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science for global insight

Integrating industrial ecology analysis and IAMs

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Material courtesy of

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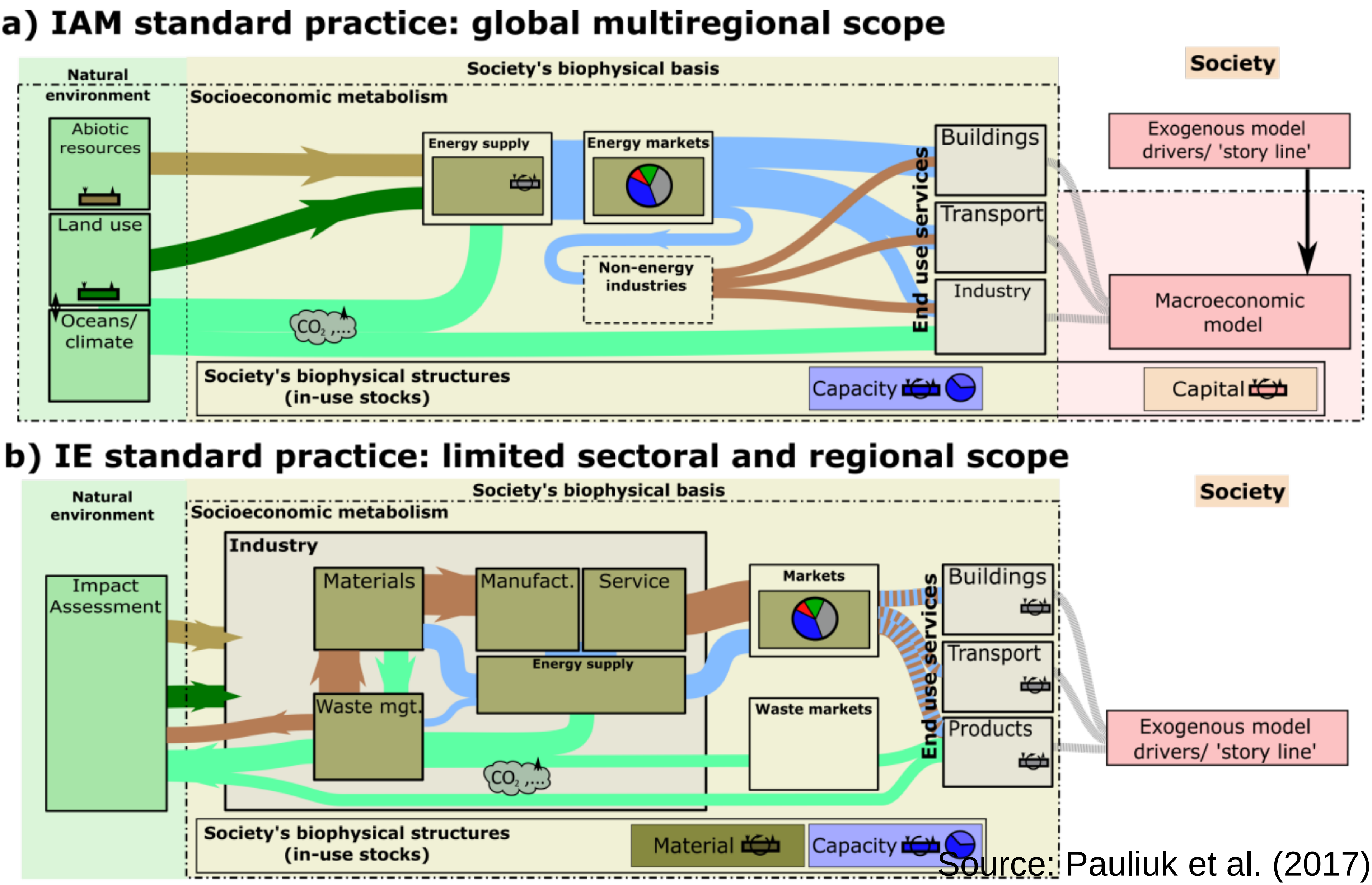
Embedding climate change analysis in the context of SDGs

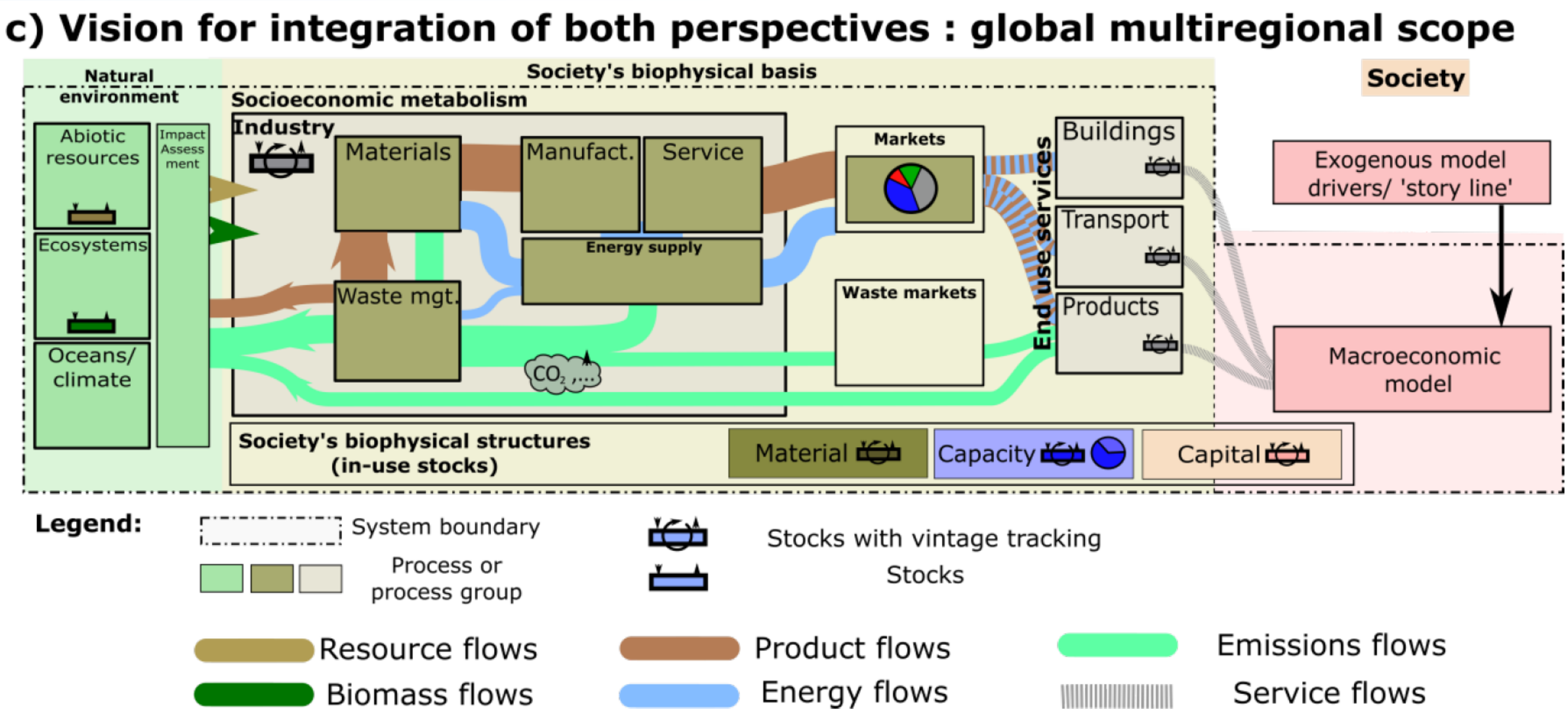
COP21 • CMP11
PARIS 2015
UN CLIMATE CHANGE CONFERENCE

IAM vs. IE perspectives on social metabolism



Source: Pauliuk et al. (2017)

Integrated IAM-IE vision on social metabolism

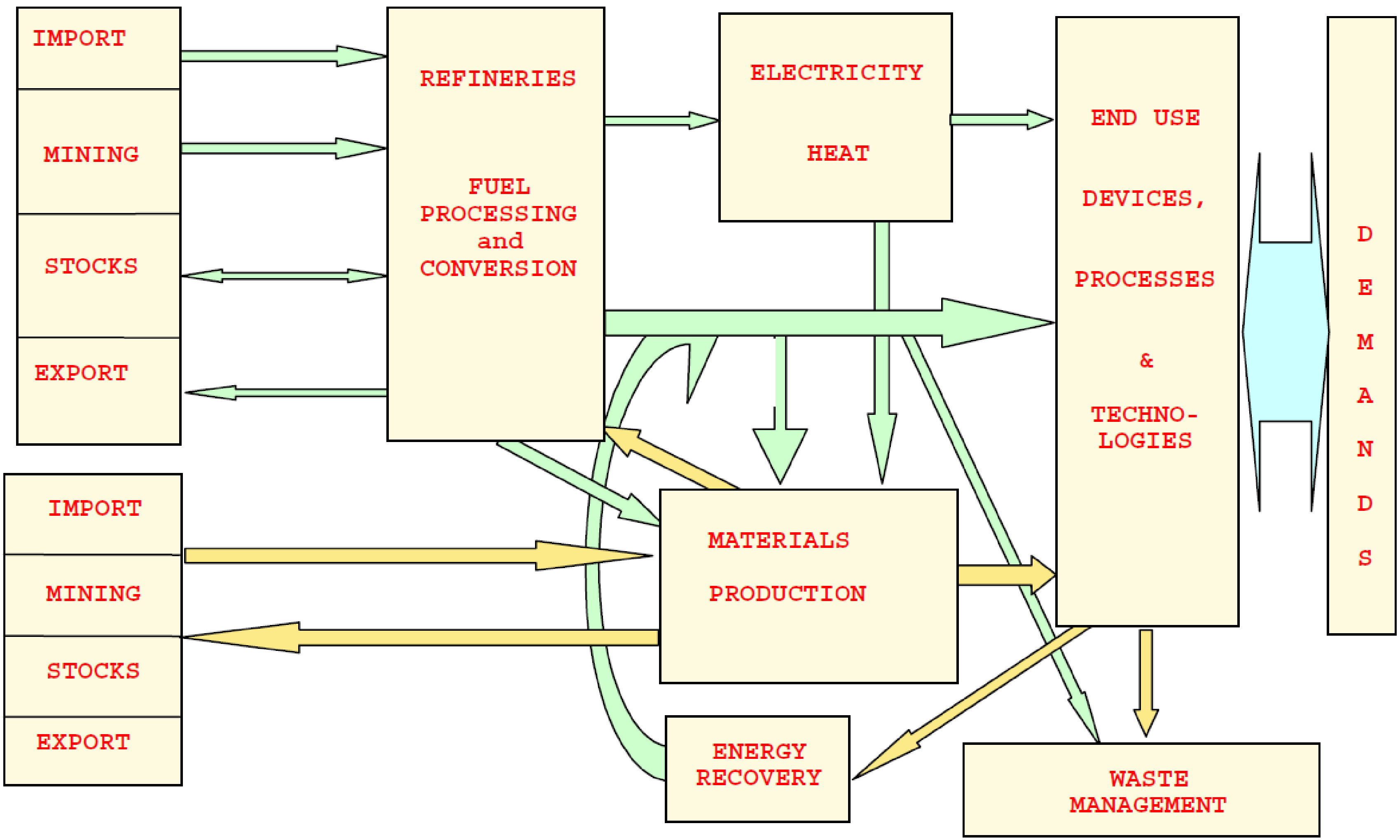


Source: Pauliuk et al. (2017)

Combining IAMs with LCA and MFA

This work has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 308329.

An early example: MARKAL-MATTER



Source: Sijm et al. 2002

MARKAL-MATTER

Coverage of materials in Western European MARKAL-MATTER model

SEPTEMBER 1998 ECN-C--98-065

MATTER 1.0

A MARKAL Energy and Materials System Model Characterisation

D.J. Gielen
T. Gerlagh
A.J.M. Bos

Source: Gielen et al. 1998

Table 2.2 *Materials in the Western European MARKAL model*

Code	Material	Code	Material
MCA	CONCRETE BUILDING BLOCKS [T]	MPA	CELLOPHANE [T]
MCB	BRICKS [T]	MPB	PHB/PHV (BIOPOL) [T]
MCC	CEMENT [T]	MPC	BUTADIENE RUBBER (BR) [T]
MCD	READY MIX CONCRETE [T CONCR. EQUIV.]	MPE	POLYETHYLENE [T]
MCE	PREFAB CONCRETE [T CONCR. EQUIV.]	MPF	ACRYLONITRILE BUTADIENE STYRENE [T]
MCH	HIGH STRENGTH CEMENT [T CONV. CEM. EQUI]	MPG	STYRENE BUTADIENE RUBBER [T]
MCK	PORTLAND CEMENT CLINKER [T]	MPM	NYLON 6.6 [T]
MCL	SAND-LIME BRICKS [T]	MPN	NYLON 6 [T]
MCM	MARBLE AND GRANITE STONES [T]	MPP	POLYPROPYLENE [T]
MCQ	QUICKLIME (CaO) [T]	MPR	UF RESINS [T]
MCS	FLOOR TILES + STONEWARE [T]	MPS	POLYSTYRENE [T]
MCT	GLASS [T]	MPT	POLYETHYLENE TEREPHTHALATE [T]
MCY	GYPSUM [T]	MPU	PVC [T EXCL. ADDITIVES]
MCZ	KAOLIN [T]	MPV	PVC [T INCL. ADDITIVES]
MIA	NITRIC ACID [T]	MPW	PUR [T]
MIC	CHLORINE [T]	MSA	ASPHALT [T]
MIF	AMMONIA [T NH3 EQUIV.]	MSB	BENZENE [T]
MIK	POTASH [T K2O EQUIV.]	MSC	CAPROLACTAM [T]
MIN	NAOH [T]	MSD	DETERGENTS [T]
MIP	PHOSPHORIC ACID [T P2O5 EQUIV.]	MSE	ETHYLENE [T]
MIS	SODA [T]	MSF	PROPYLENE [T]
MIZ	SODIUM CHLORIDE [T]	MSG	C4-FRACTION [T]
MMA	ALUMINIUM [T]	MSH	BUTADIENE [T]
MMB	COPPER CATHODE [T]	MSI	BUTYLENE [T]
MMC	CAST IRON [T]	MSJ	BTX [T]
MMD	DRI QUALITY STEEL [T]	MSK	TOLUENE [T]
MMF	DIRECT REDUCED IRON [T]	MSL	LUBRICANTS [T]
MMH	HIGH QUALITY CRUDE STEEL [T]	MSM	CYCLOHEXANE [T]
MMI	IRON [T]	MSN	CUMENE [T]
MML	LOW QUALITY CRUDE STEEL [T]	MSO	DIETHYLENE GLYCOL [T]
MMM	MEDIUM QUALITY CRUDE STEEL [T]	MSP	PAINT [T PAINT EQUIVALENTS]
MMN	REINFORCEMENT STEEL [T]	MSQ	XYLENES (MIXED) [T]
MMO	HOT ROLLED SECTION STEEL [T]	MSR	NATURAL ELASTOMERES (RUBBER) [T]
MMP	HOT ROLLED COIL STEEL [T]	MST	ETHYLENE OXIDE [T]
MMQ	COLD ROLLED COIL STEEL [T]	MSU	ETHYLENE GLYCOL [T]
MMR	COLD ROLLED COIL AT&F STEEL [T]	MSV	PROPYLENE OXIDE [T]
MMS	COLD ROLLED COIL F&P STEEL [T]	MSW	ACRYLONITRILE [T]
MMT	HEAVY PLATE STEEL [T]	MSX	P-XYLENE [T]
MMU	WIRE ROD STEEL [T]	MSY	O-XYLENE [T]
MMV	ALLOY STEEL [T]	MSZ	XYLENE RESIDUE [T]
MMW	GALVANIZED/TINPLATE STEEL [T]	MTA	TEREPHTHALIC ACID [T]
MMX	COPPER CONCENTRATE [T]	MTB	BUTANOL [T]
MMY	SEMI-FINISHED COPPER [T]	MTC	ACETONE [T]
MNA	COMPOST (15% H2O) [T]	MTD	PHENOL [T]
MNB	ROUNDWOOD (15% H2O) [T]	MTE	PHTHALIC ANHYDRIDE [T]
MNC	CHIPBOARD [T]	MTF	STYRENE [T]
MNF	FIBER BOARD [T]	MTG	VINYL CHLORIDE MONOMER (VCM) [T]
MNG	GRAVEL AND SAND [T]	MTH	FORMALDEHYDE [T]
MNK	PALM KERNEL OIL [T]	MTI	UREA [T]
MNL	MARIGOLD FLOWER OIL [T]	MTJ	ANILINE [T]
MNM	HIGH QUALITY WASTE PAPER PULP [T]	MTK	ACETIC ACID [T]
MNN	LOW QUALITY WASTE PAPER PULP [T]	MTL	HEXAMETHYLENEDIAMINE [T]
MNO	MECHANICAL PULP [T]	MTM	NITRO-BENZENE [T]
MNP	PACKAGING PAPER AND SANITARY PAPER [T]	MTN	METHYL ETHYL KETON (MEK) [T]
MNQ	GRAPHIC PAPER [T]	MTO	ADIPIC ACID [T]
MNR	NEWSPRINT [T]	MTP	I-PROPANOL [T]
MNS	WOOL [T]	MTQ	TOLUENEDIISOCYANATE [T]
MNT	SAWN TROPICAL HARDWOOD (15 % H2O) [T]	MTR	2-ETHYLHEXANOL [T]
MNU	CHEMICAL PULP [T]	MTS	CARBON BLACK [T]
MNV	VISCOSE/RAYON [T]	MTU	SURFACTANT (AES) [T]
MNW	OTHER SAWN WOOD/PLYWOOD (15 % H2O) [T]	MTV	ACETIC ANHYDRIDE [T]
		ORE	IRON ORE [T]
		OXY	OXYGEN [T]
		PEL	PELLETS [T IRON EQUIV.]
		SIN	SINTER [T IRON EQUIV.]

Environmental assessment of alternative power sector decarbonization strategies

Key research questions:

- What are environmental co-benefits and adverse side-effects of the low-carbon transformation?
- How do alternative decarbonization pathways perform in terms of their environmental impacts?

Key publications:

- Pehl et al. (2017) “Understanding Future Emissions from Low-Carbon Power Systems by Integration of Life-Cycle Assessment and Integrated Energy Modelling.” *Nature Energy* 2 (11). https://doi.org/10.1038/s41560-017-0032-9.
- Arvesen et al. (2018). Deriving life cycle assessment coefficients for application in integrated assessment modelling. *Environmental Modelling and Software*, *99*, 111–125. https://doi.org/10.1016/j.envsoft.2017.09.010
- Luderer et al. (2019): Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies, *Nature Communications* 10:5229. https://doi.org/10.1038/s41467-019-13067-8

Integrating IAM and LCA approaches

- **Integrated Assessment Modeling (IAM)** community considers the dynamics of the long-term transformation, but so far focused on climate change mitigation. Policy interventions can be considered explicitly using scenario approaches.
- **Life cycle assessment (LCA)** considers broad set of impacts, but mostly focuses on individual technologies and apply static assumptions, thus not considering the long-term system evolution

Prospective LCA methodology

- Aspects of future **technological change** addressed within the LCA
  - Changing performance of individual electricity generation technologies
  - Projected improvements in selected industrial processes
- **Coherent life cycle descriptions** for power generation options based on multiple case studies to allow for uncertainty estimates, choice of impacts based on ReCiPe methodology
- Separate **construction, operation, end-of-life** phases to be combined with tracking of capacity vintages in IAM
- **Embodied (upstream) energy requirements** of power technologies to account for indirect effects

References

- **Gibon, T.**, Wood, R., Arvesen, A., Bergesen, J.D., Suh, S., Hertwich, E.G., 2015. A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change. Environmental Science & Technology.
- **Hertwich, E.G.,** Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. PNAS 112(20)

Workflow

Integrated Assessment Model

Capacities and production
- New Construction [MW/yr]
- Electricity Production [kWh_{el}/yr]
- Decomissions [MW/yr]

Impacts represented directly
- Air pollution
- Water use
- Fossil resources, CO2 storage

MAgPIE bioenergy scearios

Prospective Life-Cycle Assessment (THEMIS)

Mid-point coefficients (technology-specific) per kWh_{el}, MW, e.g.,
- Toxicity
- Land occupation
- Eutrophication
- Metal depletion
- Ionizing radiation

Embodied energy coefficients

Related **midpoint impacts**, *including indirect effects* due to embodied energy
- Air pollution (PM, O3, TAC)
- Water
- Fossil depletion, CCS

Joint assessment of midpoint and endpoint impacts

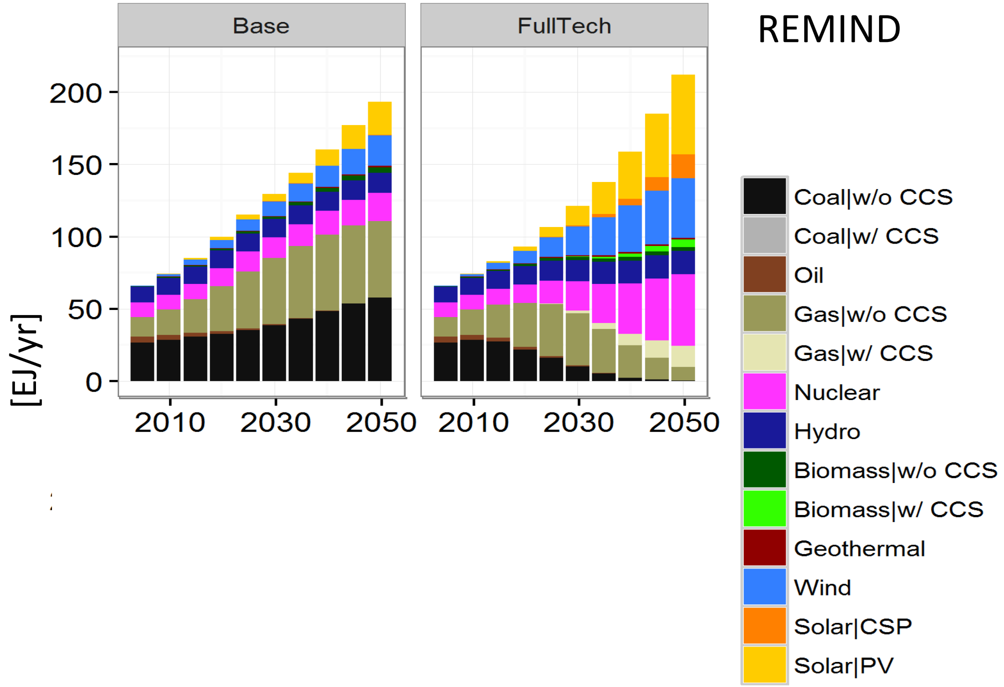
Innovations

- **Integration of Integrated Assessment Modeling and Life-Cycle-Assessment**
- **Air pollution** and **water use** represented by source in IAMs
- **Biomass** land and fertilizer requirements, as well as land-use change emissions from the MAgPIE land-use model
- **Comprehensive coverage** of all major power technologies
- Other impact categories (**toxicity, material resource requirements, land occupation, ionizing radiation,…**) from prospective LCA model THEMIS, accounting for future changes in technology performance
- **Grid and storage requirements** estimated based on DLR's REMix model (Berrill et al., 2016; Scholz et al., 2016; Pietzcker et al., 2016)
- **Systematic uncertainty analysis** based on multiple case studies (LCA) and multi-model IAM ensemble

IAM scenarios considered

Climate policy implementation

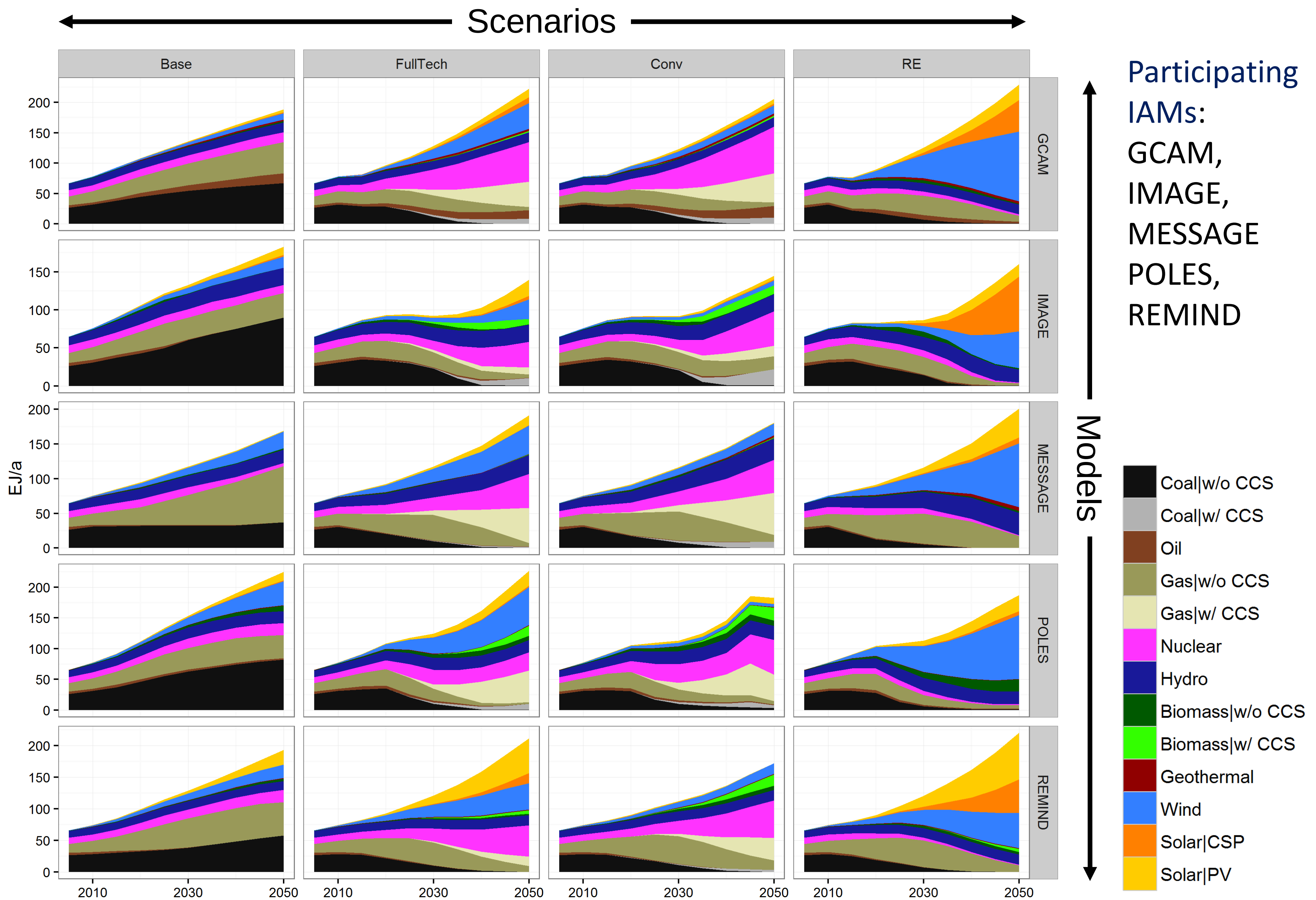
- Policy scenarios with constraint on cumulative 2011-2050 power sector emissions of 240 $GtCO_2$
- Comparable policy ambition in other sectors



Three different technology scenarios:

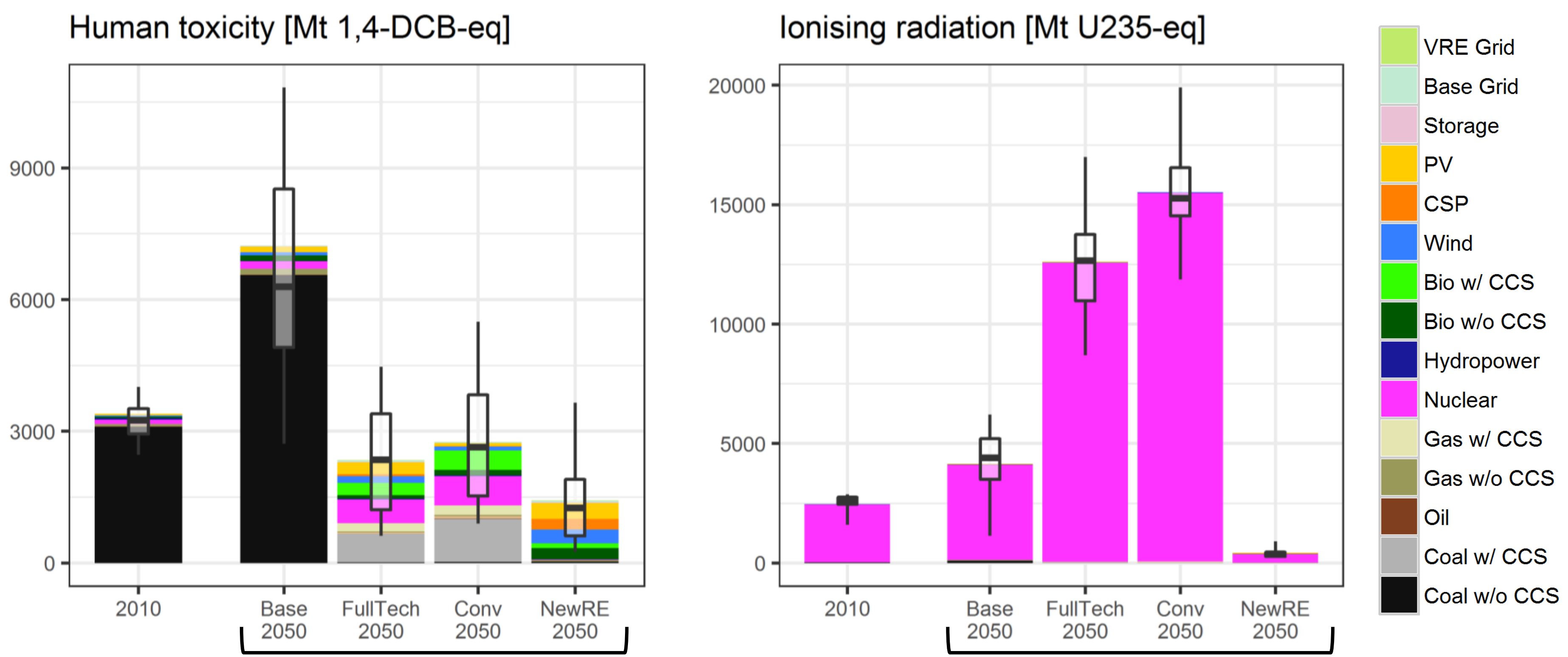
- **FullTech**
- **Conventional** (Wind and solar limited to 10%)
- **Renewable** (nuclear phase-out, no CCS for power stations)

IAM scenarios considered

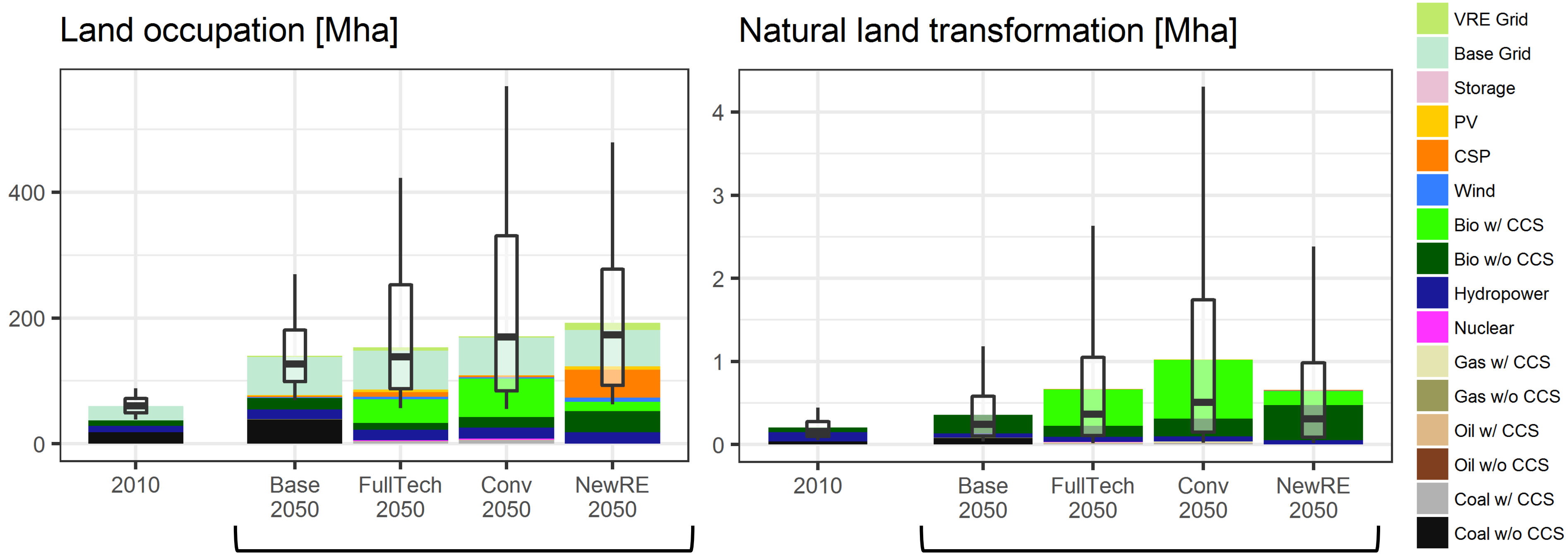


Participating IAMs: GCAM, IMAGE, MESSAGE POLES, REMIND

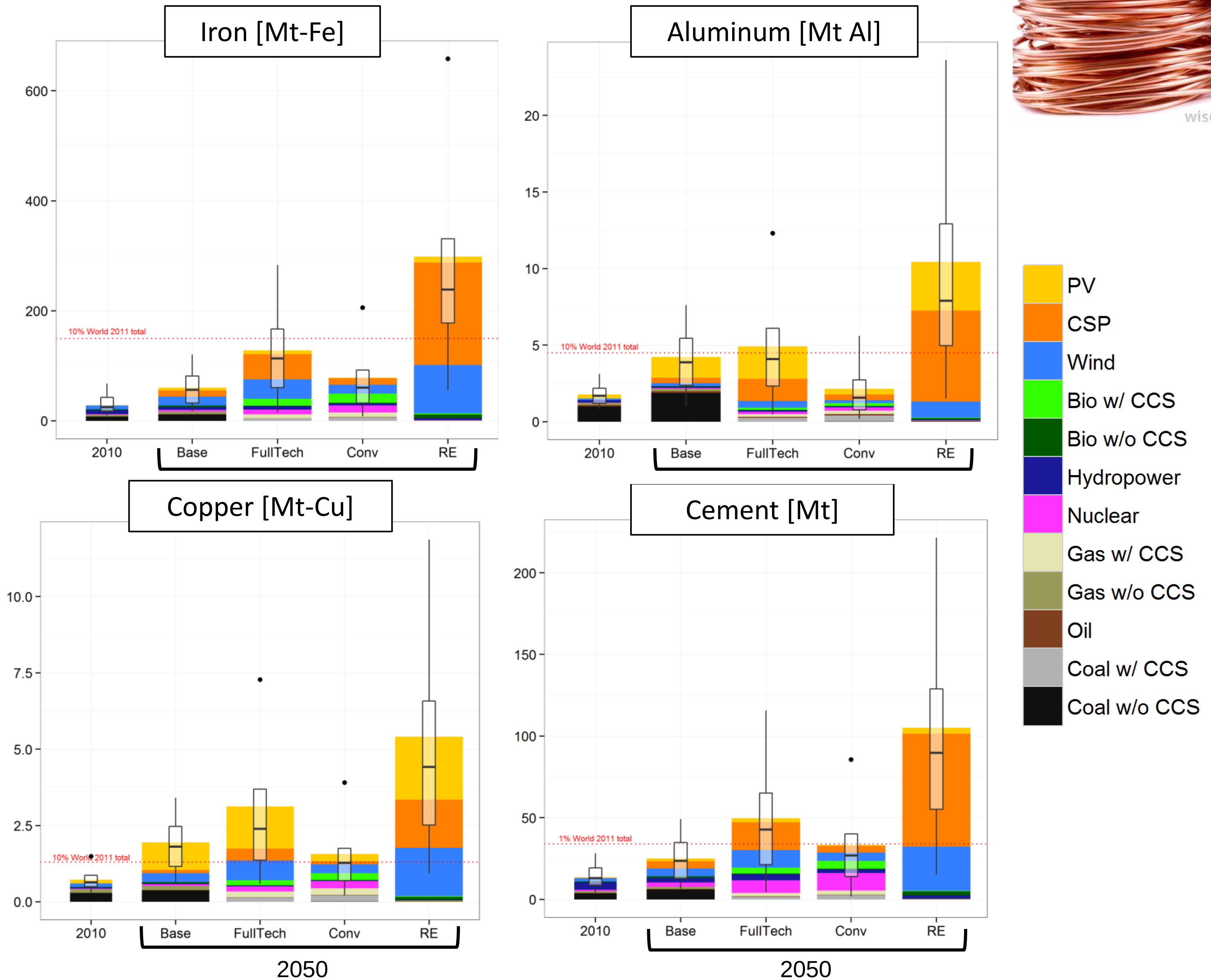
Health impacts (excl. air pollution)



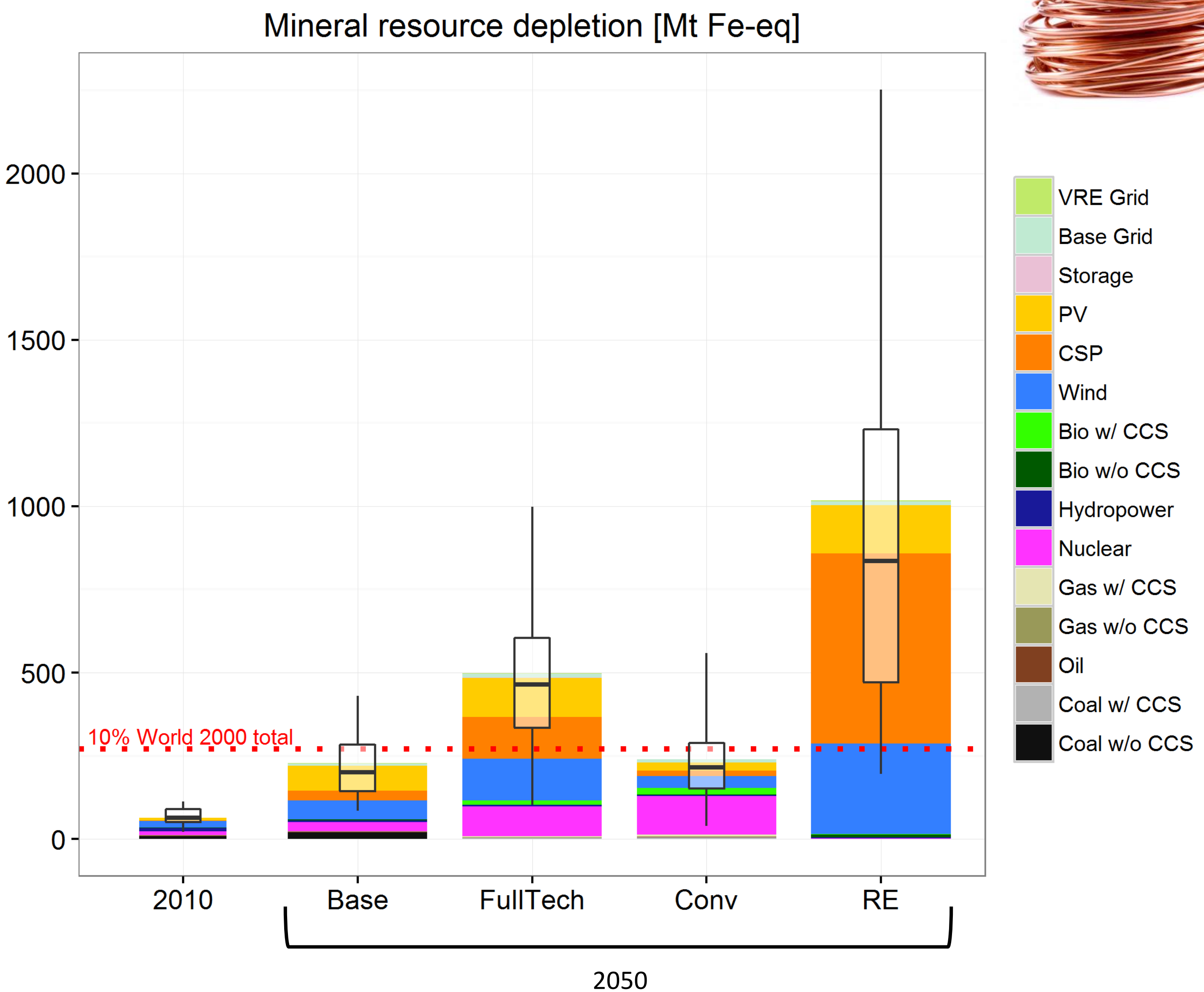
Land occupation and transformation

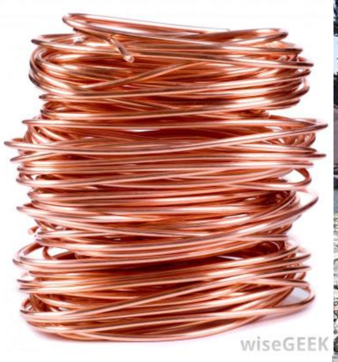


Bulk resource requirements

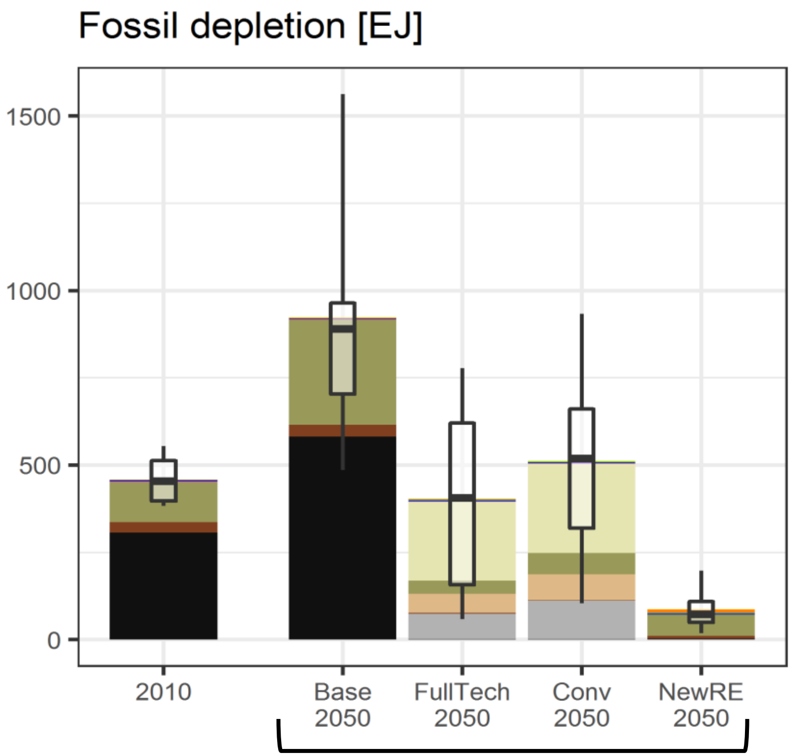


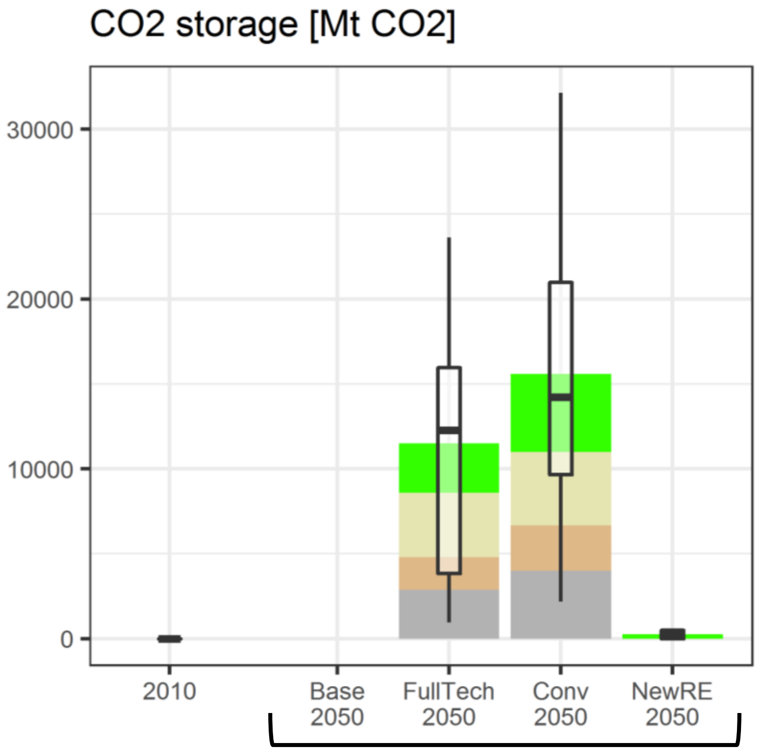
Mineral resource depletion



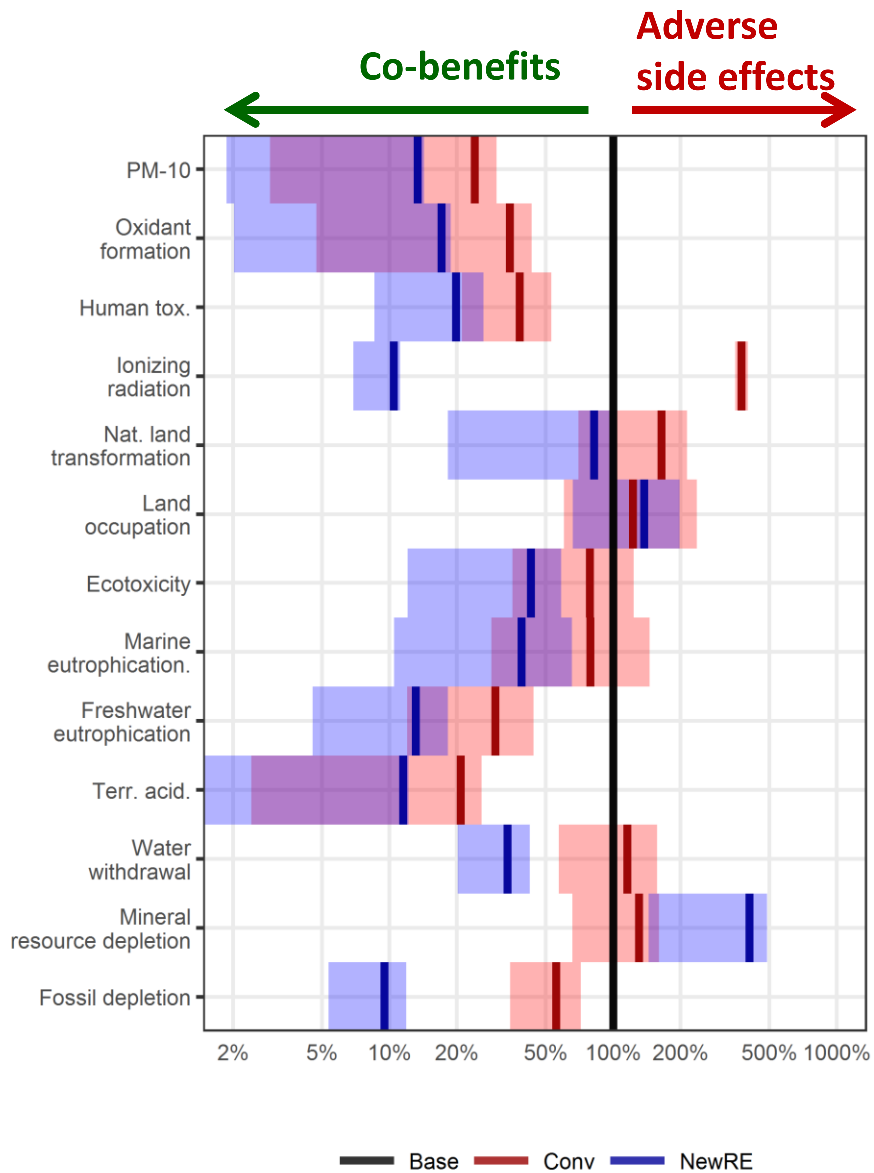


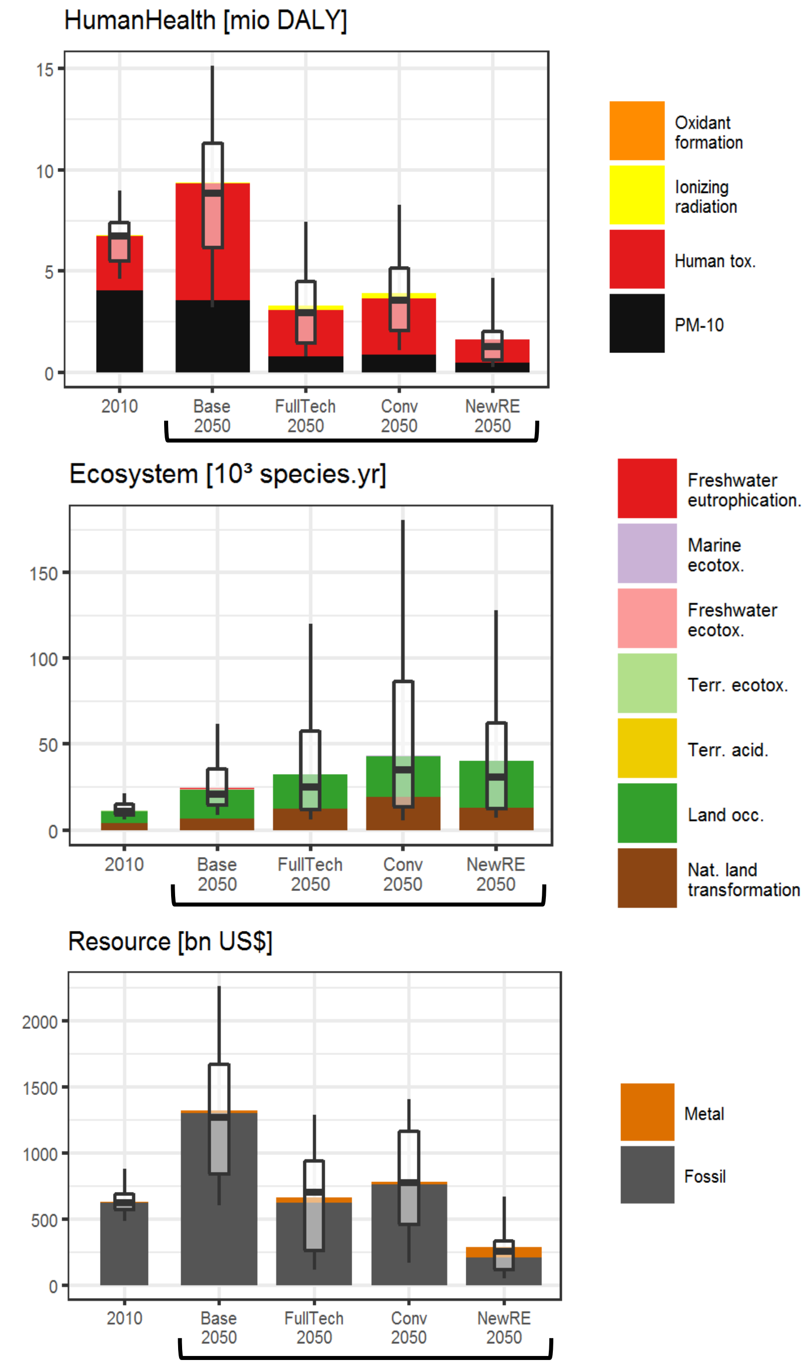
Fossil depletion and carbon storage





Combined assessment





Key insights

- Decarbonizing power supply has substantial co-benefits, especially for air and water pollution
- However, low-carbon transformation pathways have higher raw material requirements, higher risks related to radioactive substances, and increased land requirements
- Bioenergy has much greater adverse side-effects than the other renewables
- Conventional vs renewable power sector decarbonization strategies have distinctly different environmental risk profiles
    - Nuclear and CCS-based strategies are more water-intensive, higher radiation, and have fewer environmental co-benefits
    - Decarbonization based on wind and solar increases the requirements for raw materials

PIK

Water for Energy

Water for Energy

Key Research Questions

- How will climate change mitigation affect water withdrawal, consumption and thermal pollution of the energy sector?
- What are effective strategies to reduce water consumption in the energy sector?

Key Publications

- Fricko et al. (2016). Energy sector water use implications of a 2°C climate policy. *Environmental Research Letters*, *11*(3). https://doi.org/10.1088/1748-9326/11/3/034011
- Parkinson et al. (2019). Balancing clean water-climate change mitigation trade-offs. *Environmental Research Letters*, *14*(1). https://doi.org/10.1088/1748-9326/aaf2a3

Worldwide, **most electricity** is produced by **thermoelectric** (80%) and **hydropower** generation (17%)

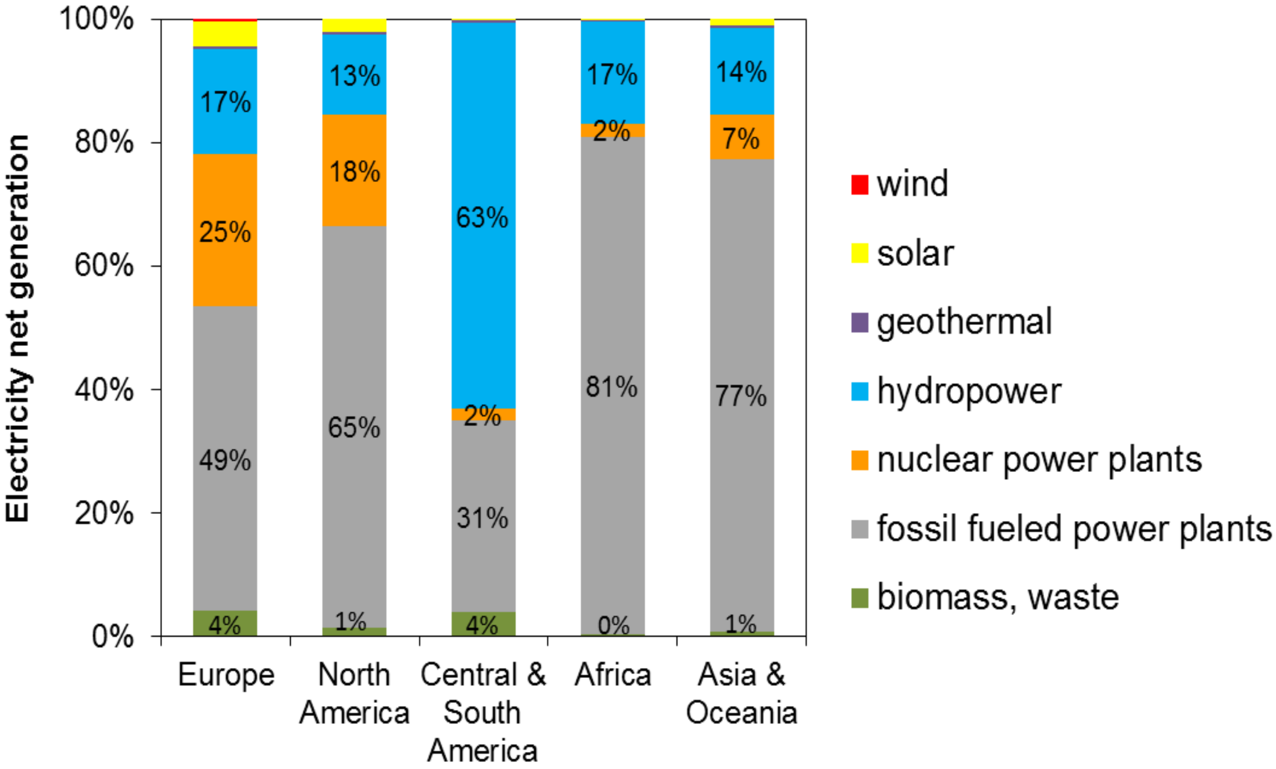


Figure: Regional power plant portfolios by fuel type. Based on EIA data for 2010 . Source: [M. van Vliet, 2014]

Thermoelectric water consumption increased **by a factor of 18** between 1950 and 2010. [Floerke et al, 2011].

Source: courtesy of S. Parkinson

Understanding cooling requirements

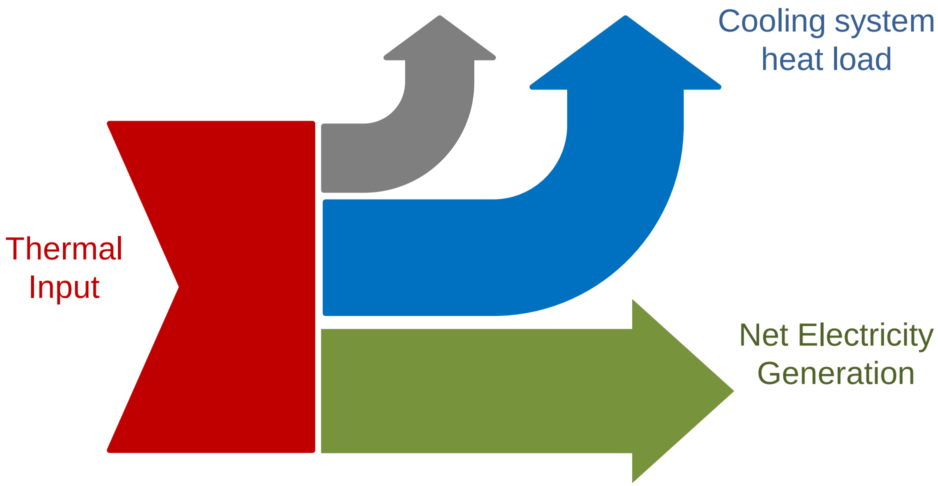


Figure: Simplified power plant energy balance

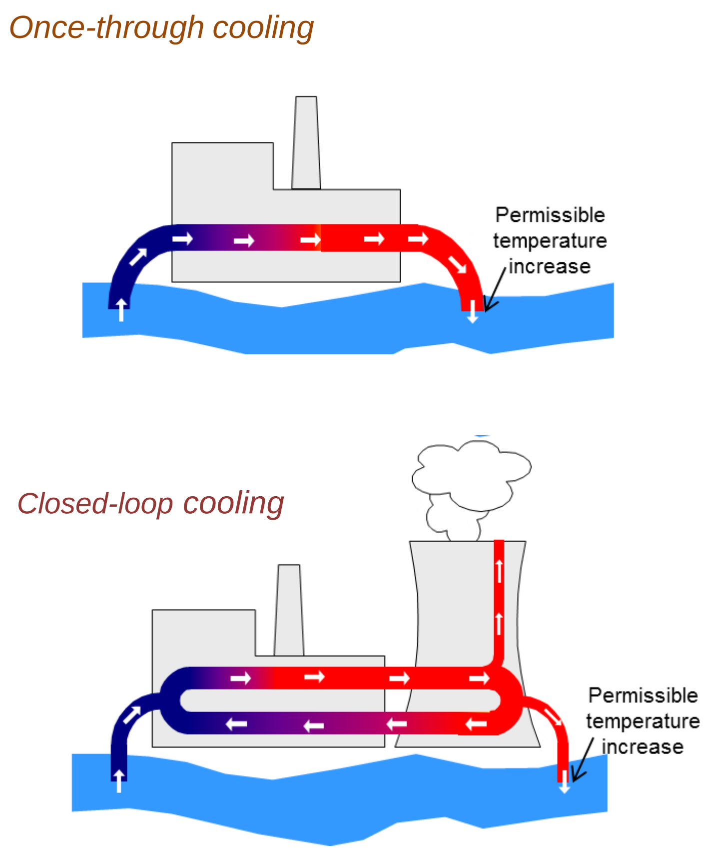


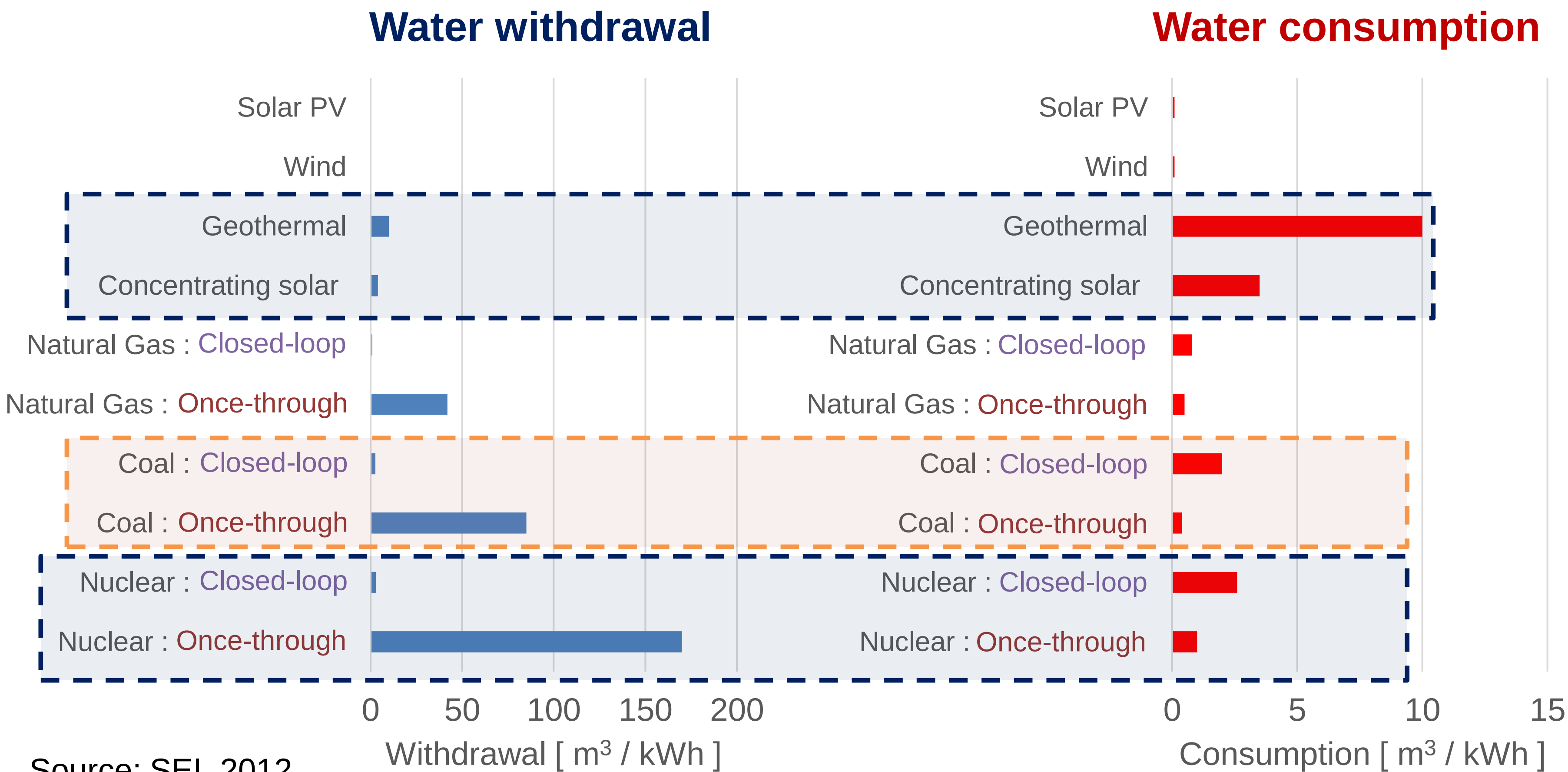
Figure: Cooling systems that use water

Cooling Technology	Water Withdrawal	Water Consumption	Investment Costs	Efficiency
Once Through	High	Med	Low	High
Closed-Loop	Med	High	Med	High
Air Cooling	Low	Low	High	Low

Table. Trade-offs between cooling system types

Source: courtesy of S. Parkinson

Average water performance by plant type



Source: SEI, 2012

Water requirements proportional to heat-rate/efficiency

Low-carbon does not always mean water-efficient

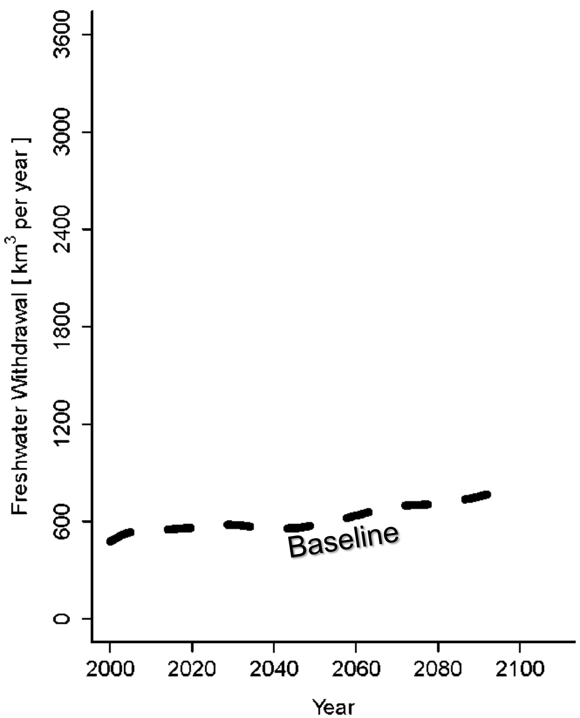
Source: courtesy of S. Parkinson

Methods: Different Approaches

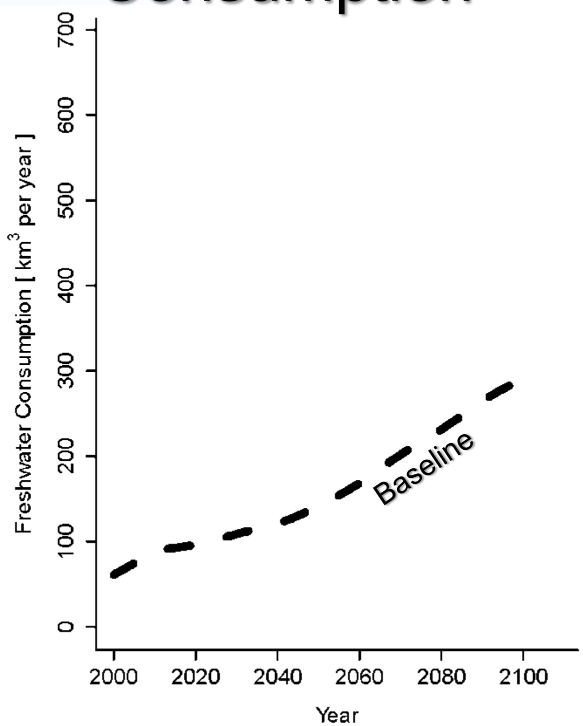
- Ex-post calculation of water indicators based on exogenous assumptions of water-technologies (see also LCA)
- Endogenous modeling of water-technologies (e.g., power plant cooling)
  - Based on simple water-balancing
  - Based on water availability assessed in hydrological models (incl. other sectors)
- Integrated *water for energy* and *energy for water* (e.g., water treatment) modeling

Impact of Energy Sector on Water

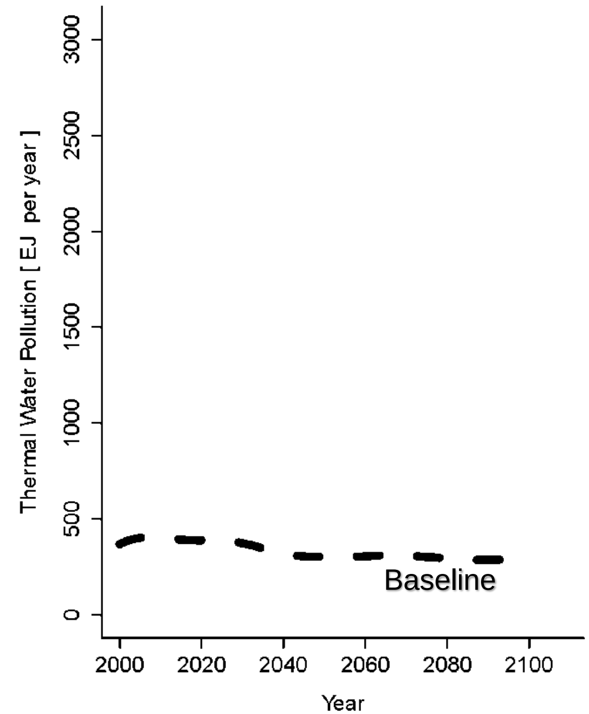
Withdrawal



Consumption



Thermal Pollution

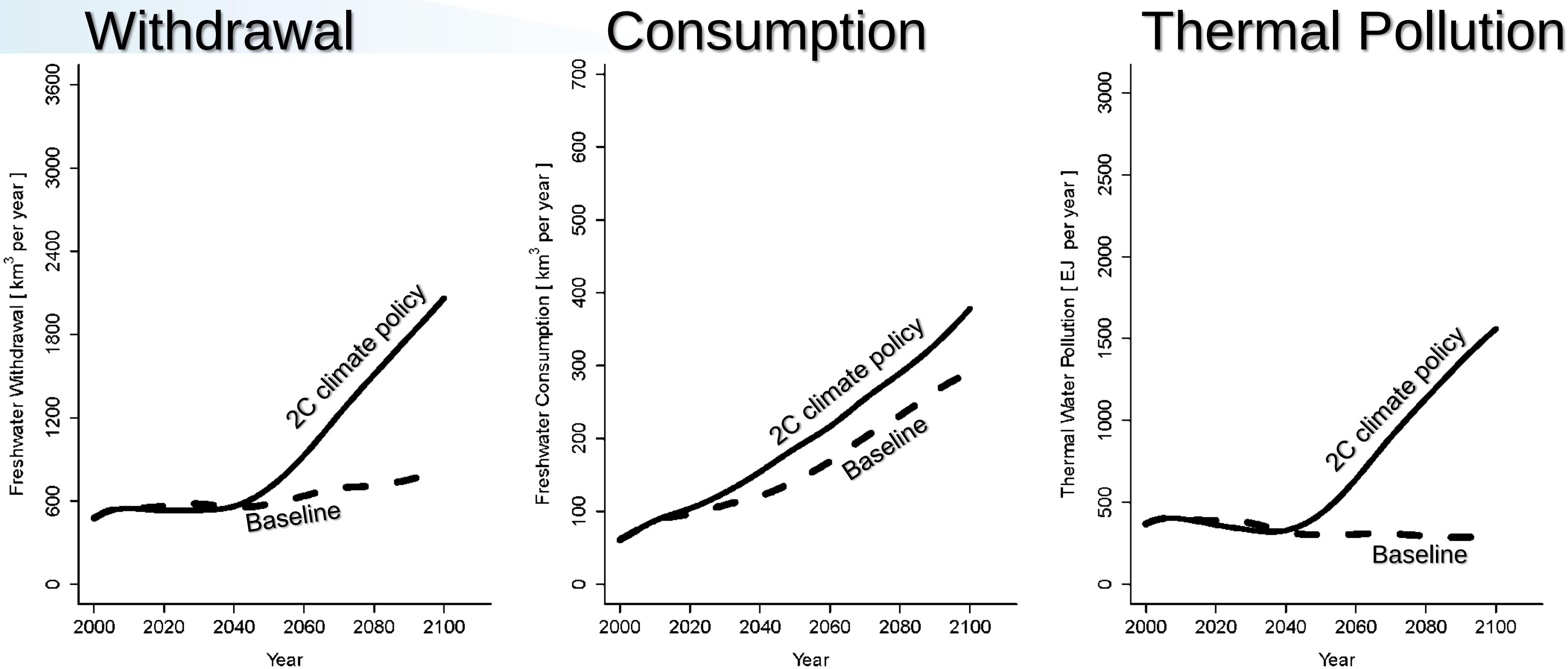


No climate policy

Reference

Source: Fricko, Parkinson et al., 2016

Impact of Energy Sector on Water



No climate policy

Reference

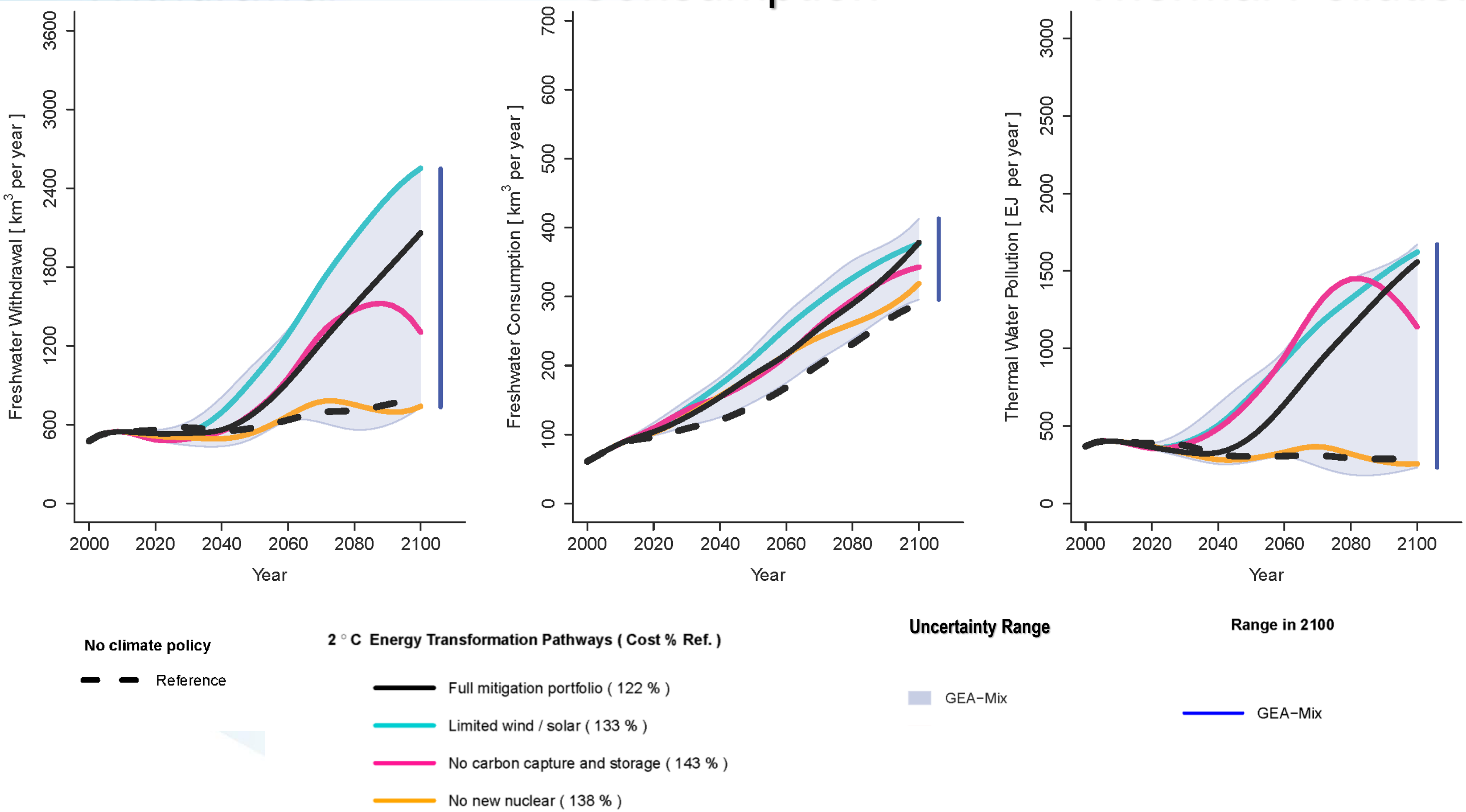
2 ° C Energy Transformation Pathways (Cost % Ref.)

Source: Fricko, Parkinson et al., 2016

Impact of Energy Sector on Water

Alternative Technology Choices for 2C (intermediate energy demand)

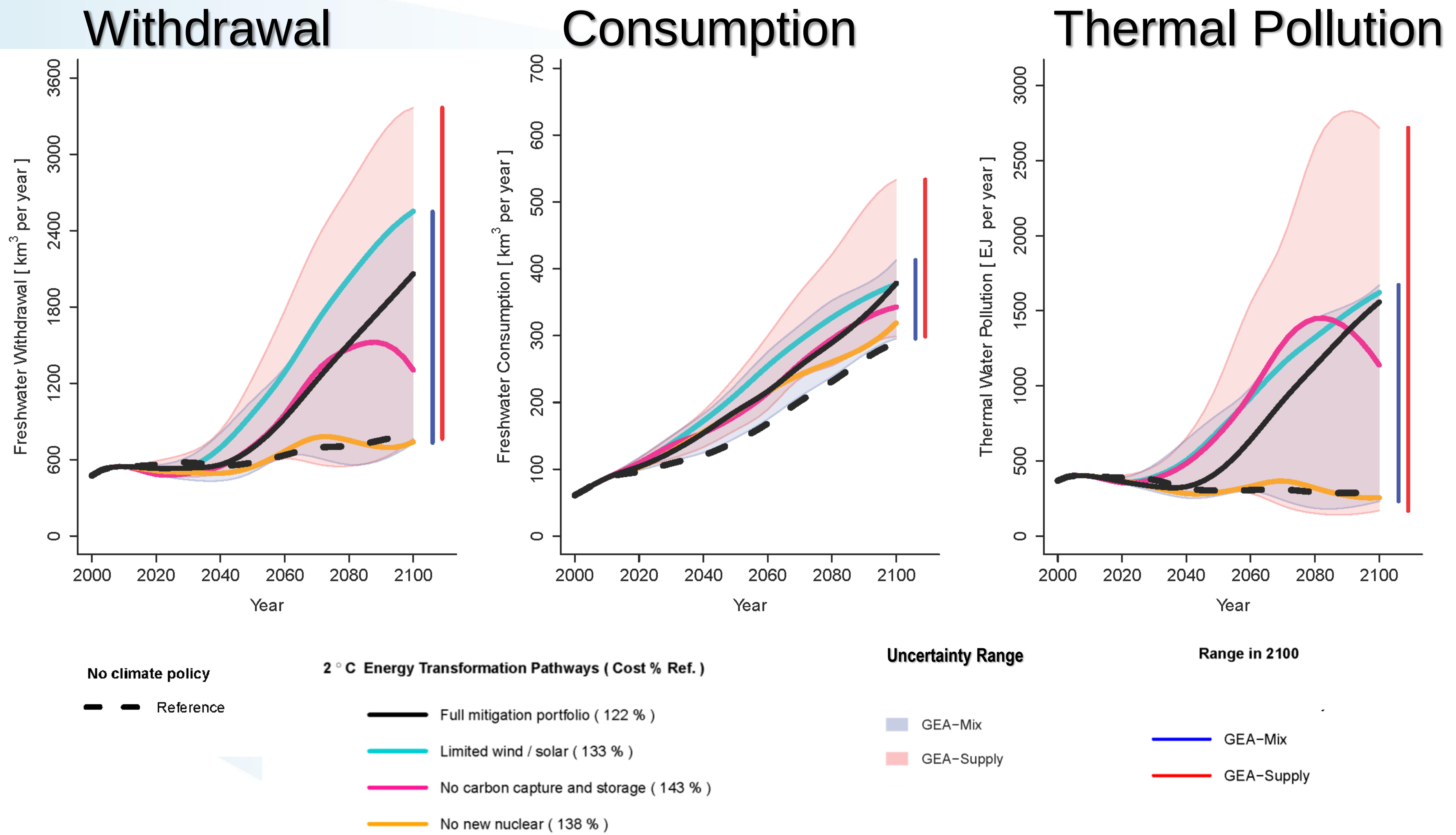
Withdrawal Consumption Thermal Pollution



Source: Fricko, Parkinson et al., 2016

Impact of Energy Sector on Water

High Energy Demand

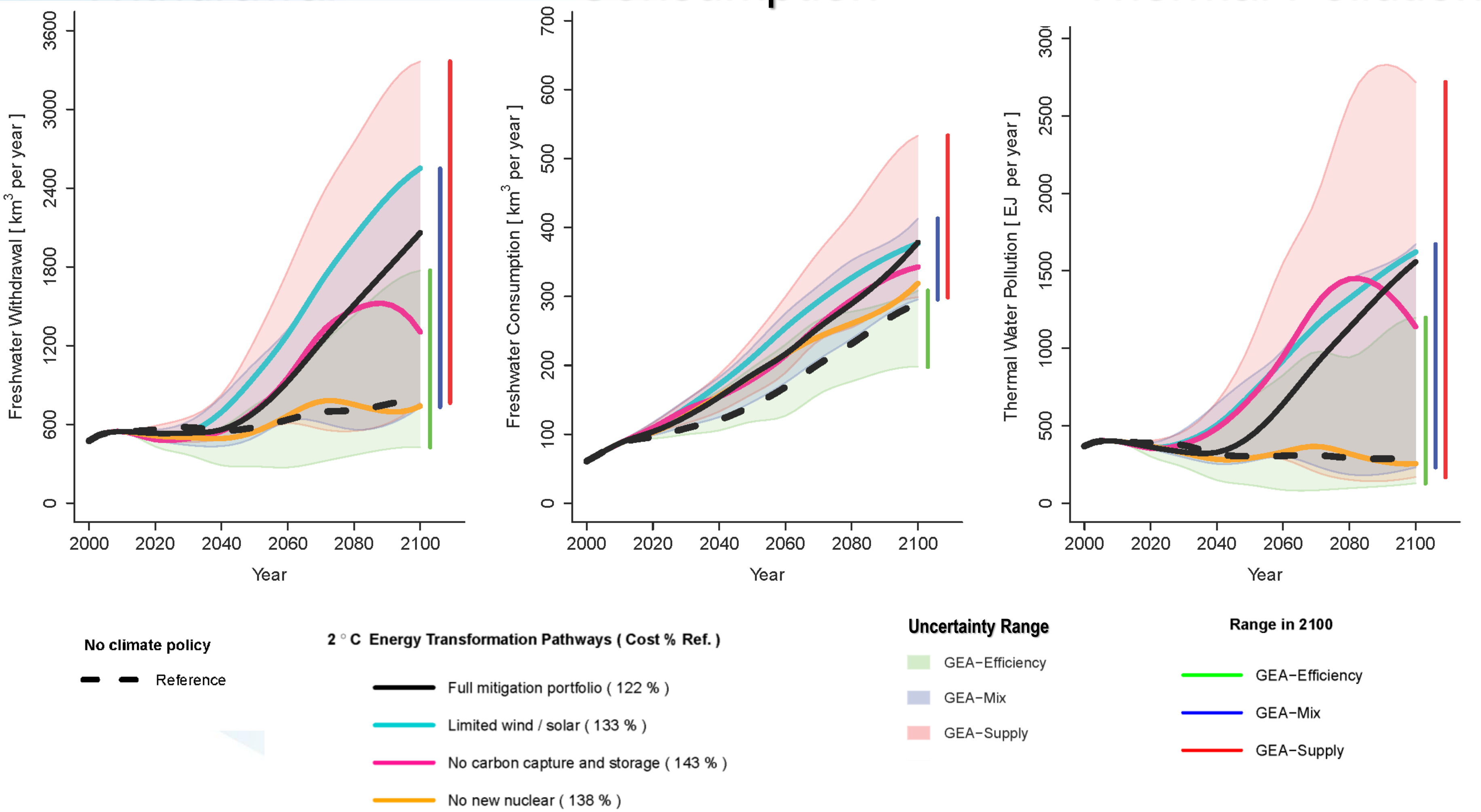


Source: Fricko, Parkinson et al., 2016

Impact of Energy Sector on Water

Low Energy Demand (Efficiency)

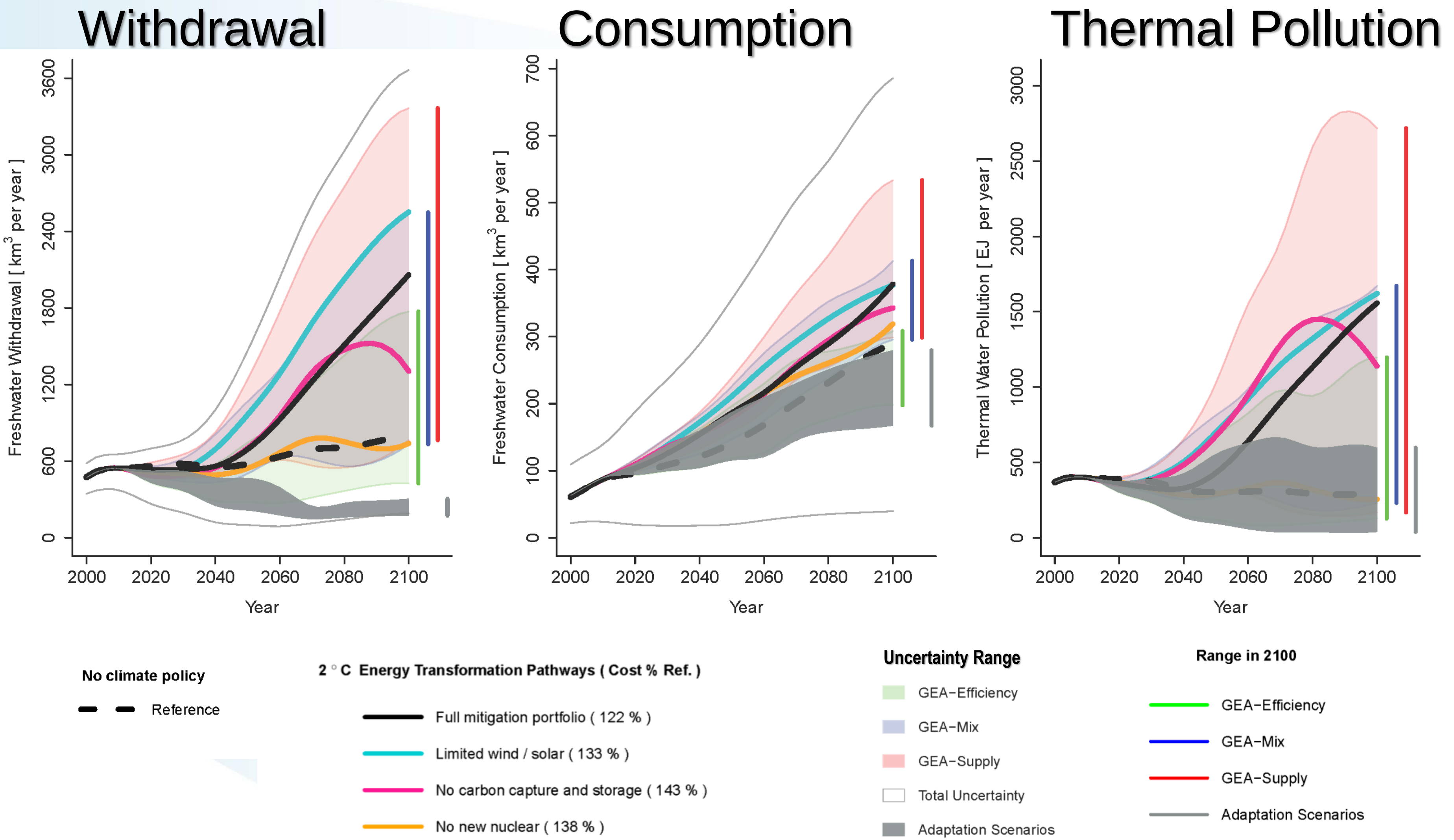
Withdrawal | Consumption | Thermal Pollution



Source: Fricko, Parkinson et al., 2016

Impact of Energy Sector on Water

Efficiency + Water Adaptation Policies



Source: Fricko, Parkinson et al., 2016

Summary

- Water needs of different energy and electricity generation portfolios vary greatly
- Adaptation of water-efficient technologies (e.g., dry cooling) help reducing needs
- Energy efficiency reduces water needs across the entire system

Thank you!

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