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# 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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*http://www.momscleanairforce.org/*

# 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**

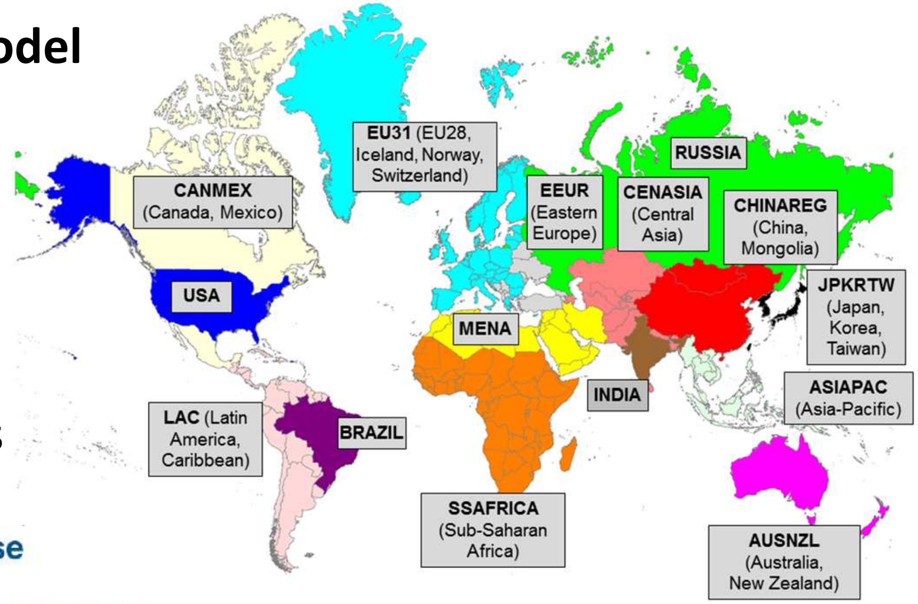
- Multi-dimensional analysis of energy system transformation pathways
- Identification of trade-offs of energy system transformation pathways
- Supporting decision-making in the context of climate change mitigation

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

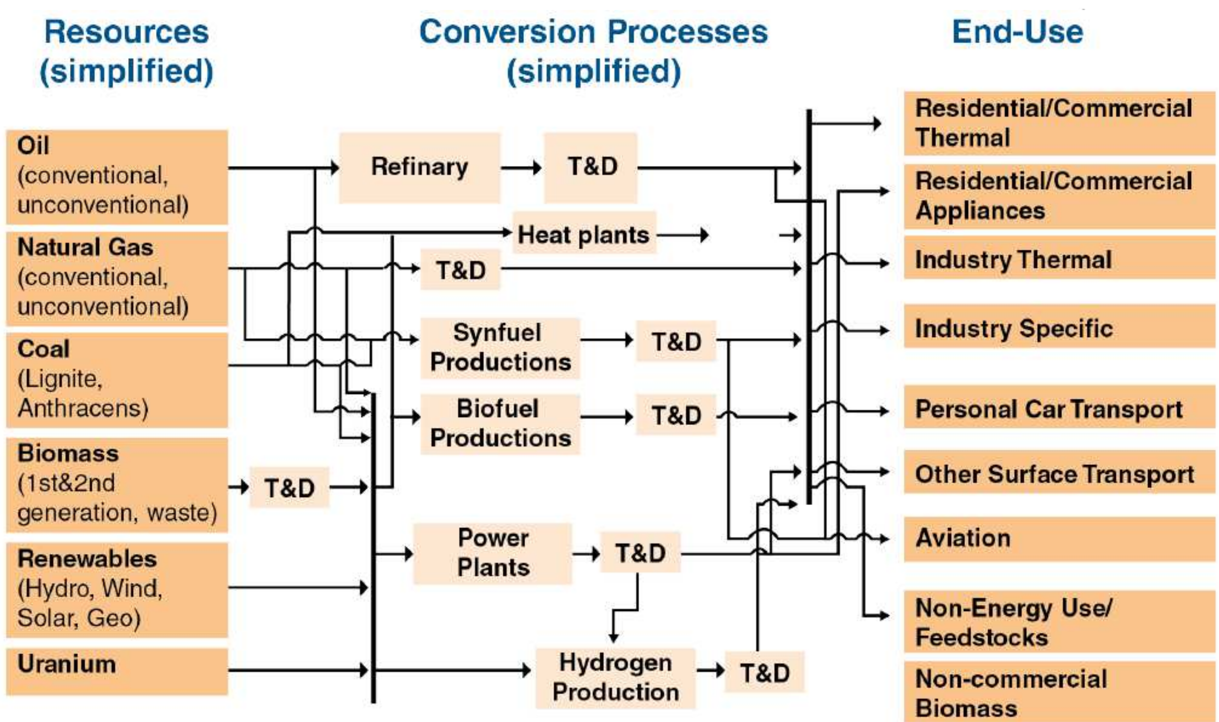
# Modelling framework: Model

## 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)*

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# Modelling framework: Scenarios

| | Delayed climate action scenario | Climate action scenario |
|---|---|---|
| **Population** | Increase | Strong increase |
| **GDP** | GDP growth has priority | Less GDP growth |
| **Climate change** | Adaptation | Mitigation |
| **$CO_2$ markets** | Develop slowly (23-45 \$/t $CO_2$ in 2050) | Rapid state control (70-80 \$/t CO2 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 |

*WEC/PSI (2013)*

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# Modelling framework: Policy objectives

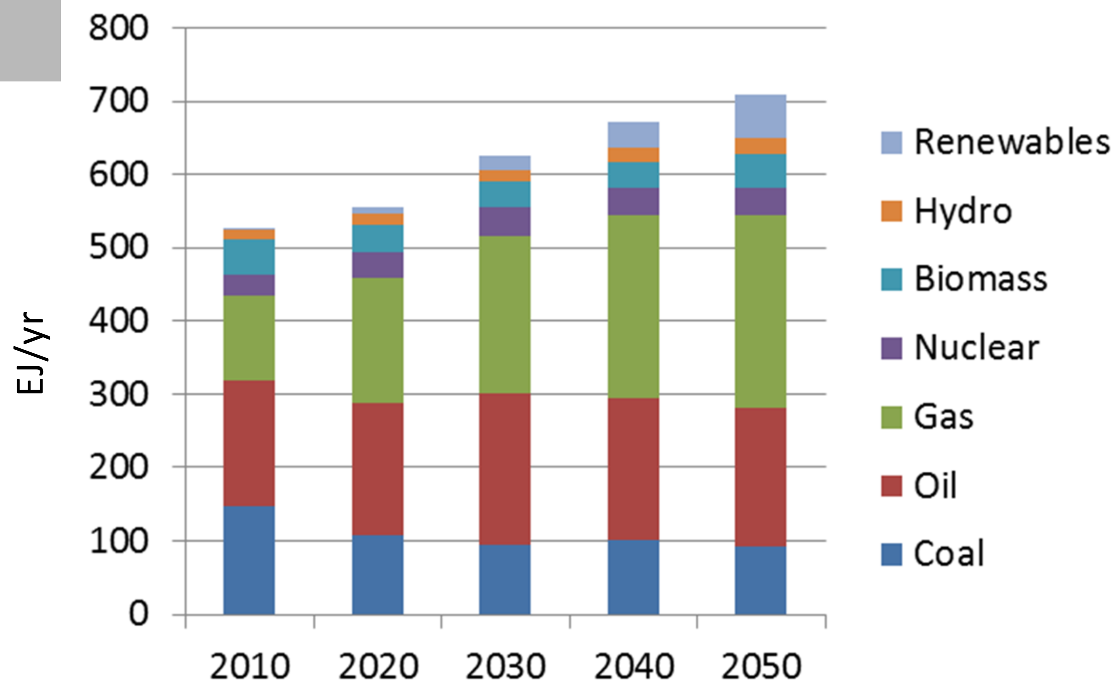
The assessment is based on an illustrative set of objectives:

- Economy
  - Total discounted system costs, in M$
- Environment
  - LCA-based greenhouse gas emissions, in Mt $CO_2$-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

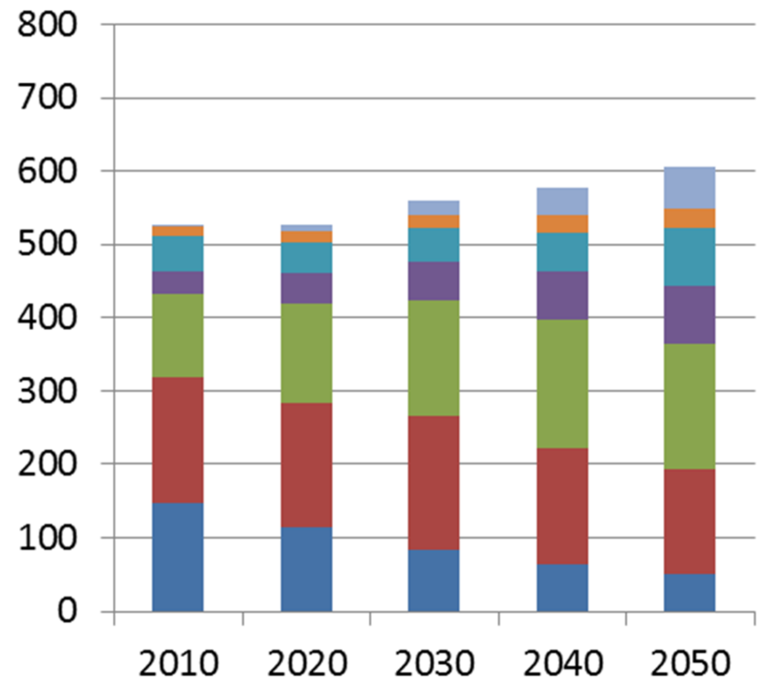
# Results: Total Primary Energy Supply

**Delayed climate action scenario**




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

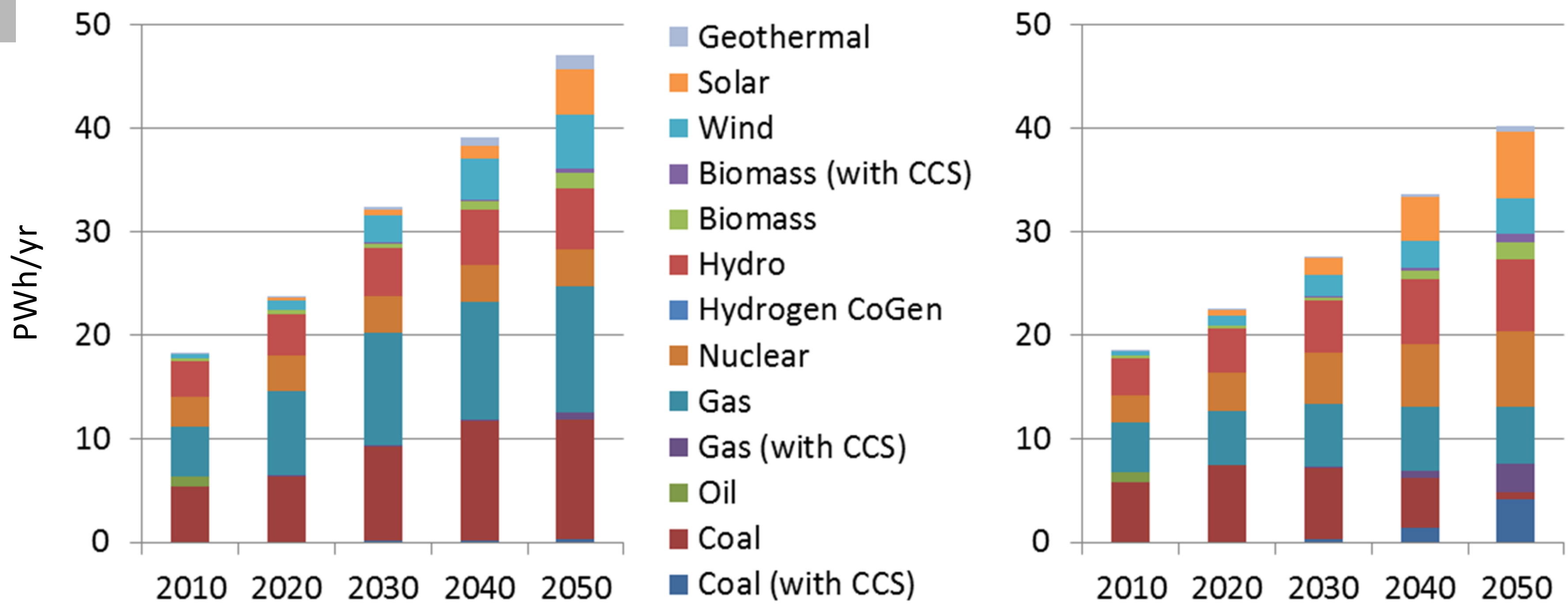
**Climate action scenario**




- 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** | **Climate action scenario**

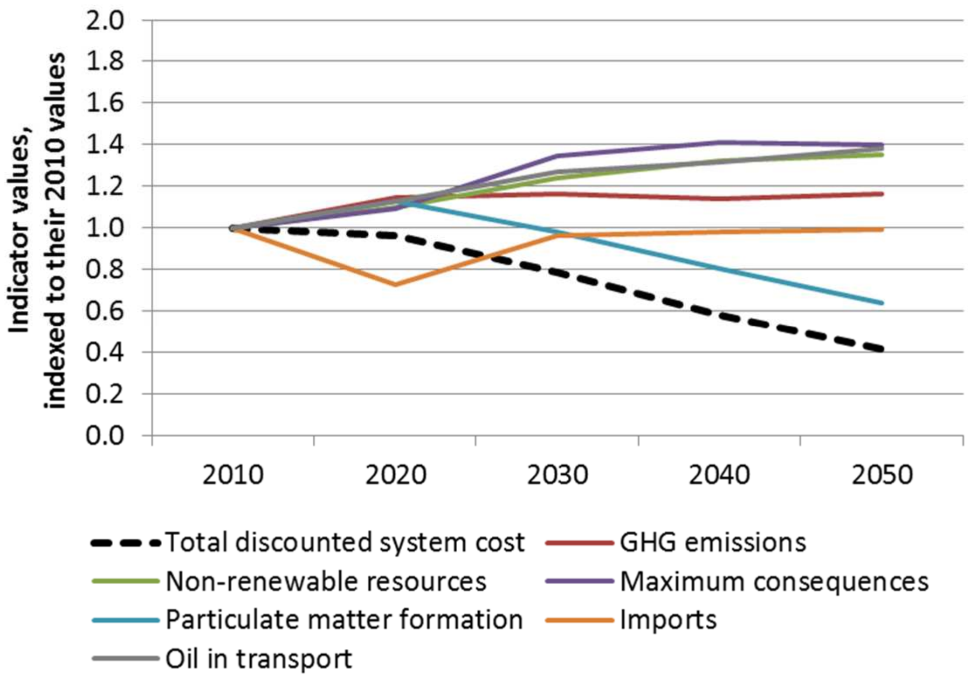



- Coal and gas power increase
- Nuclear generation is stable
- Hydro power increases slightly
- Renewable energies expand

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

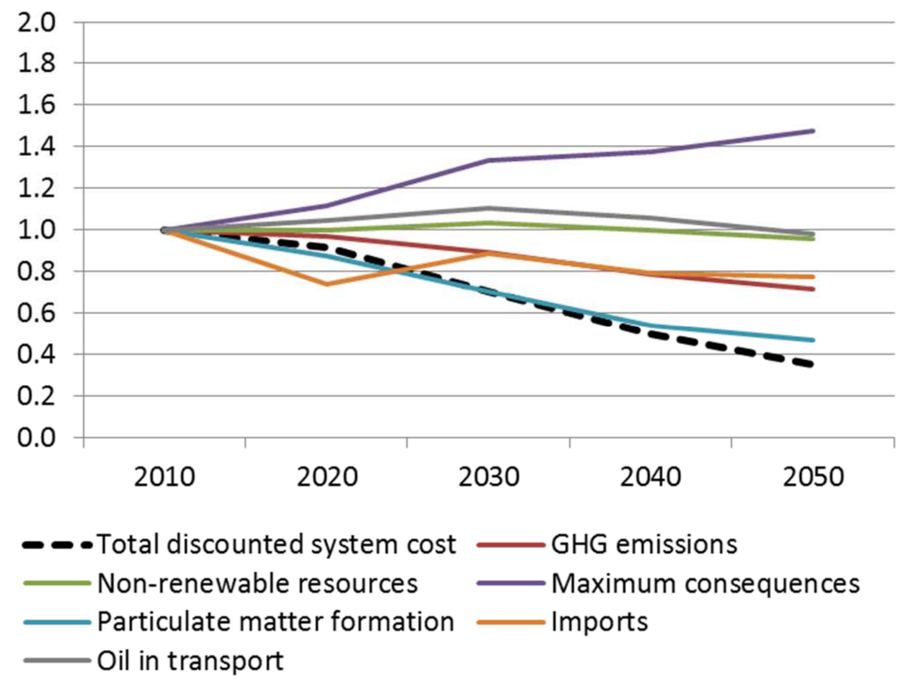
# Results: Co-benefits and adverse side-effects

**Delayed climate action scenario**




- GHG emissions, non-renewable energy use, oil in suface 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

# Conclusions

Based on the small set of objectives, the co-benefits and adverse side-effects of climate action compared to a less stringent $CO_2$ policy pathway are:

- Environment
  - Not only $CO_2$ 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 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

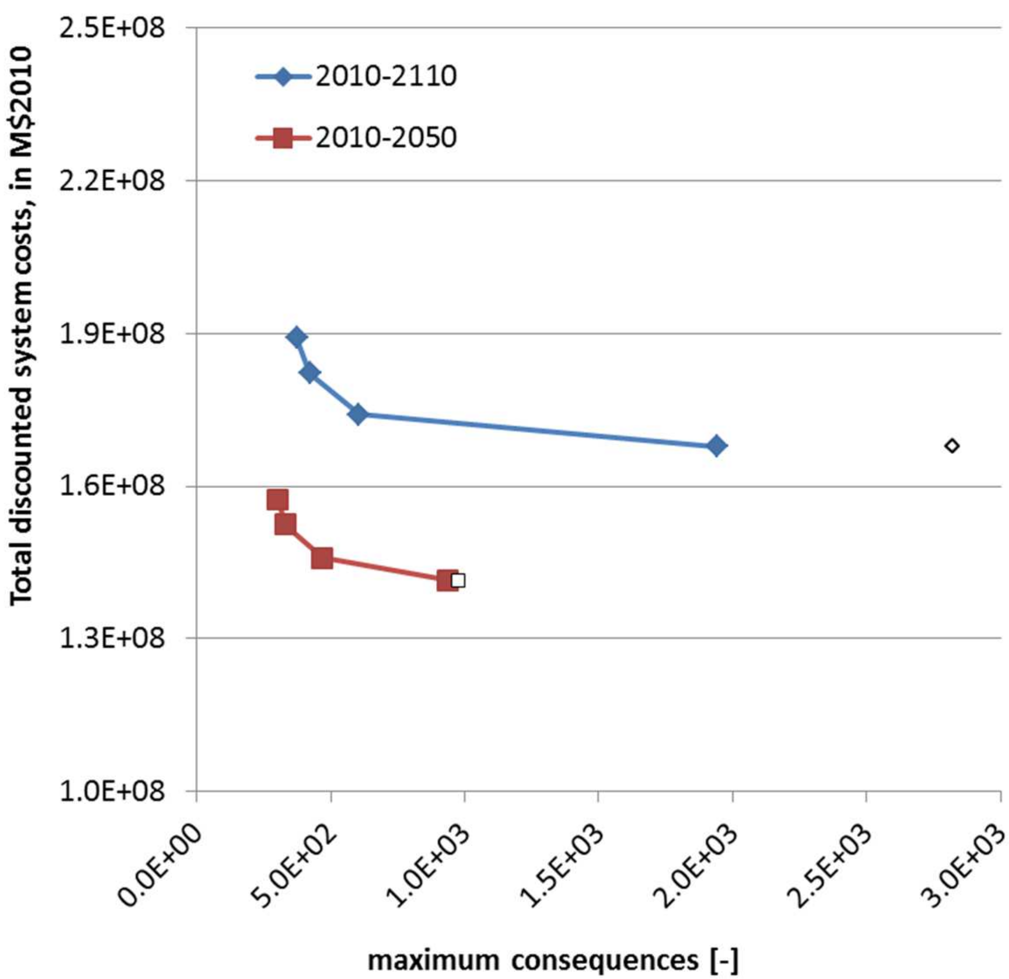
$$\min(\text{cost}) \rightarrow \min(w_{cost} * \text{cost} + w_{other} * \text{other indicator})$$

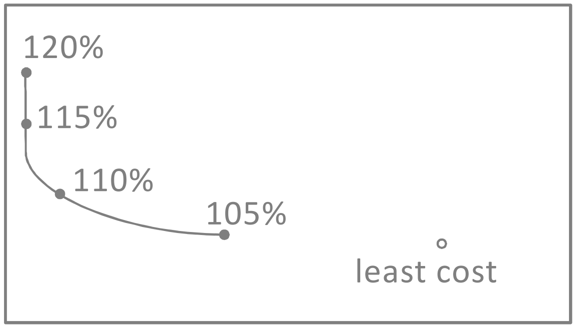
  - Epsilon-constraint approach

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

# Results: Epsilon constraint method

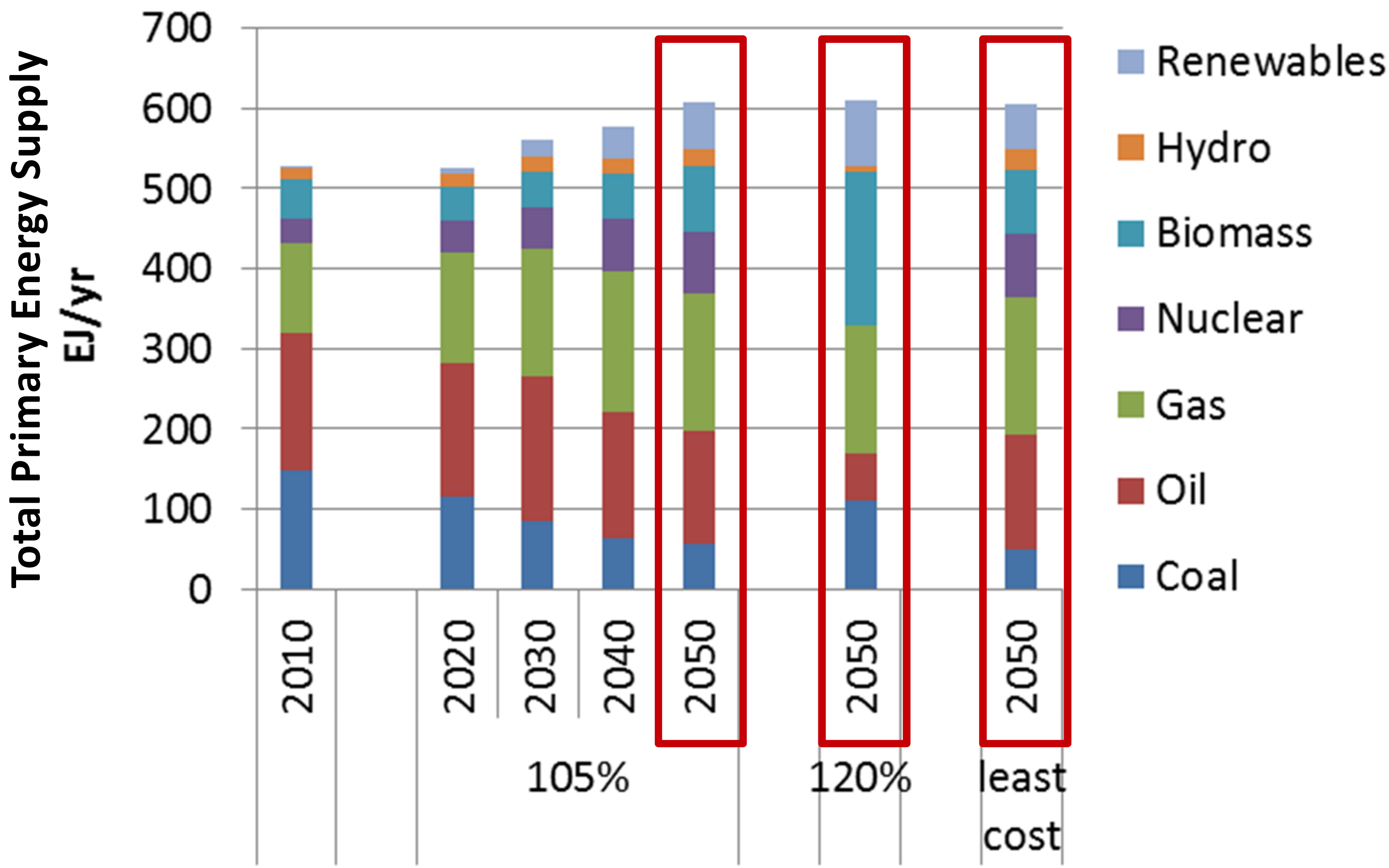
- Minimization: maximum consequences
- Constraint: 120%/115%/110%/105% of total discounted system costs in the least cost run



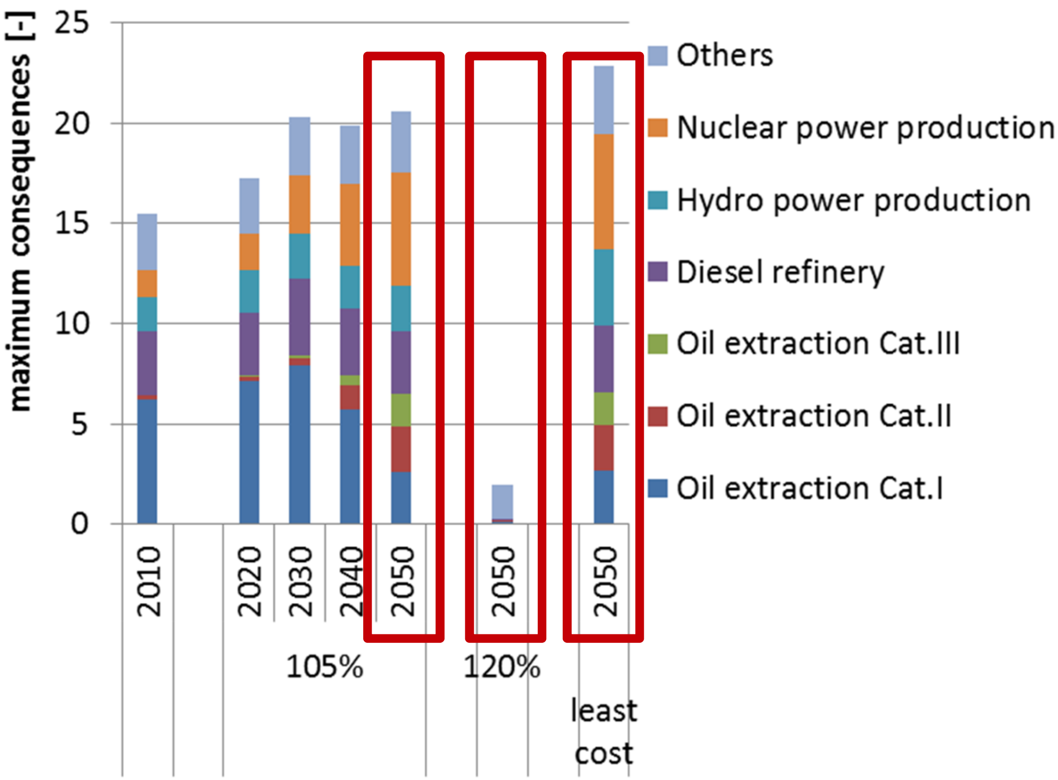
# Results: Epsilon constraint method

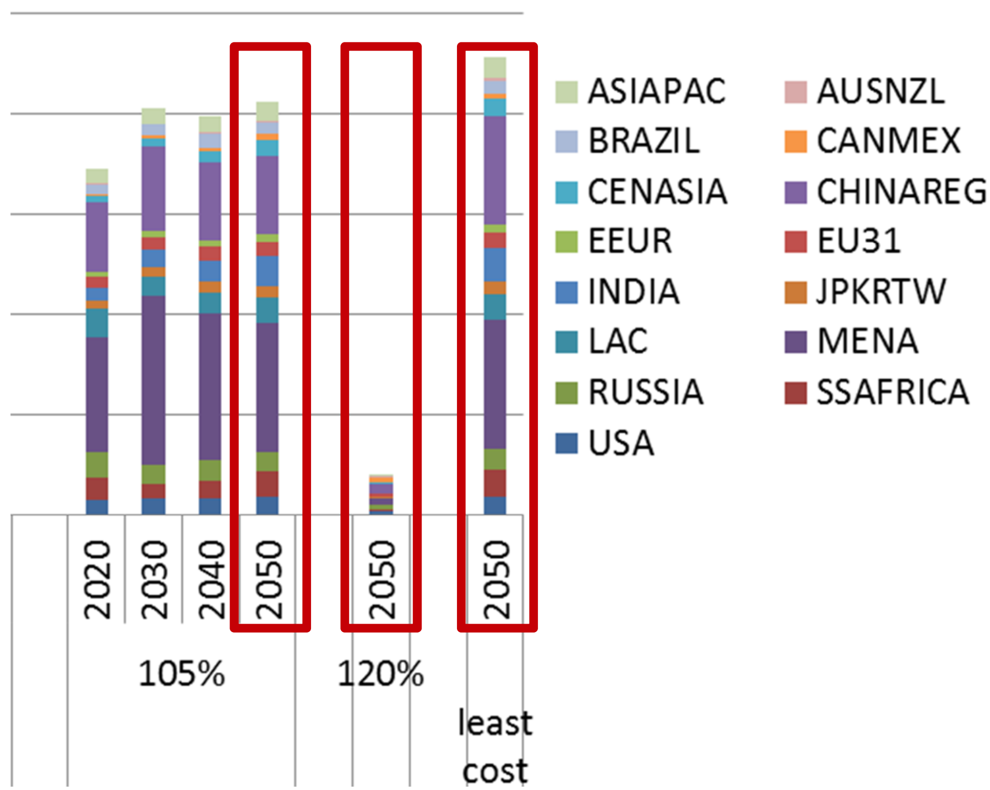
- Climate action scenario
- Minimization: maximum consequences
- Constraint: 105%/120% of total discounted system costs in the least cost run



# Results: Epsilon constraint method

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



# Conclusions

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

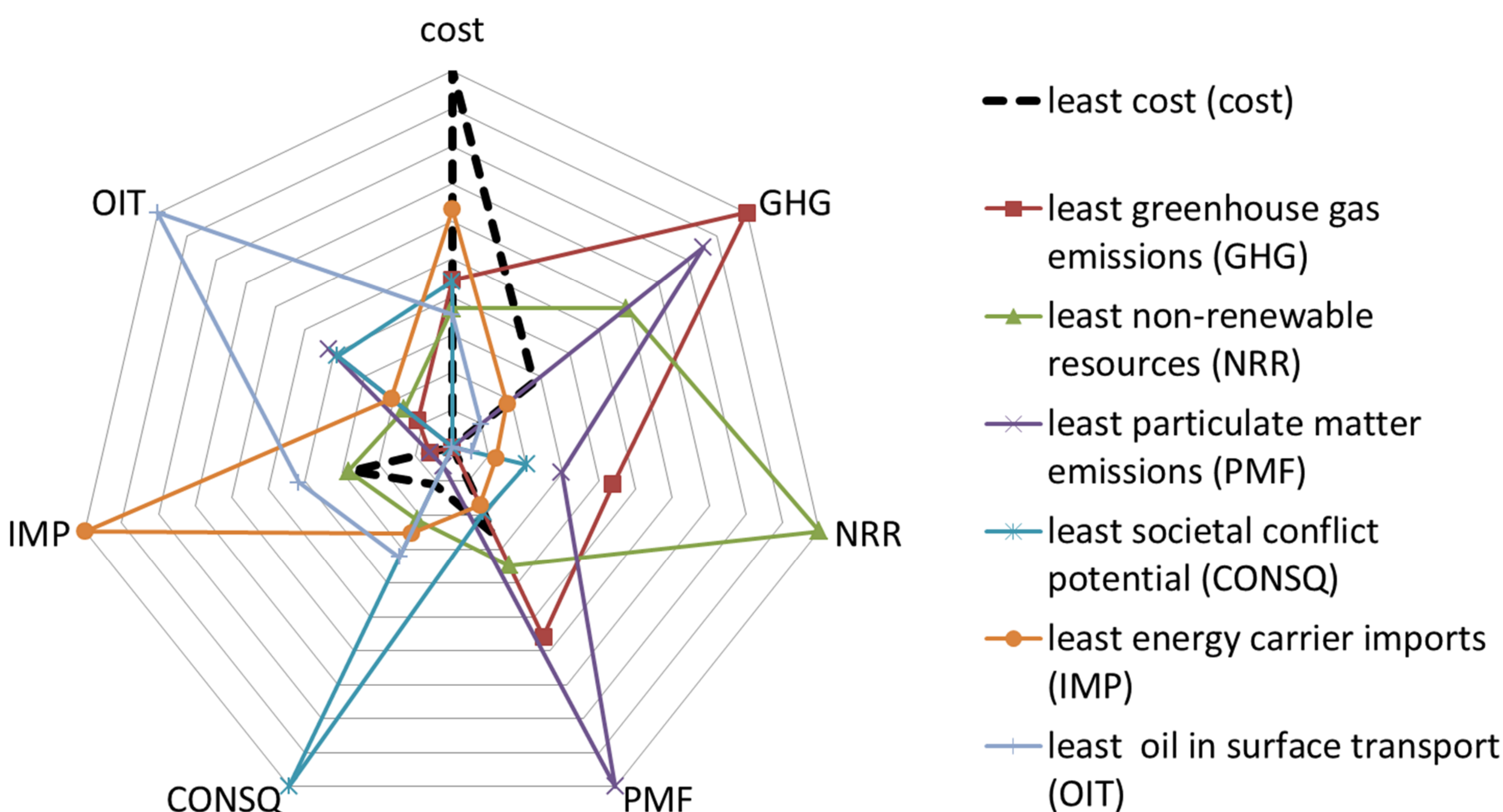
- Delayed climate action scenario
- Constraint: 105% of total discounted system costs in the least cost run
- Period: 2010-50
  - Cumulative reduction potential compared to the least cost run
  - Co-benefits

| | 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 |
| 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%** |

Relative to cost min

# Results: Overview epsilon constraint method

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



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# 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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