INEC INSTITUTE FOR INDUSTRIAL ECOLOGY
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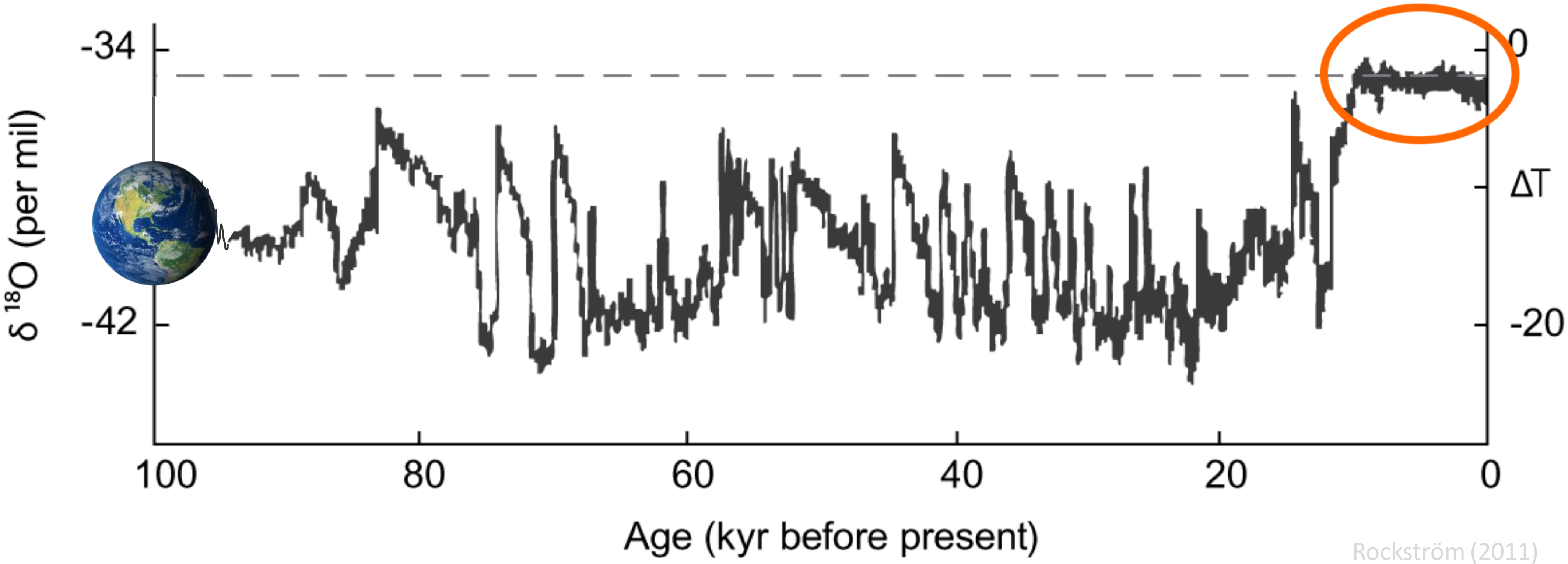
INTEGRATING ENERGY SYSTEM MODELLING AND LIFE CYCLE ASSESSMENT FOR BOTH COST AND ENVIRONMENTAL OPTIMISATION OF A DECENTRALISED RESIDENTIAL ENERGY SYSTEM

INTRODUCTION
STABILITY OF THE HOLOCENE



Rockström (2011)

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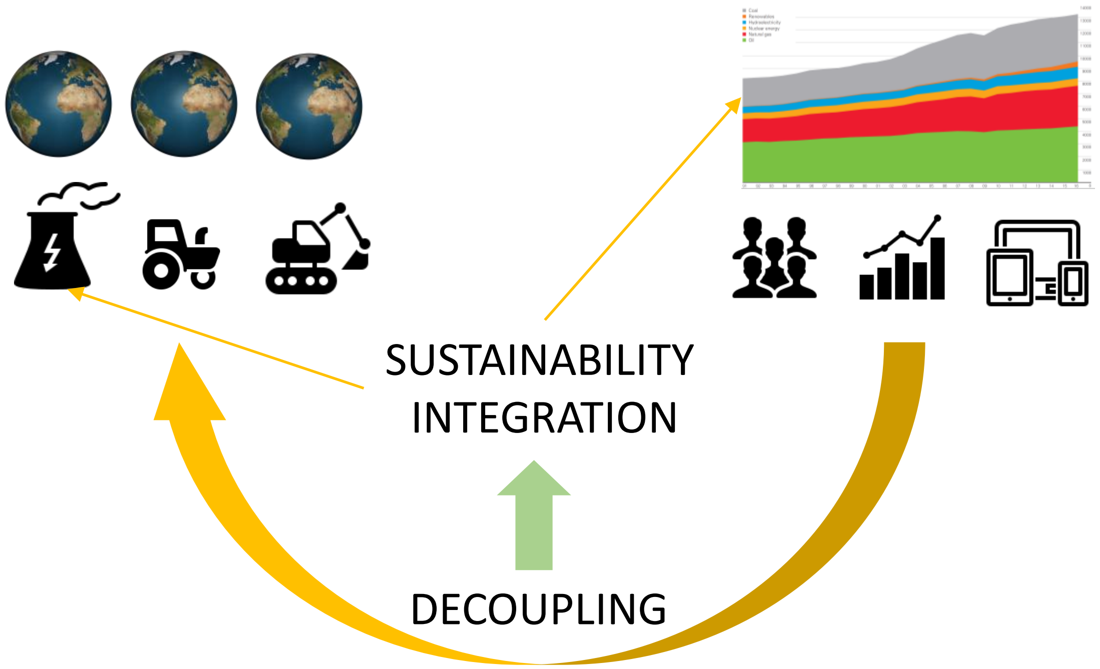
INTRODUCTION

MOTIVATION & OBJECTIVES



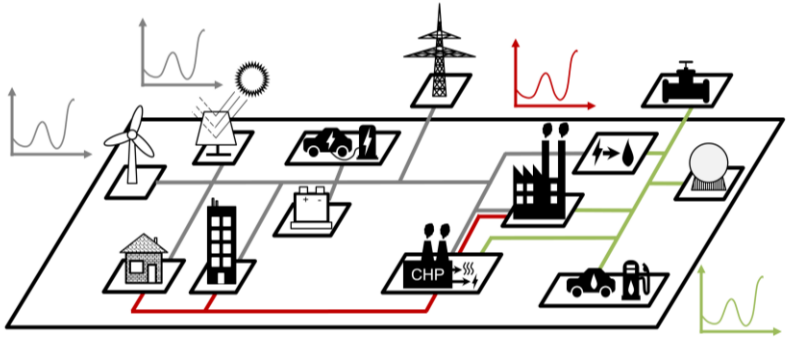
1. Find a method to couple energy modelling and environmental assessment
2. Integrate environmental indicators into the optimisation process
3. Develop combined economic and environmental optimisation and assessment indicators

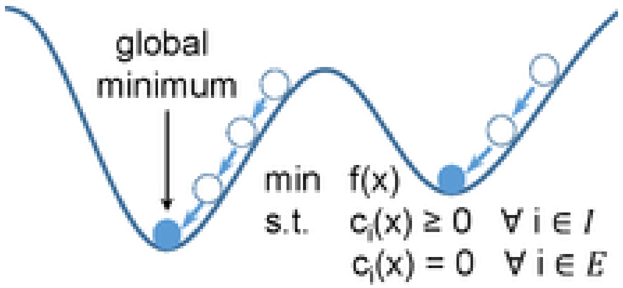
http://pngimg.com/download/25370, https://icons8.de/, BP (2017)

STATE OF THE ART

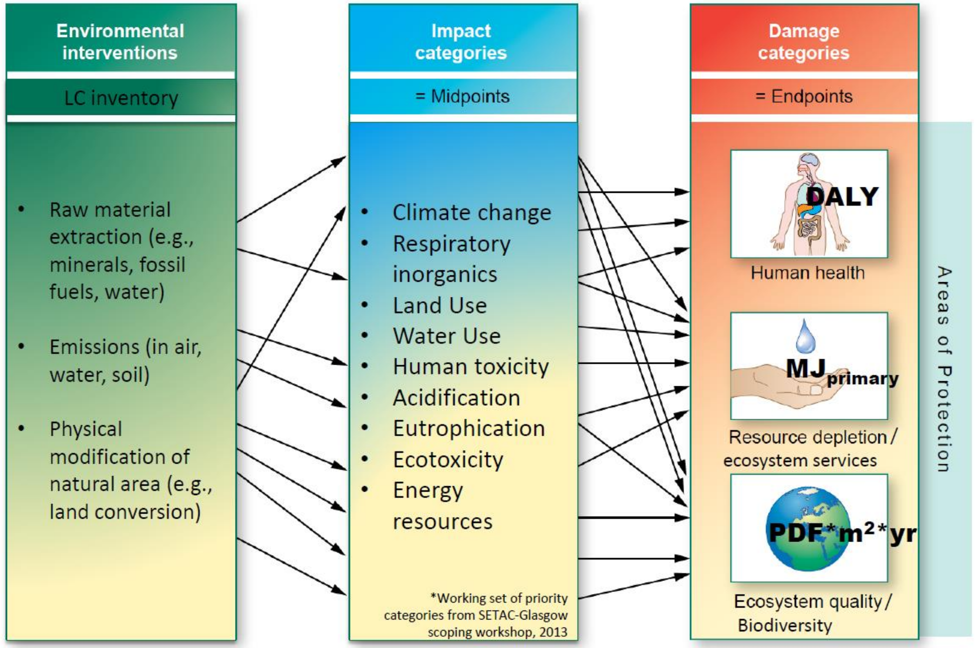
BACKGROUND

Energy system modelling (ESM)





Life Cycle Assessment (LCA)



https://www.fz-juelich.de/iek/iek-10/EN/Home/home_node.html,
https://www.nicepng.com/png/full/150-1503607_product-lifecycle-infographic-product.png, Heller (2013)

STATE OF THE ART

LINKING ESM AND LCA

Frameworks / Models:

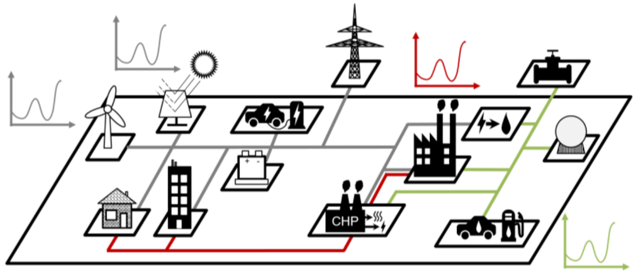
- *Arvesen et al., 2018; Azapagic and Clift, 1999; Carapellucci and Giordano, 2012; Onat et al., 2016; Pauliuk et al., 2017; Yue et al., 2016; Zhang et al., 2016*

Applications:

- *Azapagic et al. (2016): DESIRES model*
- *García-Gusano et al. (2016): TIMES model + LCA*
- *Rauner & Budzinski (2017): equilibrium model + ReCiPe single score optimisation*

Resulting research question

- Flexible, dynamic, complete, expandable and transparent linking feasible?



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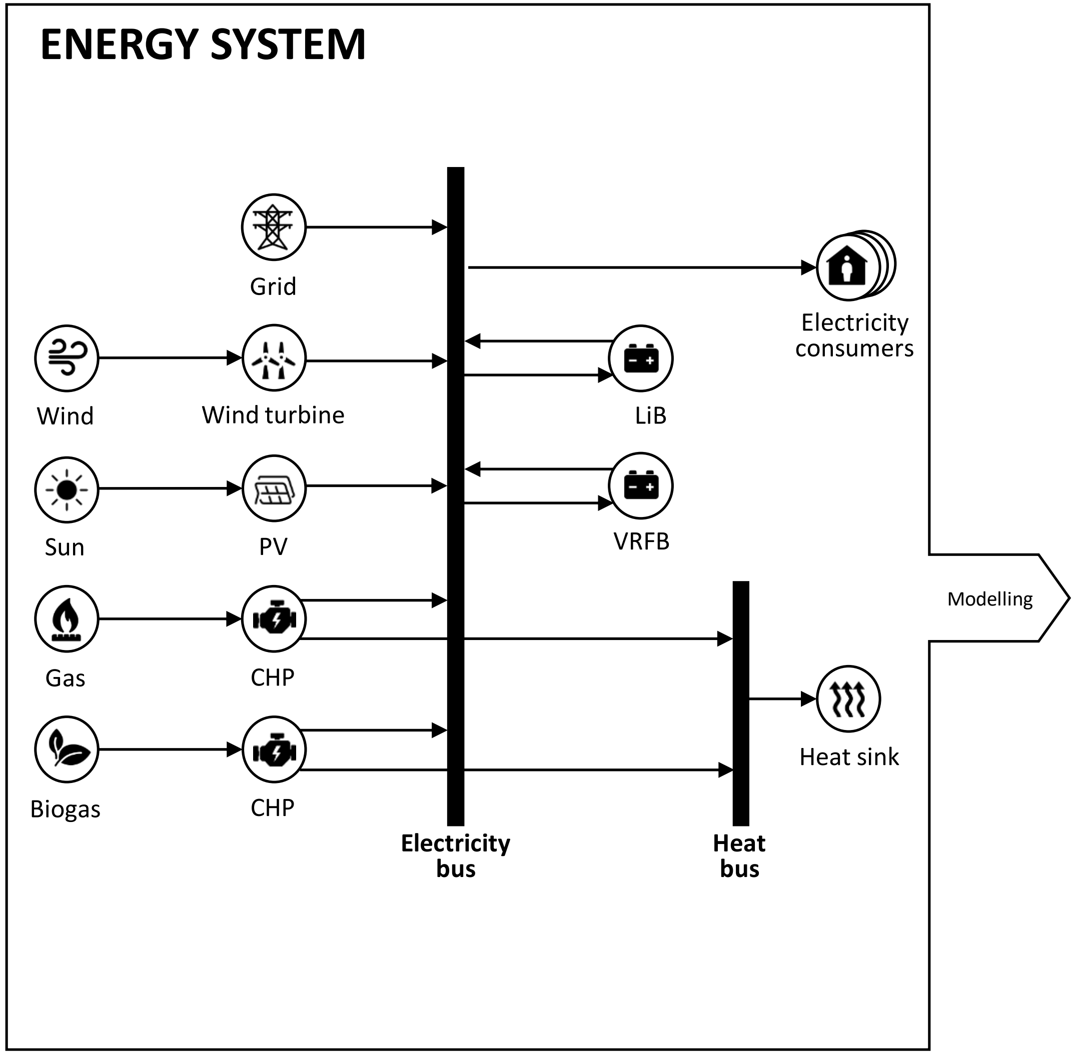
https://www.nicepng.com/png/full/150-1503607_product-lifecycle-infographic-product.png
https://www.fz-juelich.de/iek/iek-10/EN/Home/home_node.html

METHODOLOGY



METHODOLOGY
OBJECTIVE FUNCTION

- Extension of the objective function with variable costs:

$$\min \sum_{t \in T} \sum_{(i,o) \in E} [c_{(i,o)} \cdot w^{c}_{(i,o)}(t) + e_{(i,o)} \cdot w^{e}_{(i,o)}(t)] x_{(i,o)}(t) + \sum_{t \in T} \sum_{k \in K} [c_{(n)} \cdot w^{c}_{(i,o)}(t) + e_{(i,o)} \cdot w^{e}_{(i,o)}(t)] x_{(i,o)}(t)$$

t – time
c – costs
w – weight
e – environmental impact
x - flow

- and investment costs

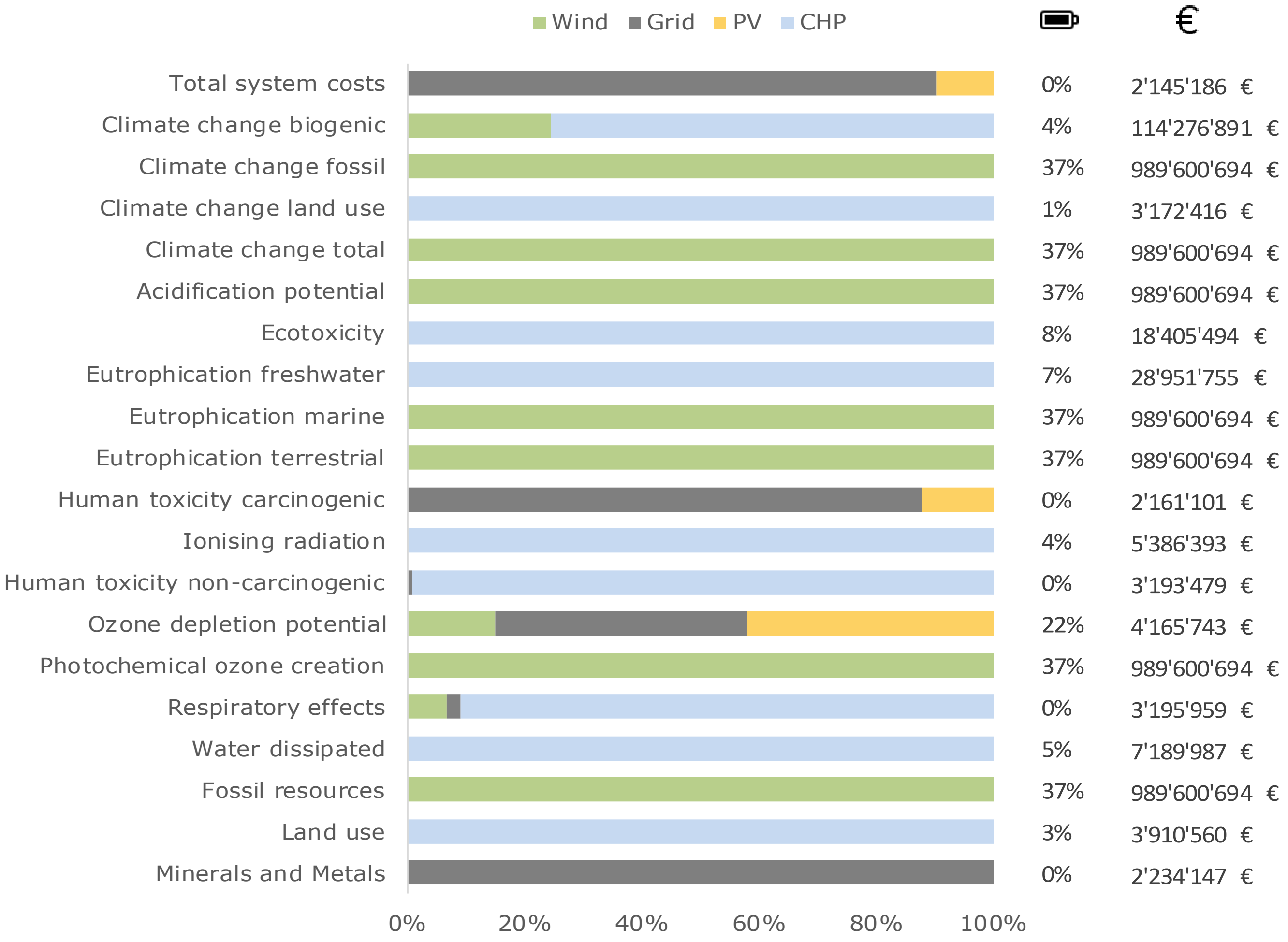
$$\min \sum_{n \in N} \sum_{(i,o) \in E} [epc_{(i,o)} \cdot w^{c}_{(i,o)}(n) + e_{(i,o)} \cdot w^{e}_{(i,o)}(n)] x_{(i,o)}(n) + \sum_{t \in T} \sum_{k \in K} [epc_{(n)} \cdot w^{c}_{(i,o)}(n) + e_{(i,o)} \cdot w^{e}_{(i,o)}(n)] x_{(i,o)}(n)$$

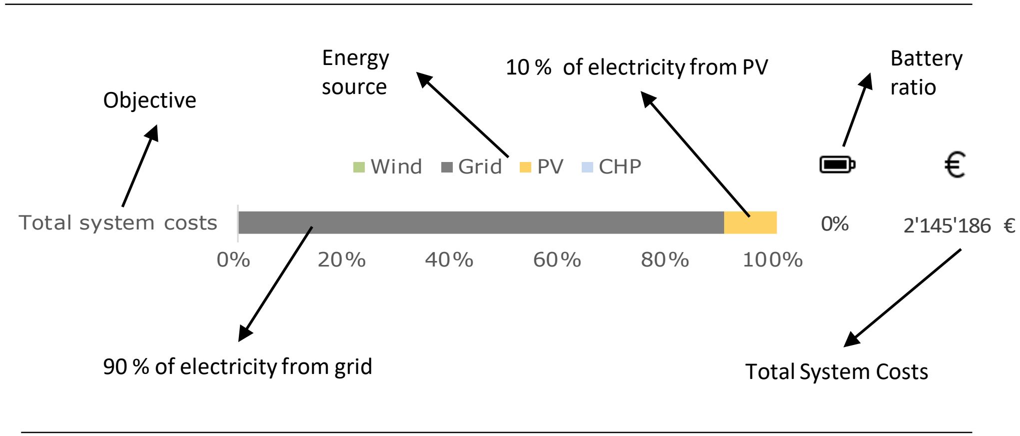
epc – equivalent periodical costs
n – years

- environmental impact *e* if multi-criteria optimisation is applied
  - JRCII: Weighting and Normalisation following ILCD
  - 5050: 50 % costs, normalised with the world GDP, 50 % JRCII

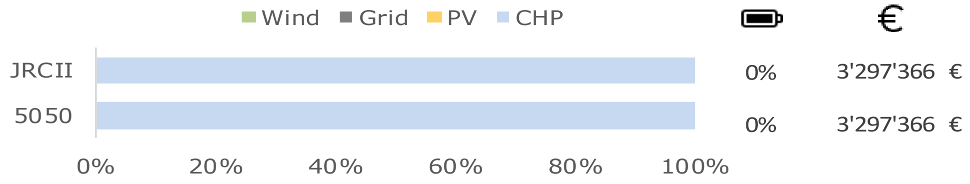
PRELIMINARY RESULTS

SINGLE CRITERIA





MULTI CRITERIA



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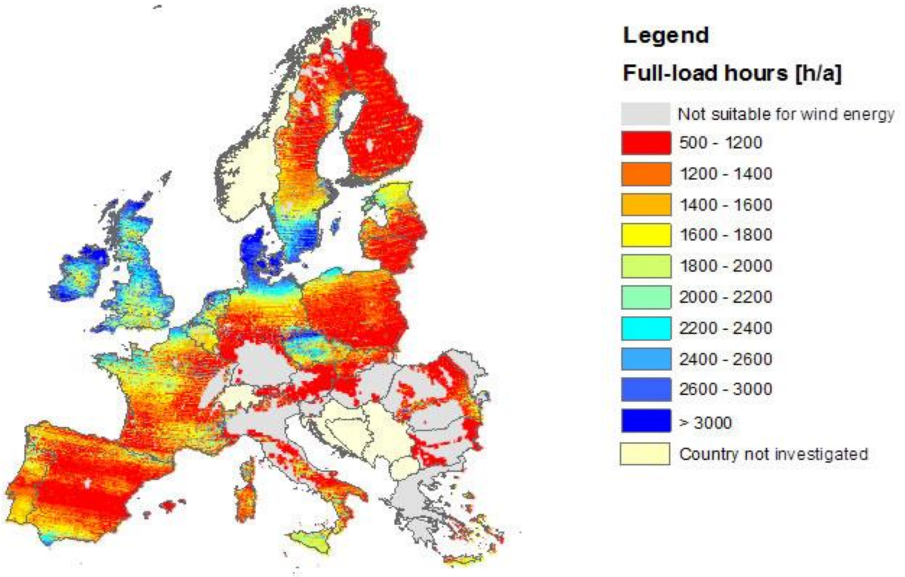
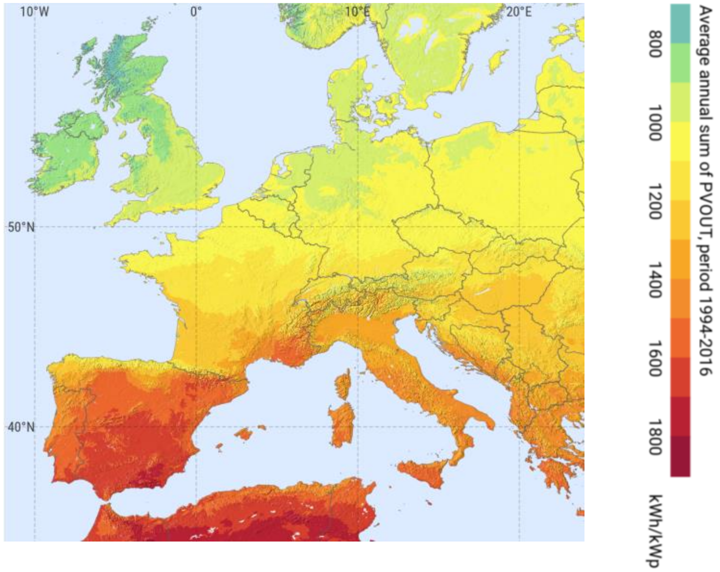
PRELIMINARY RESULTS
SENSITIVITY ANALYSIS

- Photovoltaics' impact reduction: turning point at 55 % reduction
- Two alternative weather locations:
  - Norden, Germany (wind-intensive): 2 further impact categories switch to wind, 2 % cost reduction, 85 % grid power
  - Tarife, Spain (sun-intensive): Higher PV and wind share, 9 % cost reduction
- Battery cost reduction: With 96 % reduction more PV with storage than grid power





https://solargis.com/maps-and-gis-data/download/europe
https://green-x.at/RS-potdb/potdb-long_term_potentials.php

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DISCUSSION & CONCLUSIONS

- Models (ESM a. LCA) as simplified reflection of the real system, valid within system boundaries with the specific data, technical, economic and environmental parameters
- LCA data: representativity, topicality, asymetry
- LCIA: methodological uncertainties (e.g. toxicity, local/global impacts)
- Minimum distances not defined, small changes can lead to great system shifts (penny switching effect)
- Extension of the models with heat, EVs and additional constraints (CO_2 goals) are necessary

- An **implementation of environmental indicators** in the optimisation is necessary especially in consideration of the global planetary boundaries
- **„Single scores“ are not recommendable** to achieve a comprehensive assessment
- Grid power with 10 % PV is cost-effective
- **Wind power, battery storage and CHP are environmentally beneficial** in most of the impact categories compared to grid power
- Further research necessary in environmental impact integration, single score indicators and result communication

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MANY THANKS FOR YOUR ATTENTION!

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FURTHER ASSUMPTIONS

Table 1: Costs, efficiency and life time per energy technology, CHP = Combined heat and power, PV = Photovoltaics.

Costs / Technology	**Variable [€/kWh$_{el}$]**	**Fixed [€/kW$_{el}$/a]**	**Investment [€/kW$_{el}$]**	**Effi-ciency**	**Life time**	**Reference**
Grid electricity	0.14	N/A	N/A	N/A	N/A	Fraunhofer ISE (2019a), Vattenfall (2019)
CHP gas	0.01	N/A	module: 760, transport: 46, installation: 342	el. 37 %, th. 49 %	20 yr.	ASUE (2014)
CHP biogas	0.02	N/A	module: 764, transport: 46, installation: 342	el. 37 %, th. 49 %	20 yr.	ASUE (2014)
PV	N/A	1 % of investment	1300	14 %	20 yr.	Wirth (2019), European Commission (2017)
Wind	0.03	59	1558	N/A	20 yr.	IRENA (2018) converted from USD (0.89 EUR/USD)
Lithium-ion battery (LiB)	≈ 0.11	25	Batt.mgmt.: 374, inverter: 500, installation: 125, approvals: 50	90 %, C/6	8000 cycles	Baumann *et al.* (2018; 2017), Peters *et al.* (2017)
Vanadium-redox flow battery (VRFB)	≈ 0.05	40	Batt.mgmt.: 374, inverter: 500, installation: 125, approvals: 50	75 %, C/6	8000 cycles	Baumann *et al.* (2018; 2017), Peters *et al.* (2017)

METHODOLOGY
LCIA

Table 2 LCIA model data set names, reference source, and associated unit groups for recommended and interim CFs in ILCD dataset

LCIA model	Flow property	Unit group[9] data set (+ ref. unit)	Level of recomme-ndation*
EF - Climate change; midpoint; GWP_{100}; IPPC2013	Mass CO_2-equivalents	Units of mass (kg)	I
EF - Ozone depletion; midpoint; ODP; WMO1999	Mass CFC-11-equivalents	Units of mass (kg)	I
EF - Cancer human health effects; midpoint; CTUh; USEtox™, Rosenbaum et al 2008	Comparative Toxic Unit for human (CTUh)	Units of items (cases)	II/III
EF - Non-cancer human health effects; midpoint; CTUh; USEtox™, Rosenbaum et al 2008	Comparative Toxic Unit for human (CTUh)	Units of items (cases)	II/III
EF - Respiratory inorganics; midpoint; PM2.5 eq; UNEP, Fantke et al. 2016	Mass $PM_{2.5}$-equivalents	Units of mass (kg)	I
EF- Ionizing radiation - human health; midpoint; ionising radiation potential; Frischknecht et al. (2000)	Mass U_{235}-equivalents	Units of mass (kg)	II
EF - Photochemical ozone formation; midpoint - human health; POCP; Van Zelm et al. (2008)	Mass NMVOC equivalents	Units of mass (kg)	II
EF - Acidification; midpoint; Accumulated Exceedance; Seppala et al 2006, Posch et al (2008);	Mole H^+-equivalents	Units of mole	II
EF - Eutrophication terrestrial; midpoint; Accumulated Exceedance; Seppala et al.2006, Posch et al 2008	Mole N-equivalents	Units of mole	II
EF - Eutrophication freshwater; midpoint; P equivalents; ReCiPe2008;	Mass P-equivalents	Units of mass (kg)	II
EF - Eutrophication marine; midpoint; N equivalents; ReCiPe2008;	Mass N-equivalents	Units of mass (kg)	II
EF - Ecotoxicity freshwater; midpoint; CTUe; USEtox™ , Rosenbaum et al 2008	Comparative Toxic Unit for ecosystems (CTUe)	Units of volume* time (m^3*a)	II/III
EF - Land use; midpoint; soil quality indicator; LANCA, Bos et al. 2016.	Soil Quality Index	Quality Score	III
EF – water use; midpoint; water scarcity; AWARE, Boulay et al. in UNEP 2016	Water scarcity	Units of mass (kg)[10]	III
EF - Resource use mineral and metals; midpoint; ADP ultimate reserve; Van Oers et al 2002	Mass Sb-equivalents	Units of mass (kg)	III
EF - Resource use energy carriers; midpoint; ADP energy; Van Oers et al 2002	MJ	Units of energy (MJ)	III
According to ILCD levels: **"Level I"** (recommended and satisfactory), **"Level II"** (recommended but in need of some improvements) or **"Level III"** (recommended, but to be applied with caution);i			

Table 1 recommended models for EF scheme, including indicator, units and model package

Recommendation at midpoint				
Impact category	**Indicator**	**Unit**	**Recommended default LCIA model**	**Source of CFs**
Climate change[3]	Radiative forcing as Global Warming Potential (GWP100)	kg $CO_{2\,eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)	EF-2017[4]
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11eq	Steady-state ODPs as in (WMO 1999)	EF - 2017
Human toxicity, cancer effects*	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model (Rosenbaum et al, 2008)	EF - 2017
Human toxicity, non- cancer effects*	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model (Rosenbaum et al, 2008)	EF - 2017
Particulate matter/Respiratory inorganics	Human health effects associated with exposure to $PM_{2.5}$	Disease incidences[5]	PM model recommended by UNEP (UNEP 2016)	EF - 2017
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	EF - 2017
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe 2008	EF - 2017
Acidification	Accumulated Exceedance (AE)	mol H+ eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	EF - 2017
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	EF - 2017
Eutrophication, aquatic freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	EF - 2017
Eutrophication, aquatic marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	EF - 2017
Ecotoxicity (freshwater)*	Comparative Toxic Unit for ecosystems (CTU_e)	CTUe	USEtox model, (Rosenbaum et al, 2008)	EF - 2017
Land use	Soil quality index[6] (Biotic production, Erosion resistance, Mechanical filtration and Groundwater replenishment	Dimensionless, aggregated index of: kg biotic production/ (m^2*a)[7] kg soil/ (m^2*a) m^3 water/ (m^2*a) m^3 g.water/ (m2*a)	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)	EF - 2017
Water scarcity	User deprivation potential (deprivation-weighted water consumption)	kg world eq. deprived	Available WAter REmaining (AWARE) in UNEP, 2016	EF - 2017
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML Guinée et al. (2002) and van Oers et al. (2002).	EF - 2017
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)[8]	MJ	CML Guinée et al. (2002) and van Oers et al. (2002)	EF - 2017

[3] Three additional sub-indicators may be requested for reporting, depending on the PEFCR. The sub-indicators are further described in dedicated section

[4] The full list of characterization factors (EF-2017) is available thorugh the link provided in annex 2

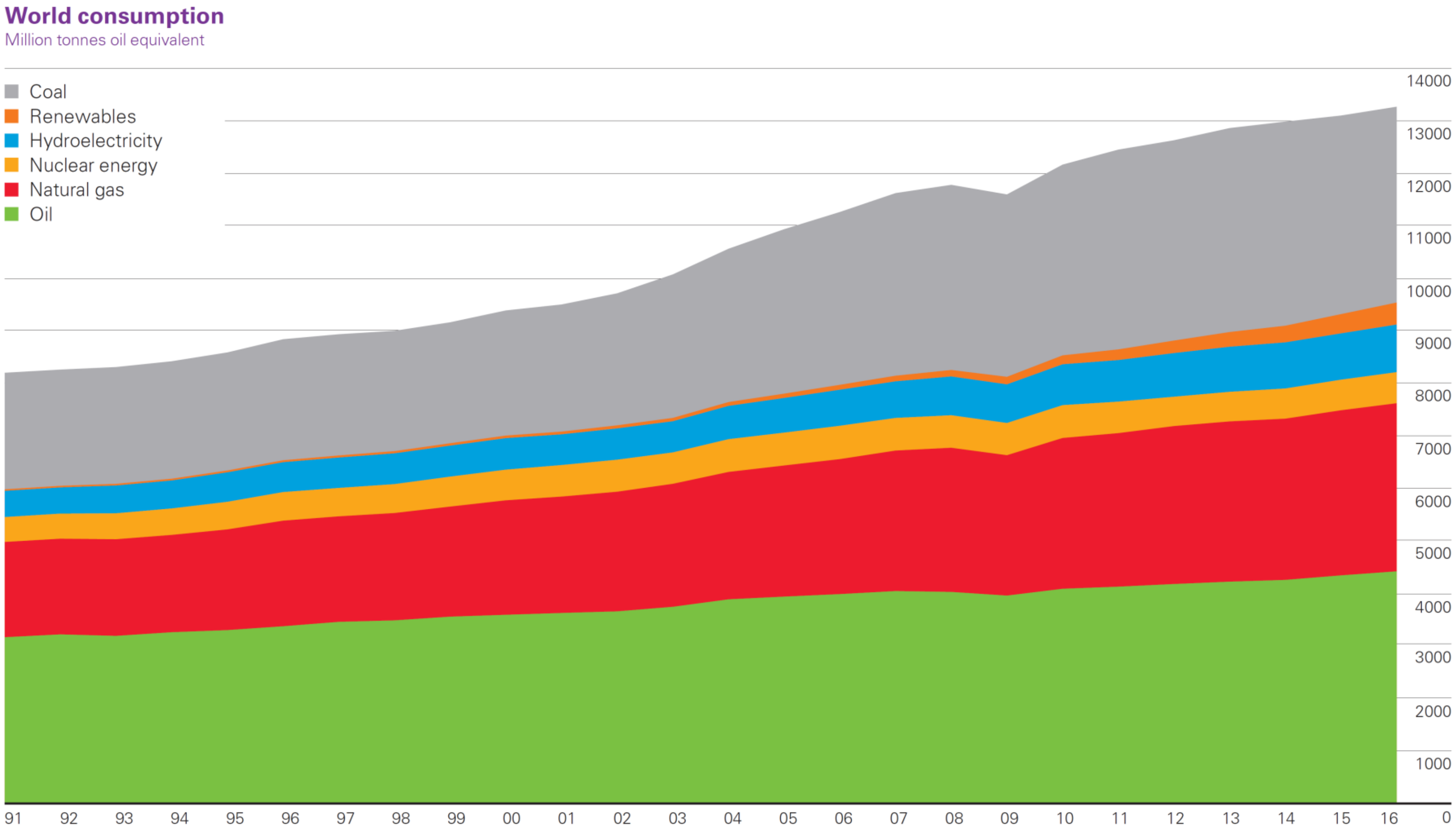
[5] The name of the unit is changed from "Deaths" in the original source (UNEP, 2016) to "Disease incidences". The CFs are the same as in the original source (except for adaptation of specific flows, as explained in chapter 4.4)

[6] This index is the result of the aggregation, performed by JRC, of the 4 indicators provided by LANCA model as indicators for land use

[7] This refers to occupation and transformation

INTRODUCTION

ENERGY CONSUMPTION



BP (2017)