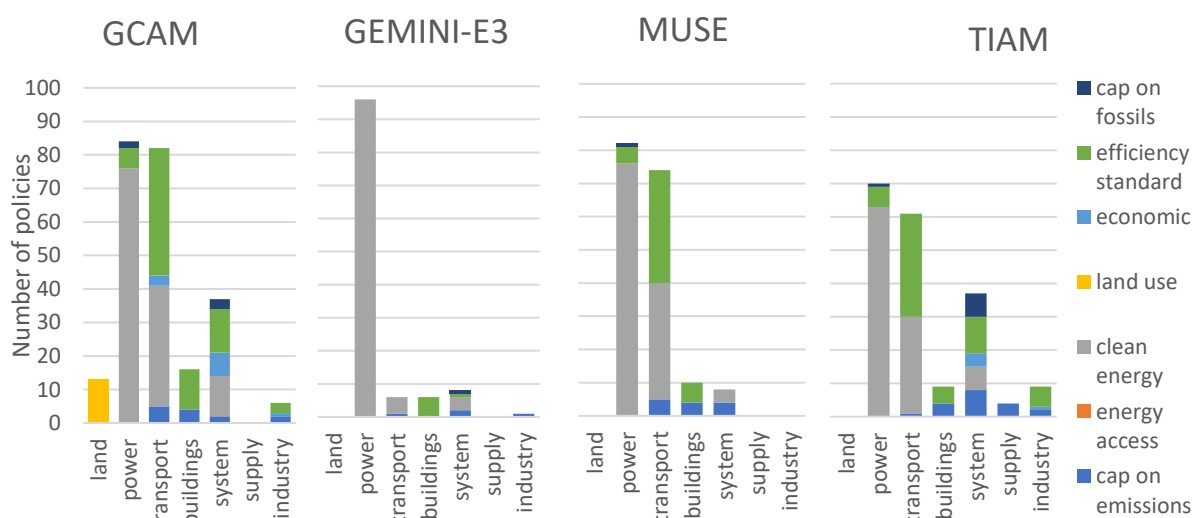
Supplementary information for: **A multi-model analysis of post-Glasgow climate targets and feasibility challenges**

Supplementary section 1: Applied pledges and policies

For all scenarios in this study, the applied models an extended set of implemented policies and concrete policy targets for G20 countries and the entire European Union. The primary source for those policies is the Climate Policy Database (<https://climatepolicydatabase.org>), while complemented by other sources such as the IEA (<https://www.iea.org/policies>) and specific national sources (i.e. Hultman et al¹). The precise selection and implementation of policies differs from model to model, depending on model coverage, capabilities as well as baseline trajectories. Supplementary Figures 1 and 2 provide information about the geographical and sectoral coverage of the policies applied in each model. Supplementary Data 1 provides details on all policies applied in this study.



Supplementary Figure 1: Applied policies per region by model



Supplementary Figure 2: Applied policies by sector and policy, by model

For emission targets, we focus on Nationally Determined Contribution (NDC) targets (Supplementary Table 1) and Long-Term Targets (Supplementary Table 2). The primary source for these data is ClimateWatch (<https://www.climatewatchdata.org/>), with June 2022 as the cut-off date for applied emission targets.

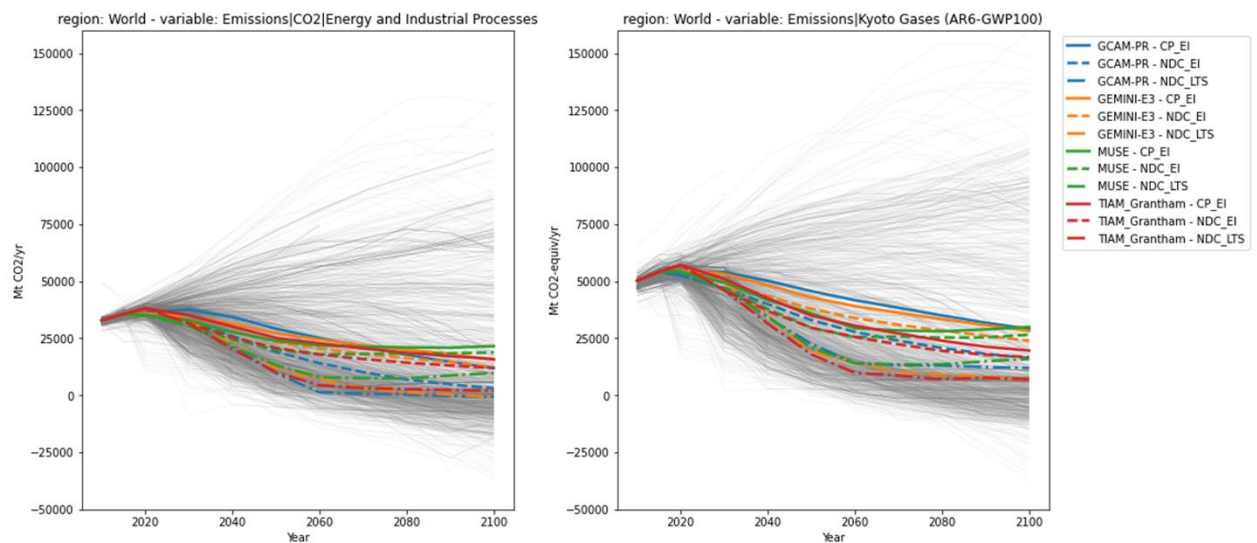
Supplementary table 1: Post-Glasgow updated NDC pledges to be applied in the second global modelling iteration.

Country	Target type*	New target value (lower value applied)	Base year	Target year	Relative to previous target
China	GDP Intensity	over 65% reduction	2005	2030	Improved target
India	GDP Intensity	40-45% reduction	2005	2030	Improved target
USA	Base year	50-52% reduction	2005	2030	Improved target
EU	Base year	55% reduction	1990	2030	Improved target
UK	Base year	68% reduction	1990	2030	Improved target
Norway	Base year	50-55% reduction	1990	2030	Improved target
Japan	Base year	46% reduction	2013	2030	Improved target
South Korea	Base year	40% reduction	2018	2030	Improved target
Canada	Base year	40-45% reduction	2005	2030	Improved target
Australia	Base year	43% reduction	2005	2030	Improved target
Argentina	BAU	39% reduction	2030	2030	Improved target
Chile	Cap	95 Mt CO ₂ eq		2030	Improved target (change from BAU to cap)
Colombia	BAU	51% reduction	2030	2030	Improved target
Equador	BAU	9-20.9% reduction	2025	2025	no target last iteration
Peru	BAU	30-40% reduction	2030	2030	Improved target
Indonesia	BAU	29.1-41.3% reduction	2030	2030	adapted (higher) BAU
Malaysia	GDP Intensity	45% reduction	2005	2030	Improved target
Singapore	Cap	65 Mt CO ₂ eq		2030	Improved target
Belarus	Base year	35% reduction	1990	2030	Improved target
Ukraine	Base year	65% reduction	1990	2030	Improved target
Viet Nam	BAU	9-27% reduction	2030	2030	adapted (higher) BAU

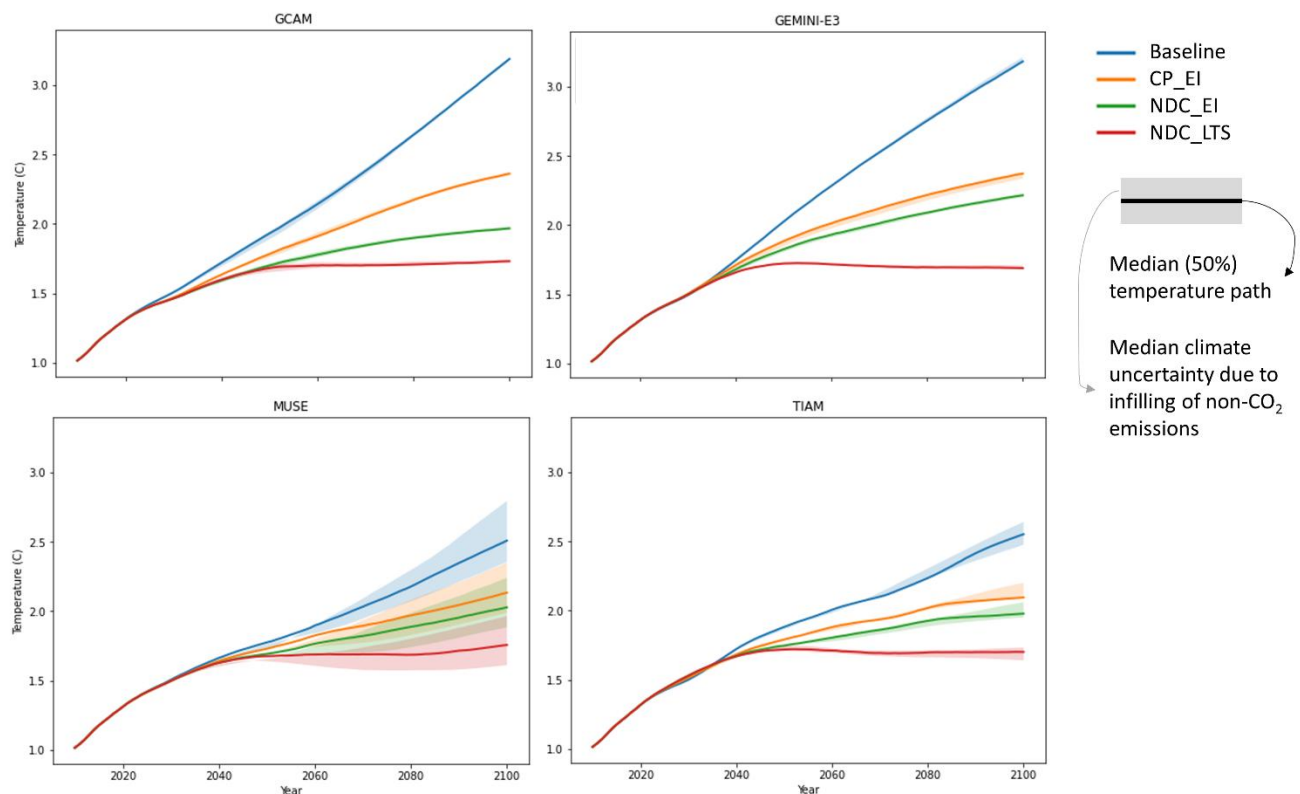
Supplementary table 2: Long-term emissions targets to be applied in the second global modelling iteration.

Country	Year	Target type	Target status	All GHG	Comment
USA	2050	Net-zero	In policy document	yes	
UK	2050	Net-zero	in law	yes	
Sweden	2045	Net-zero	in law	yes	
European union	2050	Net-zero	in law	yes	
Germany	2045	Net-zero	in law	yes	
India	2070	Net-zero	Gov. announcement		
China	2060	Carbon neutrality	In policy document		
Canada	2050	Net-zero	in law	yes	
Australia	2050	Net-zero	in policy document	yes	
New Zealand	2050	Net-zero	in law	yes	biogenic methane is excluded
Nigeria	2060	Net-zero	in law		
Saudi Arabia	2060	Net-zero	Gov. announcement		
Russian Federation	2060	Carbon neutrality	Gov. announcement		
South-Korea	2050	Net-zero	in law	yes	
Japan	2050	Net-zero	in law	yes	
Brazil	2050	Net-zero	In policy document		
South Africa	2050	Net-zero	In policy document		
Malawi	2050	Net-zero	In policy document		
Argentina	2050	Net-zero	Gov. announcement		
Chile	2050	Net-zero	In policy document	yes	Plans to reach net zero through domestic actions
Vietnam	2050	Net-zero	Gov. announcement		
Thailand	2065	Net-zero	Gov. announcement		carbon neutrality by 2050 and net zero emissions by 2065
Colombia	2050	Net-zero	Gov. announcement		
Kazakhstan	2060	Carbon neutrality			carbon neutrality
Turkey	2053	Net-zero	Gov. announcement		
Italy	2050	Net-zero	Gov. announcement		
UAE	2050	Net-zero	Gov. announcement	no	only co2 is covered
Switzerland	2050	Net-zero	In policy document		
Denmark	2050	Net-zero	in law	yes	
Peru	2050	Net-zero	Gov. announcement		
France	2050	Net-zero	in law	yes	
Norway	2050	90-95% reduction			
Mexico	2050	50% below 2000 emissions			

Supplementary section 2: Additional figures on emission infilling for temperature assessment



Supplementary Figure 3: Emissions from Fossil CO₂ (left) and all Kyoto Gases (right) in our scenarios, plotted on top of results for all scenarios in the AR6 database².



Supplementary Figure 4: Median temperature pathways until 2100 for all models and scenarios in this study, and a no-policy baseline scenario for comparison. The shaded ranges reflect the uncertainty related with infilling the emission databases with unreported gases. See Methods section in manuscript for more details.

Supplementary section 3: Feasibility analysis details and sources

This section explains which thresholds are used and their sources or motivation, as well as which formulas are used to quantify the measured feasibility concerns.

Carbon pricing

Putting a price on CO₂ emissions is traditionally the most common way in models to achieve mitigation. While the impact of carbon pricing on households depends largely on how the revenues are recycled, carbon pricing often faces societal opposition if the costs are too high or increase too fast relative to overall costs and incomes³. Therefore, to reflect a feasible cost path as the threshold for this indicator, we adapted the “medium concern” level from Brutschin et al (2021)⁴ of a global average price of 60 USD in 2020, increasing by 5% per annum. Since we perform the feasibility analysis separately for each model region in this study, we adapted the thresholds value for each model region, based on the GDP per capita level relative to the global average GDP per capita level, and multiplied this with the global threshold carbon price level over time.

Supplementary Table 3: Carbon price threshold levels

Year	2020	2030	2040	2050
Global average Carbon price threshold (\$2020/tCO ₂)	60	98	159	259

Final energy consumption

Traditionally, consumers continually increase their demand for energy services due to increasing incomes and technological growth providing new products and services⁵. While end-use efficiency of energy services also tends to increase over time, the balance in terms of final energy demand relies on how fast demand for energy services grows relative to how fast end-use efficiency improves. However, end-use efficiency is often also a factor, which by itself increases demand due to lower energy service prices, known as the Jevons paradox⁶. In recent literature on climate change mitigation, the reliance on voluntary consumer demand reductions through changes in lifestyles is becoming increasingly important⁷. Nevertheless, the extent to which societies can reduce demand based on voluntary lifestyle changes is not endless, and involuntary reductions in final energy demand through policies or pricing will likely face societal opposition, similarly as carbon prices⁸. We, therefore, apply the same “medium concern” threshold level as in Brutschin et al (2021)⁴ of 10% per capita energy demand decline per decade, separately for the three different end-use sectors: industry, buildings, and transport. However, in order to isolate the effect to only end-use efficiency and reduced end-use consumption, we cancel out the efficiency effects that could be the result of fuel switching in end-use sectors by using fuel- and sector-specific multipliers for each energy carrier (see Table 4 in Bertram et al 2021⁹).

Technology scale-up

Climate change mitigation typically depends largely on renewable or low-carbon technologies replacing carbon-intensive technologies throughout all sectors. However, the extent to which clean technologies can ramp up from relatively small shares of the current energy mix towards dominating

the energy mix by 2050, depends largely on how fast such technologies can ramp up¹⁰. In scenarios with increasing demand for energy, ramp up capacity even needs to be higher.

Power technology scale-up: For power technologies, we measure feasibility by the increasing share of a low-carbon technology in the entire power mix in a certain model region during one decade. To also cover the effect of scale, we then multiply the increase in a technology share by the total amount of electricity production. Hence, the required ramp-up for a technology to increase from 10 to 20% of the power mix would need to be double if electricity production also doubles in that same decade. We selected thresholds for power technology scale-up that are largely similar to the “medium concern” thresholds in Brutschin et al (2021)⁴. These thresholds are 10% for emerging technologies such as wind, solar, hydro, and ocean, and 5% for more conventional low-carbon technologies such as biomass and nuclear, as well as for thermal technologies with CCS (see Supplementary Table 4). This value of 5% for biomass and CCS technologies is higher than the “medium concern” value in Brutschin et al (2021)⁴ (2%) because, in their estimate, physical limitations of biomass production and carbon storage are taken into account, while we treat these limitations separately in other feasibility indicators.

Energy demand sector technology scale-up: For the three energy demand sectors (industry, buildings, and transport), we apply the same logic of how the thresholds affects feasibility—i.e., as the percentage increase in share of a low-carbon technology in the final energy mix of that specific sector. However, we do not take the scale effect into account, because total final energy use in many cases may drop in time due to a transition towards electricity use, which is generally more efficient than thermal technologies. However, a shift from thermal to electric technologies (e.g., from an internal combustion to an electric vehicle for passenger transport) does usually not imply a reduction in technology use (e.g., number of cars), but a reduction of energy use from the same number of end-use technologies (e.g., higher efficiency of cars). Hence, the scale effect cannot be taken into account so straightforwardly in energy demand sectors. We apply the same “medium-concern” threshold level in all sectors as used in the final energy indicators in the transport sector by Brutschin et al (2021)⁴, which is 10% for each low-carbon end-use technology (based on electricity, hydrogen, or bioenergy) (see Supplementary Table 4).

Supplementary Table 4: Technology scale-up threshold levels

Technology category	Threshold level for decadal surge in power/final-energy mix
Thermal power technologies (Biomass with/without CCS, Gas/Coal with CCS, Nuclear, Geothermal)	5
Non-thermal power technologies (Hydro, Solar, Wind, Ocean)	10
Transport fuel technologies (Electricity, Hydrogen, Bioliquids, Biogas)	10
Industry fuel technologies (Electricity, Hydrogen, Solid biomass, Bioliquids, Biogas)	10
Building fuel technologies (Electricity, Hydrogen, Solid biomass, Biogas)	10

Bioenergy supply

The global supply of bioenergy is constrained by various factors, ranging from hard limits such as land availability to soft limits such as biodiversity impacts and ecosystem functioning¹¹. The traditional best-practice method for bioenergy production is through waste streams and by-products from forestry and agricultural practices, as—contrary to purpose-grown bioenergy resources—using

waste streams avoids the competition with other land uses as well as other sustainability aspects¹². Therefore, in this study, we applied regional physical potentials for bioenergy production under sustainable conditions, separately for forestry¹³ and agriculture¹⁴. Considering minimal use of purpose-grown biomass and ensuring biodiversity production, these studies show potential global supplies of ~50 EJ and ~105 EJ by 2050 for, respectively, forestry and agriculture (see Supplementary Table 5). We add up these regional potentials and treat these as feasibility thresholds and assume the total threshold will increase linearly from consumed levels in 2020 to these potentials in 2050. While, in reality, the majority of bioenergy resources are consumed in the same region that are produced, some trade flows exist, and future bioenergy trade could increase with higher reliance on bioenergy¹⁵. Therefore, we apply a multiplier to the regionally identified feasibility concern levels, based on global bioenergy consumption relative to the global threshold level. This multiplier reflects that, if bioenergy demand in one region exceeds its sustainable supply, but globally there is still a significant amount of untapped sustainable supply, the feasibility concern will be corrected downwards. Conversely, if global bioenergy demand also exceeds the global threshold, regional feasibility concerns are corrected upwards.

Supplementary Table 5: Bioenergy threshold levels by aggregate region

	Sustainable bioenergy supply by 2050 (EJ)			Consumption in 2020
	Forest residues	Agriculture (residues and marginal land)	Total	
	(Lauri et al., 2014) ¹³	(Wu et al., 2019) ¹⁴		(IEA 2022) ¹⁶
Europe	3.7	9.9	13.6	7.7
Africa	9.2	24.0	33.2	16.0
Asia	11.8	23.7	35.5	21.3
Russia	2.6	7.9	10.5	0.5
North-America	6.6	15.5	22.1	5.5
South-America	16.2	24.0	40.2	6.0
Global	50.1	105.0	155.1	57.0

Carbon storage

Mitigation scenarios in IAMs often rely on the concept of geological carbon storage, which is a potential to store captured CO₂ emissions in geological structures for centuries or millennia in order to avoid these reaching the atmosphere and contributing to climate change¹⁷. Apart from storage, there are also several technologies for carbon usage¹⁸. Currently, enhanced oil recovery is the most common way of carbon use and storage¹⁹. Since oil and gas fields are commonly included in potential storage sites for carbon capture and storage, we do not focus on carbon use technologies beyond enhanced oil recovery. While the traditionally reported potentials for carbon storage are large, the technology suffers from technical, economic, financial, political, and societal issues²⁰, complicating the definition of realistic regional threshold values. For the analysis to stay as scientifically sound as possible, we use estimates from a relatively recent assessment of carbon storage potentials by country, which also looks at the economics of implementation taking into account geographical differences between CO₂ sources and storage areas as well as the economics of carbon storage¹⁹. For each region, we identify the potential storage capacity separately in oil and gas basins and saline aquifers. Given that oil and gas basins tend to be closer to emission source points and that storage is more economic due to the combination with enhanced oil recovery, we translate these complexities to a rule of thumb assuming 75% of oil and gas basins could ultimately

be used, and 25% of saline aquifers. This translates in a total global capacity of 214 Gt CO₂ (see Supplementary Table 6) for cumulative carbon storage. As with the bioenergy supply feasibility assessment, we assume that this level of storage needs to build up towards 2050, and so we apply a linear path from zero in 2010 to the full potential in 2050, separately for each region. If the accumulated amount of stored carbon surpasses the assumed feasible constraint in a given region and year, this will translate into feasibility concerns. Like with bioenergy, regional feasibility concerns are multiplied with the global demand for carbon storage relative to the global feasible potential to reflect possibilities to store CO₂ in foreign storage locations nearby borders.

Supplementary Table 6: Carbon storage threshold levels by region

	Storage potential (Gt CO ₂)		
	Oil & Gas fields	Saline Aquifers	Total adjusted *
	Wei et al (2021) ¹⁹		
Africa	4.0	54.1	16.5
Oceania	5.0	34.0	12.3
Canada	4.0	24.0	9.0
China	6.0	36.0	13.5
Central and South Asia	5.3	54.1	17.5
Europe	7.0	26.0	11.8
Former Soviet Union	14.0	65.0	26.8
India	1.1	27.1	7.6
Japan	0.1	2.7	0.8
Middle East	39.6	27.1	36.4
Mexico	5.0	16.0	7.8
Other Developing Asia	9.7	54.1	20.8
South Korea	0.1	1.6	0.5
USA	31.0	38.0	32.8
World	132.0	459.8	213.9
* A rule of thumb is applied, assuming the economic availability of 75% of oil and gas basin storage, and 25% of saline aquifer basin storage (see text)			

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