Interpreting Energy Technology & Policy Implications of Climate Stabilization Scenarios

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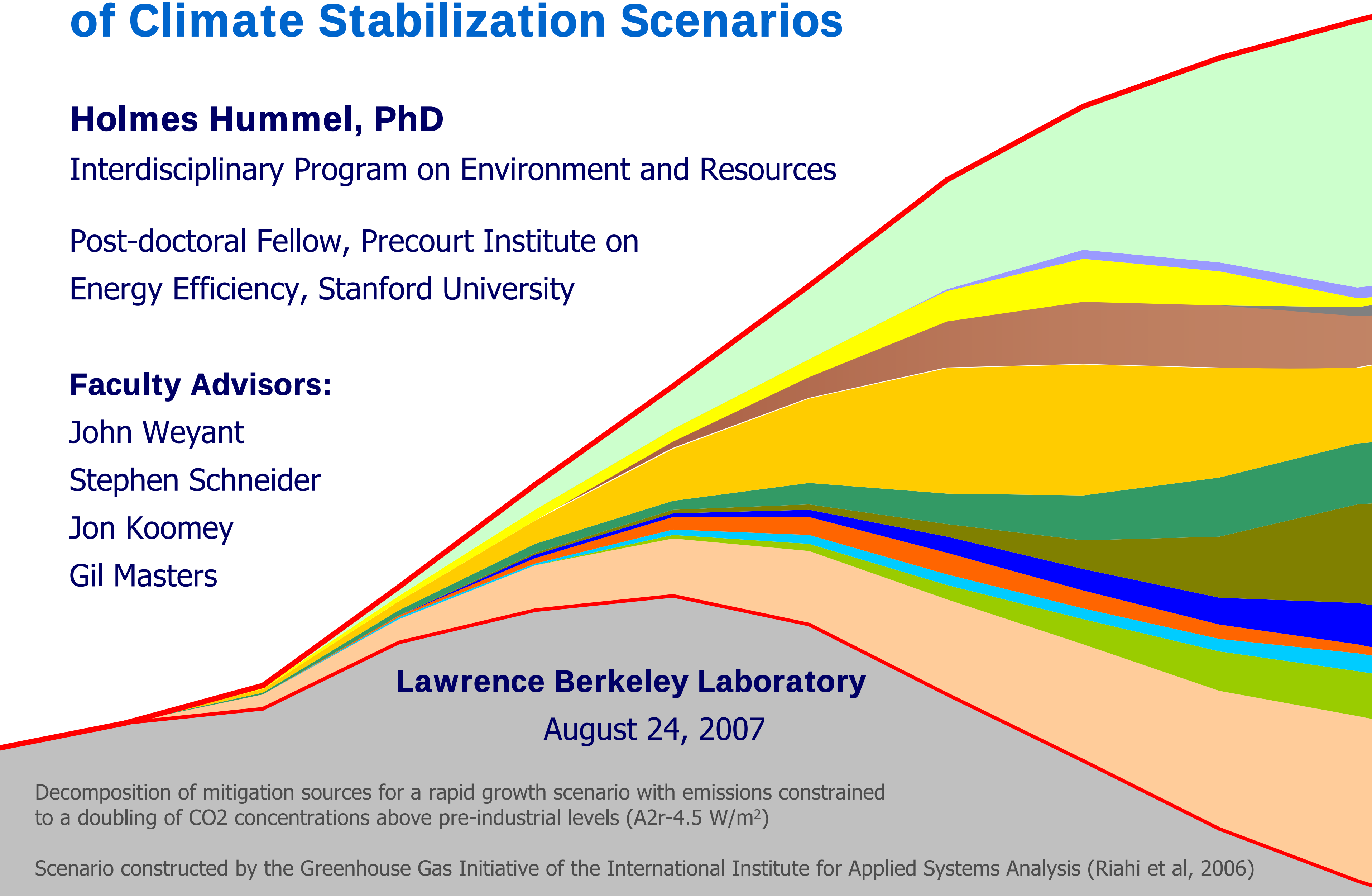
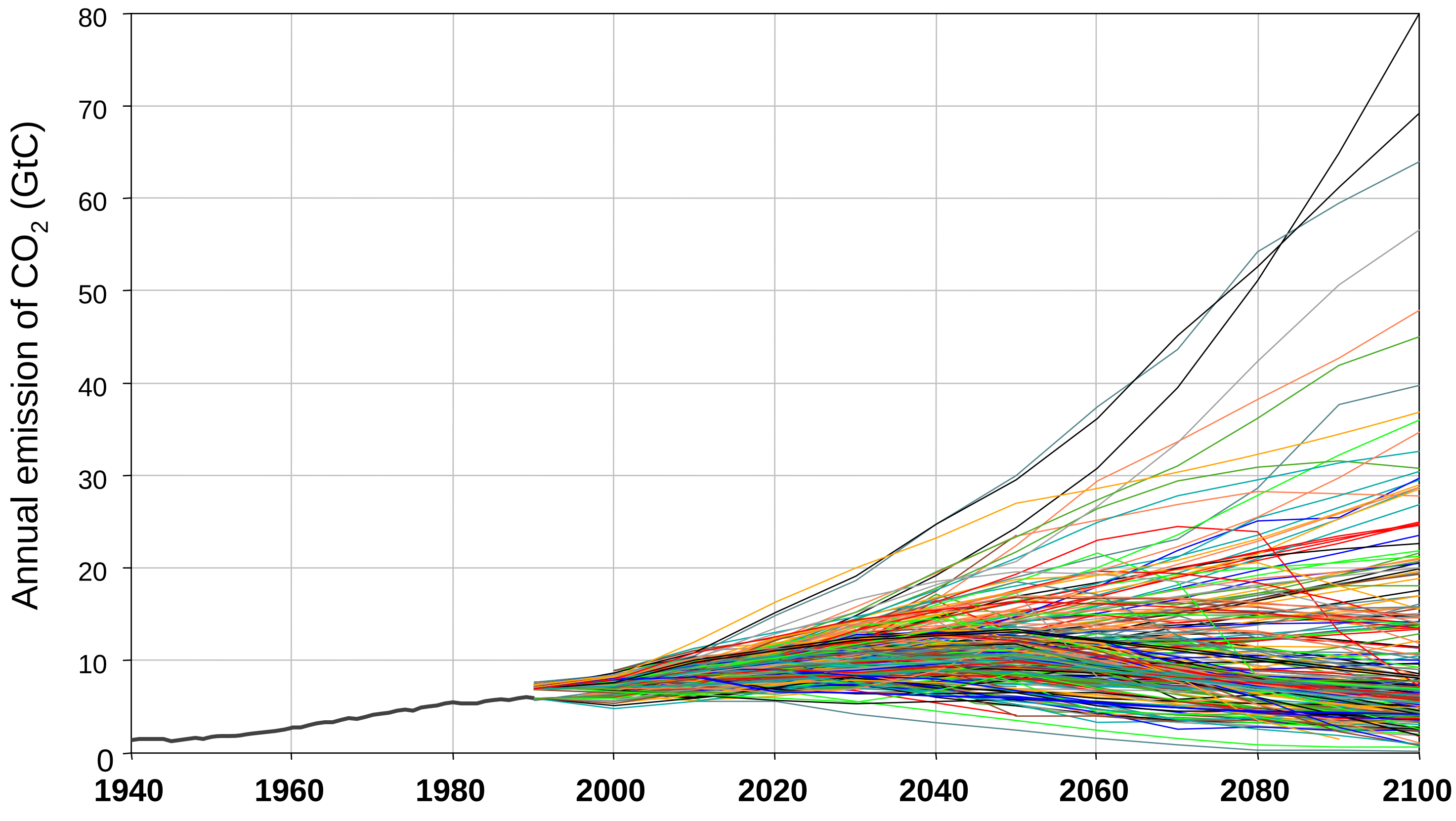


Decomposition of mitigation sources for a rapid growth scenario with emissions constrained to a doubling of CO_2 concentrations above pre-industrial levels (A2r-4.5 W/m^2)

Scenario constructed by the Greenhouse Gas Initiative of the International Institute for Applied Systems Analysis (Riahi et al, 2006)

Century-Scale Energy & Emissions Scenarios



Data: National Institute for Environmental Studies, Japan; Graph: International Institute for Applied Systems Analysis

What do they mean?

How do I know?

Does it make sense?

Exploring Energy Futures

model agnostic

- Constructing a common framework for interpretation
  - How do policy interventions affect key drivers of emissions?
  - What are the sources of mitigation in stabilization scenarios?
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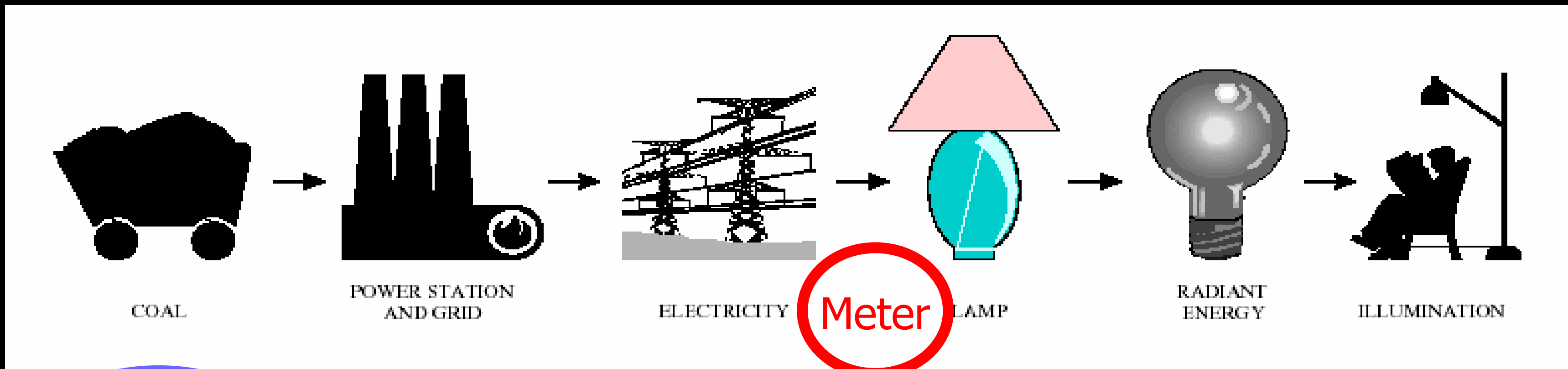
People · Average Income · Energy Intensity of Economy · Carbon Intensity of Energy · Carbon Emissions

$$\cancel{P} \cdot \frac{\cancel{GDP}}{\cancel{P}} \cdot \frac{\cancel{E}}{\cancel{GDP}} \cdot \frac{C}{\cancel{E}} = C$$

"Kaya Identity" *(Kaya, 1990)*



Primary Energy

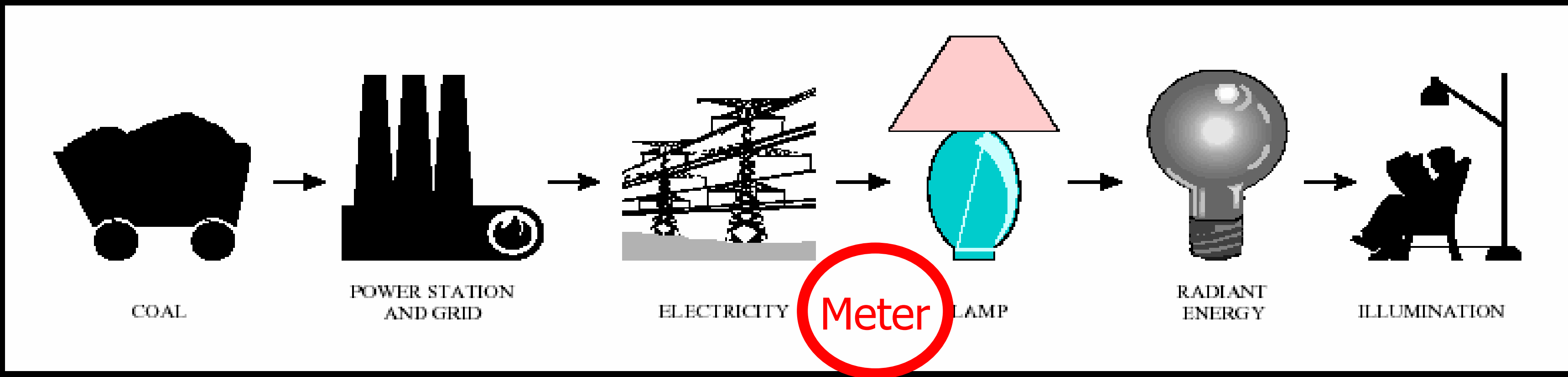
Final Energy

End Use

Energy Service

People · Average Income · Energy Intensity of Economy · Carbon Intensity of Energy = Carbon Emissions

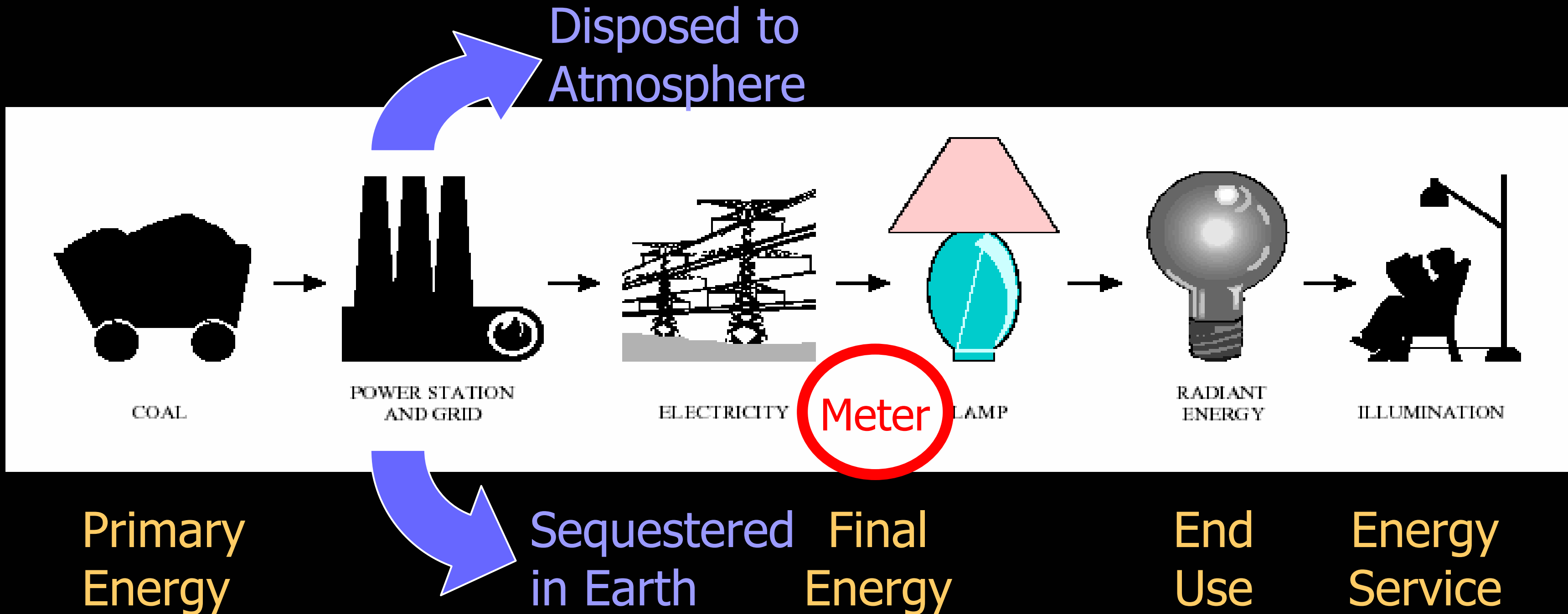
$$P \cdot \frac{GDP}{P} \cdot \frac{E}{GDP} \cdot \frac{C}{E} = C$$



Primary Energy — Final Energy — End Use — Energy Service

People · Average Income · Energy Intensity of Economy · Energy Supply Loss Factor · Carbon Intensity of Energy = Carbon Emissions

$$P \cdot \frac{GDP}{P} \cdot \frac{FE}{GDP} \cdot \frac{PE}{FE} \cdot \frac{C}{PE} = C$$

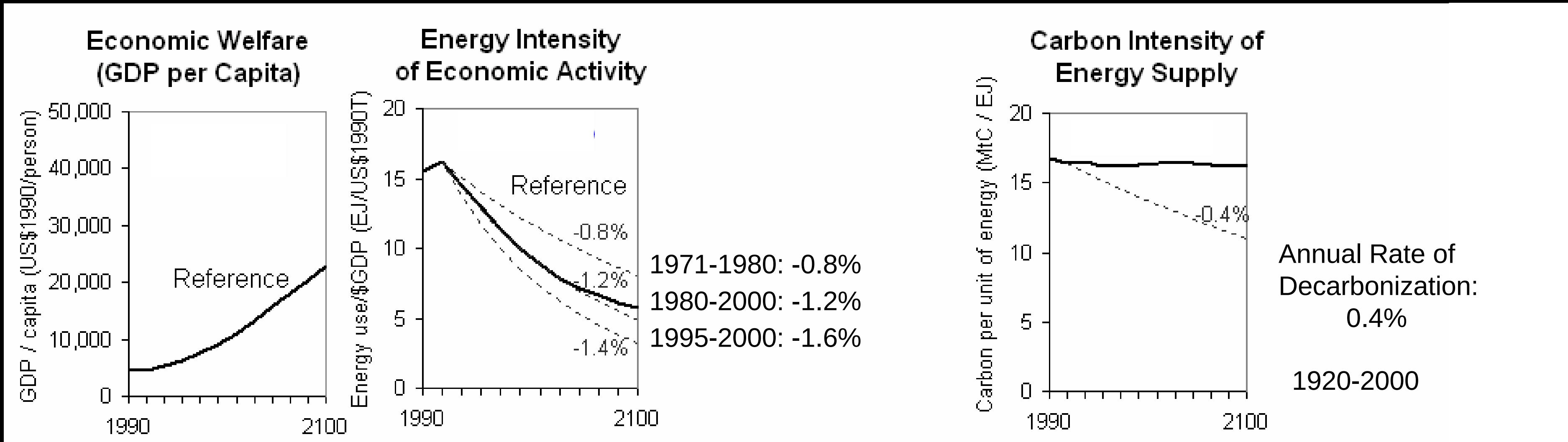


$$\overbrace{P}^{\text{People}} \cdot \overbrace{\frac{GDP}{P}}^{\text{Average Income}} \cdot \overbrace{\frac{FE}{GDP}}^{\text{Energy Intensity of Economy}} \cdot \overbrace{\frac{PE}{FE}}^{\text{Energy Supply Loss Factor}} \cdot \overbrace{\frac{TC}{PE}}^{\text{Carbon Intensity of Energy}} \cdot \overbrace{\frac{C}{TC}}^{\text{Fraction Disposed to Atmosphere}} = \overbrace{C}^{\text{Carbon Emissions}}$$

Total Carbon

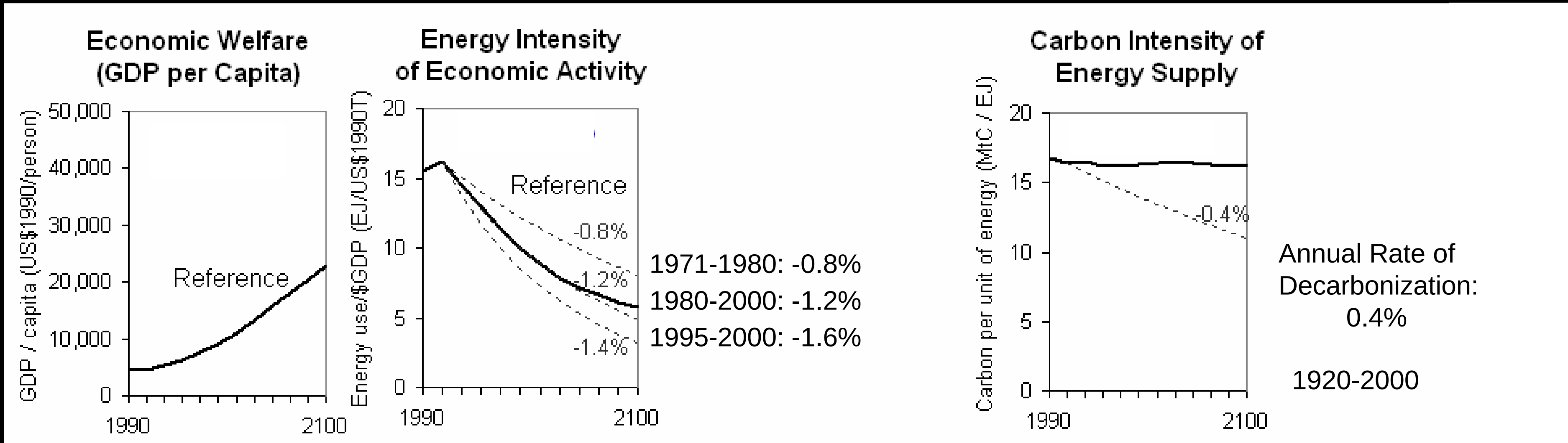
First, using the familiar Kaya Identity…

$$\frac{GDP}{P} \qquad \frac{PE}{GDP} \qquad \qquad \frac{C}{PE}$$

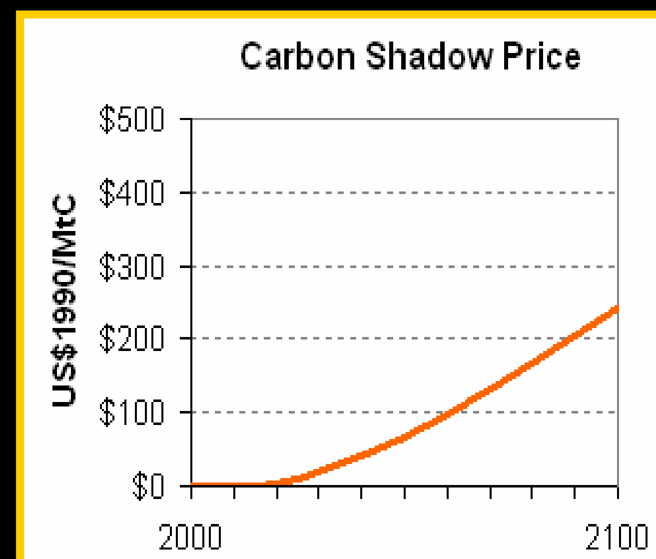


$$\frac{GDP}{P} \qquad \frac{PE}{GDP} \qquad \frac{C}{PE}$$

Reference: “Dynamics as Usual” (B2) Stabilization target: 550ppm CO2 Model: MiniCAM



$$\frac{GDP}{P} \qquad \frac{PE}{GDP} \qquad \frac{C}{PE}$$



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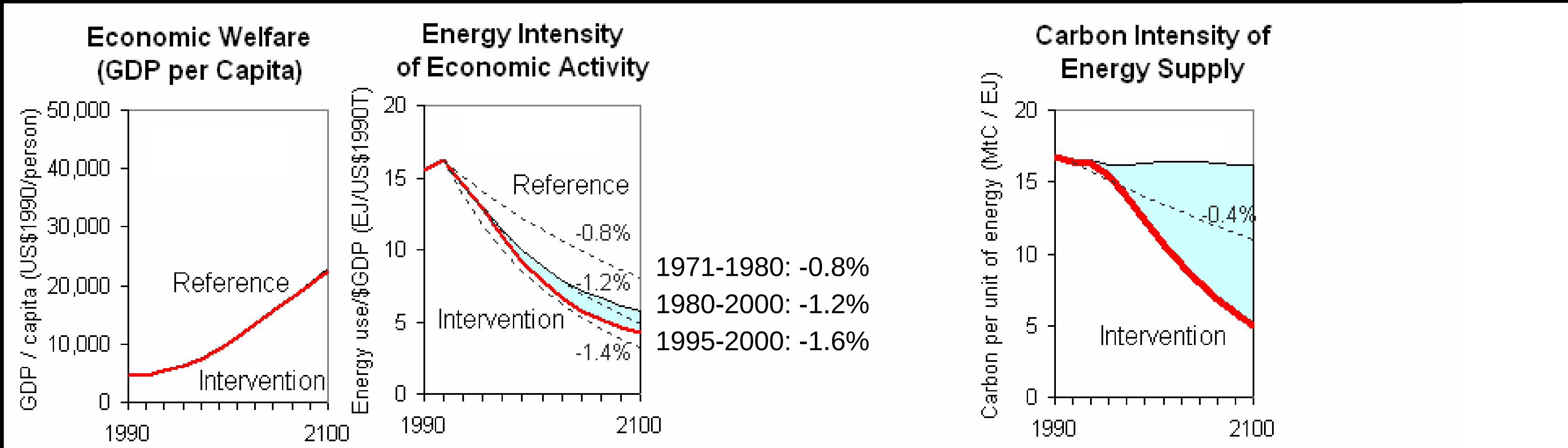

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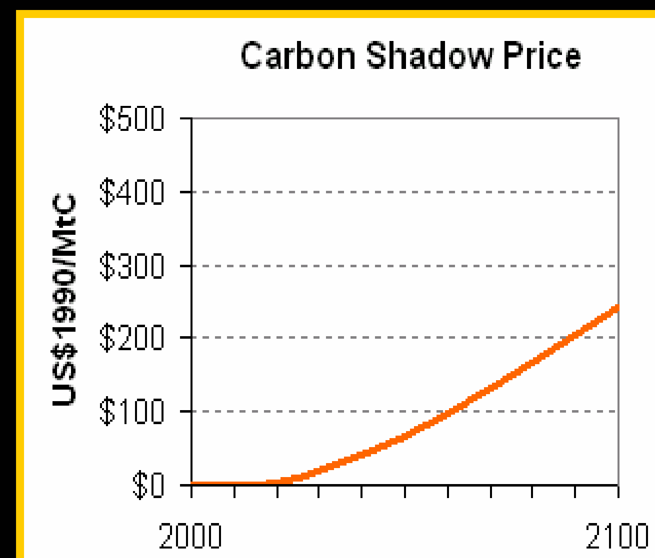

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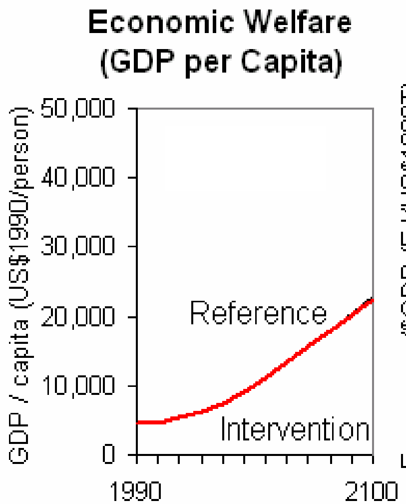
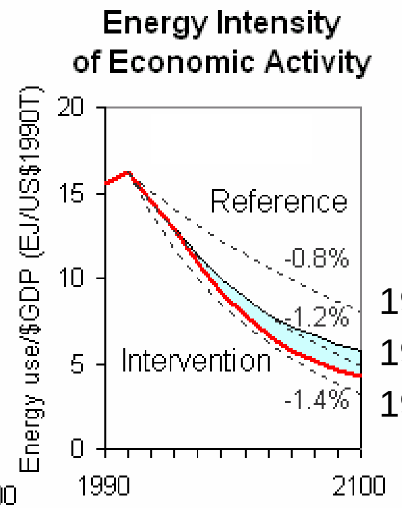
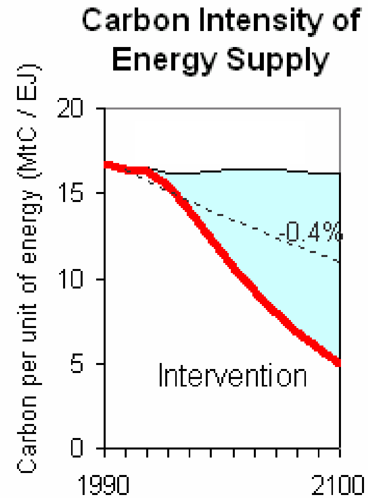




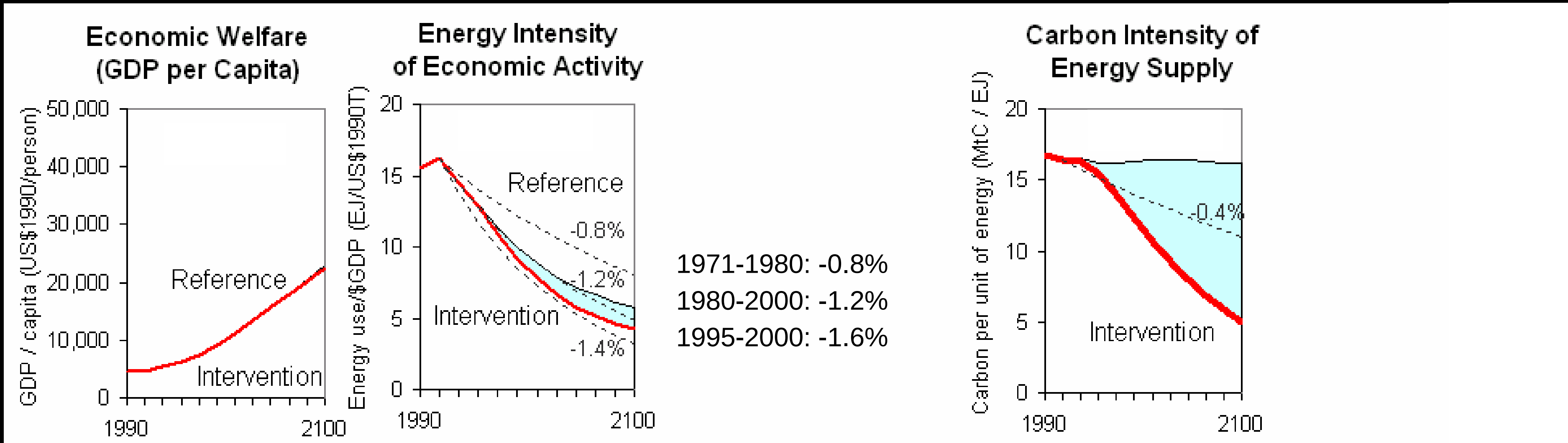
1971-1980: -0.8%
1980-2000: -1.2%
1995-2000: -1.6%



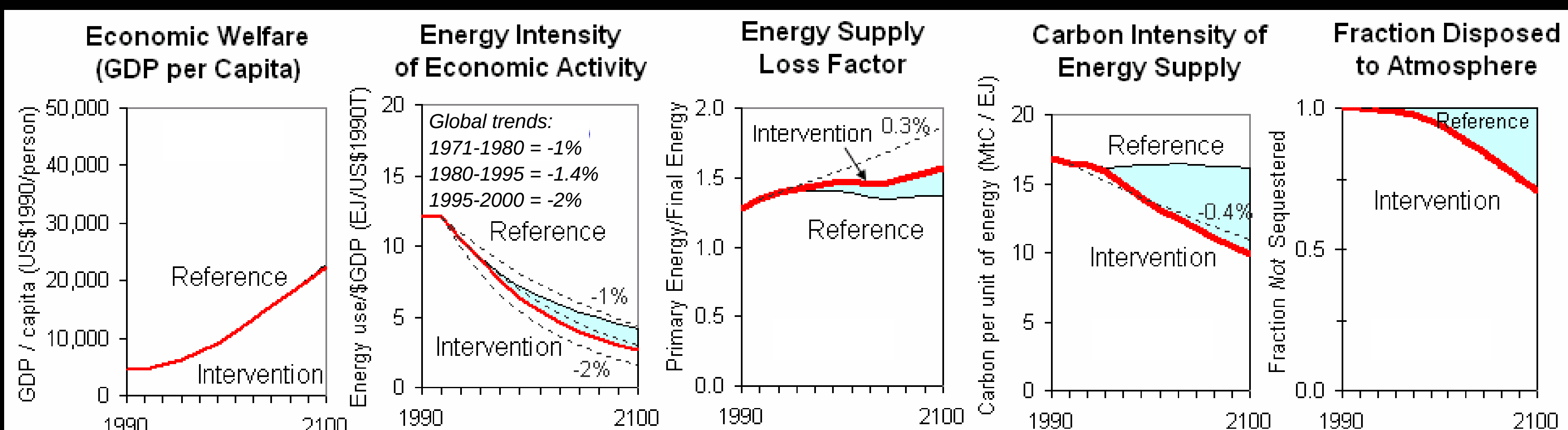
$\frac{GDP}{P}$ $\frac{PE}{GDP}$ $\frac{C}{PE}$

Next, using the expanded decomposition…

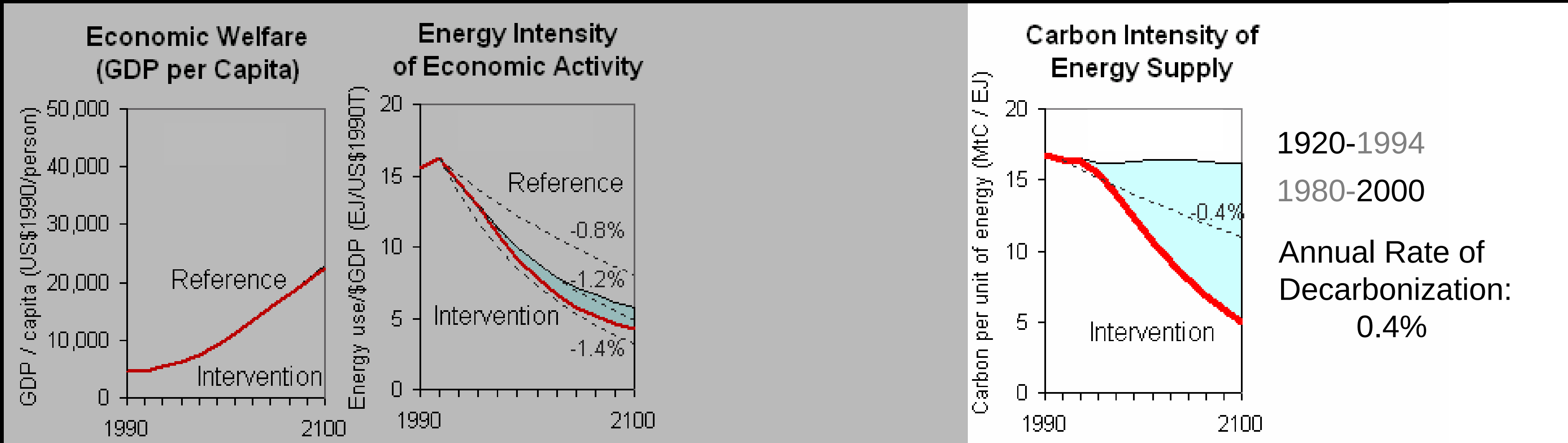
Reference: "Dynamics as Usual" (B2) Stabilization target: 550ppm CO2 Model: MiniCAM



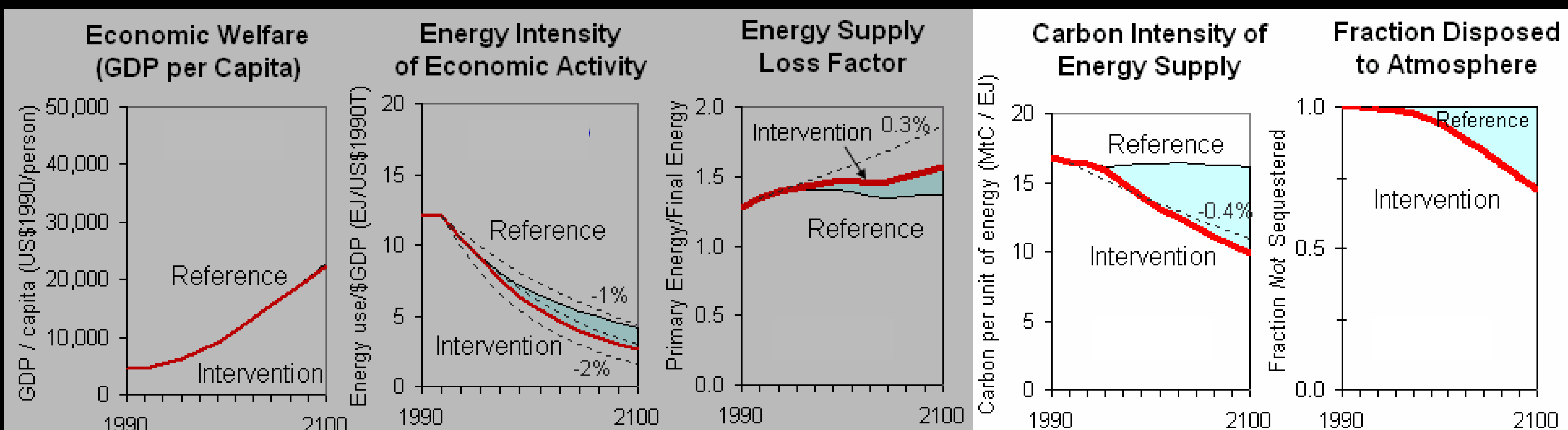
$$\frac{GDP}{P} \quad \frac{PE}{GDP} \quad \frac{C}{PE}$$



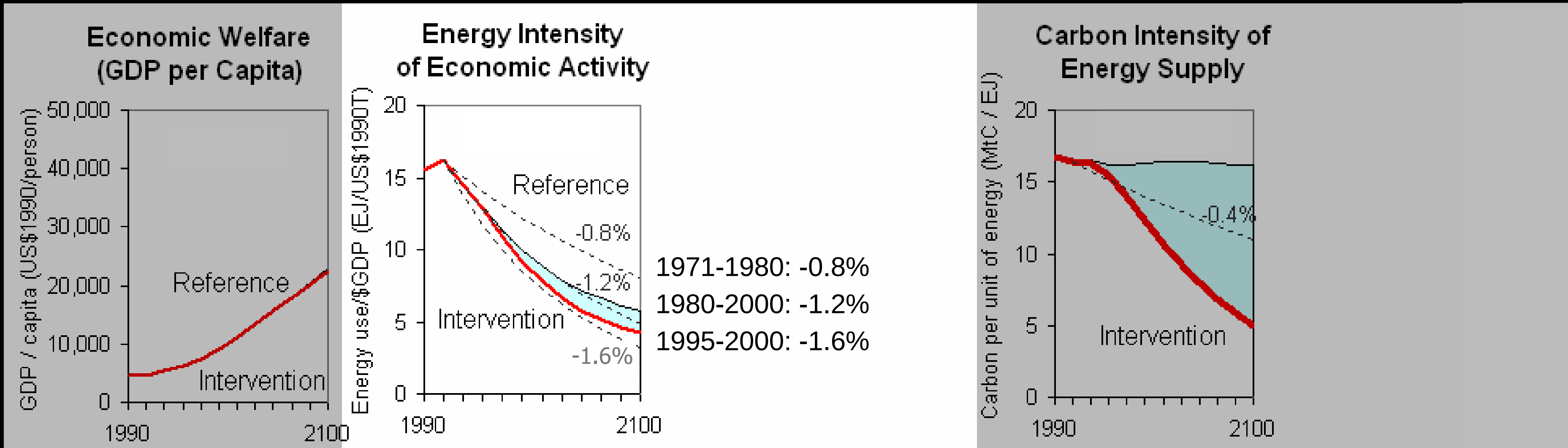
$$\frac{GDP}{P} \bullet \frac{FE}{GDP} \bullet \frac{PE}{FE} \bullet \frac{TC}{PE} \bullet \frac{C}{TC}$$



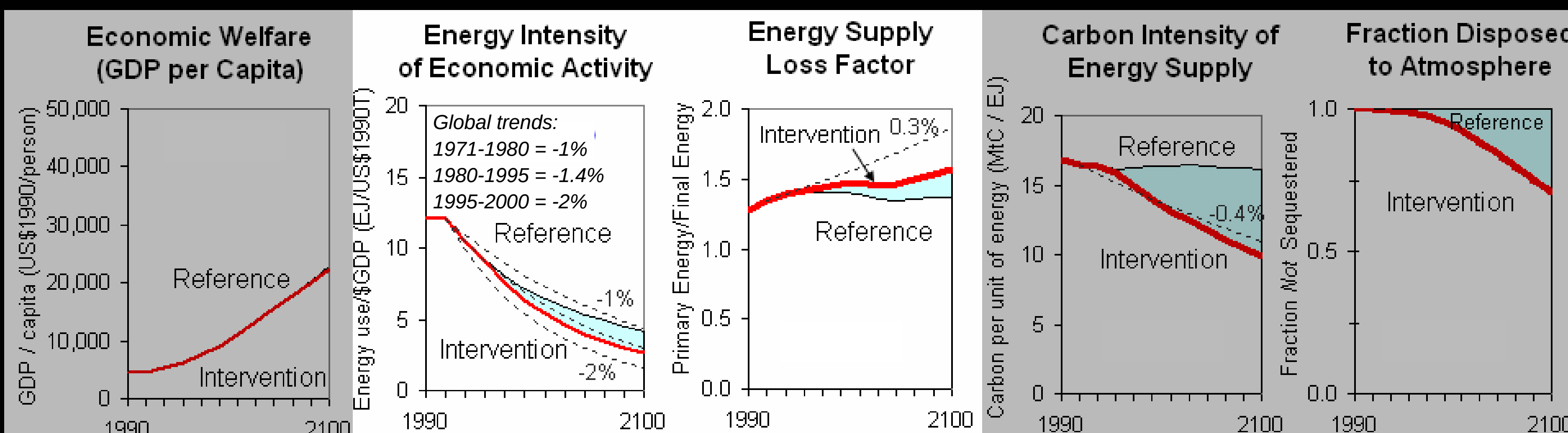
$$\frac{GDP}{P} \qquad \frac{PE}{GDP} \qquad \frac{C}{PE}$$



$$\frac{GDP}{P} \bullet \frac{FE}{GDP} \bullet \frac{PE}{FE} \bullet \frac{TC}{PE} \bullet \frac{C}{TC}$$

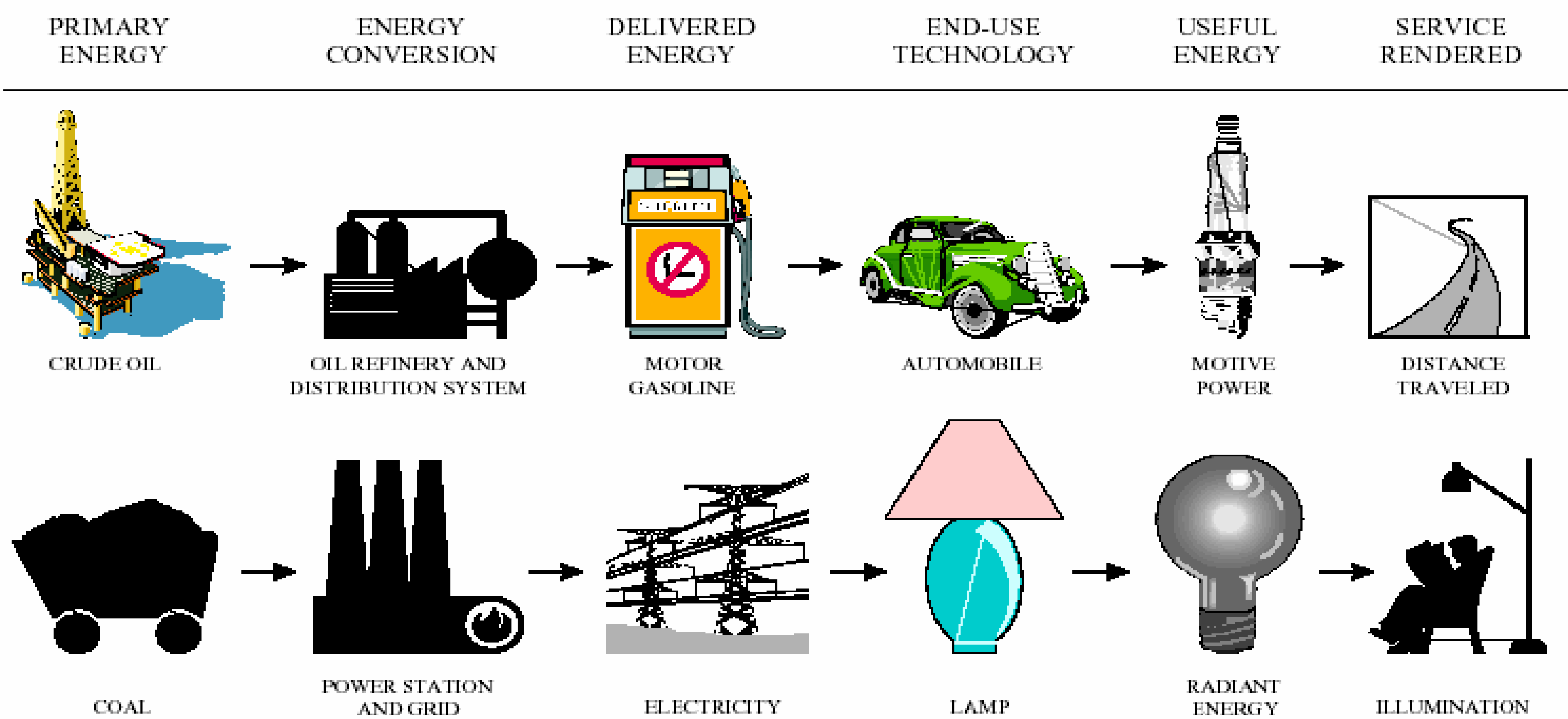


$$\frac{GDP}{P} \qquad \frac{PE}{GDP} \qquad \frac{C}{PE}$$



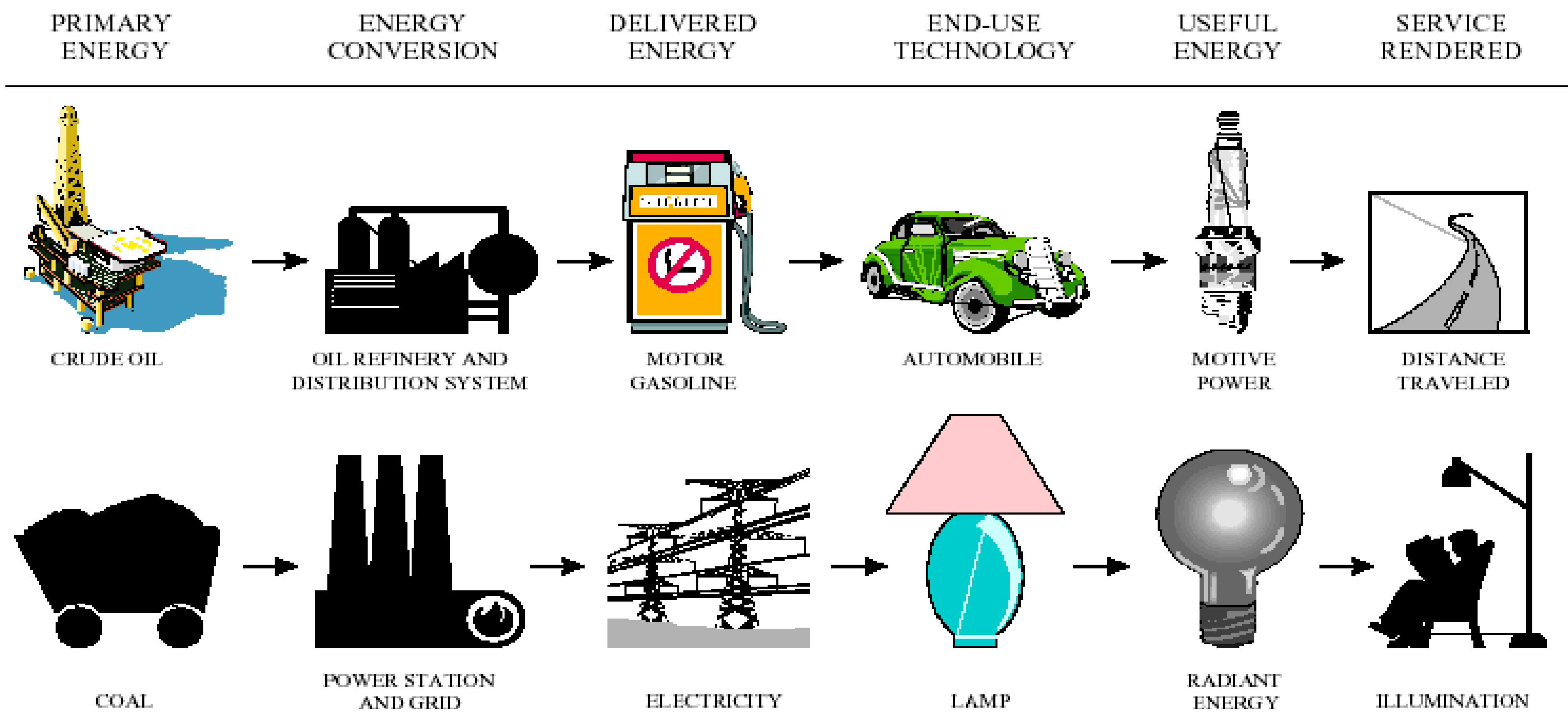
$$\frac{GDP}{P} \cdot \frac{FE}{GDP} \cdot \frac{PE}{FE} \cdot \frac{TC}{PE} \cdot \frac{C}{TC}$$

Primary Energy | Final Energy | Productive Use



- **Efficiency:** More energy delivered per energy input
- **Fuel Switching:** Moving from coal to natural gas
- **Electrification:** Changing the share of electricity in FE

Primary Energy — Final Energy — Productive Use



- **Conservation:** Less non-productive energy use
- **Energy Intensity:** More productivity per energy input
- **Structural Change:** Same productivity, less energy use (Shift toward service economy)

Exploring Energy Futures

model agnostic

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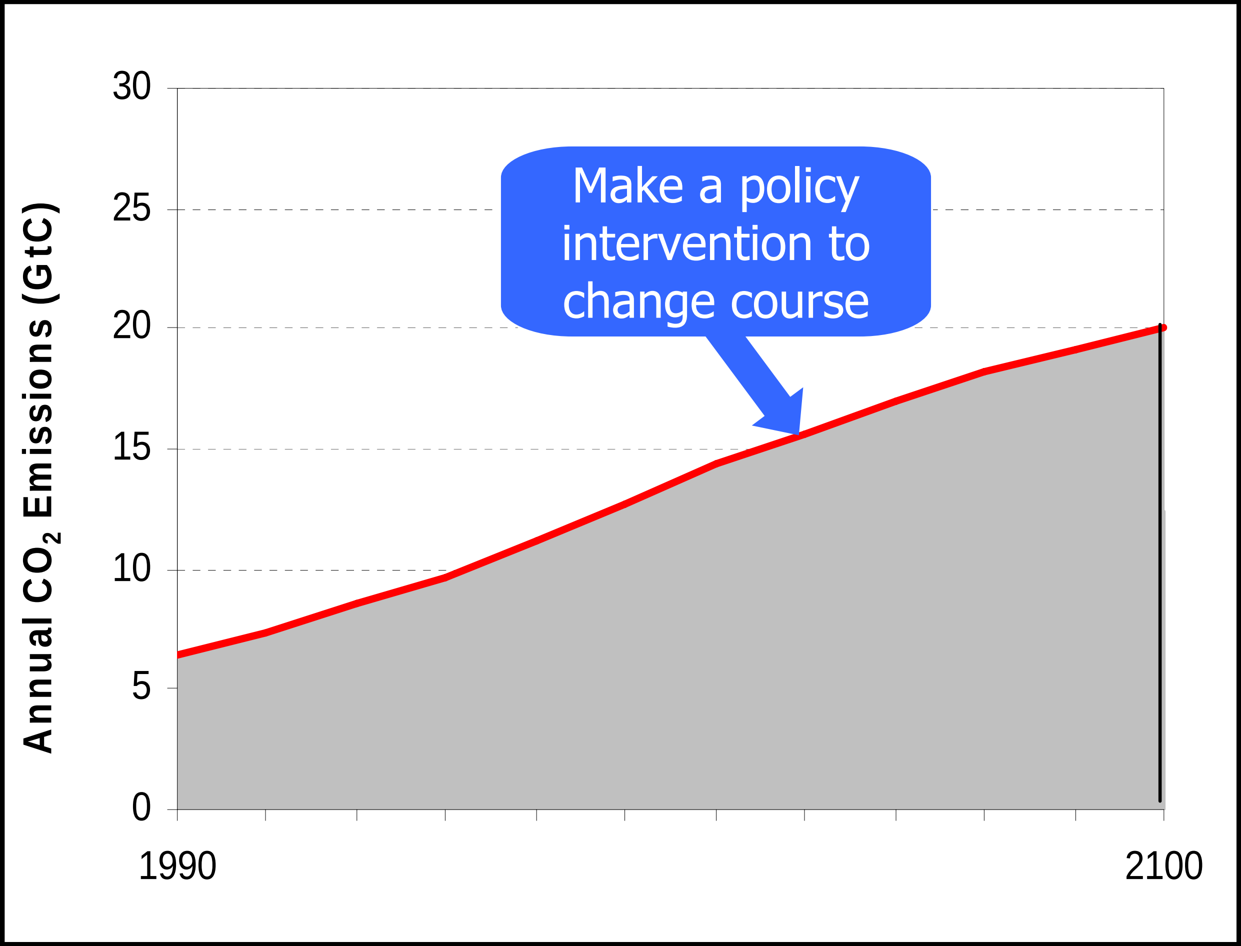
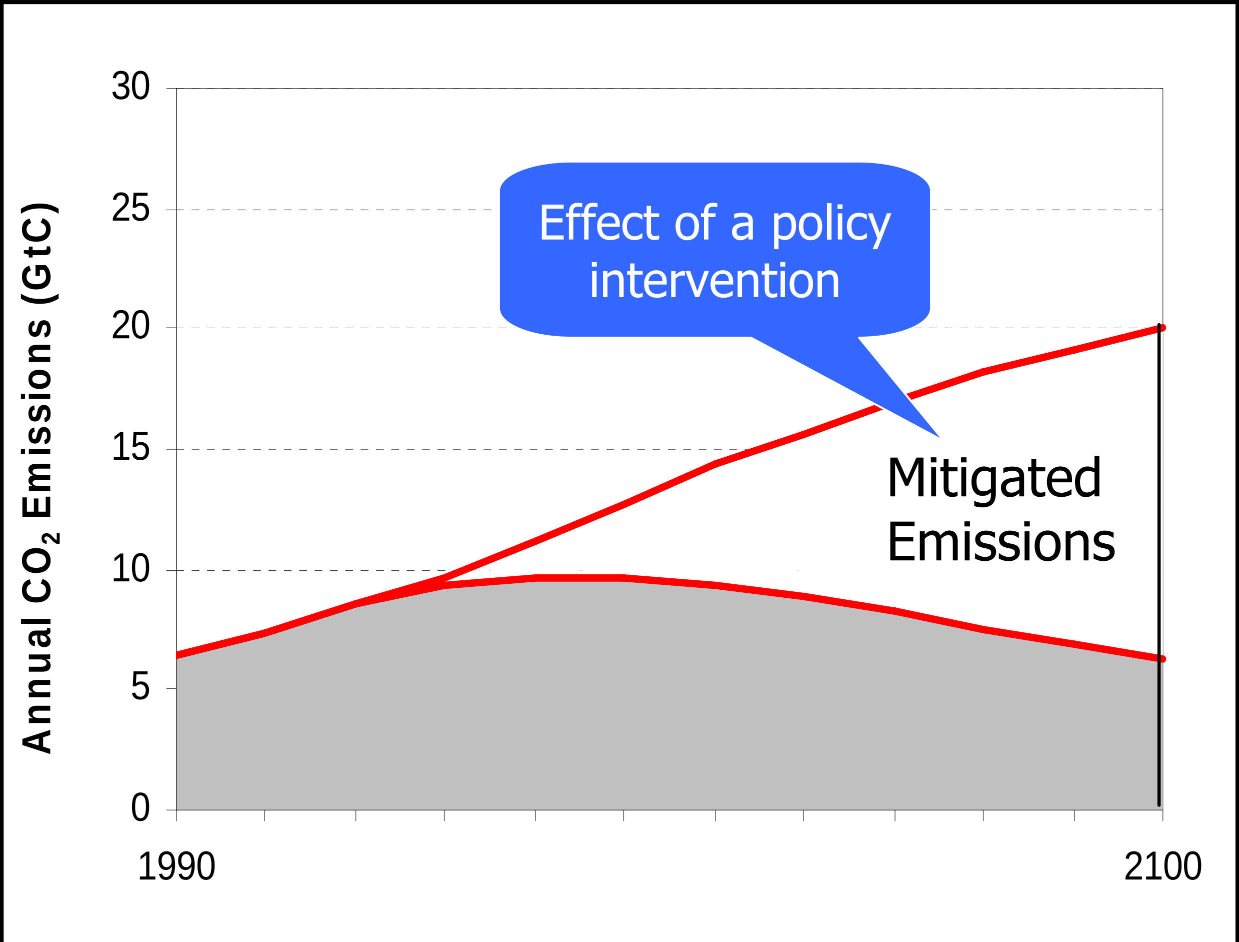
Basic emissions scenario analysis



Emissions Profile of a Possible Future World

Basic emissions scenario analysis



Emissions Profile of a Possible Future World

Path to Stabilization

What intervention policy is most frequently applied?

A benevolent omniscient dictator institutes a worldwide

cap-and-trade program in which everyone plays,

no players are obligated to mitigate more than others,

and everyone can mitigate anywhere at anytime with low transaction costs.

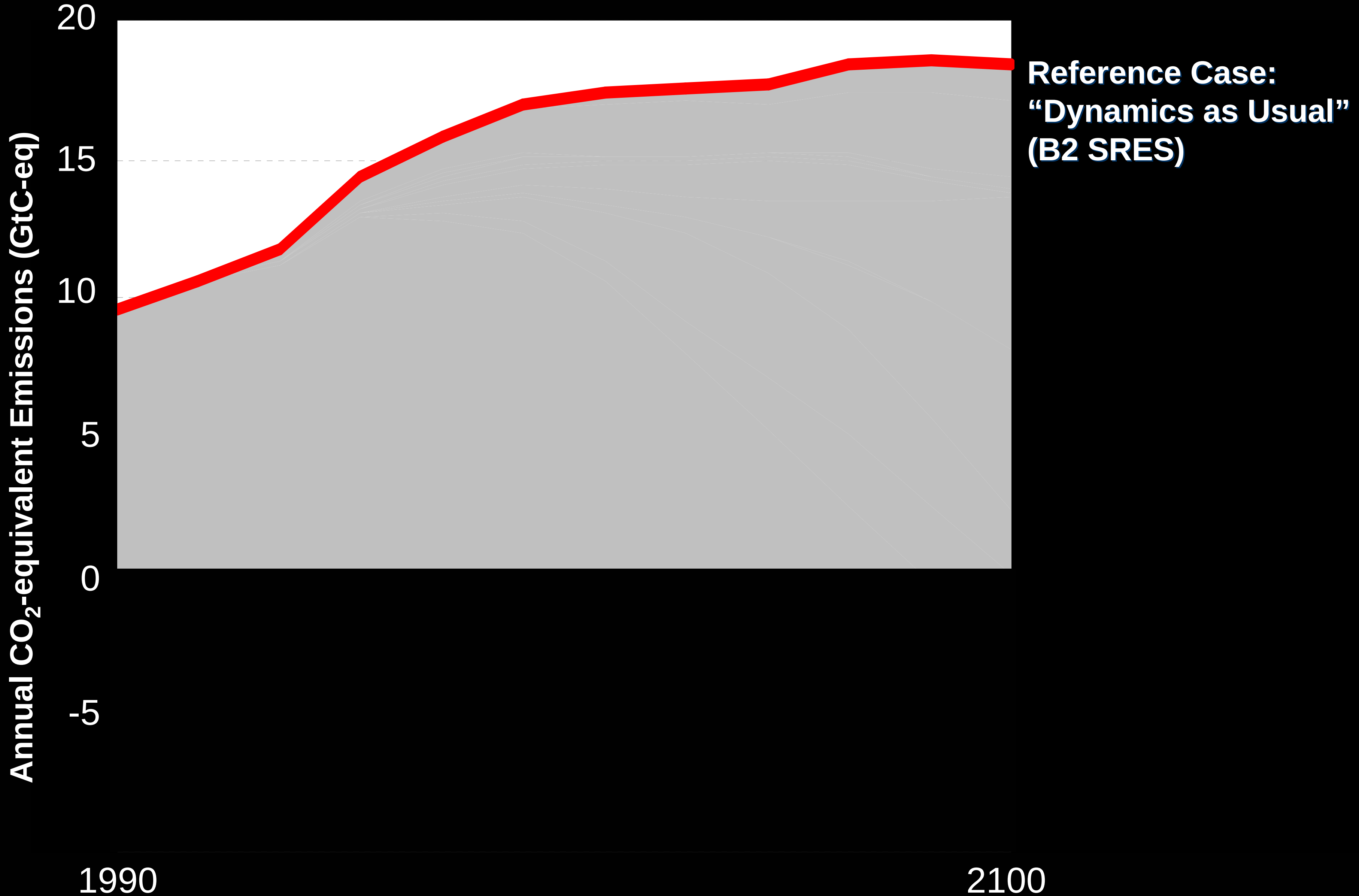
As a result, everyone faces the same global carbon price, equal to the marginal cost of abatement.

Though this policy is not feasible to implement, it is used as a proxy:

"A global uniform carbon price has been applied as a proxy of pressure on the system to induce a variety of mitigation measures."

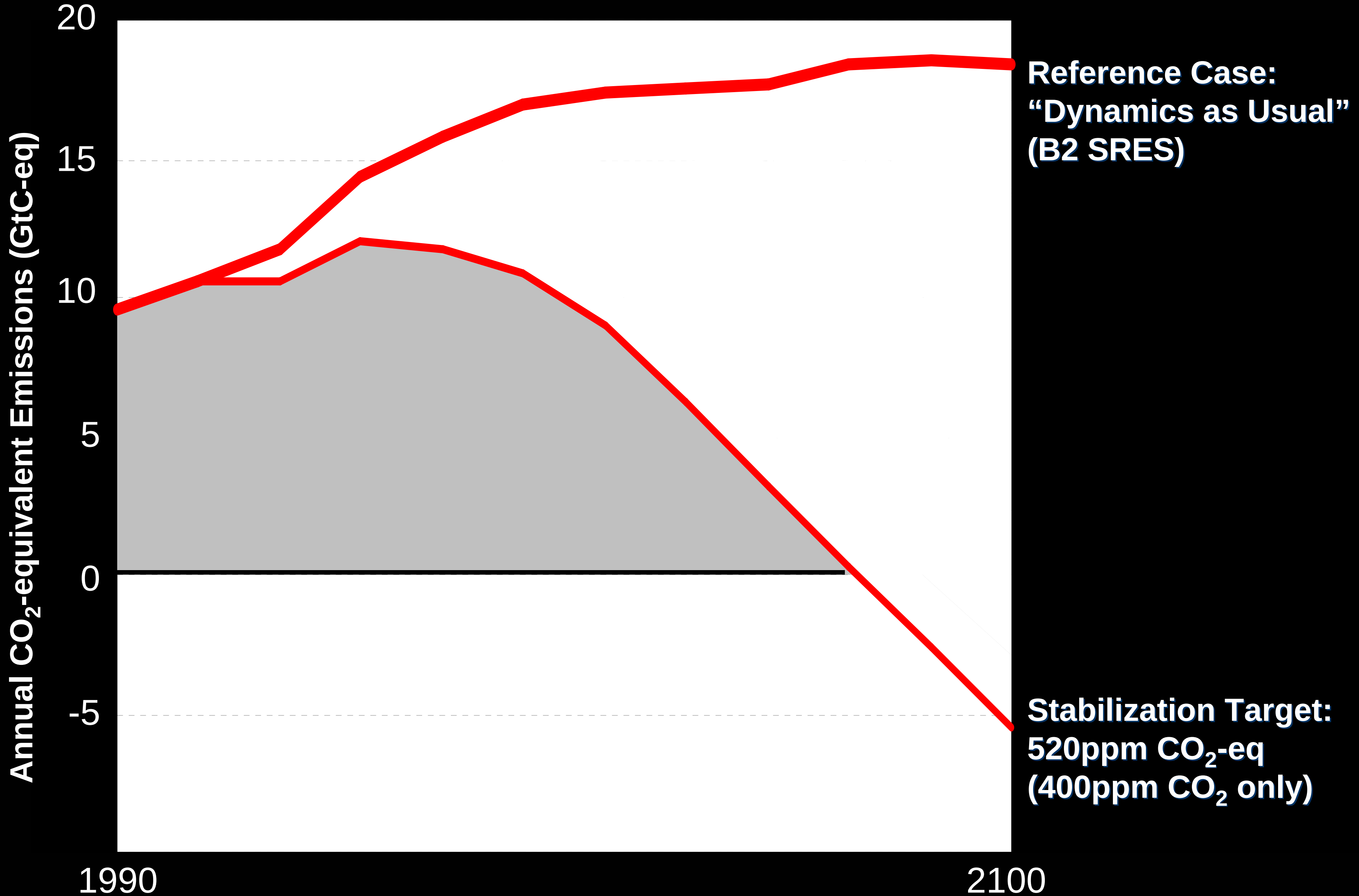
- van Vuuren, RIVM 2001

Decomposing Sources of Mitigation



Model: MESSAGE-MACRO (IIASA GGI, 2006)

Decomposing Sources of Mitigation



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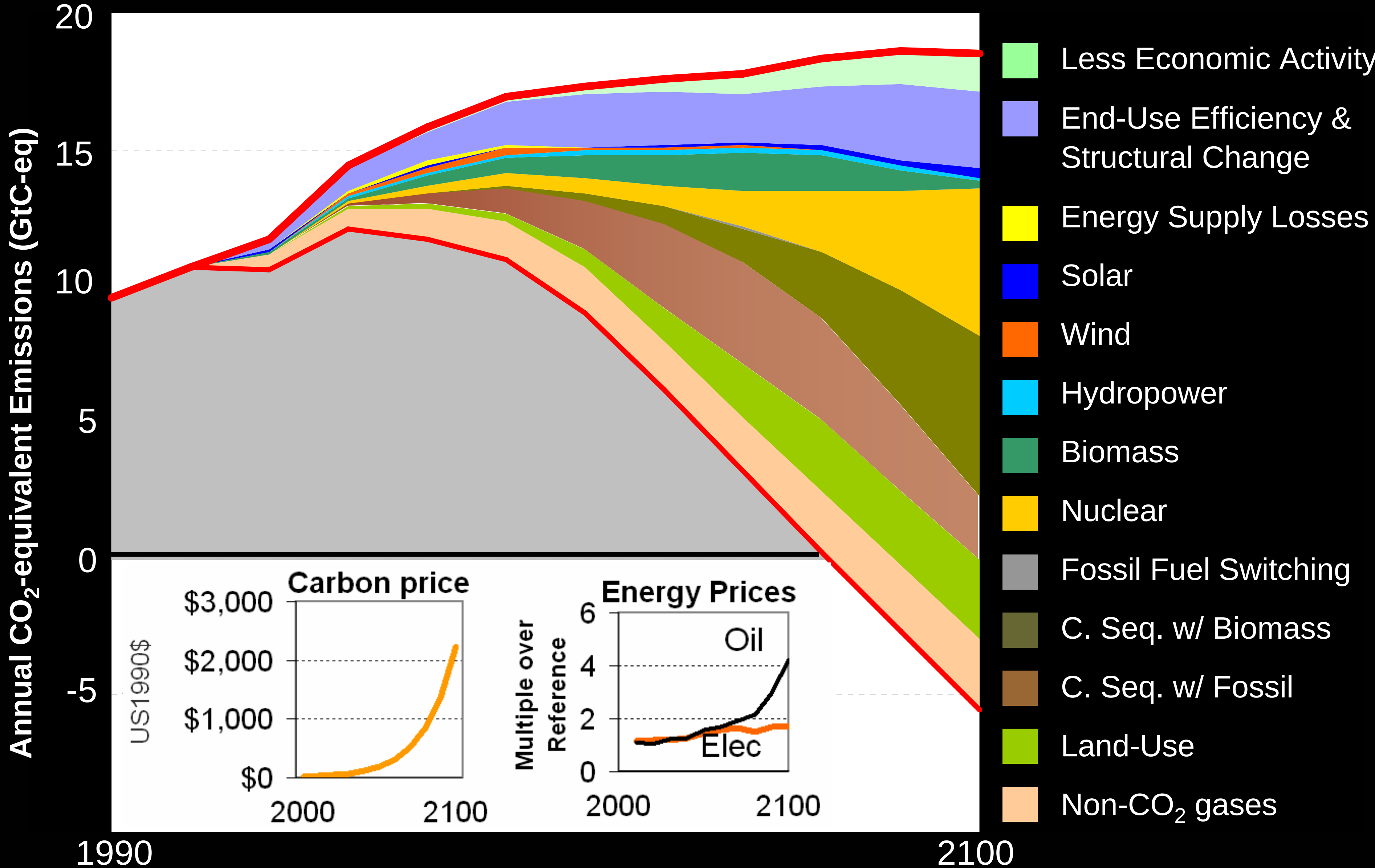
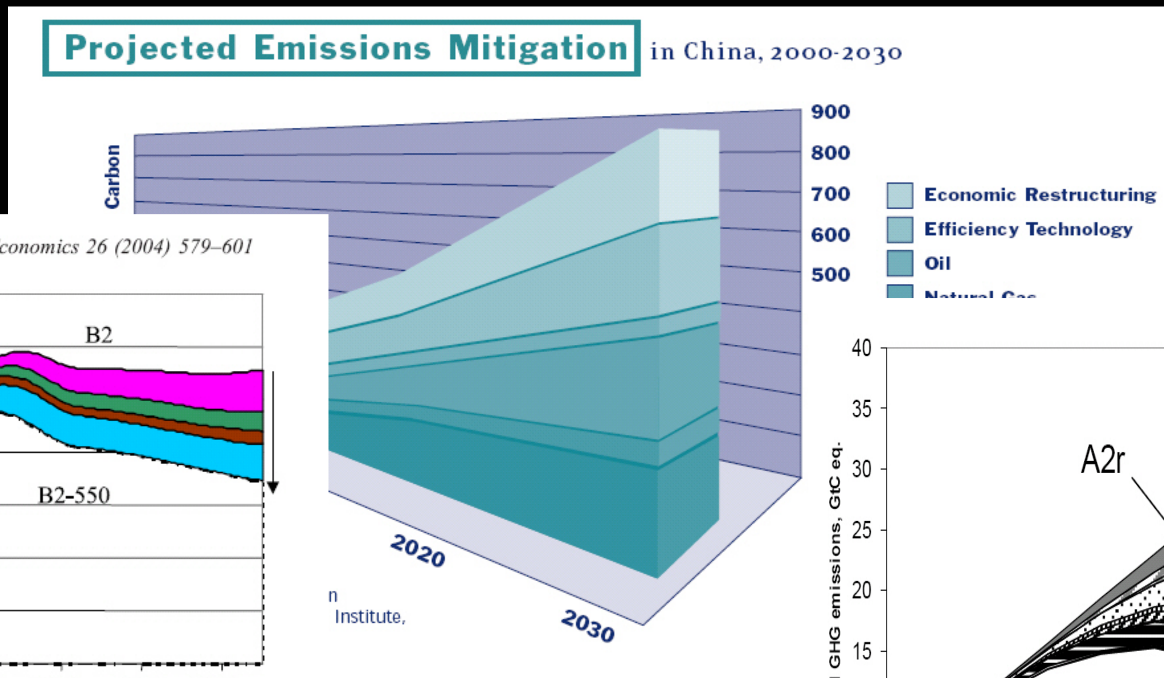
Decomposing Sources of Mitigation

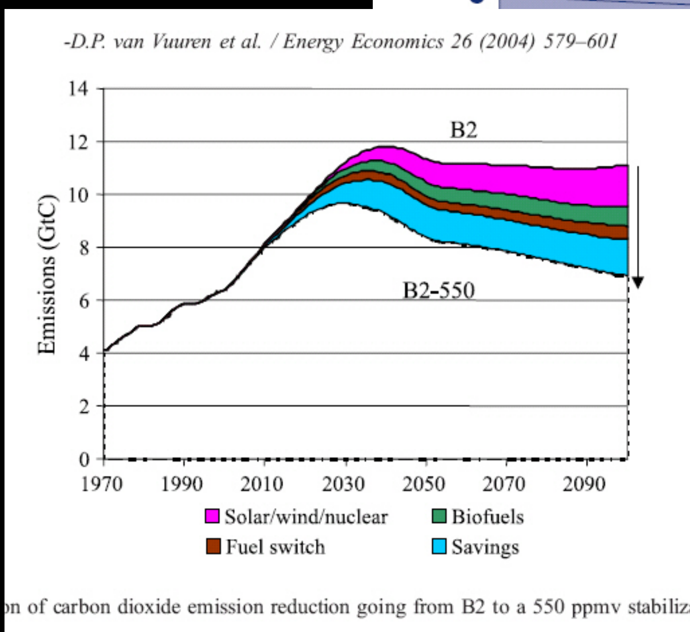


Mid-range reference case (B2) limited to 520ppm CO2-eq (IIASA GGI, 2006)

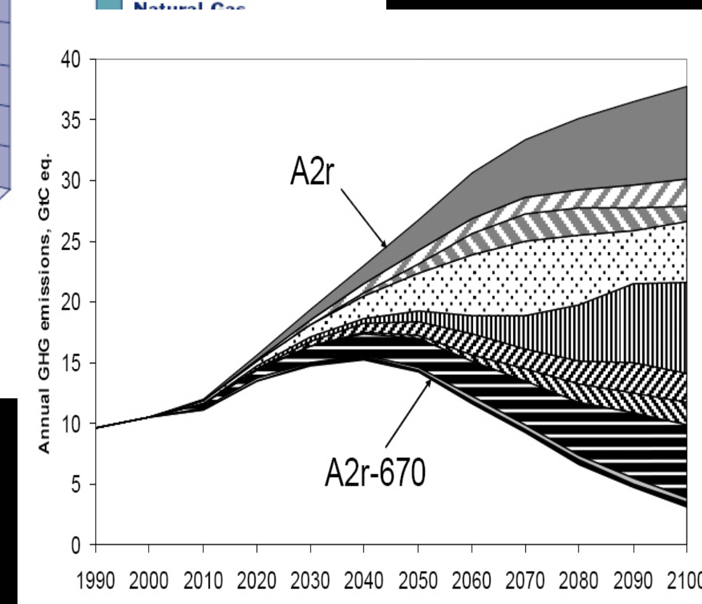
Decomposing Sources of Mitigation: Earlier instances in the literature



Chandler et al, 2002

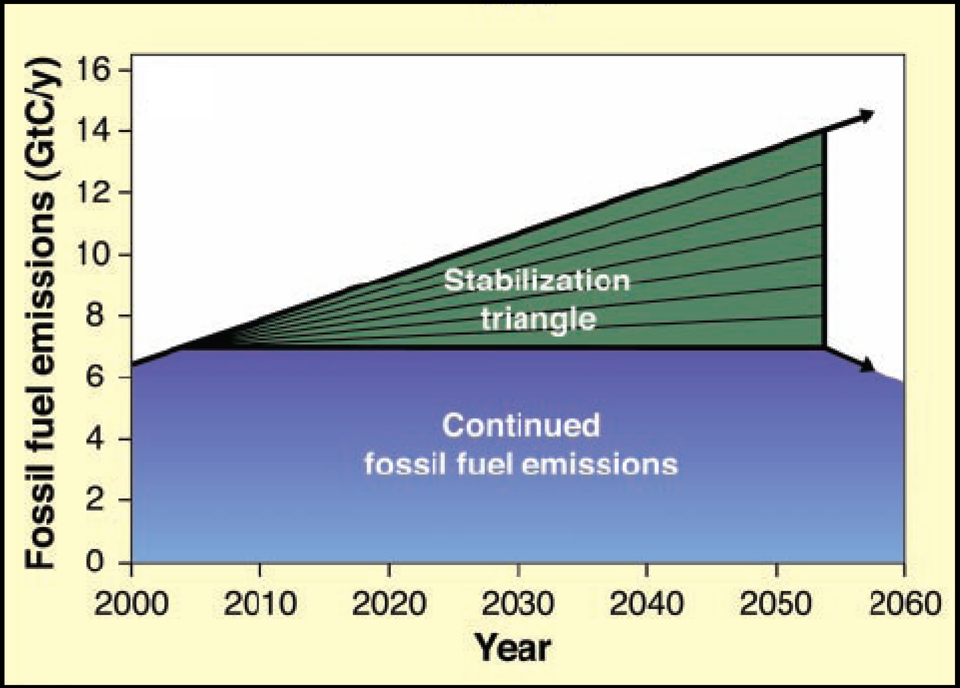


van Vuuren et al, 2004



Riahi et al, 2006

Comparison with “stabilization wedges” concept



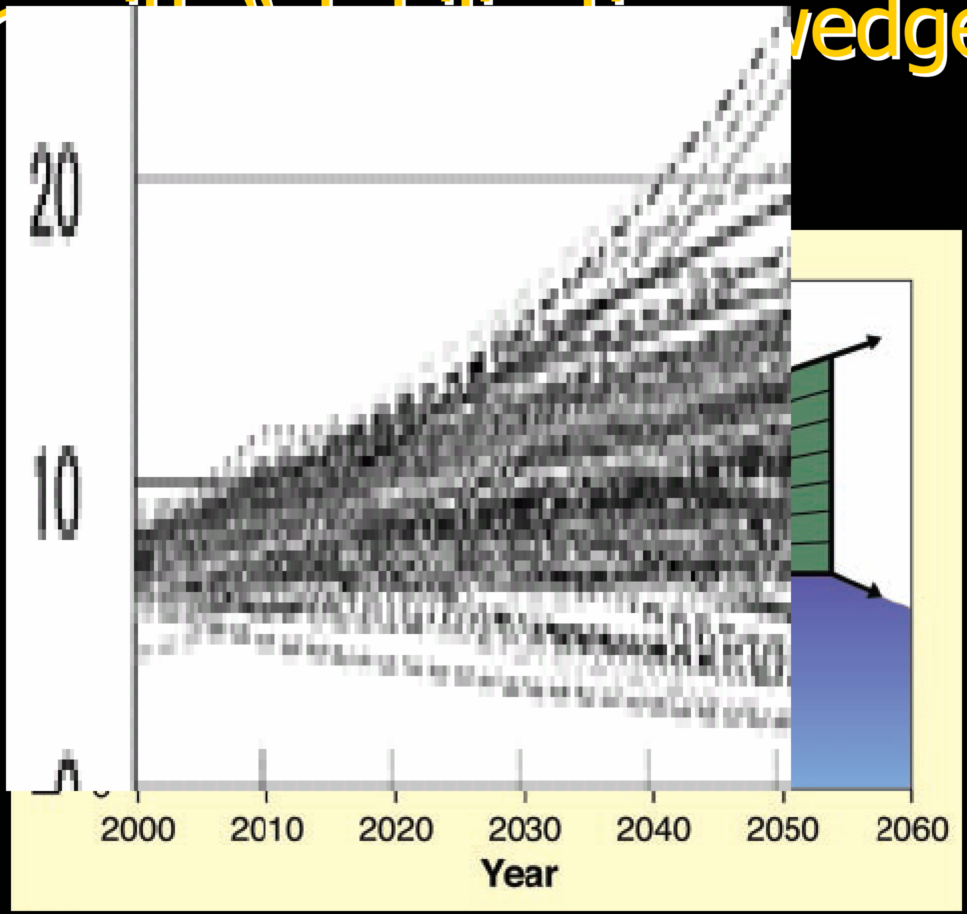
Pacala, S. and R. Socolow. 2004. “Stabilization Wedges,” Science, Vol 305

Presents fixed reference and stabilization paths,

then offers mix & match technologies

in units of a “stabilization wedge” (25 GtC).

Comparison with "stabilization wedges" concept



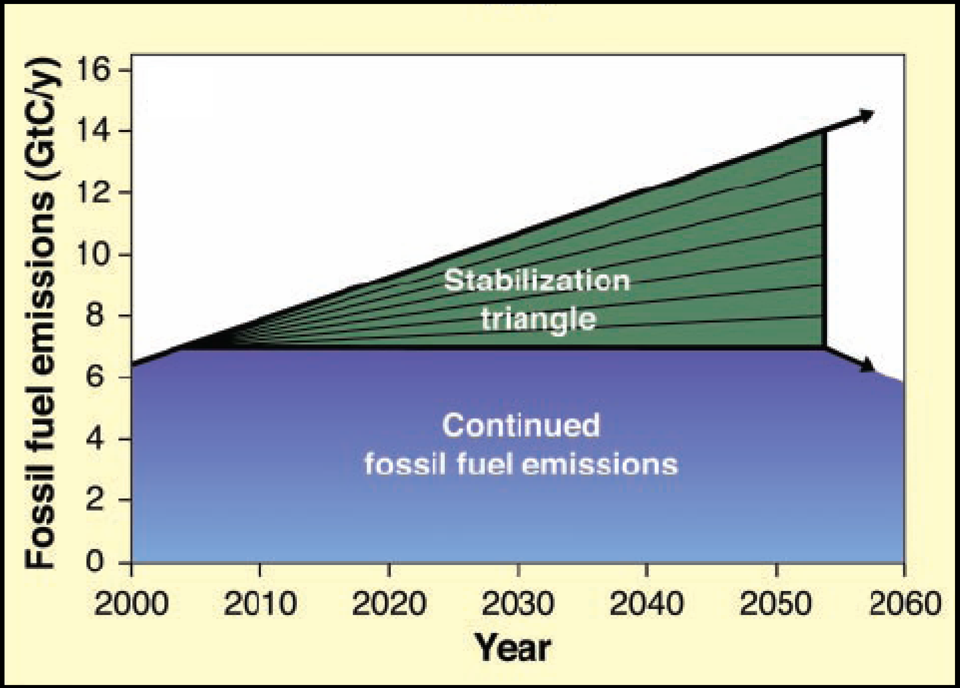
Pacala, S. and R. Socolow. 2004. "Stabilization Wedges," Science, Vol 305
Hanaoka, et al. 2006. Greenhouse Gas Emissions Scenarios Database, NIES. (Fig 3.4)

Uncertainty is fundamental to the problem.

then offers mix & match technologies

in units of a "stabilization wedge" (25 GtC).

Comparison with "stabilization wedges" concept



Pacala, S. and R. Socolow. 2004. "Stabilization Wedges," Science, Vol 305

Uncertainty is fundamental to the problem.

Technological innovation paths are interdependent.

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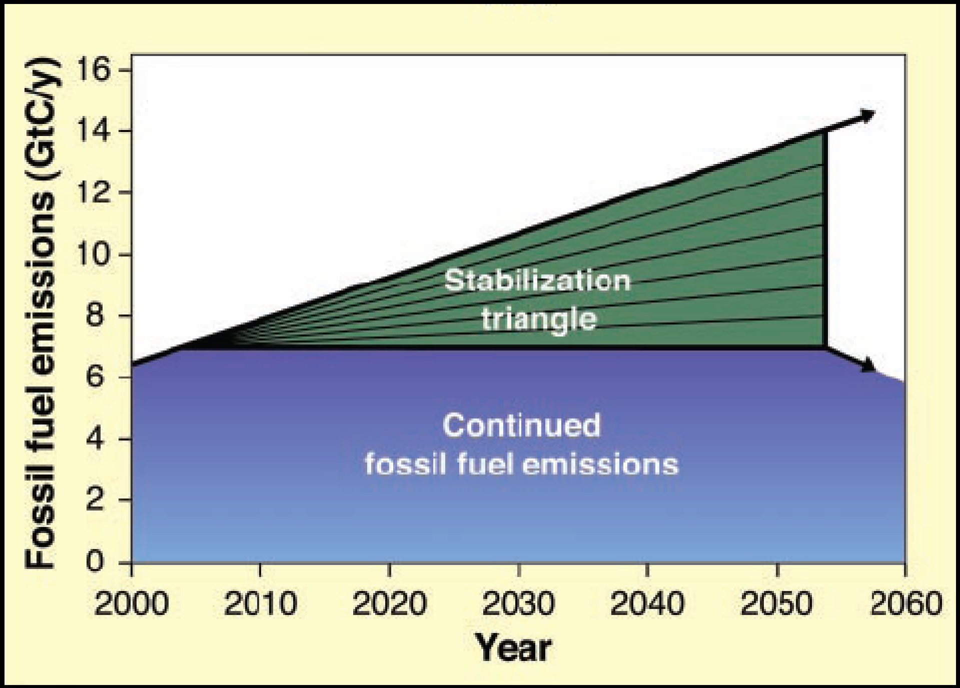
Comparison with "stabilization wedges" concept



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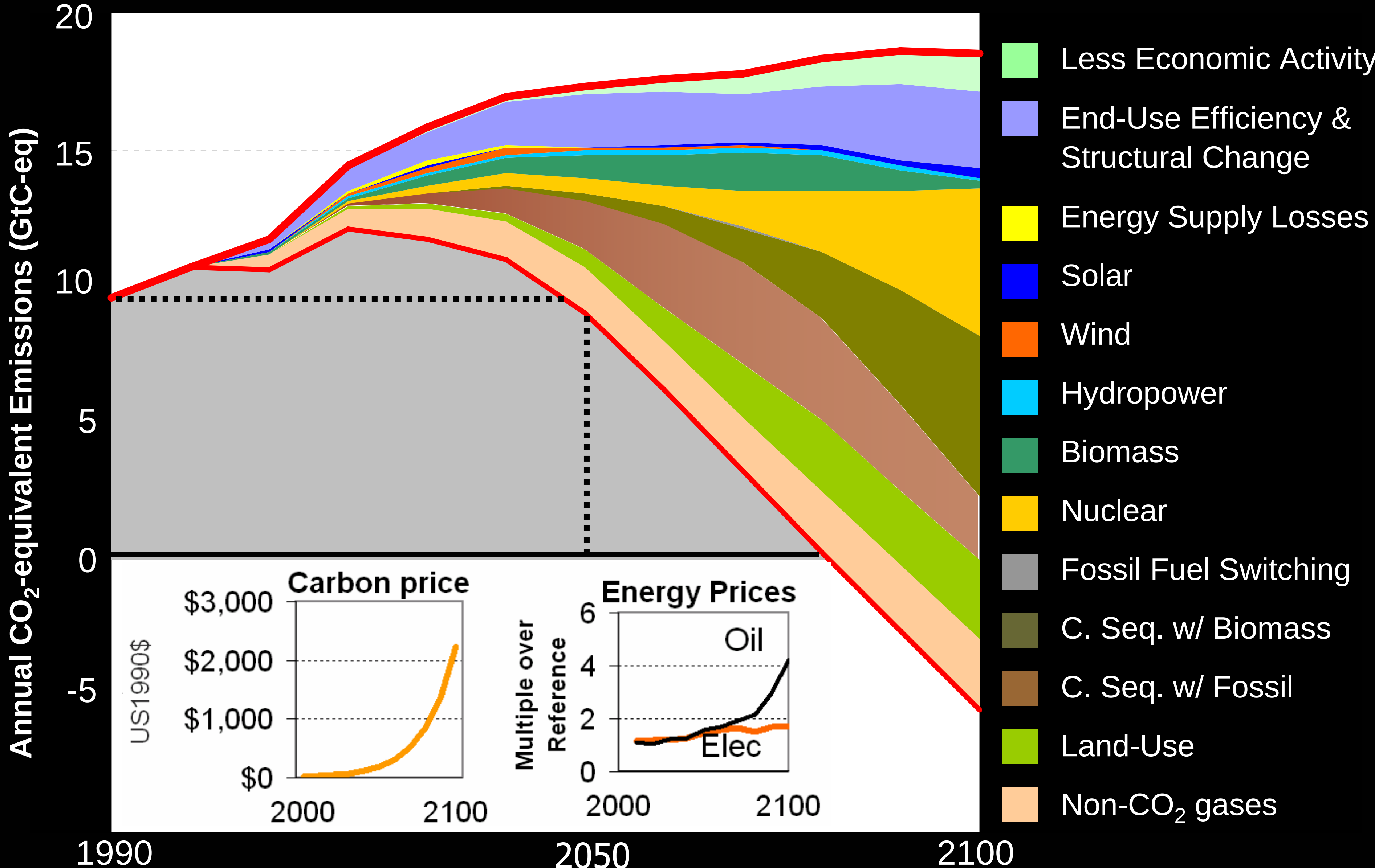
Uncertainty is fundamental to the problem.

Technological innovation paths are interdependent.

Proportion and timing of mitigation measures matter.

Comparison with "stabilization wedges" concept



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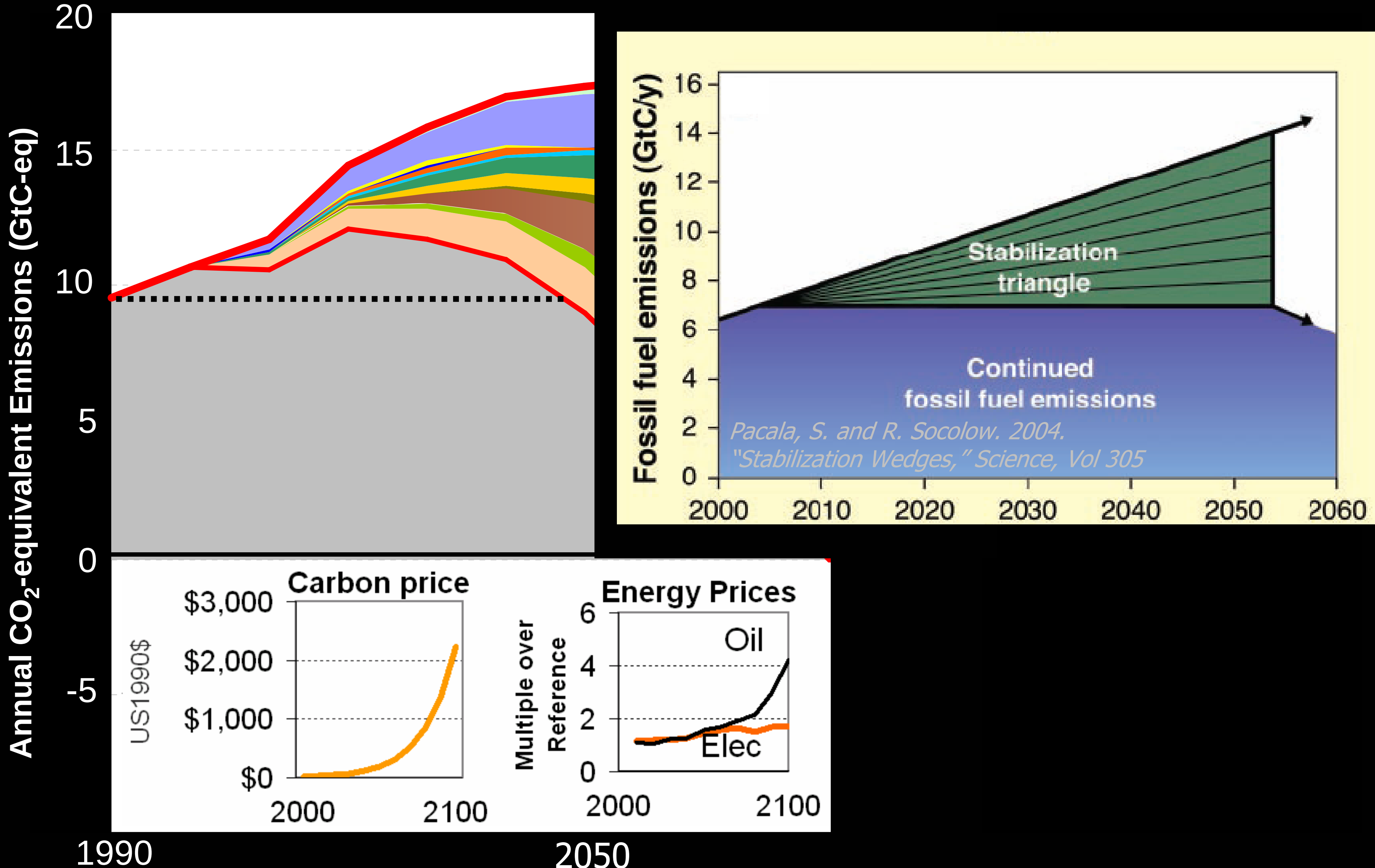
Comparison with "stabilization wedges" concept



Mid-range reference case (B2) limited to 520ppm CO2-eq (GGI, 2006)

Exploring Energy Futures

model agnostic

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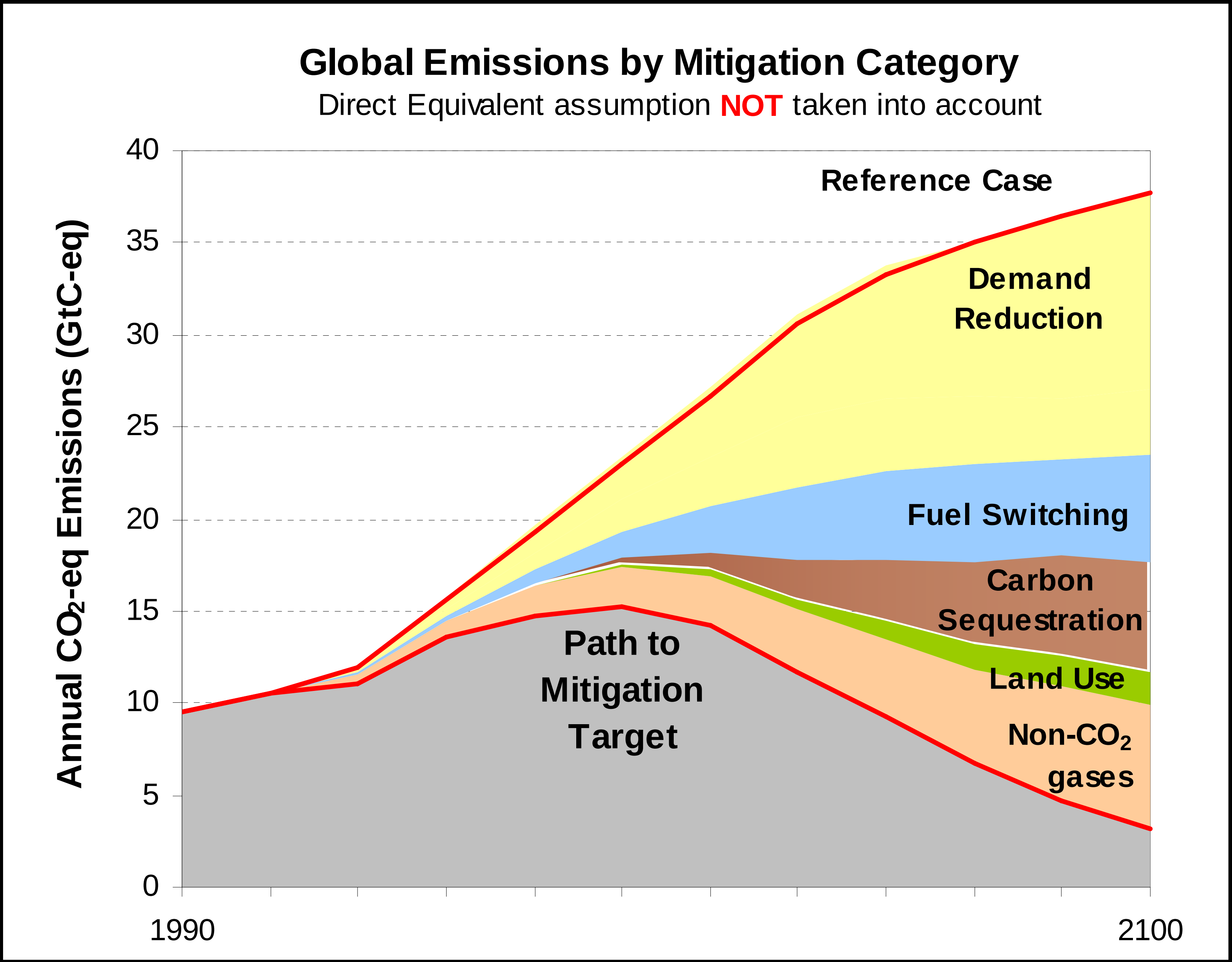
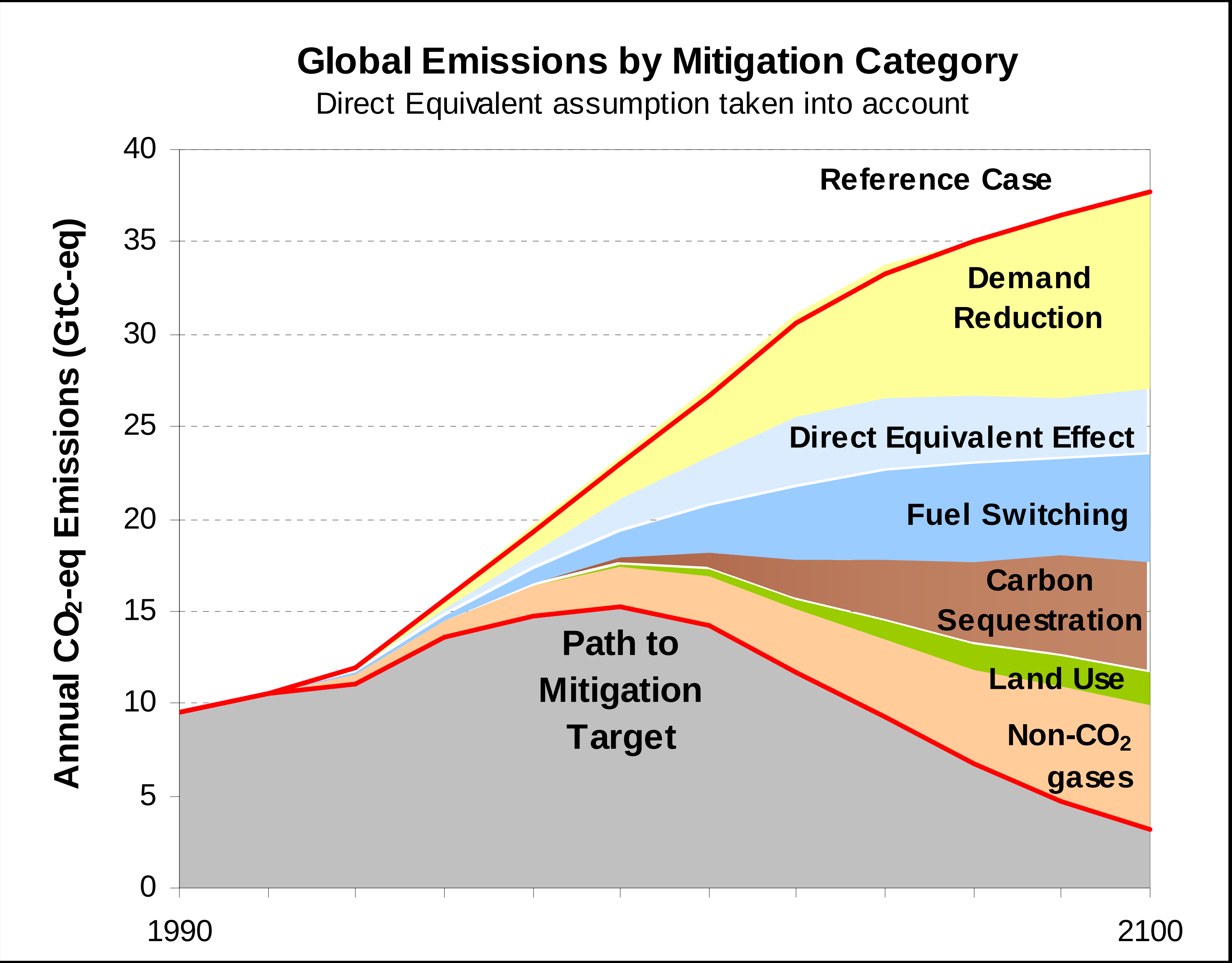
Accounting for the Direct Equivalent method

- The direct equivalent method sets primary energy directly equal to the heat content of delivered final energy – giving appearance of 100% efficiency.
- The scale of the distortion in a decomposition increases as more solar, hydro, and wind power displace fossil fuels. IPCC SRES scenarios also treat nuclear power as a direct equivalent source.
- Use of data based on the direct equivalent method will result in inflated indicators for efficiency improvements, overstating actual reduction in demand.
- Primary energy accounting must be addressed because it affects results of both the decomposition of key drivers and the decomposition of mitigation sources.



High Growth (A2r GGI), Stabilization: 670ppm CO_2-eq, Model: MESSAGE-MACRO



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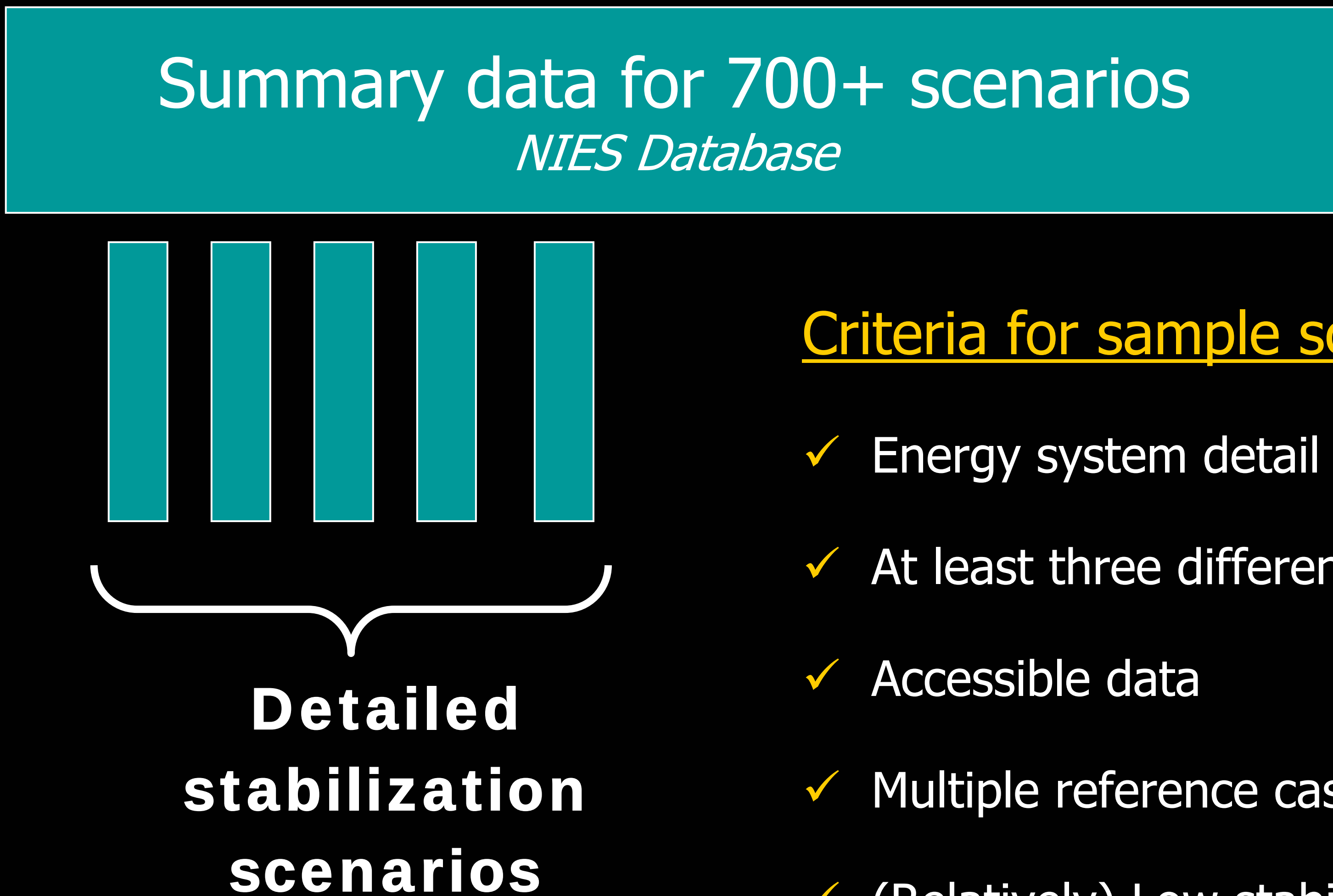
Data



<u>Criteria for sample scenarios:</u>

- ✓ Energy system detail
- ✓ At least three different models
- ✓ Accessible data
- ✓ Multiple reference cases
- ✓ (Relatively) Low stabilization levels

Interval Data Disclosure

Energy

- ✓ Primary Energy by Source
- ✓ Final Energy by Type
- ✓ End-Use Demand by Sector (*if available*)

Emissions

- ✓ CO_2 Emissions by Source (Energy, Industry, Land Use)
- ✓ Carbon Sequestration
- ✓ CO_2 Equivalent Emissions for other greenhouse gases (*if available*)

Costs

- ✓ Shadow carbon price
- ✓ GDP
- ✓ Marginal abatment cost curve data (*if available*)
- ✓ Investment in the energy sector (*if available*)
- ✓ Aggregate annual energy system costs (*if available*)

Demographic

- ✓ Population

Electric Power Sector

- ✓ Electricity Generation Output by Fuel Source
- ✓ Primary Energy Input to Electric Power Generation by Fuel Source

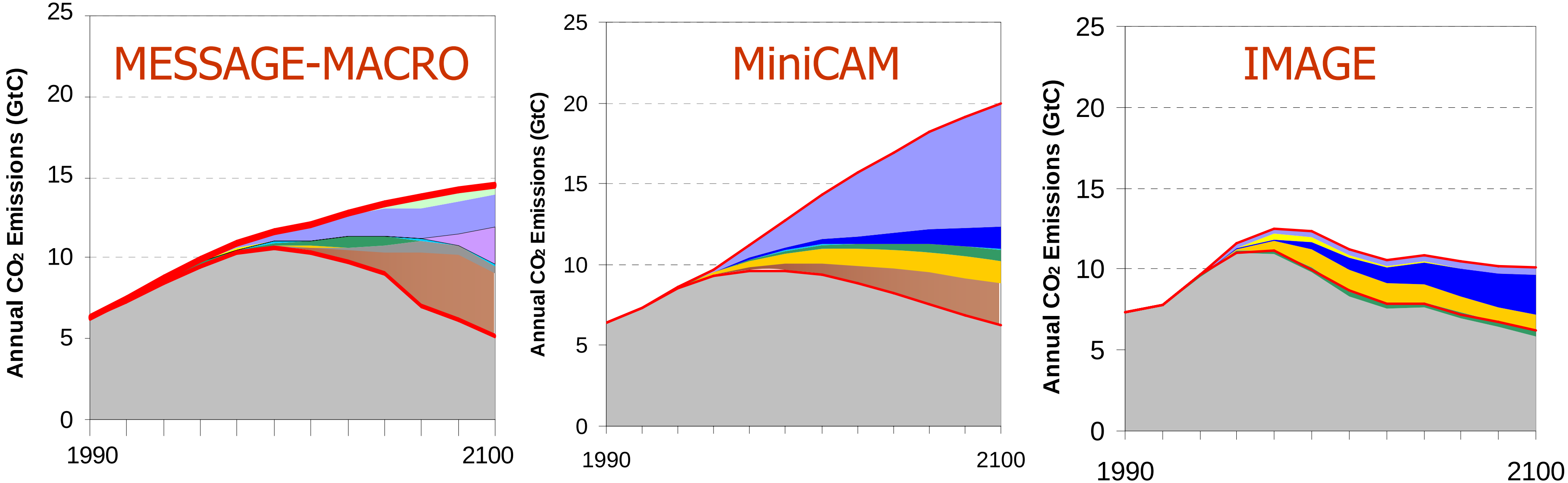
Sample Stabilization Scenarios

Scenario Study	Reference Case	Stabilization Case	Model
EMF-19	B2	550 CO_2	MiniCAM
EMF-19	B2	550 CO_2	IMAGE
EMF-19	B2	550 CO_2	MSG-MCR
WBGU	A1T*	450 CO_2	MSG-MCR
WBGU	B1*	400 CO_2	MSG-MCR
IPCC TAR	A2	550 CO_2	MSG-MCR
GGI	A2	670 CO_2 eq	MSG-MCR
GGI	B2	480 CO_2 eq	MSG-MCR
GGI	B1	480 CO_2 eq	MSG-MCR
MNP	B1	400 CO_2	IMAGE
IPCC TAR	A1B	550 CO_2	IMAGE

Impact of model & modeler assumptions:

Same reference & stabilization target

Different models & technology assumptions



Decomposition of: Riahi et al, 2004 Edmonds et al, 2004 van Vuuren et al, 2004

Reference: “Dynamics as Usual” (B2 SRES)

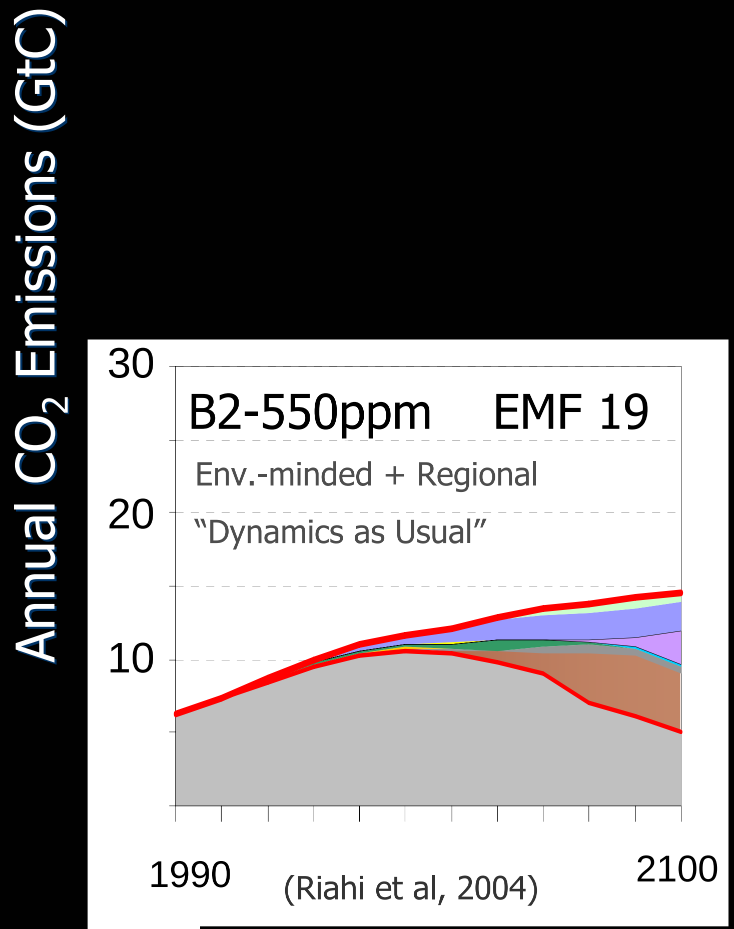
Mitigation Target: 550ppm CO_2 (doubling of pre-industrial levels)

Study: Energy Modeling Forum, Study #19

Impact of Technology Assumptions:

Same Model (MESSAGE-MACRO, 2000-2004)

Different Reference cases & Stabilization targets



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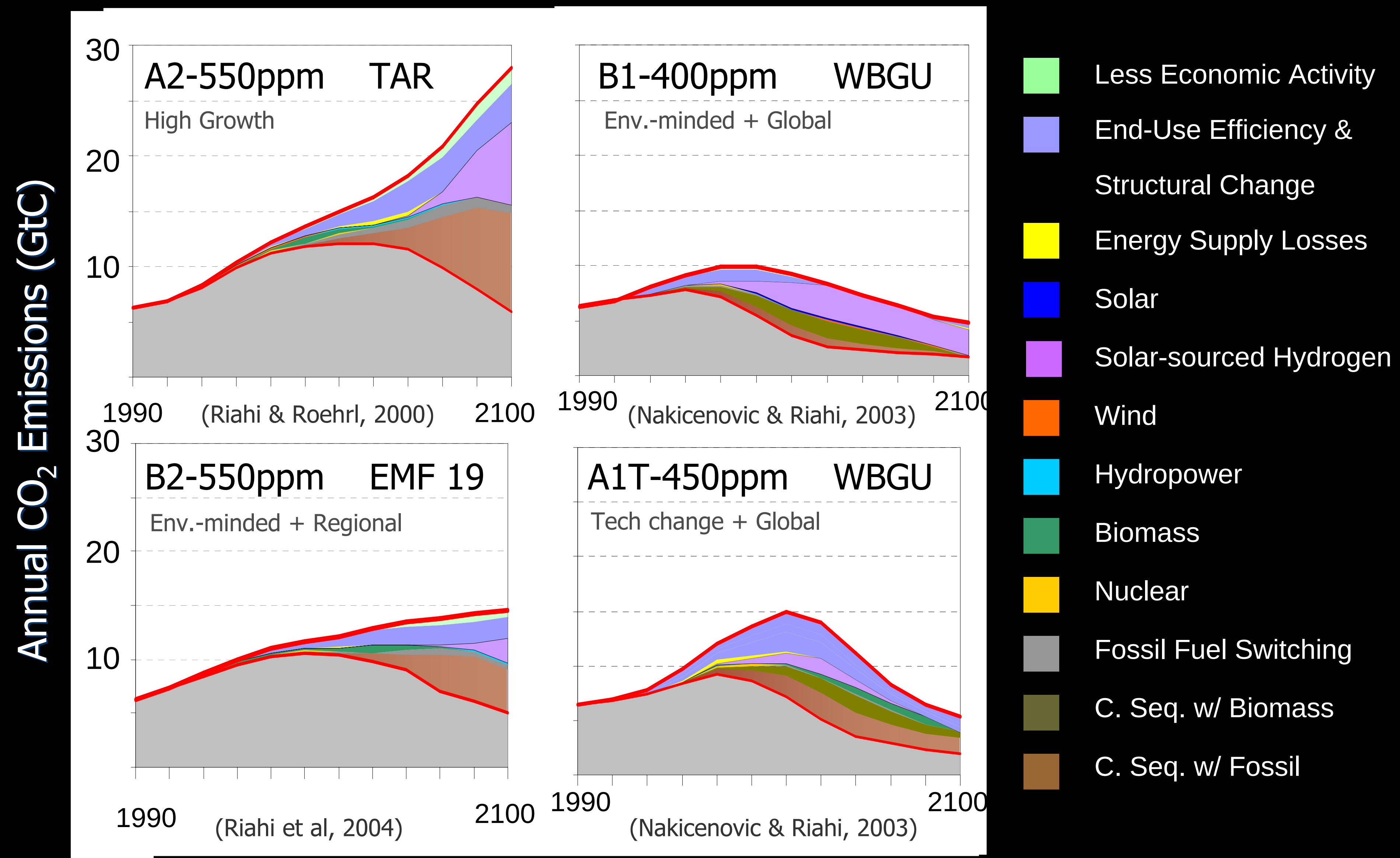

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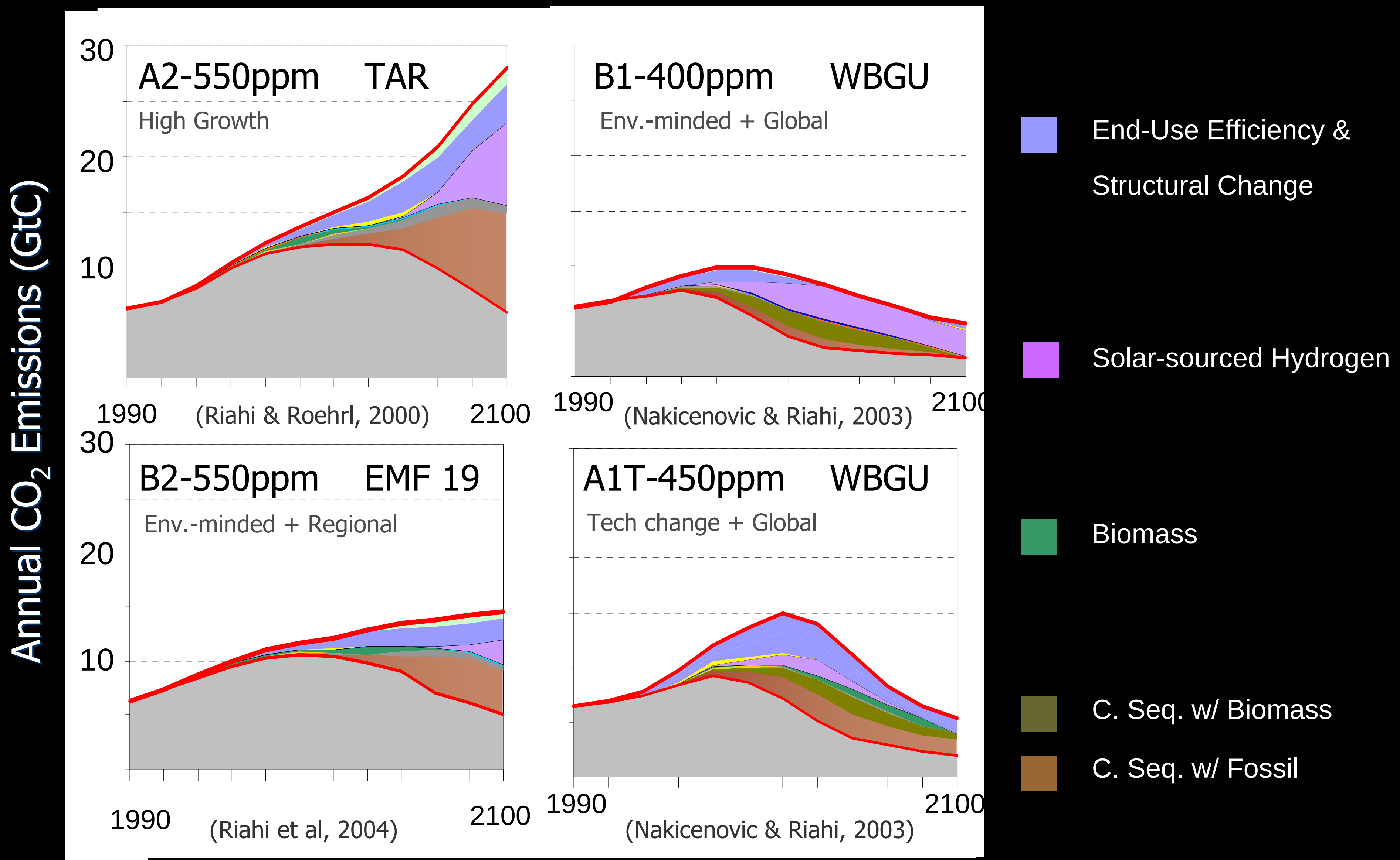

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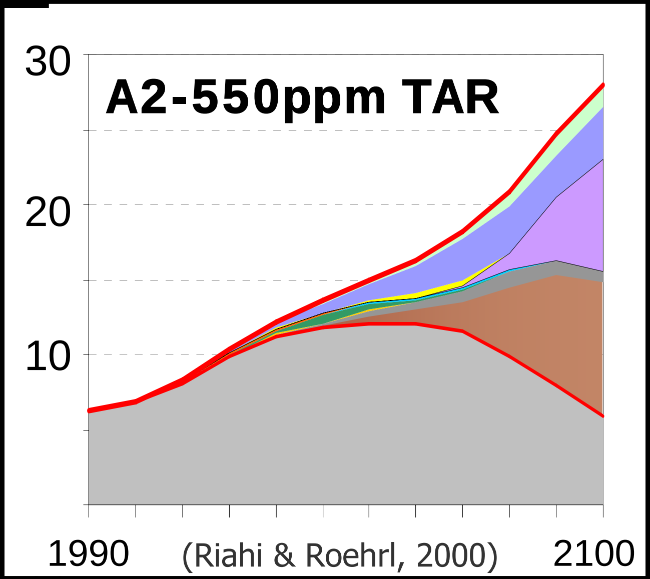
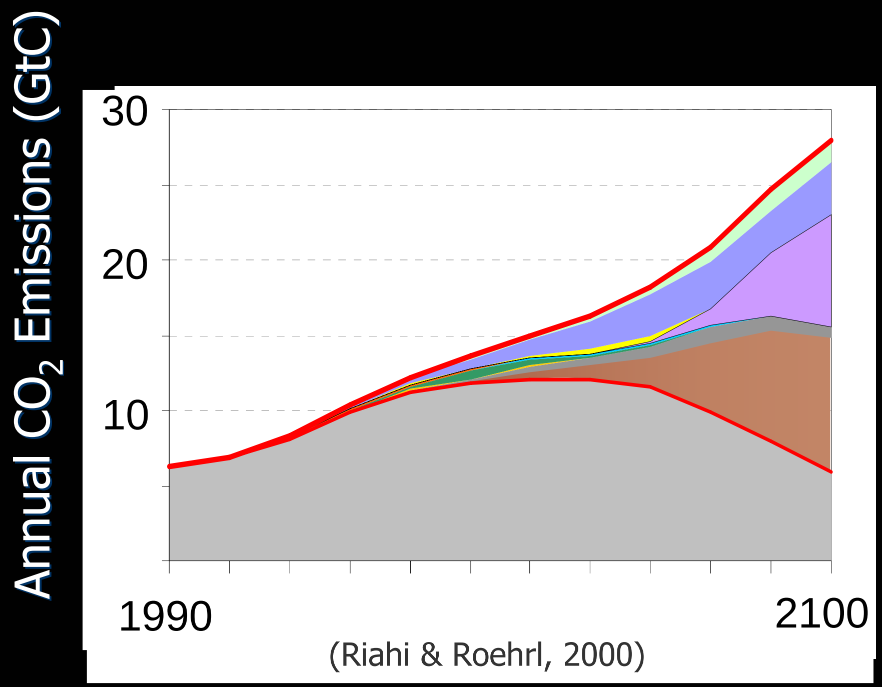
Annual CO_2 Emissions (GtC)



Impact of technology assumptions:

Similar high growth reference case and stabilization target from the same model with different technology assumptions



Reference: A2 (SRES)
Target: 550 ppm CO_2 only
Model: MESSAGE-MACRO

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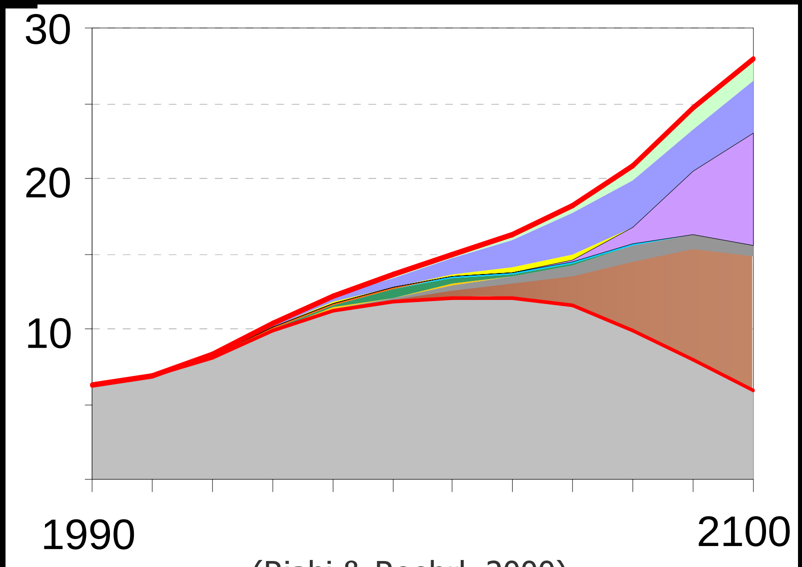
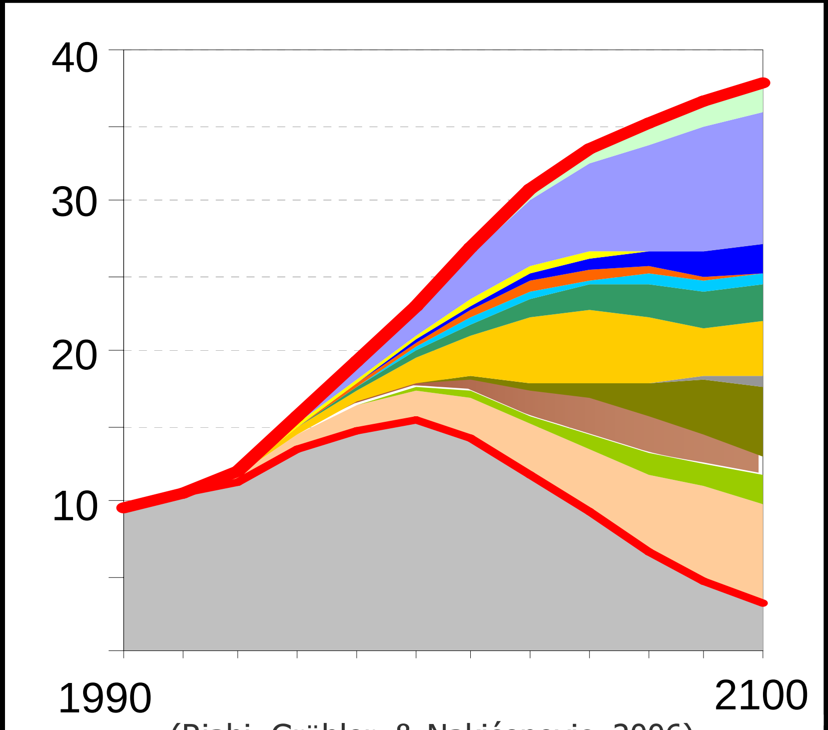
Annual CO_2 Emissions (GtC)



(Riahi & Roehrl, 2000)



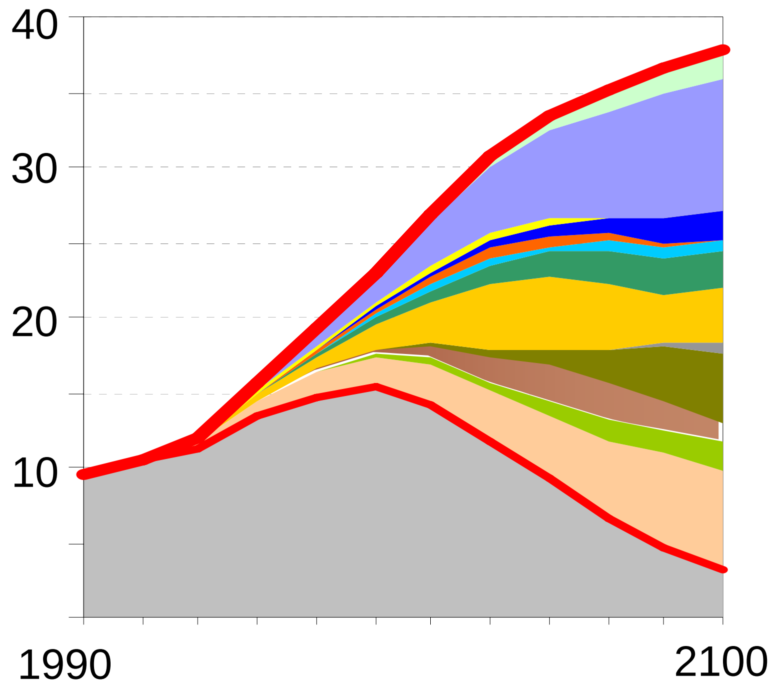
(Riahi, Grübler, & Nakićenovic, 2006)

Reference: A2 (SRES)
Target: 550 ppm CO_2 only
Model: MESSAGE-MACRO

Reference: A2 (SRES) multi-gas
Target: 4.5 W/m² (670ppm CO_2-eq) multi-gas
Model: MESSAGE-MACRO

Impact of technology assumptions:

Similar high growth reference case and stabilization target from the same model with different technology assumptions



(Riahi, Grübler, & Nakićenovic, 2006)

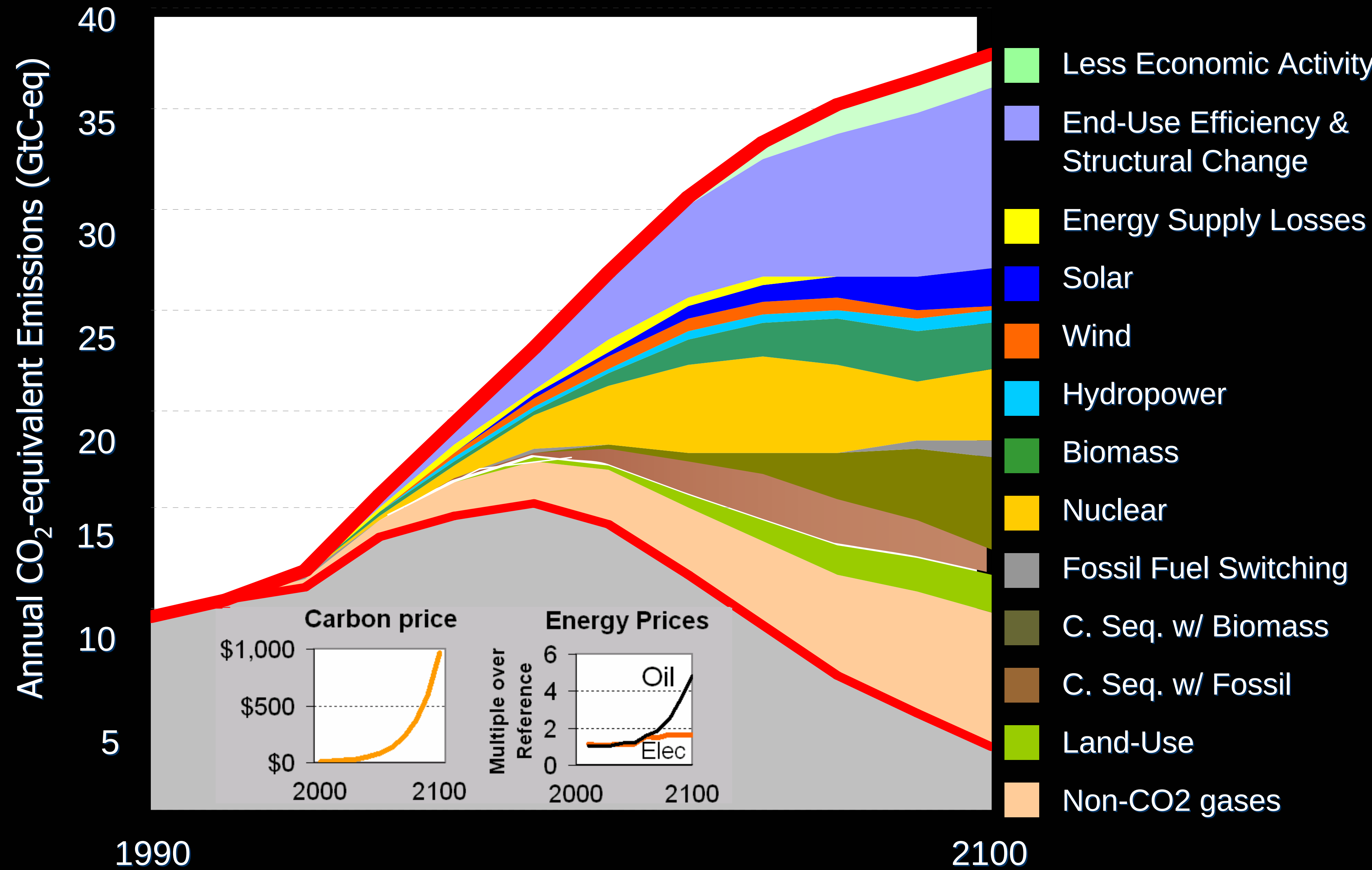
Reference: A2 (SRES) multi-gas
Target: 4.5 W/m² (670ppm CO_2-eq) multi-gas
Model: MESSAGE-MACRO

Exploring Energy Futures

model agnostic

- Constructing a common framework for interpretation
  - How do policy interventions affect key drivers of emissions?
  - What are the sources of mitigation in stabilization scenarios?
  - Accounting for direct equivalent energy accounting
- Insights from analyzing sample energy scenarios
- What is the role of energy efficiency?
- Summary of findings, and your questions

Examining the Role of Efficiency

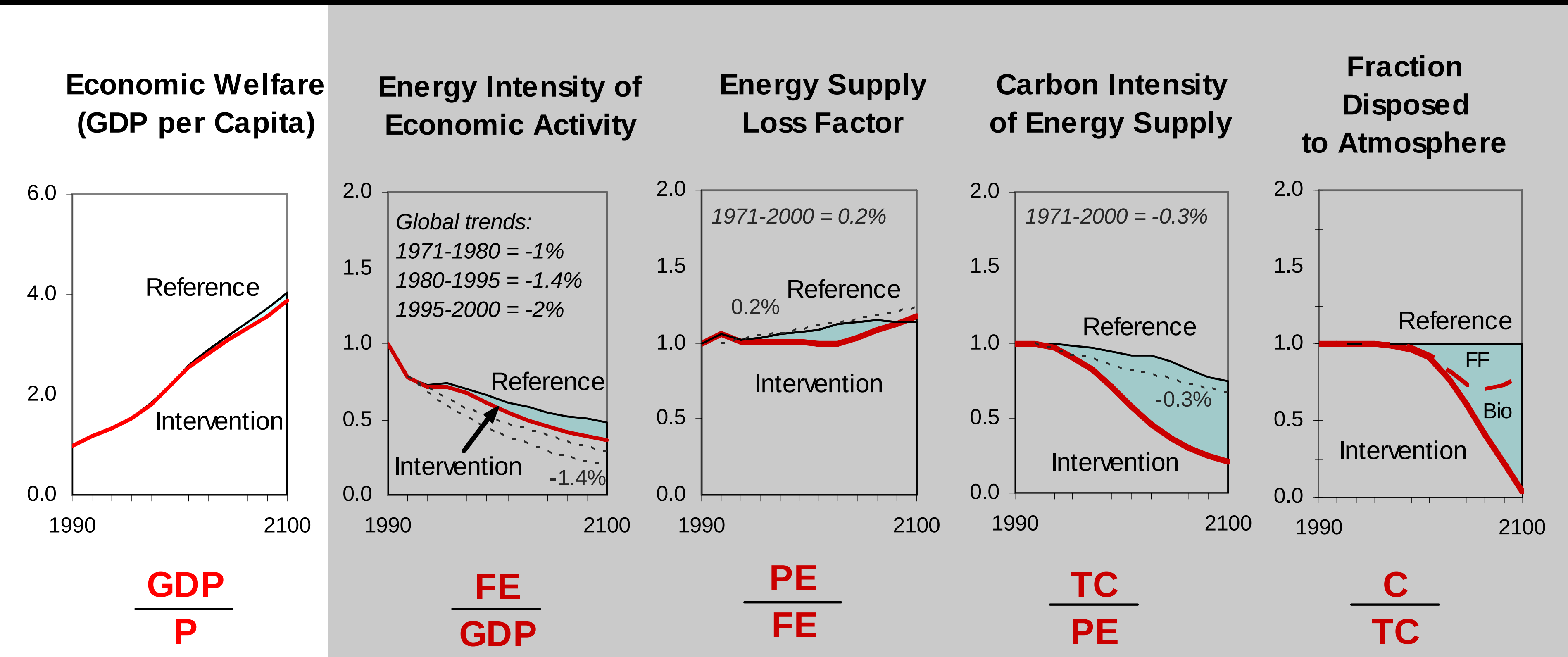


High growth reference case (A2) limited to 670ppm CO2-eq (MSG-MACRO, IIASA GGI, 2006)

Examining the Role of Efficiency

Economic Welfare (GDP per Capita)	Energy Intensity of Economic Activity	Energy Supply Loss Factor	Carbon Intensity of Energy Supply	Fraction Disposed to Atmosphere
$\frac{GDP}{P}$	$\frac{FE}{GDP}$	$\frac{PE}{FE}$	$\frac{TC}{PE}$	$\frac{C}{TC}$

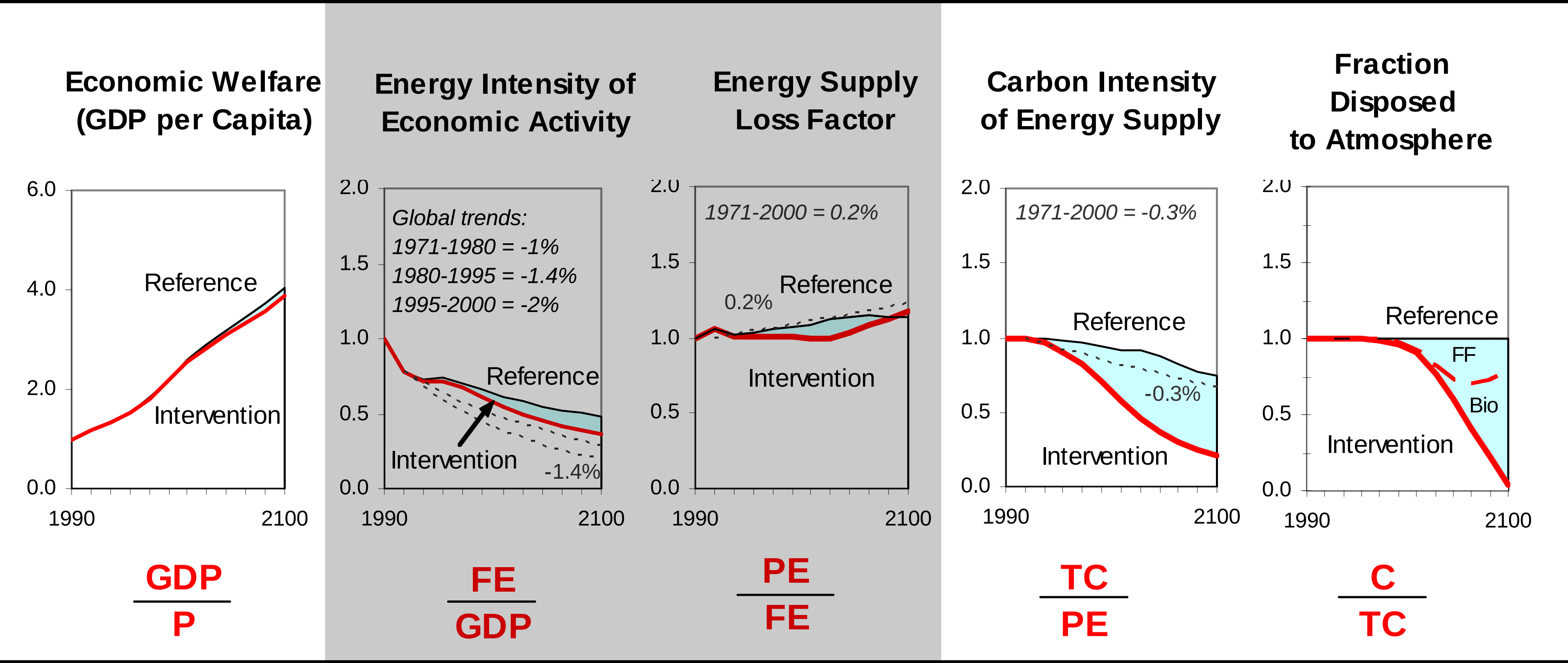
Examining the Role of Efficiency



Indexed to 1990=1

High growth reference case (A2) limited to 670ppm CO2-eq (MSG-MACRO, IIASA GGI, 2006)

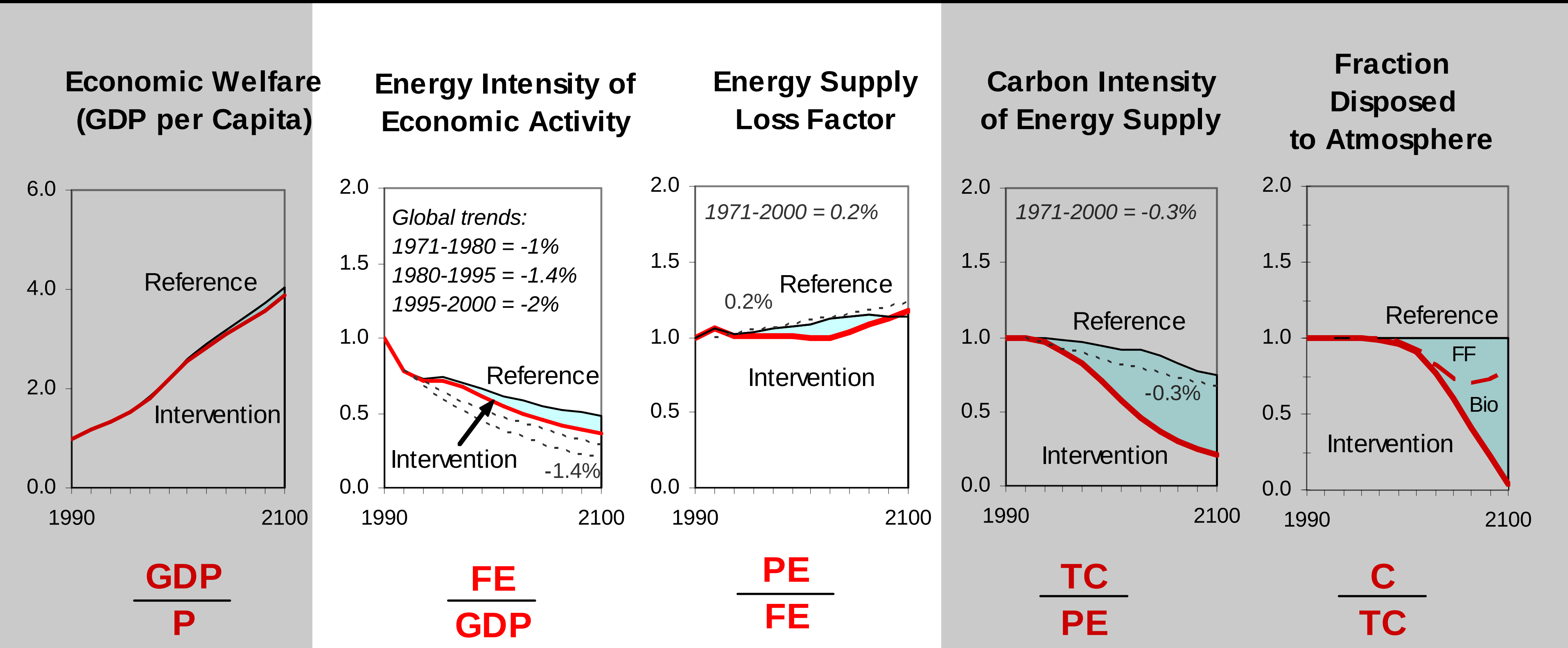
Examining the Role of Efficiency



Indexed to 1990=1

High growth reference case (A2) limited to 670ppm CO2-eq (MSG-MACRO, IIASA GGI, 2006)

Examining the Role of Efficiency

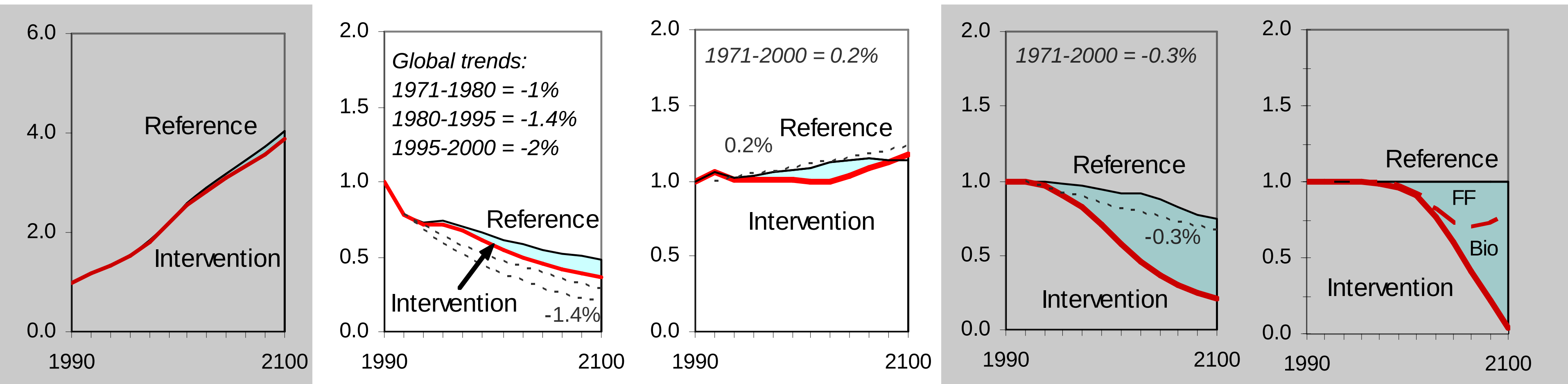


Indexed to 1990=1

High growth reference case (A2) limited to 670ppm CO2-eq (MSG-MACRO, IIASA GGI, 2006)

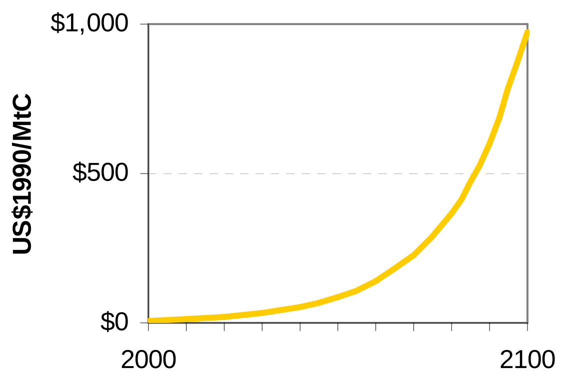
Examining the Role of Efficiency

Economic Welfare (GDP per Capita) | **Energy Intensity of Economic Activity** | **Energy Supply Loss Factor** | **Carbon Intensity of Energy Supply** | **Fraction Disposed to Atmosphere**



$\frac{GDP}{P}$ $\frac{FE}{GDP}$ $\frac{PE}{FE}$

Carbon Shadow Price



What if…?

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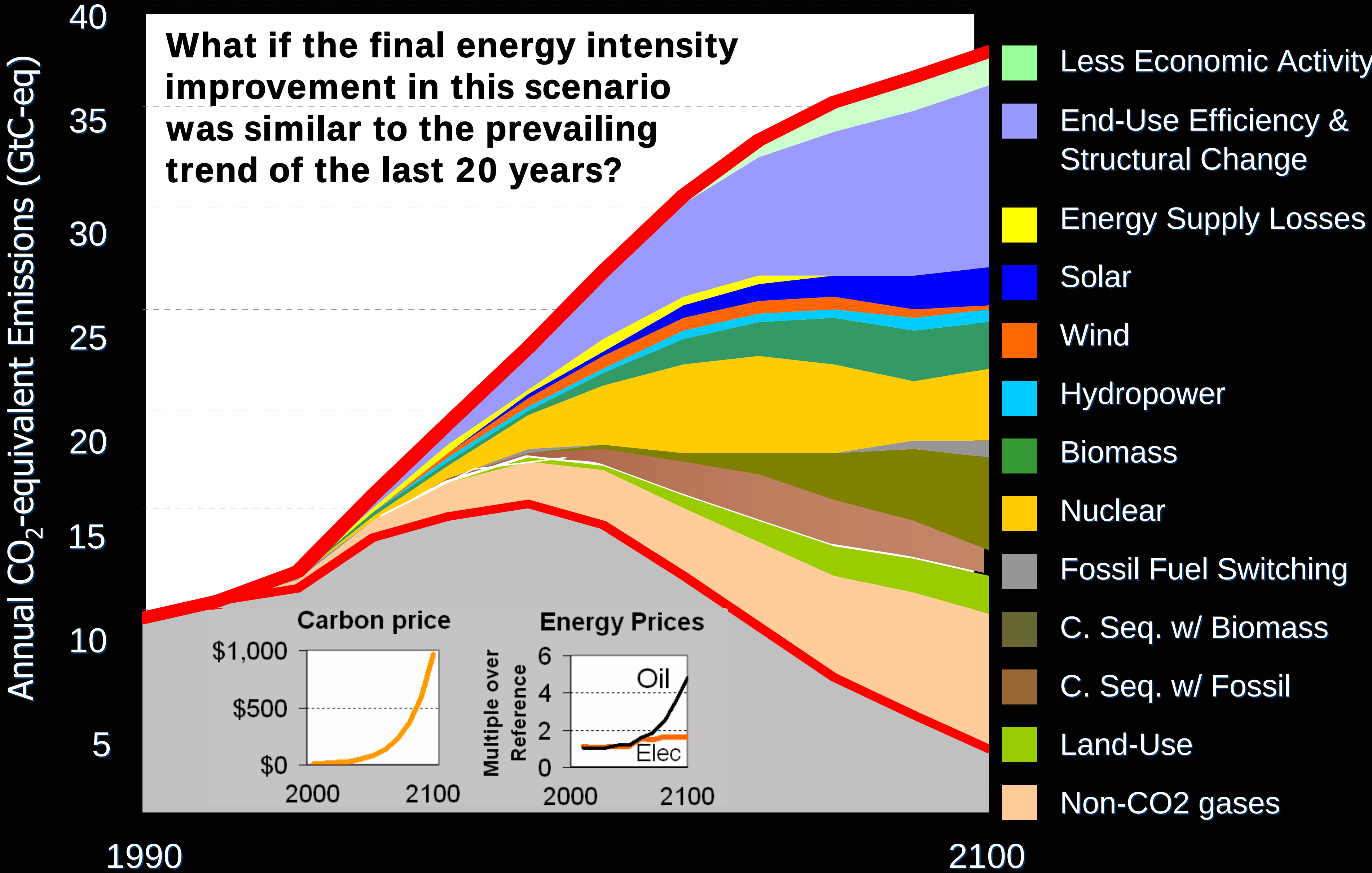
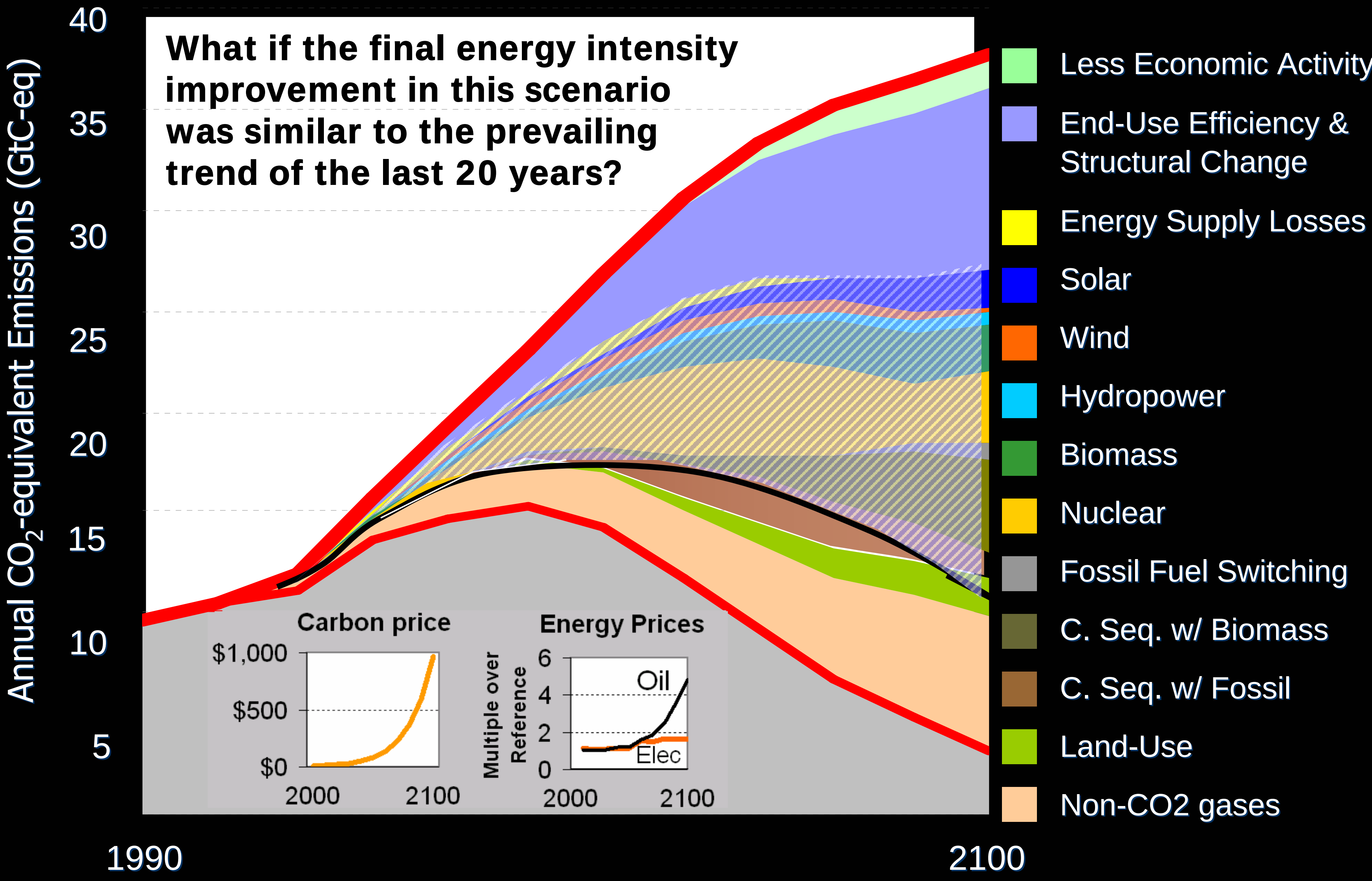
What difference does 0.5% make?



What difference does 0.5% make?



Exploring Energy Futures

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Summary of Findings

- Standard practice for data disclosure should provide *at least* the fields needed to identify sources of mitigation and impact on key drivers of emissions.

- When sufficient data is disclosed, the two decomposition techniques demonstrated can be applied to a wide range of energy scenarios to perform initial validation and assessment of diverse energy futures from a variety of sources, including bottom-up and top-down models.

- The direct equivalent method deserves more attention, even reconsideration (esp. for nuclear power), and must be taken into account in any policy analysis that promotes fuel switching.

- Modeling teams can apply consistent decomposition algorithms as part of standard reporting, and if not, third party analysts can do the analysis themselves (e.g. IEA report on the role of renewables in global energy scenarios).

Summary of Findings

- The decomposition techniques are helpful for discerning policy-relevant implications of scenarios generated with (infeasible) proxy policy interventions.

- Application of these decomposition techniques to sample scenarios indicates that the contribution of energy efficiency is often understated, straining energy supply options and leading scenarios to deploy high-risk technologies on a large scale.

- Environmental and social impacts of most large-scale supply-side mitigation have not been well investigated. ("We tend to like best the things about which we know the least." - Holdren)

- Even when ambitious assumptions about efficiency are taken into account, the level of effort implied by 400-550ppm stabilization scenarios is <u>staggering</u>.

- To convey the challenge and some solutions, common decomposition techniques can improve transparency, coherency, and comparability of scenario results.

Thank you

Acknowledgements

TNT, ECS & Energy Teams, IIASA

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Environmental Leadership Program

Interdisciplinary Program on Environment & Resources

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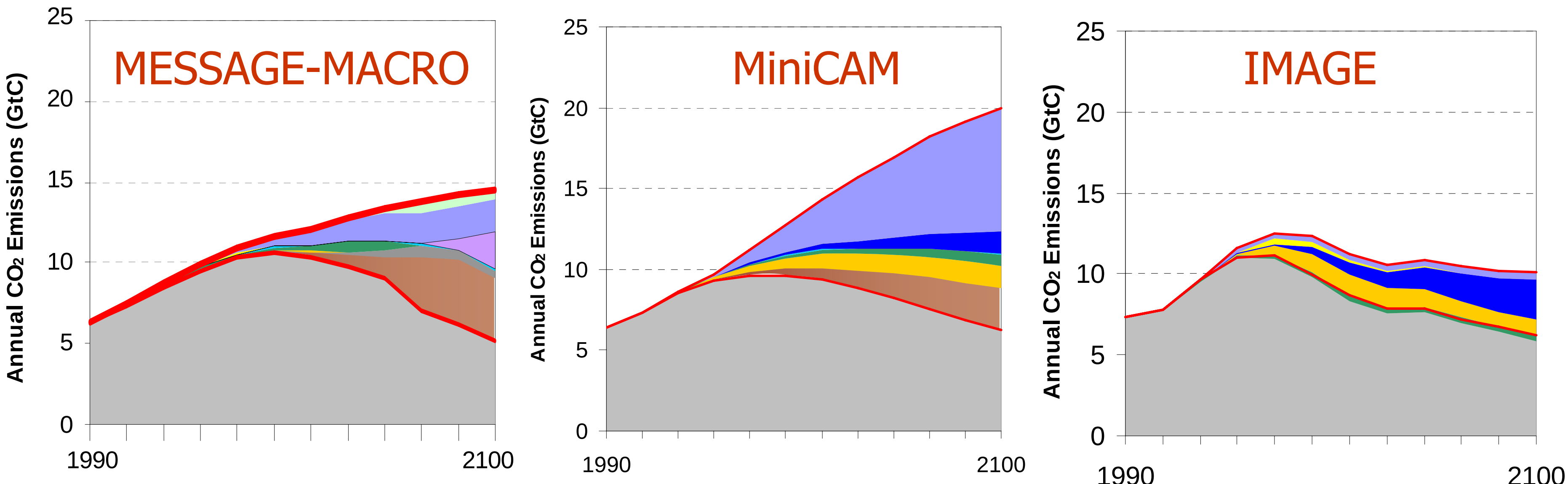
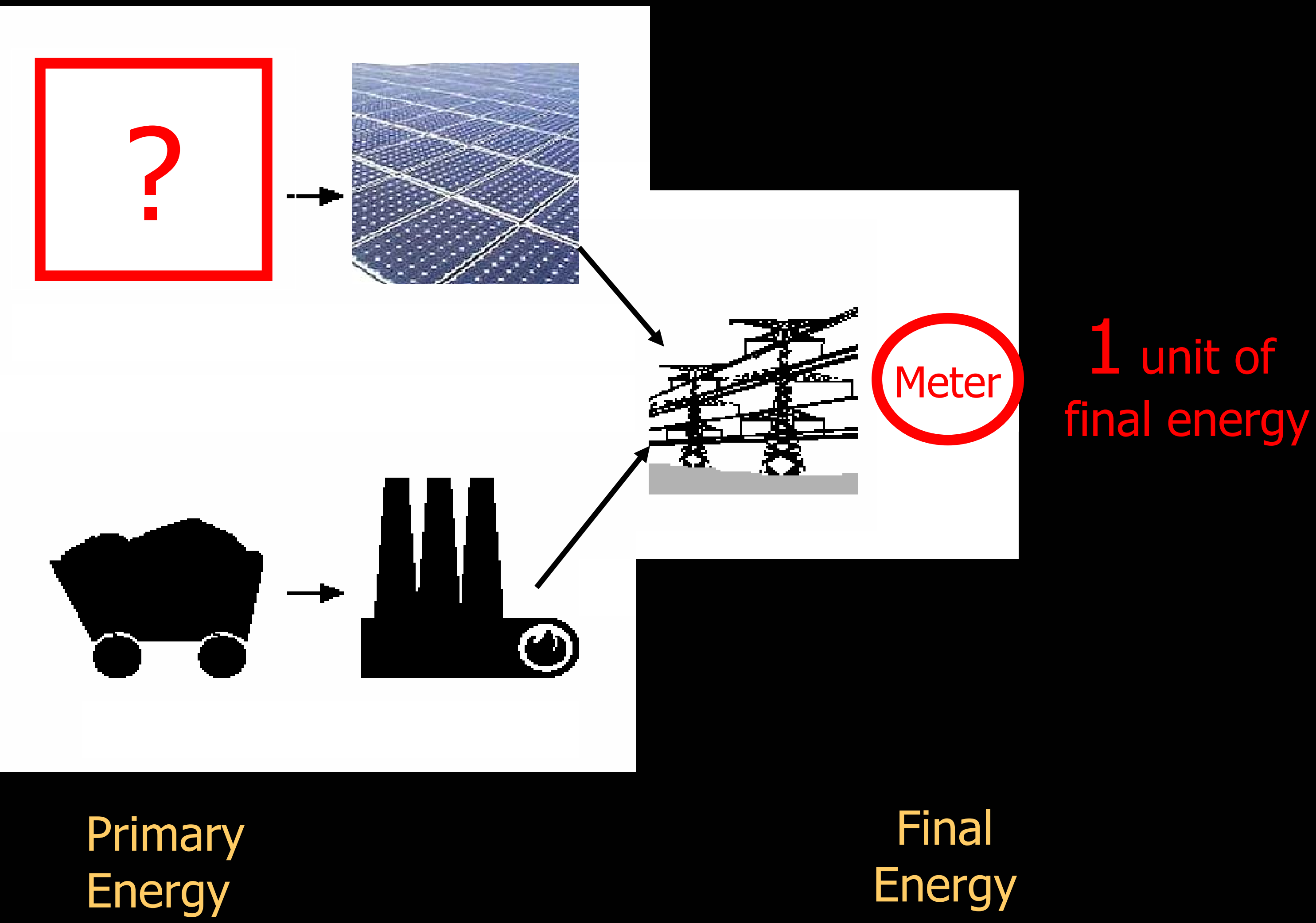
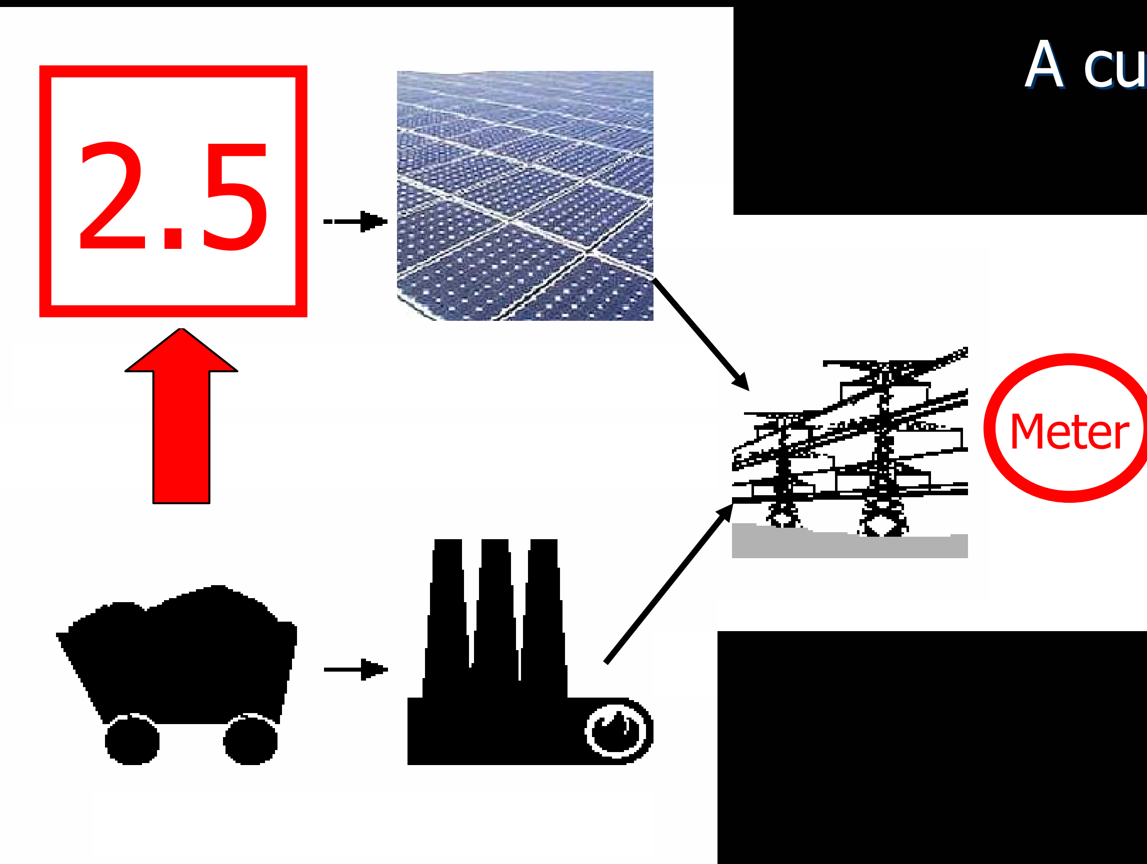


What quantity of primary energy should be credited with delivering one unit of final energy?



Thermal equivalent method: Solar power is treated as if it is a thermal power plant.

A customary practice: **38.6％**.



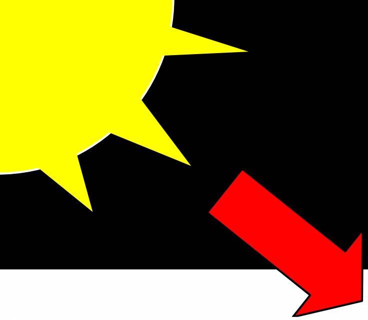
1 unit of final energy

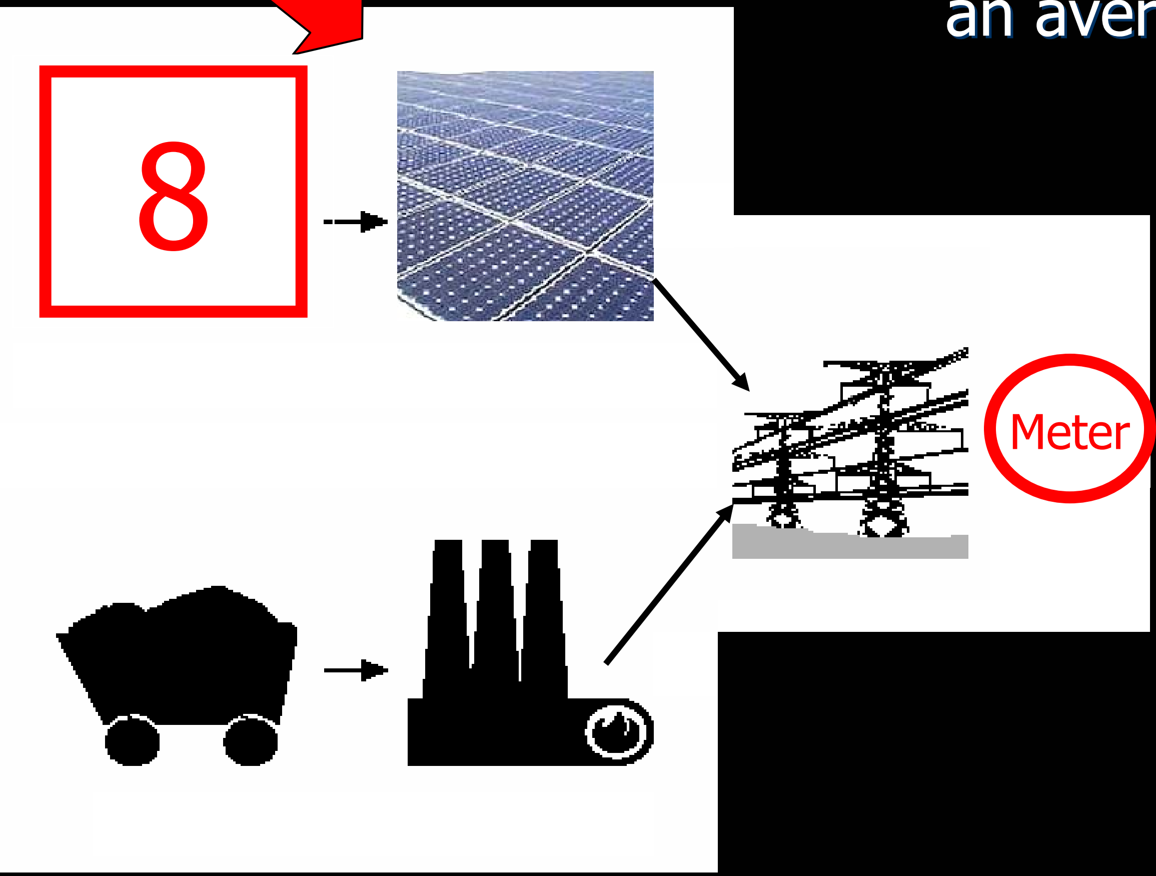
Primary Energy

Final Energy

Engineering method:

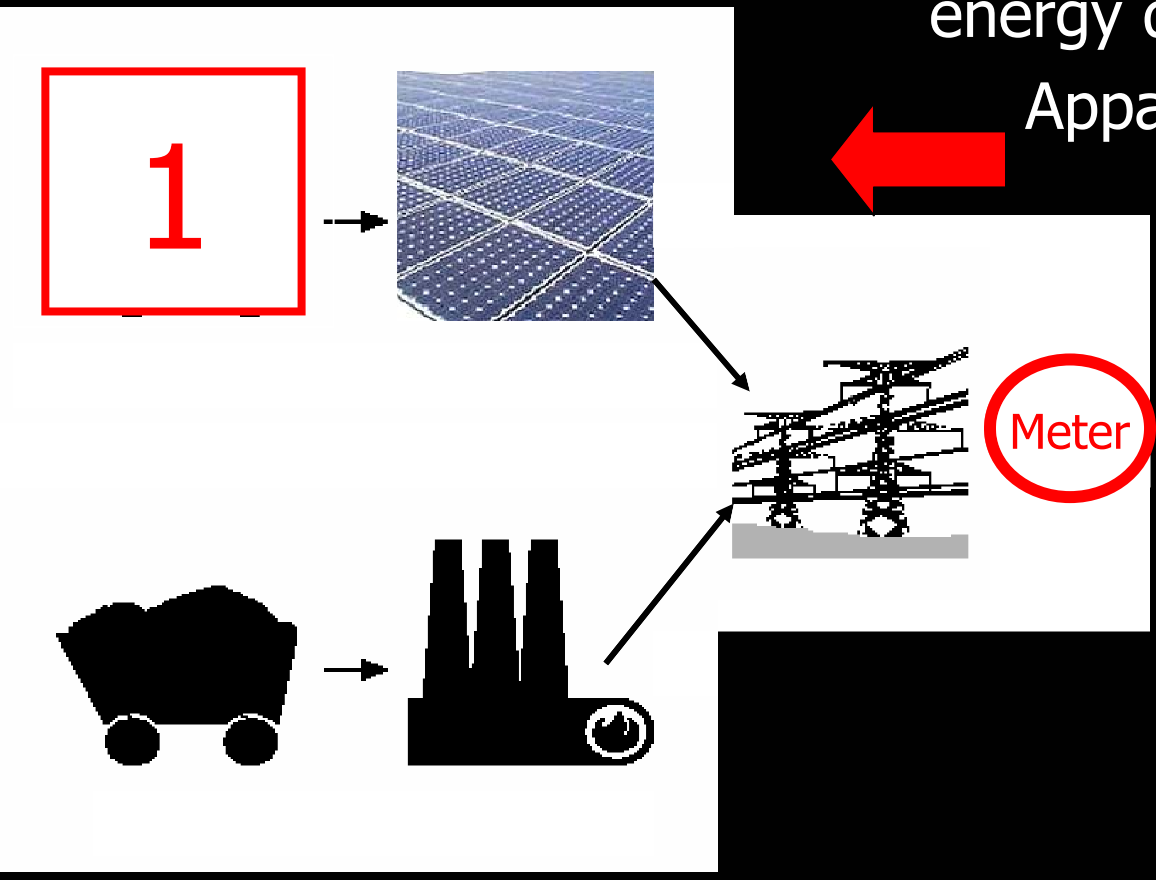
Solar cells convert sunlight with an average efficiency of **12%**.





Direct Equivalent method: Primary energy is set to be equal to the heat content of the final energy delivered.

Apparent efficiency: **100%**.

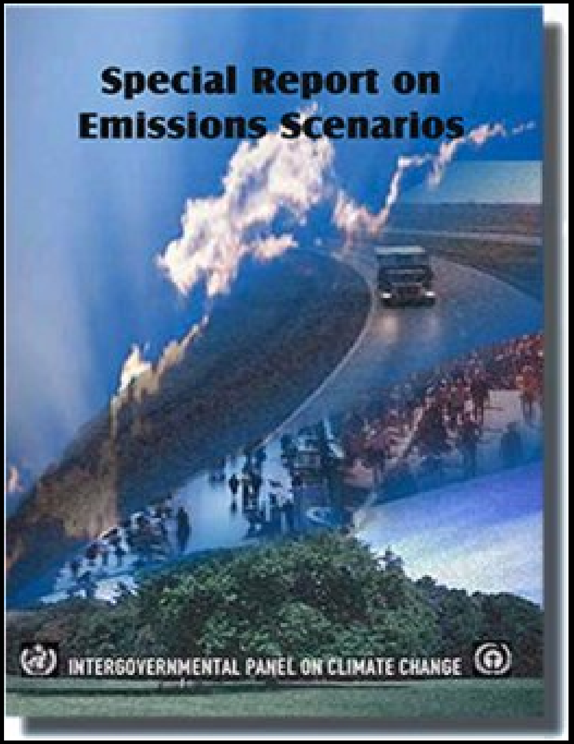


1 unit of final energy

Primary Energy

Final Energy

In the IPCC SRES scenario report:



The direct equivalent method applies to all non-thermal uses of nuclear and renewable energy.

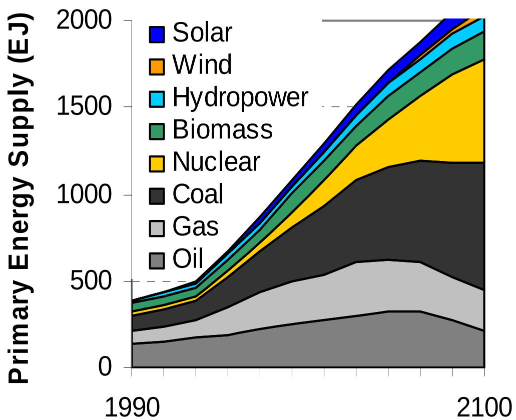
So the *apparent* system efficiency rises as more of these sources are used

Demand Elimination via Primary Energy Accounting

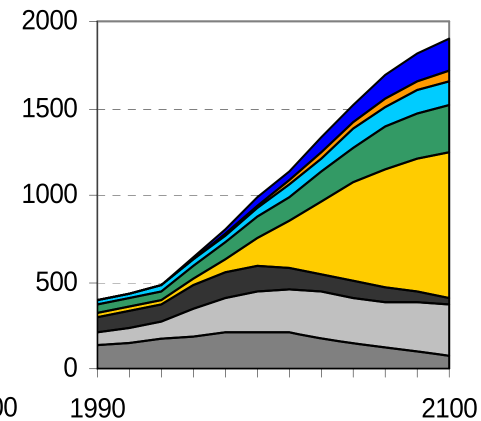
Thermal Equivalent Basis

A2-670ppm CO2-eq MESSAGE-MACRO

Reference Case

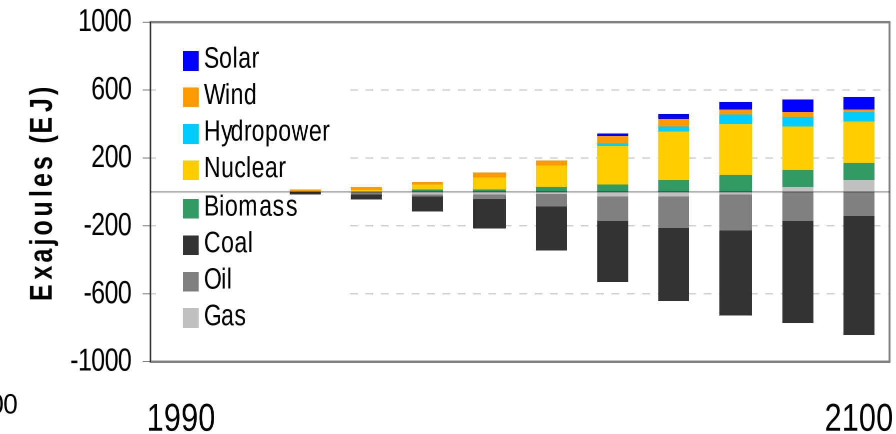


Mitigation Case



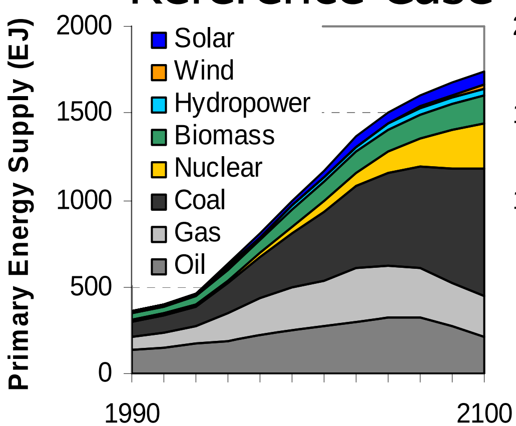
Change in Global Primary Energy Supply by Sourc

Thermal Equivalent Basis

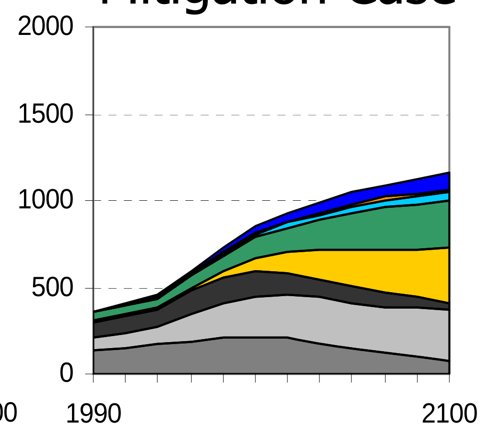


Direct Equivalent Basis

Reference Case



Mitigation Case



Change in Global Primary Energy Supply by Sourc

Direct Equivalent Basis