

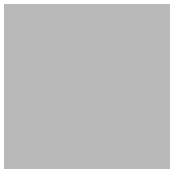
PAUL SCHERRER INSTITUT



Kathrin Volkart, Martin Densing, Evangelos Panos, Christopher Mutel (PSI)
Nagore Sabio, Neil Strachan (UCL)

Implementation of multi-objective optimization in the MARKAL framework for simultaneously analysing the economic, societal and environmental performance of the global energy system

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Climate change – what else?

- Climate change dominates the current environmental discussion and the main reason for the transformation of our energy systems.
- The energy system transformation has impacts that go beyond climate change. These multiple dimensions have been acknowledged by:
 - UNFCCC (2002):
The requirements to be met by the National Adaption Programmes of Action [...] are appropriate and ambitious, notably [...] demonstrating clear priority choices [...] concerning social, economic and ecologic-environmental dimensions [...]
 - IPCC WG III (2014):
Climate change mitigation is [...] a multi-objective problem embedded in a broader sustainable development and equity context.
- The multi-dimensional impacts are also referred to as:
 - *Energy Trilemma* by the World Energy Council, and
 - *Pillars of Sustainability* by the United Nations.

Goals of this study

In IPCC WG III (2014), the following policy objectives are listed to be aligned with climate mitigation strategies :

- Air pollution and health
- Energy security
- Energy access
- Employment
- Biodiversity conservation
- Water use

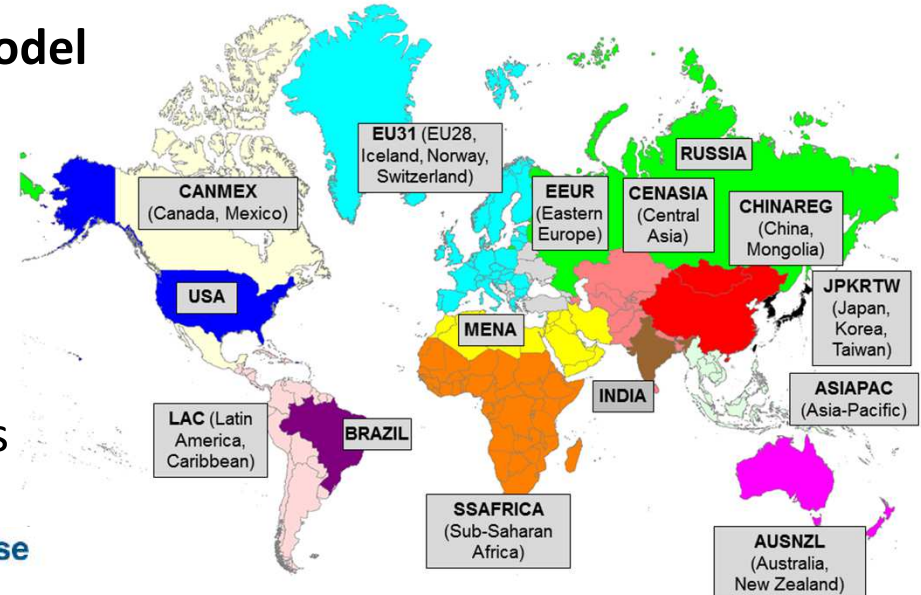
Goals

- Multi-dimensional analysis of energy system transformation pathways
- Identification of trade-offs of energy system transformation pathways
- Supporting decision-making in the context of climate change mitigation

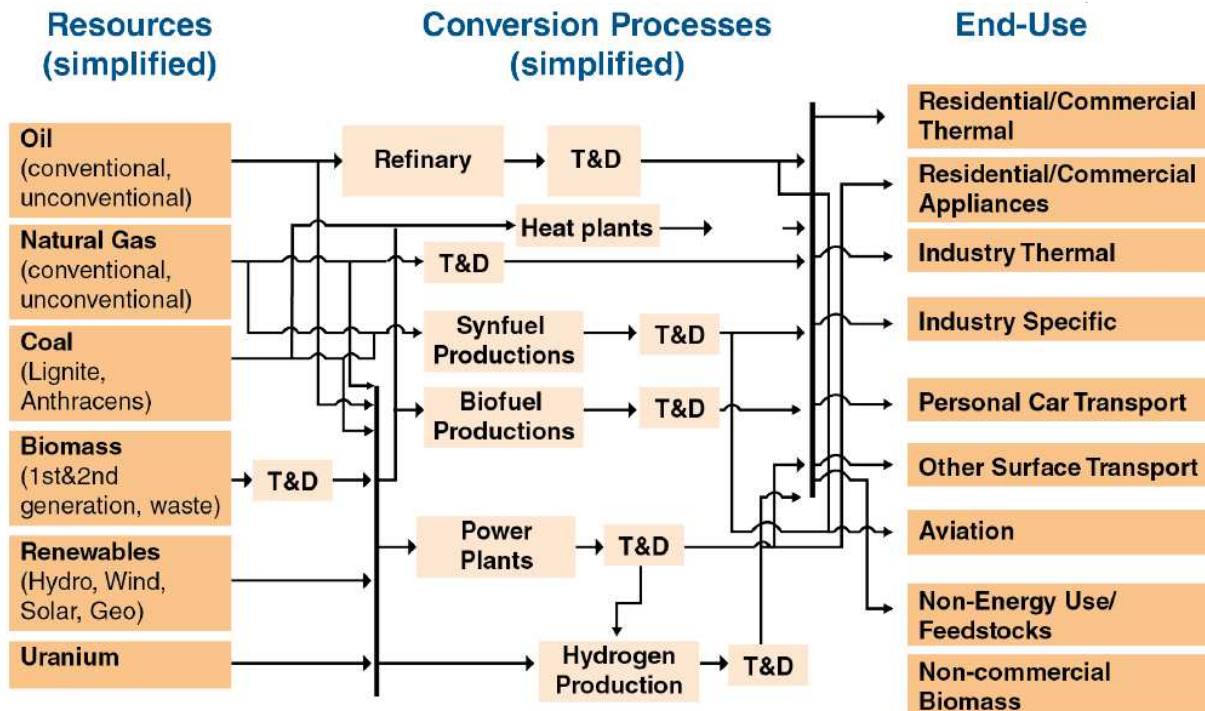
- Simultaneously addressing the complexity and multi-dimensionality of energy systems

Global Multi-regional MARKAL (GMM) model

- Energy system model
- Least-cost optimization framework
- 15 world regions
- Time horizon of 100 years
- Developed at PSI over the last 15 years



WEC/PSI (2013)



WEC/PSI (2013)

	Delayed climate action scenario	Climate action scenario
Population	Increase	Strong increase
GDP	GDP growth has priority	Less GDP growth
Climate change	Adaptation	Mitigation
CO₂ markets	Develop slowly (23-45 \$/t CO ₂ in 2050)	Rapid state control (70-80 \$/t CO ₂ in 2050))
Unconventional resources	Opening of markets; incentive to use due to high demand	Regulated; little incentive to use due to lower demand
Renewable energy	Limited promotion	Selective state promotion
CCS	Market driven	State support
Nuclear	plants under construction partially not in operation	State support
Energy efficiency	Based on economic criteria	State promotion

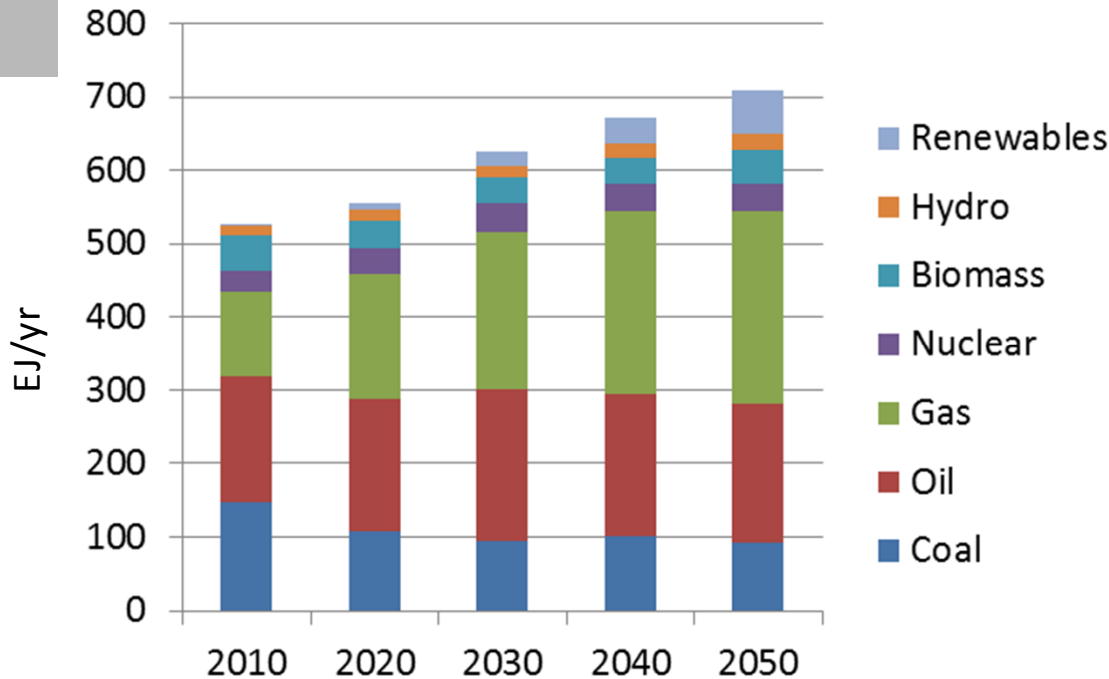
The assessment is based on an illustrative set of objectives:

- Economy
 - Total discounted system costs, in M\$
- Environment
 - LCA-based greenhouse gas emissions, in Mt CO₂-eq
 - Non-renewable energy use, in PJ
- Society
 - Maximum fatalities in accidents, ratio scale
 - LCA-based particulate matter emissions, in Mt PM10-eq
- Security of supply
 - Import of energy carriers, in PJ
 - Oil use in surface transport, in PJ

LCA = Life-cycle assessment

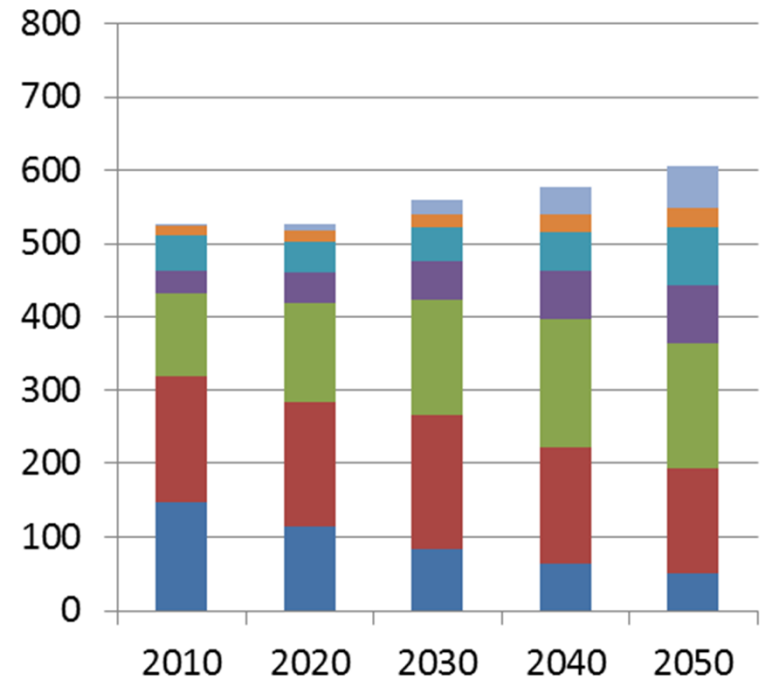
Results: Total Primary Energy Supply

Delayed climate action scenario



- Coal use decreases slowly
- Gas use strongly increases
- Oil and renewables grow slowly
- Nuclear, biomass and hydro are stable

Climate action scenario

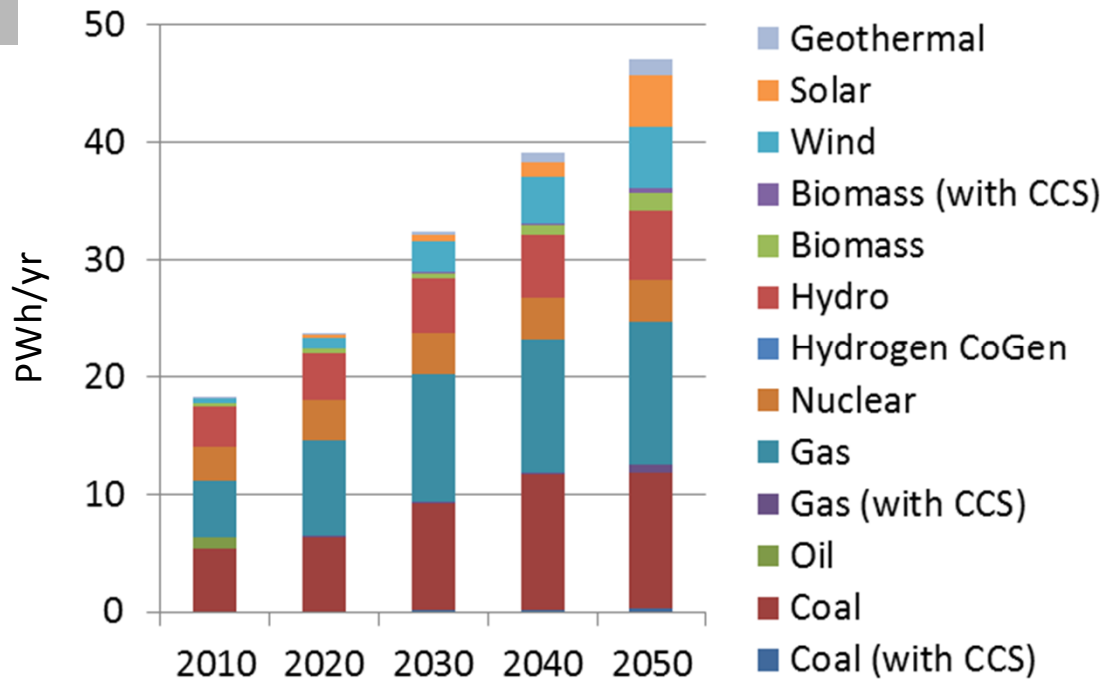


- Coal use strongly decreases
- Gas use strongly increases
- Nuclear and biomass grow strongly
- Renewables and hydro grow slowly



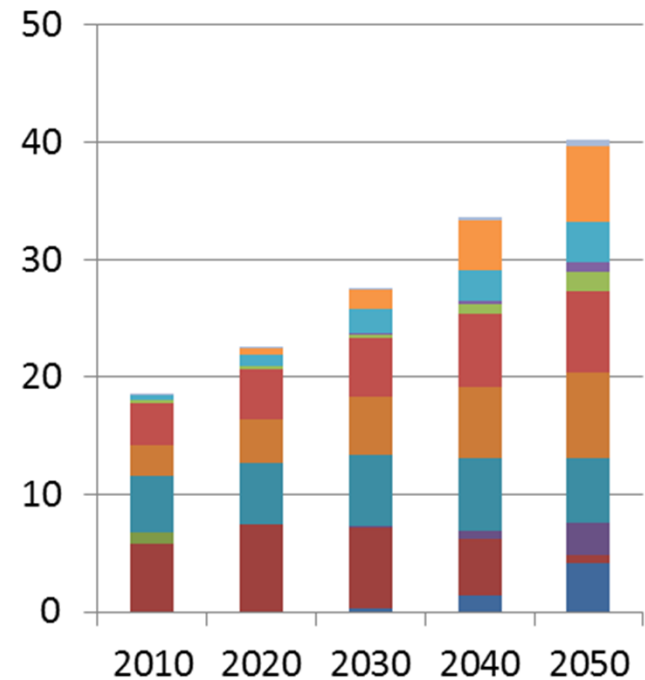
Results: Electricity generation

Delayed climate action scenario



- Coal and gas power increase
- Nuclear generation is stable
- Hydro power increases slightly
- Renewable energies expand

Climate action scenario

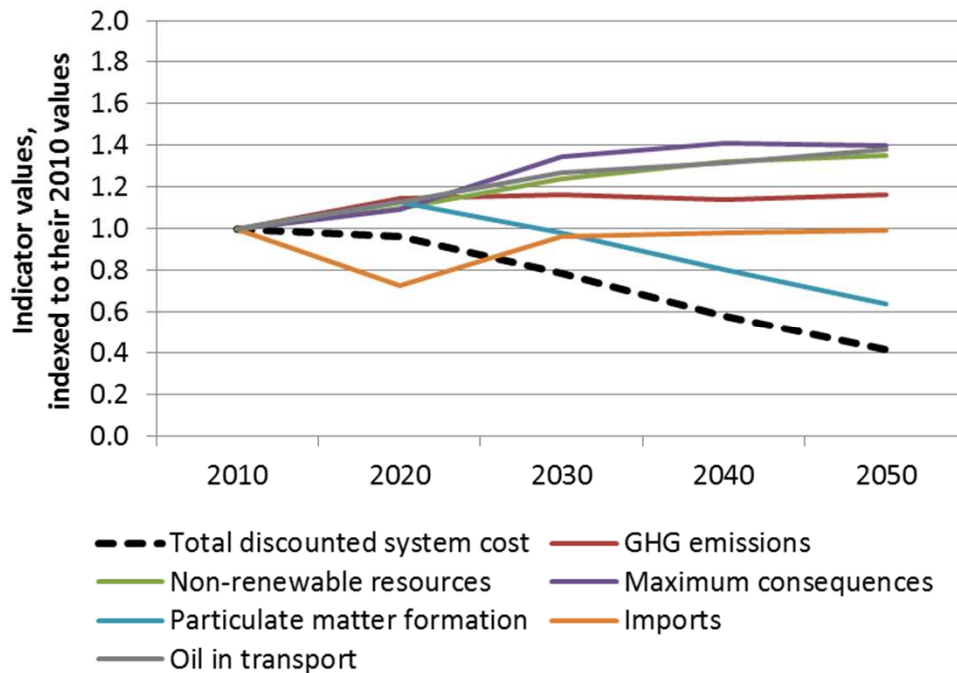


- Coal and gas power with CCS introduced
- Nuclear generation increases strongly
- Hydro power increases
- Renewable energies expand



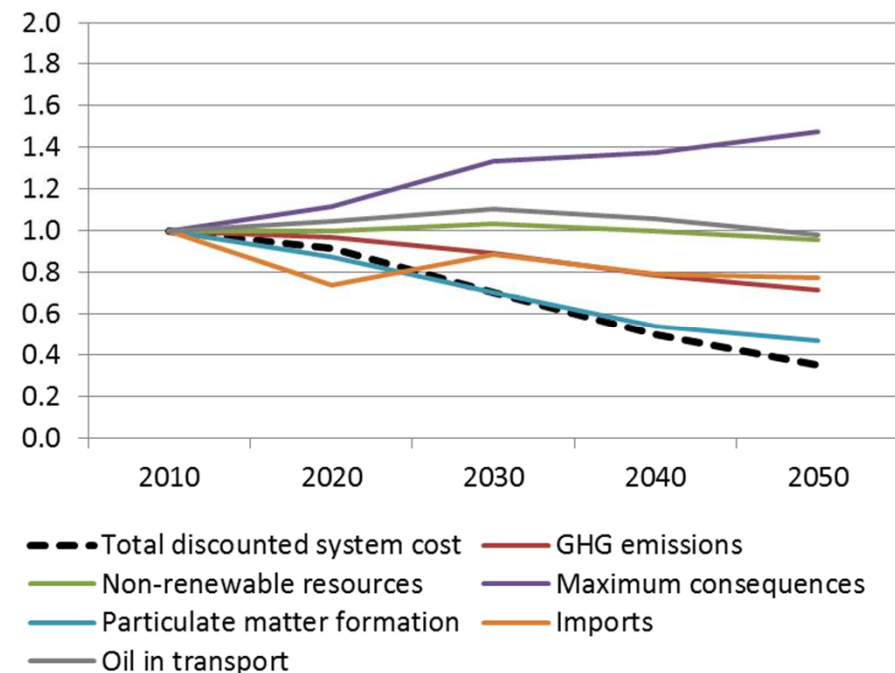
Results: Co-benefits and adverse side-effects

Delayed climate action scenario



- GHG emissions, non-renewable energy use, oil in surface transport and maximum consequences increase
- Imports are stable
- PM emissions decrease

Climate action scenario



- Maximum consequences increase
- Non-renewable energy use and oil in surface transport are stable
- GHG emissions, imports and PM emissions decrease

Based on the small set of objectives, the co-benefits and adverse side-effects of climate action compared to a less stringent CO₂ policy pathway are:

- Environment
 - Not only CO₂ but also the sum of all **GHG emissions** decreases.
 - The increasing energy demand is mainly covered by renewable energies what leads to stable use of **non-renewable resources**.
- Society
 - The expansion of low-carbon nuclear and hydro power generation leads to increasing **maximum consequences**.
 - Due to the decrease in use of fossil energy, the **particulate matter emissions** decrease faster and stronger.
- Security of supply
 - With the use of more domestic renewable energies, the **import of energy carriers** is reduced.
 - **Oil use in surface transport** is reduced and replaced by alternative fuels.

Tackling the adverse side-effects

- In our limited set of objectives, we found increasing maximum consequences as an adverse side-effect of climate action.
- Questions:
 - Which technologies are responsible for this side-effect?
 - How can we reduce this side effect at low cost?
 - In which sectors and regions are these «low-hanging fruit»?
- Idea:
 - Change the modelling framework to allow for optimizing for multiple objectives instead of cost only
- Approaches:
 - Weighted-sum approach

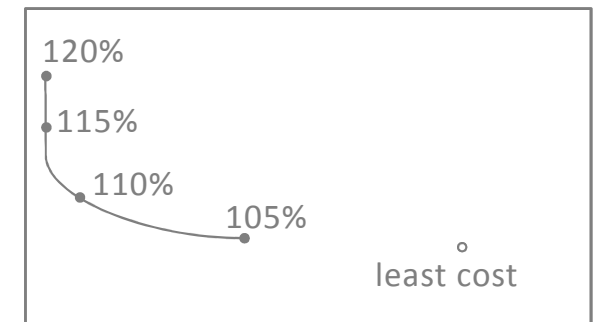
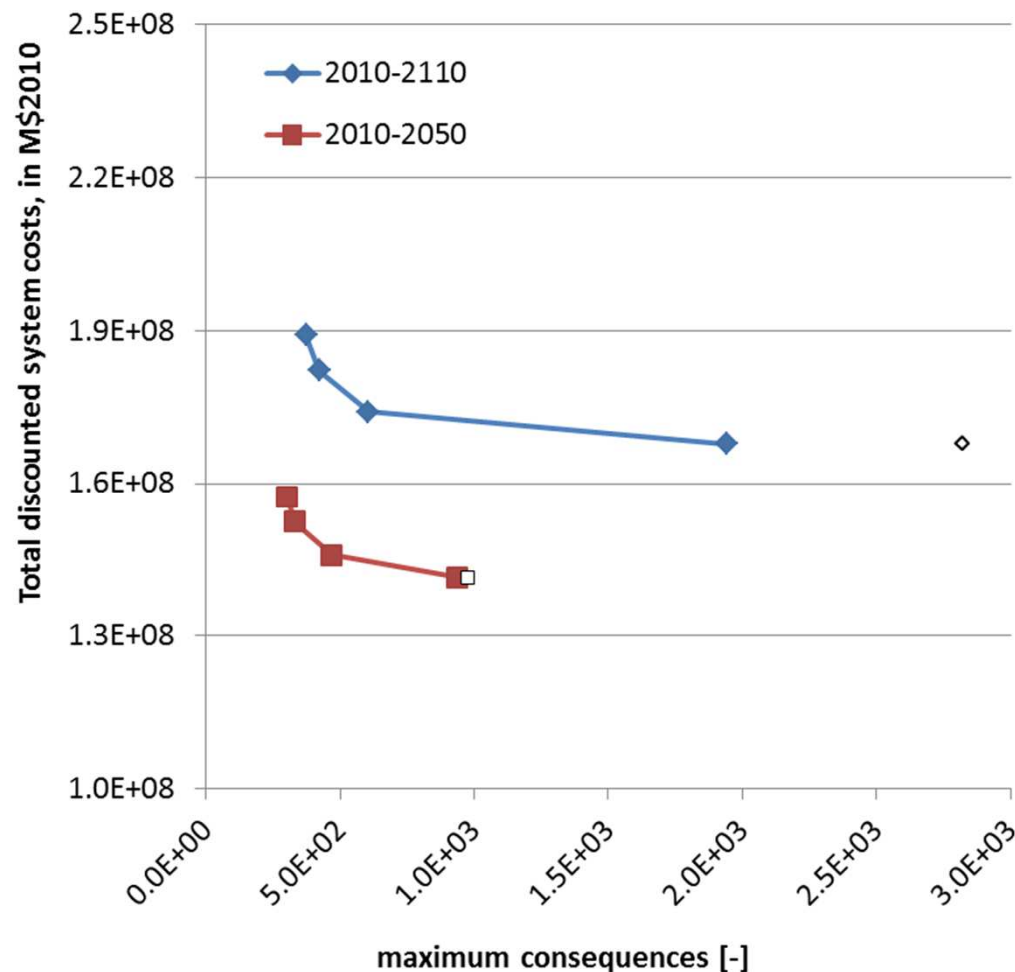
$$\min(\text{cost}) \rightarrow \min(w_{\text{cost}} * \text{cost} + w_{\text{other}} * \text{other indicator})$$

- Epsilon-constraint approach

$$\min(\text{cost}) \rightarrow \min(\text{other indicator}) \text{ s.t. cost constraint}$$

Results: Epsilon constraint method

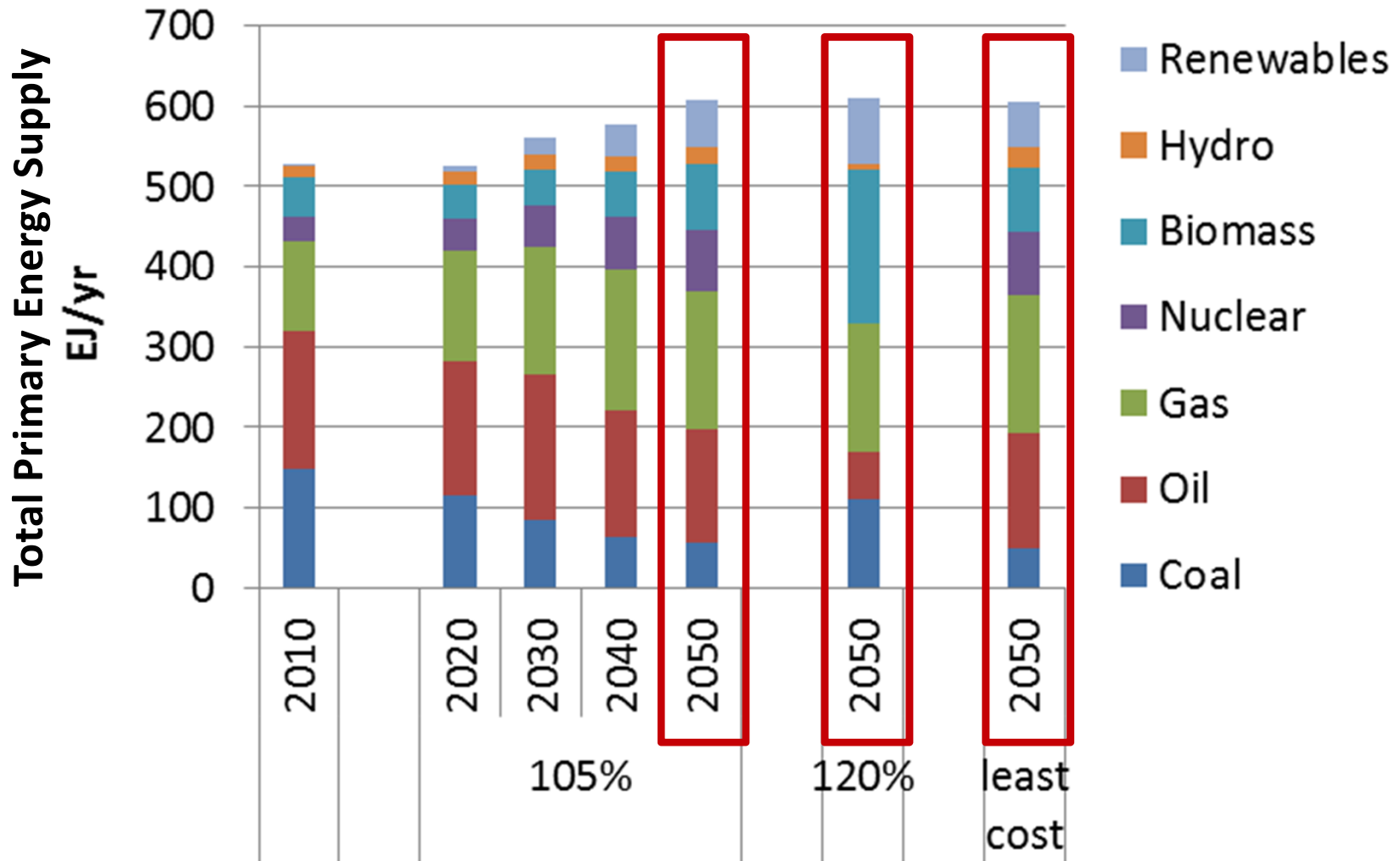
- Minimization: maximum consequences
- Constraint: 120%/115%/110%/105% of total discounted system costs in the least cost run





Results: Epsilon constraint method

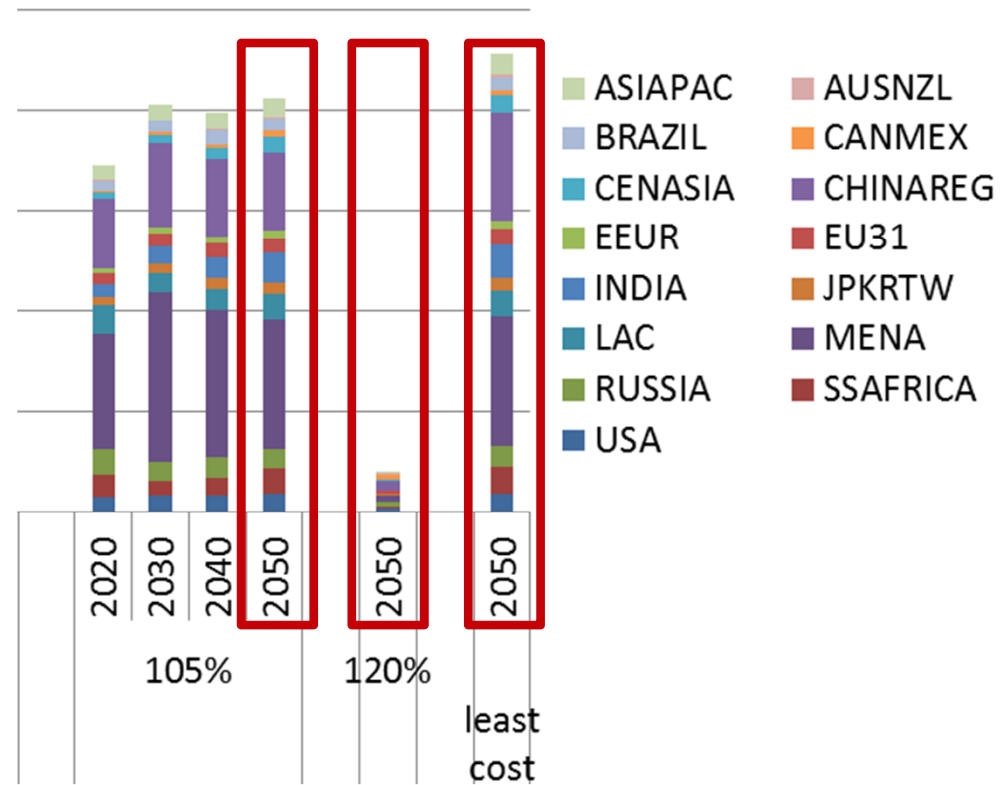
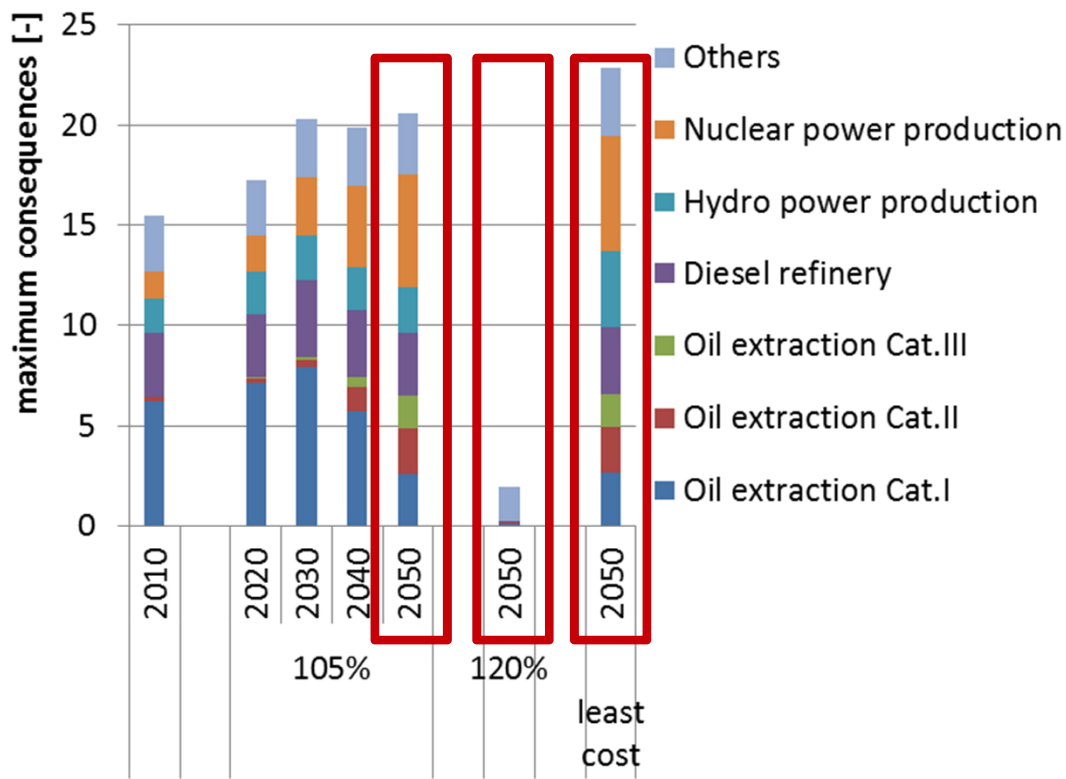
- Climate action scenario
- Minimization: maximum consequences
- Constraint: 105%/120% of total discounted system costs in the least cost run





Results: Epsilon constraint method

- Climate action scenario
- Minimization: maximum consequences
- Constraint: 105% of total discounted system costs in the least cost run



Applying the epsilon constraint method to analyse the adverse side effect of high maximum consequences of the climate pathway, leads to the following conclusions:

- Which technologies are responsible for this side-effect?
 - Oil extraction
 - Oil refining
 - Hydro power generation
 - Nuclear power generation

- How can we reduce this side effect at low cost?
 - Difficult to reduce the maximum consequences at low cost
 - Considerable investment is required to reach low levels

- In which sectors and regions are these «low-hanging fruit»?
 - Mainly hydro power
 - Mainly CHINAREG



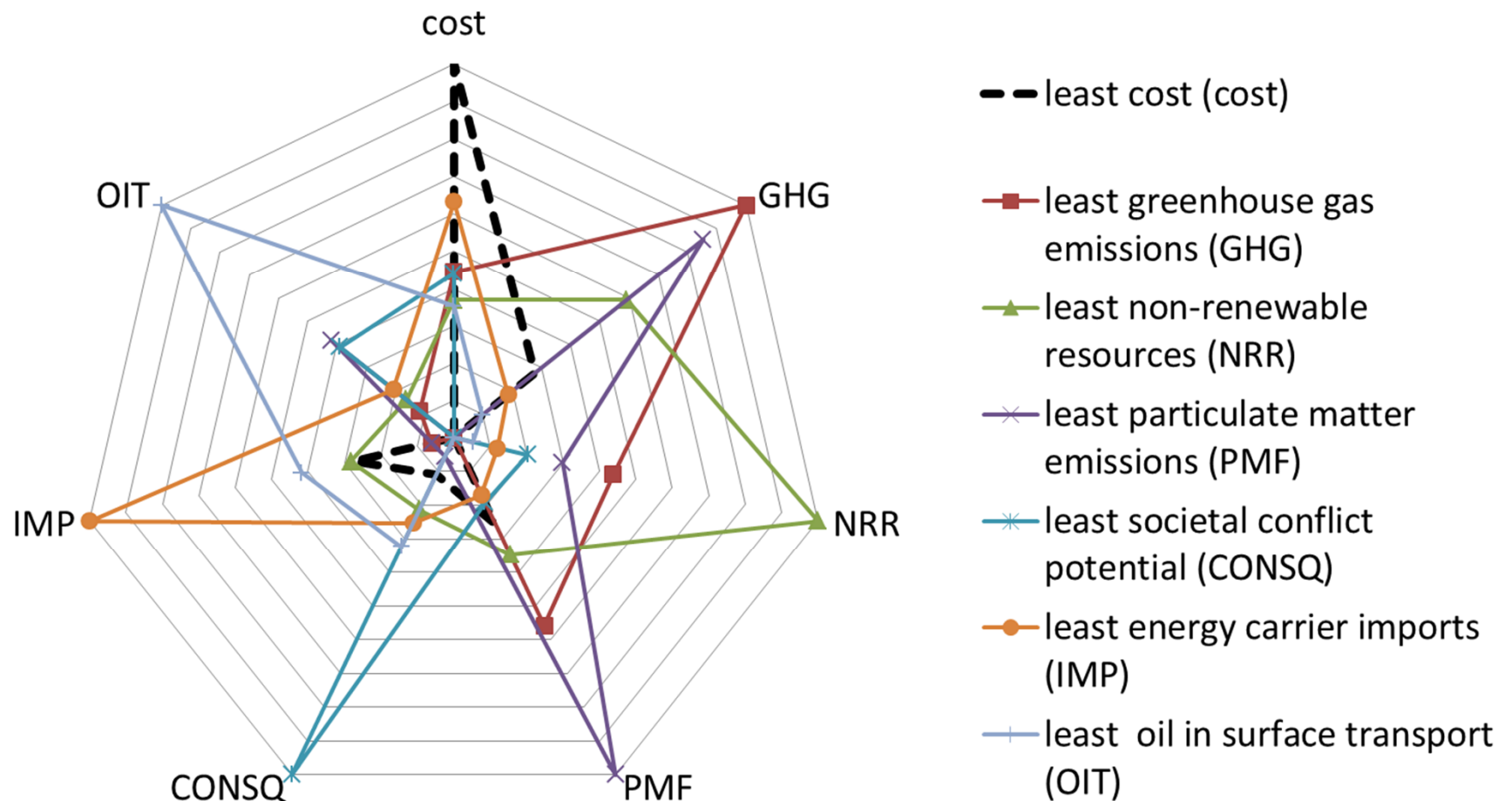
Results: Overview epsilon constraint method

- Delayed climate action scenario
- Constraint: 105% of total discounted system costs in the least cost run
- Period: 2010-50
 - Cumulative reduction potential compared to the least cost run
 - Co-benefits

	Cost [M US\$]	GHG [Mt CO ₂ -eq]	NRR [PJ]	CONSQ [-]	PMF [Mt PM10-eq]	IMP [PJ]	OIT [PJ]	
Cost min	1.52E+08	1.8E+06	2.8E+07	9.7E+02	2.5E+03	9.2E+06	5.1E+06	
Relative to cost min	GHG min	+1%	-16%	-4%	+4%	-16%	+9%	-3%
	NRR min	+1%	-7%	-10%	-4%	-5%	-0%	-5%
	CONSQ min	+1%	+16%	-2%	-32%	+3%	+12%	-12%
	PMF min	+2%	-13%	-3%	+2%	-40%	+9%	-12%
	IMP min	+1%	+2%	-1%	-5%	+4%	-30%	-6%
	OIT min	+1%	+4%	-1%	-8%	+13%	-6%	-30%

Results: Overview epsilon constraint method

- Delayed climate action scenario
- Cumulative results for the period 2010-50
- Constraint: 105% of total discounted system costs in the least cost run
- Scale: center (worse) to outside (better)



Concluding remarks

- Conclusions
 - Based on a small set of objectives, we could perform a multi-dimensional analysis of two energy system transformation pathways.
 - We identified trade-offs of a climate action pathway.
 - The least cost framework MARKAL could be adjusted such that multi-objective optimization of energy systems is possible.
 - The epsilon constraint method allows for multi-objective optimisation without adverse effects of normalization and the analysis of side-effects.

- Outlook
 - Analysis of the trade-offs of climate change policies, also on regional levels
 - Expansion of the set of objectives
 - Support of decision-making by comprehensively presenting co-benefits and disadvantages of the energy system transformation pathways

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