ESA-8

Energy and Emissions Scenarios

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Energy Systems Analysis
Scenarios:

• Provide a framework for decision making
• Help understand the possible impact of alternative courses of action
• Facilitate the interpretation of possible future states (back-casting)
• Include elements that cannot be formally modeled
• Aimed at challenging prevailing mind sets
Energy and Emissions Scenarios

- Shell Scenario Group – Corporate Planning
- IIASA – 1981, IIASA-WEC, IPCC SRES, SSPs
- IPCC – 1990, IS92, SRES, TAR, AR4, AR5
- WEC – EFTW, IIASA-WEC, EFTWII
- GEA – Global Energy Assessment
- IEA – World Energy Outlook
- UN – World Energy Assessment
- US Energy Information Agency
- EU – World ETC Policy Outlook
- Greenpeace – Energy Revolution
- World Ecosystems Assessment

Energy Systems Analysis
Energy and Emissions Scenarios

- Shell Scenario Group – Corporate Planning
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- IPCC – 1990, IS92, SRES, TAR, AR4, AR5
- WEC – EFTW, IIASA-WEC, EFTWII
- GEA – Global Energy Assessment
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- EU – World ETC Policy Outlook
- Greenpeace – Energy Revolution
- World Ecosystems Assessment
- Energy Systems Analysis
Global Primary Energy
Range Across Emissions Scenarios

Nakicenovic et al.
IIASA 1998
Carbon Dioxide Emissions
Total All Sources

Nakicenovic et al. IIASA 1998
Incomes in the OECD are still four times higher than in rest of the world in 2030.
Reference Scenario: World Primary Energy Demand

Global demand grows by more than half over the next quarter of a century, with coal use rising most in absolute terms.
World oil demand grows by just over half between 2004 and 2030, with 70% of the increase coming from developing countries.
Half of the projected increase in emissions comes from new power stations, mainly using coal & mainly located in China & India.
China overtakes the US as the world’s biggest emitter before 2010, though its per capita emissions reach just 60% of those of the OECD in 2030.
The impact of new policies – though far from negligible – is less marked in the period to 2015 because of the slow pace of capital stock turnover.
Improved end-use efficiency of electricity & fossil fuels accounts for two-thirds of avoided emissions in 2030.
Proximate and Ultimate Drivers

**Proximate Drivers**
- Population
- Economy
- Technology
- Governance

**Ultimate Drivers**
- Values and Needs
- Knowledge and Understanding
- Power Structure
- Culture

Source: Paul Raskin, 2002
Dimensions of Transition

Source: Paul Raskin, 2002
Alternative Scenario Formulations

Energy Systems Analysis

Source: IPCC SRES, 2000
IPCC Special Report

IPCC Emissions Scenarios
- Extensive literature review
- Four narrative storylines
- Six modeling frameworks
- Forty emissions scenarios
- Six illustrative scenarios
SRES Scenarios

A1
Economy
Technology
Energy
Agriculture
(Land-use)

A2

B1
Global

B2
Regional

Environmental

Driving Forces

Nakicenovic et al.

SRES 2000
Global Population Projections

World Population (SRES, n=40) (pre SRES, n=62)

- **pre SRES range**

- **SRES**

- **pre SRES**

Energy Systems Analysis
Global Population Projections

World Population (post SRES, non intervention, n=64)

- post SRES, non intervention range
- Median

Energy Systems Analysis
World Economic Map
Areas of Regions Proportional to 1990 GDP (mer)

DCs = 16% of world GDP(mer); 35% of world GDP (ppp)

Energy Systems Analysis
World Economic Map
Areas of Regions Proportional to 1990 GDP

Energy Systems Analysis
Area of Regions Proportional to 1990 GDP\textsubscript{mer}

World Economic Map

Energy Systems Analysis
Per Capita Income Across SRES Scenarios

Industrialized countries (Annex-I)

Developing countries (non-Annex-I)

Income ratio:

PPP: 4
MER: 16

1990
A2
B2
B1
A1

1000 US$(90) per capita
Global Primary Energy Scenarios
Evolution of Global Primary Energy

Energy Systems Analysis
Energy Systems Analysis
Global Carbon Dioxide Emissions

Energy Systems Analysis
Night Lights

Energy Systems Analysis

2000
Surface Temperature

A1B, 2090-2099 relative to 1980-1999

Source: IPCC-AR4, 2007
Water Availability (Runoff)

A1B, 2090-2099 relative to 1980-1999
GLOBAL LAND-USE CARBON EMISSIONS

IIASA SRES 2000
GLOBAL SULFUR EMISSIONS

- Total database range
- Range of sulfur-control scenarios in the database
- Maximum in database
- Minimum in database
- 1990 range

IIASA SRES 2000
The Composition of the Atmosphere is Projected to Change Causing an Increase in Temperature and Sea Level
GHG Gases:

- Warming potentials
- Residence times
- Concentrations
- Radiative forcing
<table>
<thead>
<tr>
<th></th>
<th>$\text{H}_2\text{O}$</th>
<th>$\text{CO}_2$</th>
<th>$\text{CH}_4$</th>
<th>$\text{N}_2\text{O}$</th>
<th>CFC-11</th>
<th>CFC-12</th>
<th>$\text{O}_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residence time years</td>
<td>short</td>
<td>5-200</td>
<td>12</td>
<td>114</td>
<td>45—130</td>
<td></td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>100 year GWP (note caveats!)</td>
<td>?</td>
<td>1</td>
<td>23</td>
<td>296</td>
<td>4600—10600</td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>% contribution to</td>
<td>70%</td>
<td>23%</td>
<td>2%</td>
<td>2%</td>
<td>0</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>natural greenhouse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>effect (30°K)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthropogenic</td>
<td>??</td>
<td>60%</td>
<td>20%</td>
<td>6%</td>
<td>14%</td>
<td></td>
<td>??</td>
</tr>
<tr>
<td>since 1750 (2°K)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration in 1800</td>
<td>3000 ppm</td>
<td>280 ppm</td>
<td>.7 ppm</td>
<td>.270 ppb</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration in 2000</td>
<td>3000 ppm</td>
<td>370 ppm</td>
<td>1.75 ppm</td>
<td>.314 ppb</td>
<td>268—533 ppt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase, absolute</td>
<td>???</td>
<td>1.5 ppm</td>
<td>0.007 ppm</td>
<td>0.8 ppb</td>
<td>-1.4—4.4 ppt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase, %</td>
<td>???</td>
<td>0.4%</td>
<td>0.4% (~0% currently)</td>
<td>0.25%</td>
<td>-0.15%—0.8%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source IPCC TAR WG I TS:38 and Ch 4:244
SRES RADIATIVE FORCING
ALL DIRECT AND INDIRECT GHGs

Radiative Forcing, W/m²

Total SRES range

1990 2010 2030 2050 2070 2090

SRES range

A1FI
A2
A1B
IS92a
B2
A1T
B1

IIASA 2000
CO2-eq. Emissions and Temperature Change
Scenarios without additional climate policy

Source: IPCC-AR4, 2007
Impacts & Temperature Change

**Impacts vary by:**
- Extend of adaptation
- Rate of T-change
- Socio-economic pathway (vulnerability)

**Source:**
IPCC-AR4, 2007
Climate Change Impacts on Cereal Production Potential of Food Insecure Countries 2080s

Fischer et al., IIASA, 2001
Climate Change Impacts on Cereal Production Potential of Food Insecure Countries 2080s

ECHAM4

HadCM2

CGCM1

Fischer et al., IIASA, 2001
## Climate Change Impacts on Agriculture vs. Adaptation (R&D) Capacity

<table>
<thead>
<tr>
<th>Region</th>
<th>Climate Sensitivity* % change in cereals</th>
<th>Adaptive Capacity Agricultural R&amp;D $10^9$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>public</td>
</tr>
<tr>
<td>INDUSTRIAL</td>
<td>+11</td>
<td>6.9</td>
</tr>
<tr>
<td>Latin America</td>
<td>-23</td>
<td>1.0</td>
</tr>
<tr>
<td>Africa</td>
<td>-13</td>
<td>1.0</td>
</tr>
<tr>
<td>Asia</td>
<td>-2</td>
<td>6.1</td>
</tr>
<tr>
<td>DEVELOPING</td>
<td>-11</td>
<td>8.0</td>
</tr>
</tbody>
</table>

* Estimate for a temperature change of 1-3 °C and rainfall change of 0-10%

Stabilization of the Atmospheric Concentration of CO$_2$ Requires Significant Emissions Reductions
Carbon dioxide concentration, temperature, and sea level continue to rise long after emissions are reduced.
High versus Low Stabilization

Metz, Hare and Riahi, 2006
Without more mitigation, global mean surface temperature might increase by 3.7° to 4.8°C over the 21st century.

Lowest scenarios “likely” to stay below 2°C

IPCC AR5, 2014
Achieving low levels of temperature change requires to limit cumulative CO₂ emissions

Emissions budget for 2C is about 600-1200 GtCO₂ (historical emissions are about 1850 GtCO₂)

IPCC AR5, 2014
Major advancement since AR4: Probabilistic interpretation of the scenario literature

Unlikely to stay below 2°C

Likely to stay below 2°C

IPCC AR5, 2014
Relationship between global GHG emissions and the likelihood of different temperature targets

<table>
<thead>
<tr>
<th><strong>CO₂eq Concentrations in 2100 (CO₂eq)</strong></th>
<th><strong>Category label (concentration range)</strong></th>
<th><strong>Subcategories</strong></th>
<th><strong>Cumulative CO₂ emission</strong>&lt;sup&gt;3&lt;/sup&gt; (GtCO₂)</th>
<th><strong>Change in CO₂eq emissions compared to 2010 in (%)</strong></th>
<th><strong>Temperature change (relative to 1850–1900)</strong>&lt;sup&gt;5,6&lt;/sup&gt;</th>
<th><strong>Likelihood of staying below temperature level over the 21st century</strong>&lt;sup&gt;8&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 430</td>
<td>Total range&lt;sup&gt;1,9&lt;/sup&gt;</td>
<td>630–1180</td>
<td>-72 to -41</td>
<td>-118 to -78</td>
<td>Likely</td>
<td>More unlikely than likely</td>
</tr>
<tr>
<td>450 (430–480)</td>
<td>Total range&lt;sup&gt;1,9&lt;/sup&gt;</td>
<td>960–1430</td>
<td>-57 to -42</td>
<td>-107 to -73</td>
<td>Unlikely</td>
<td>More likely than not</td>
</tr>
<tr>
<td>500 (480–530)</td>
<td>No overshoot of 530 ppm CO₂eq</td>
<td>990–1550</td>
<td>-55 to -25</td>
<td>-114 to -90</td>
<td>Likely</td>
<td>About as likely as not</td>
</tr>
<tr>
<td>550 (530–580)</td>
<td>Overshoot of 530 ppm CO₂eq</td>
<td>1240–2240</td>
<td>-47 to -19</td>
<td>-81 to -59</td>
<td>Likely</td>
<td>Likely</td>
</tr>
<tr>
<td>(580–650)</td>
<td>No overshoot of 580 ppm CO₂eq</td>
<td>1170–2100</td>
<td>-16 to 7</td>
<td>-183 to -86</td>
<td>Likely</td>
<td>Likely</td>
</tr>
<tr>
<td>(650–720)</td>
<td>Overshoot of 580 ppm CO₂eq</td>
<td>1870–2440</td>
<td>-38 to 24</td>
<td>-134 to -50</td>
<td>Likely</td>
<td>Likely</td>
</tr>
<tr>
<td>(720–1000)</td>
<td>Total range</td>
<td>2570–3340</td>
<td>-11 to 17</td>
<td>-54 to -21</td>
<td>Unlikely</td>
<td>Unlikely</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>Total range</td>
<td>3620–4990</td>
<td>18 to 54</td>
<td>-7 to 72</td>
<td>Unlikely</td>
<td>More unlikely than likely</td>
</tr>
<tr>
<td></td>
<td>Total range</td>
<td>5350–7010</td>
<td>52 to 95</td>
<td>74 to 178</td>
<td>Unlikely</td>
<td>More unlikely than likely</td>
</tr>
</tbody>
</table>

Only a limited number of individual model studies have explored levels below 420 ppm CO₂eq

**IPCC AR5, 2014**
Mitigation requires major technological and institutional changes including the upscaling of low- and zero carbon energy

“As likely as not” 2C

“Likely” 2C

IPCC AR5, 2014
Stabilization and Emissions Peak

Stabilization class (CO$_2$-eq. concentration range)

- E (853-1129)
- D (708-853)
- C (587-708)
- B (535-587)
- A1 (487-535)
- A2 (444-487)

Peak of CO$_2$ emissions (year)

Source: IPCC-Ar4, 2007
Stabilization and Emissions Reductions

Source: IPCC-Ar4, 2007
Global costs rise with the ambition of the mitigation goal.
Availability of technology greatly influence mitigation costs.

IPCC AR5, 2014
Mitigation costs can differ significantly across regions.

Scenarios show substantial global financial flows between regions under alternative burden sharing schemes.

IPCC AR5, 2014
Acceleration of energy system change

(a) Ranges of rates of energy-intensity change in different mitigation scenarios provided by different models and model runs for 1990-2100

Long-term annual average rates of energy-intensity improvement (%)

2.5
2.0
1.5
1.0
0.5
0

HISTORICALLY ACHIEVED LEVELS

Emission stabilization levels (in ppm)

450 550 650 750

(b) Ranges of rates of carbon-intensity change in different mitigation scenarios provided by different models and model runs for 1990-2100

Long-term annual average rates of carbon-intensity improvement (%)

3.5
3.0
2.5
2.0
1.5
1.0
0.5
0

HISTORICALLY ACHIEVED LEVELS

Emission stabilization levels (in ppm)

450 550 650 750
World GHG Emissions
IIASA A2r Scenario

Annual GHG emissions (GtC equiv)

Emissions without climate policy

Baseline “Mitigation”

Energy Systems Analysis
World GHG Emissions
IIASA A2r Scenario

Energy Systems Analysis
World GHG Emissions
IIASA B1 Scenario

Annual GHG emissions (GtC equiv)

Baseline "Mitigation"
World GHG Emissions
IIASA B1 Scenario

Baseline
"Mitigation"

Energy Systems Analysis
Energy Systems Analysis

ENERGY SYSTEMS COSTS OF ALTERNATIVE BASELINES AND STABILIZATION SCENARIOS

Cumulative Discounted System Costs (1990-2100), [trillion US$]

Cumulative CO$_2$ Emissions [GtC]

450ppmv CO$_2$ stabilization

- A1C
- A1G
- A1B
- A1T

Baselines

450ppmv
550ppmv
650ppmv
750ppmv
Efficiency & Demand-side Focus (= high flexibility for supply)

- Energy savings (efficiency, conservation, and behavior)
- ~50% renewables by 2050
- Phase-out of oil in the long term (necessary)
- No expansion of nuclear (choice)
- Fossil CCS (optional bridging technology)
- Bio-CCS & negative emissions (long-term)
Supply-side Focus
(= high demand-side flexibility)

Rapid up-scaling of all supply options including renewables, nuclear and CCS

Modest efficiency focus

CCS mandatory at high demand
Global Final Energy Demand

Industry:
1. Retrofit of existing plants
2. Best available technology for new investments
3. Optimization of energy & material flows
4. Lifecycle product design & enhanced recycling
5. Electrification incl. switch to renewable energy

Residential:
1. Rapid introduction of strict building codes
2. Accelerate retrofit rate to 3% of stock per year (x 4 improvement by 2050)
3. Improved electrical appliances

Transport:
1. Technology efficiency (50%)
2. Reduced private mobility (e.g., urban planning)
3. Infrastructure for public transport + railway freight

Source: Riahi et al, 2011
Mitigation Options

- Demographic change
- Economic development
- Social behavior
- Efficiency Improvements
- Low carbon intensity
- Zero carbon (solar, nuclear)
- Carbon removal
- End deforestation
- Sink enhancements
- Non-CO2 Options (mostly non-energy)
- “geo-engineering”
RENEWABLES

Hoffert et al., Science, 2002
Existing and Planned Projects

- Sleipner Project, saline formation, North Sea
- Weyburn, EOR, Saskatuan, Canada
- In Salah, gas reservoir, Algeria (development)
- Snohvit, off-shore saline formation, North Sea
- Gorgon, saline formation, Australia (planning)

Source: Sally Benson, 2003
Hydrogen Production Systems and CCS
“synergies between new technologies”

Negative emissions!!

- 30% of total CO$_2$
- CO$_2$ in flue gas
- 70% of total CO$_2$
- pure and dense stream

Feedstocks
(Natural Gas or Biomass)

Hydrogen Production Plant

CO$_2$

H$_2$

Pipeline

End-use application

CO$_2$

Separation System

Pipeline

CO$_2$ Disposal

Energy Systems Analysis
Home Refueling System Concept

- Home-size combined system, which provides Hydrogen to FCV as well as Electricity and Heat to household.
Hydrogen Vehicles
Area Occupied by Various Transport Modes

Source: WBCSD, 2005
Energy Systems Analysis

Source: EU, 2004
<table>
<thead>
<tr>
<th>WORLD</th>
<th>Energy Investments (billion $ per year)</th>
<th>Policy Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010 present</td>
<td>2010-2050</td>
</tr>
<tr>
<td>Efficiency</td>
<td>300$^{2}</td>
<td>300-800$^{3}</td>
</tr>
<tr>
<td>Nuclear</td>
<td>5-40$^{1}</td>
<td>5-210</td>
</tr>
<tr>
<td>Renewables</td>
<td>190</td>
<td>260-1010</td>
</tr>
<tr>
<td>CCS</td>
<td>&lt;1</td>
<td>0-64</td>
</tr>
<tr>
<td>Infrastructure, including reliability$^{5}$</td>
<td>260</td>
<td>310-500</td>
</tr>
<tr>
<td>Access$^{6}$</td>
<td>n.a.</td>
<td>36-41</td>
</tr>
</tbody>
</table>
Strategies for Universal Energy Access by 2030

Present Situation - Investments and Benefits to 2030

Map (2010)
Future investments and health benefits by 2030
Health Benefits of Pollution Control

(loss of stat. life expectancy - PM)

Source: Dentener et al, 2009
The Key Energy Challenges

- Energy Access
- Climate Change
- Energy Security
- Air Pollution/Health Impacts
Policy Costs of Different Objectives

Integrated Climate-Pollution-Security Policies

Added costs of ES and PH are comparatively low when CC is taken as an entry point

All objectives fulfilled at Stringent level
At least one objective fulfilled at Intermediate level
At least one objective fulfilled at Weak level

Total Global Policy Costs (2010-2030)

CC – Climate Change
PH – Pollution & Health
ES – Energy Security

D. McCollum, V. Krey, K. Riahi (2011)
Development & Climate Change

YO! AMIGO!!
WE NEED THAT TREE
TO PROTECT US FROM
THE GREENHOUSE EFFECT!

Energy Systems Analysis
Environmental Change: Development vs. Climate

• More ecosystems will be destroyed by economic development than by the climate change that this development induces.

• Far more human lives are threatened by a lack of development than by any climate change resulting from a closure of the development gap.

• “business-as-usual” + climate control vs sustainability paradigm.
North -- South

- Responsibility: Mostly in Annex-I (but declining)
- Vulnerability: Mostly in “South” (but declining)
- Adaptation capacity: Mostly in Annex-I
- Future emission growth: Mostly in “South”

- Near-term mitigation potential: Highest in Annex-I (high emissions)
- Near-term mitigation costs: Lowest in “South” (high in-efficiency)

Energy Systems Analysis
Cumulative Carbon Emissions by Source and Region 1850-2005 (320 GtC)

Data source: http://cdiac.ornl.gov/products.html

Energy Systems Analysis
Per Capita GHGs by Region vs. Population in 2004
Source: IPCC AR4, 2007

Annex I:
Population 19.7%
GHGs: 47.7%

Non-Annex I:
Population 80.3%
GHGs: 52.3%

Average Annex I: 16.1 t CO₂eq/cap
Average non-Annex I: 4.2 t CO₂eq/cap
Kyoto-Protocol Objectives:

• All participants (states) together commit to reduce emissions compared to 1990 by 5.2% until 2012

• Parties have differentiated commitments considering projected economic growth
  – EU should reduce emissions by 8%
  – Russia (and other ETs) should keep emissions constant at 1990 level
  – No binding commitments for China, India and other developing countries

• The protocol was finalized 1997, and went into force 2005 as more than 55 states accounting for more than 55% of total emissions did ratify the protocol (due to Russia’s signature 65% or 141 countries had ratified at that time)

• Key players (e.g., US or Australia) did not ratify the protocol
The Copenhagen Accord → PARIS 2015

Copenhagen
December, 2009

✓ A goal …
   Staying below an increase of 2 degrees Celsius (1.5°C)

✓ A means to get there …
   Country pledges to control emissions (pegged to 2020 and 2030)

✓ Is there a gap between …
   What we are aiming for … Where we are heading?

Paris Agreement

- New voluntary country pledges
- Bottom-up
- (almost) all countries
Resulting Emissions of the Paris Agreement

Rogelj et al., 2016
Water
Impacts of climate change mitigation policy on thermal water pollution (energy-related)

Range of 2ºC scenarios

No climate policy

Fricko et al., 2016, Environmental Research Letters
Air Pollution and Health
Food & Hunger
Inclusive development & climate policies are key to reduce risk of hunger for simultaneous achievement of SDG 2 (hunger) and 13 (climate).
Food Security in 2050

Inclusive development & climate policies are key to reduce risk of hunger for simultaneous achievement of SDG 2 (hunger) and 13 (climate).

AIM/CGE model, Fujimori et al. (in preparation)
Inclusive development & climate policies are key to reduce risk of hunger for simultaneous achievement of SDG 2 (hunger) and 13 (climate).

AIM/CGE model, Fujimori et al. (in preparation)
Energy Transformation $\rightarrow$ SDGs

(preliminary: McCollum et al, forthcoming)

Synergies

Tradeoffs
Interest in Internships: riahi@iiasa.ac.at

Exam: 29 June, 2017