What would be the ideal combination of technologies and fuels in the energy system of the future?

Analysis of the transformation of the German energy system

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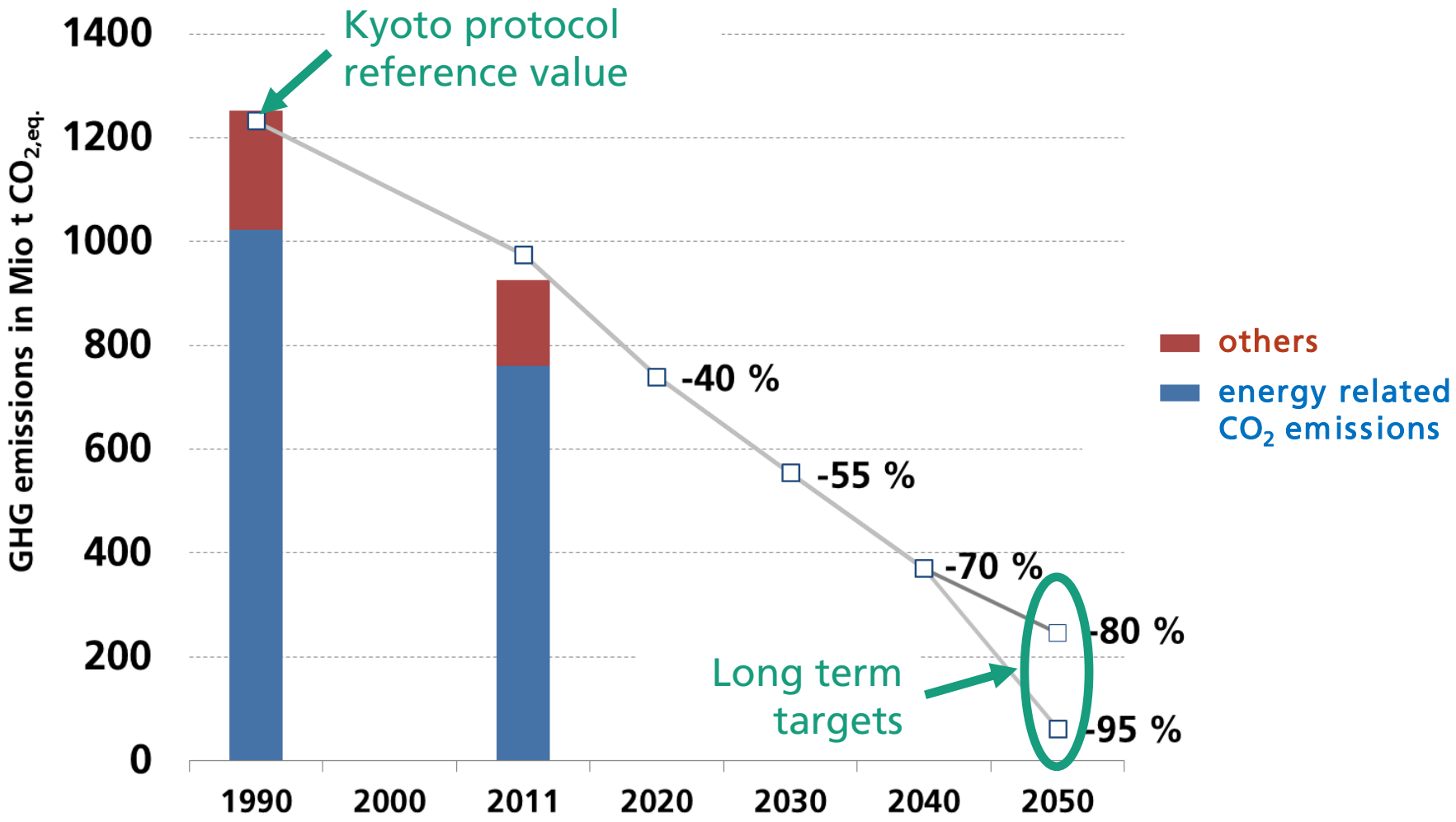
Germany's greenhouse gas emissions – history and targets



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Optimization of Germany's future energy system

Mimimize total annual cost (investment, operation, maintenance, …)

REMod-D

Renewable Energy Model – Deutschland

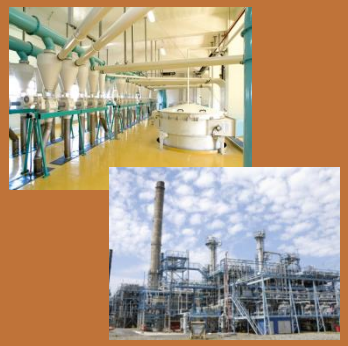
Techno-economic optimization based on comprehensive simulation (hourly time scale)

Electricity generation, storage and end-use

Fuels (including biomass and synthetic fuels from RE)

Mobility (battery-electric, hydrogen, conv. fuel mix)

Heat (buildings, incl. storage and heating networks)



Processes in industry and tertiary sector

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Optimization approach

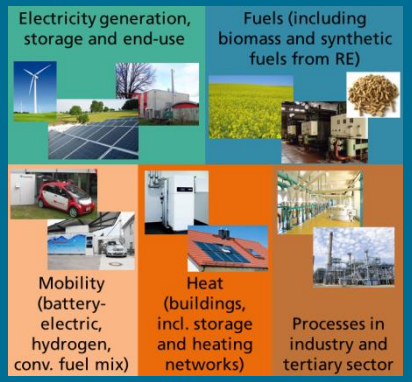
Boundary conditions

CO_2 emissions ➔ available amount of fossil energy sources

Other boundary conditions (e.g. available energy from biomass)

Optimizer

minimize total annual cost



Results

Installed capacity of energy converters

Size of storages

Range of building energy retrofit

Heating technology mix (including district heating networks)

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Optimized system: Electricity generation

Photovoltaics
~ 147 GW_{el}

Onshore Wind
~ 120 GW_{el}

Offshore Wind
~ 32 GW_{el}

Medium and large size CHP
(connected to district heating)
~ 60 GW_{el}

Source: Hans-Martin Henning, Andreas Palzer: Energiesystem Deutschland 2050. Studie des Fraunhofer ISE, November 2013

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Optimized system: Heat

Energy retrofit of buildings
~ 40 % of today's space heating demand

decentralized

Solar thermal
~ 42 GW_{th}

Heat pumps
- ~ 22 GW_{th} (el., brine)
- ~ 19 GW_{th} (el., air)
- ~ 15 GW_{th} (gas)

centralized

Solar thermal
~40 GW_{th}

CHP in heat networks
- ~ 60 GW_{el} installed capacity
- ~ 15 GW_{th} centralized heat pumps

Source: Hans-Martin Henning, Andreas Palzer: Energiesystem Deutschland 2050. Studie des Fraunhofer ISE, November 2013

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Optimized system: Storage

Stationary batteries
Total ~24 GWh (e.g. 8 Mio units with 3 kWh each)

Pumped storage power plants
42 units with a total of 60 GWh

Electrolysers with total capacity of ~33 GW_{el} (needed for mobility)

Heat buffers in buildings
Total ~320 GWh (e.g. 7 Mio units with 800 Litres each)

Large scale heat storage in district heating systems
Total ~350 GWh (e.g. 150 units with 50.000 m³ each)

Source: Hans-Martin Henning, Andreas Palzer: Energiesystem Deutschland 2050. Studie des Fraunhofer ISE, November 2013

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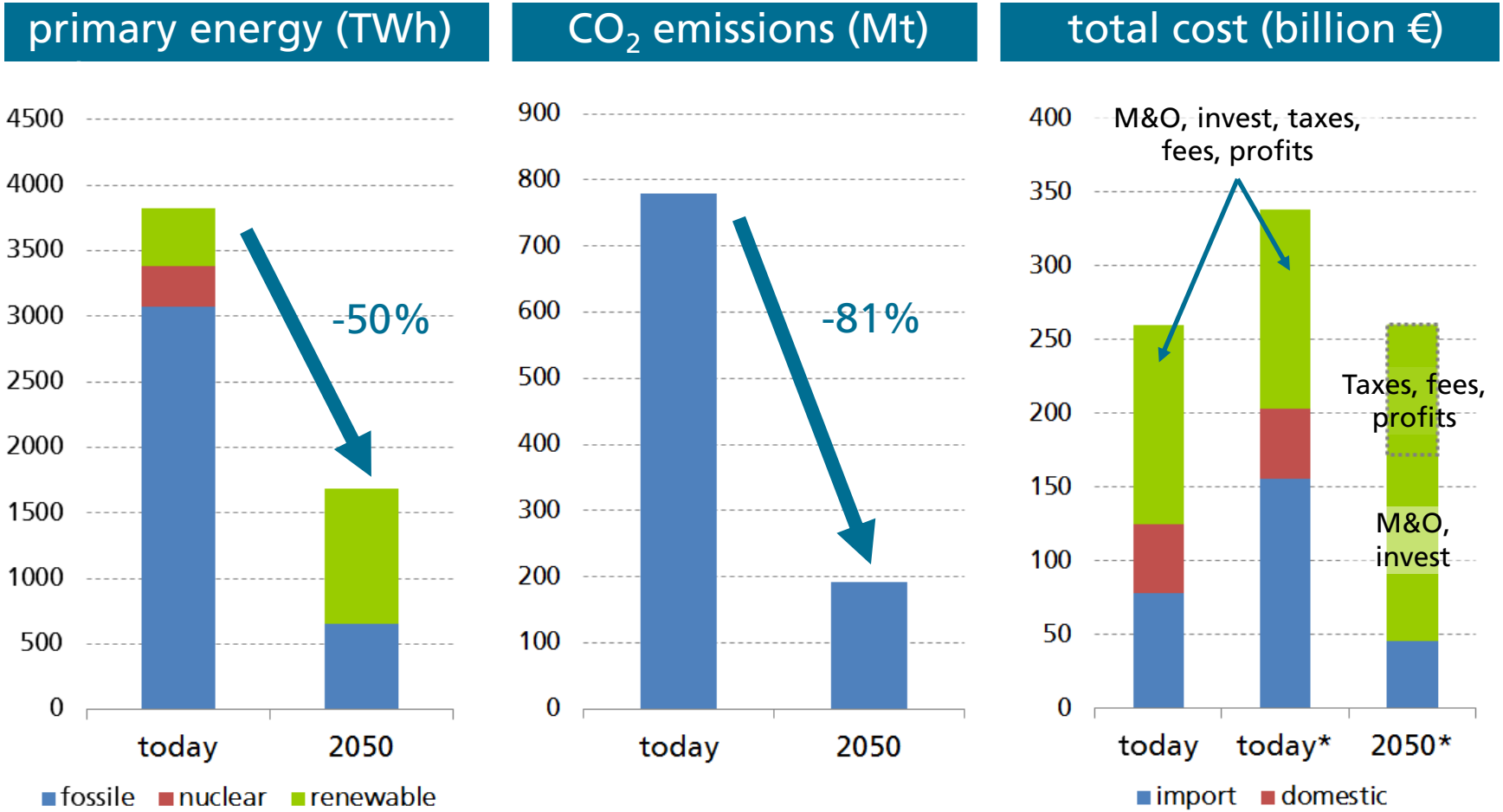
Today's system vs. optimized system in 2050



*Assumed doubling of fossil fuel prices by 2050

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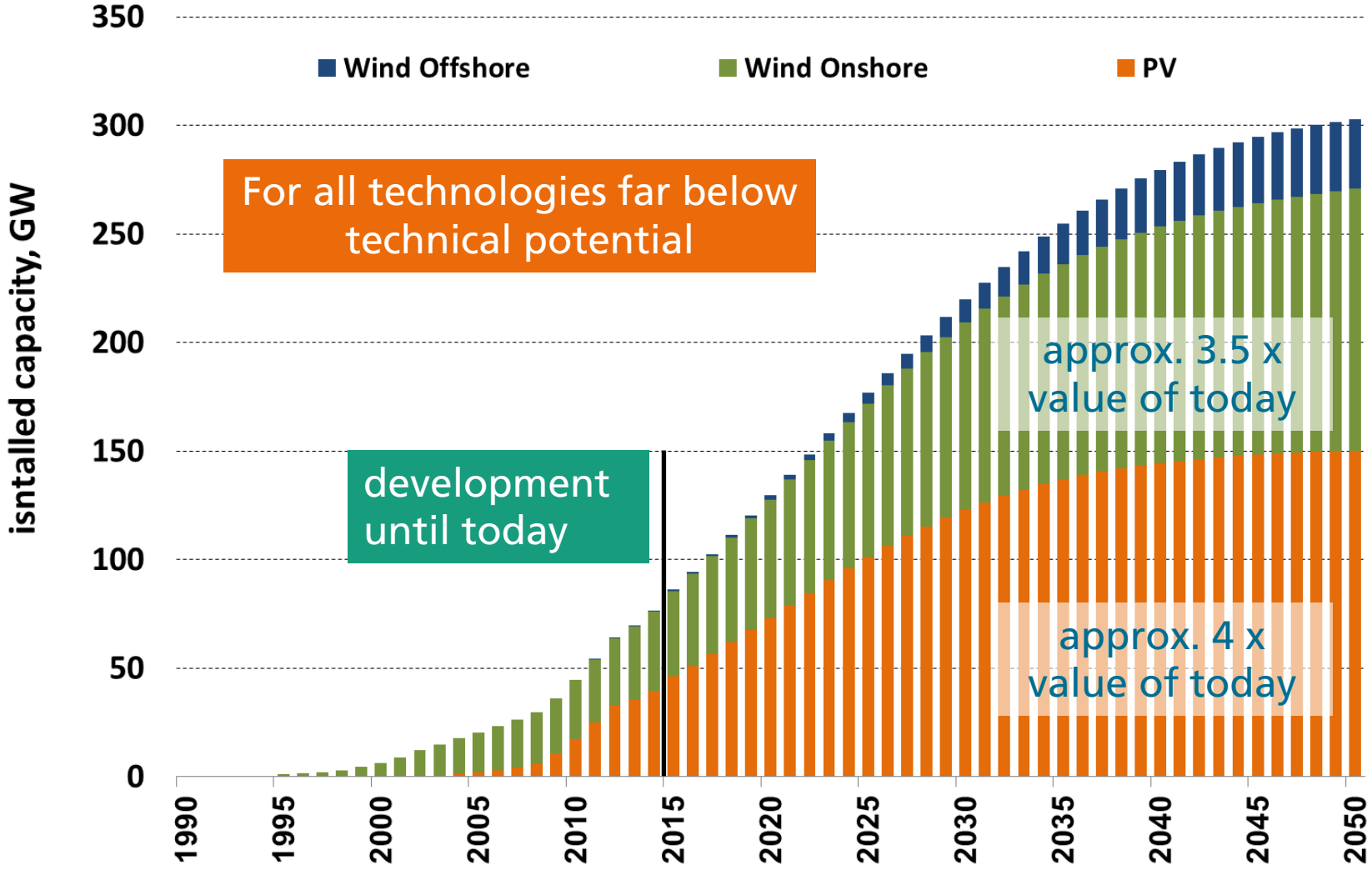
Projection of RE development (fluctuating RE electricity)



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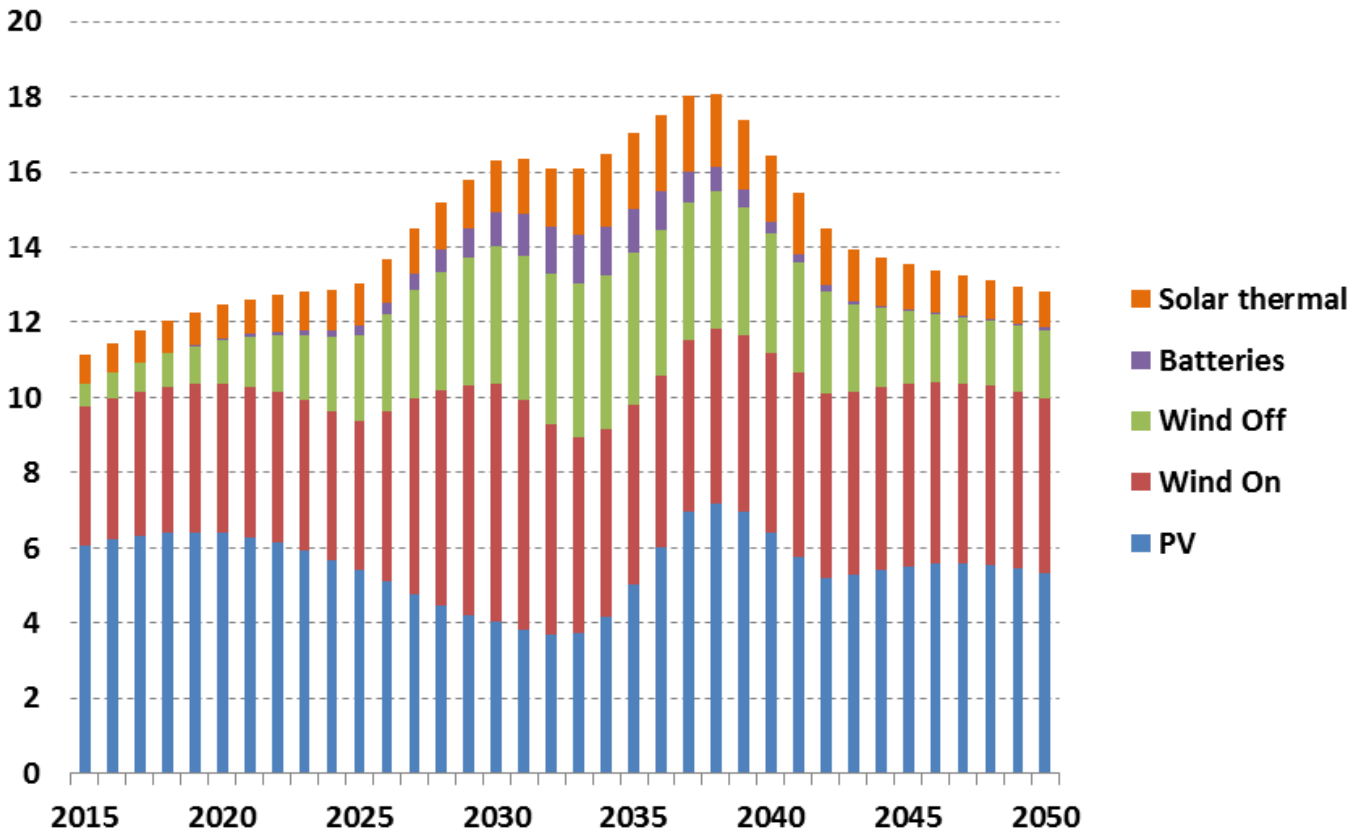
Investments for RE (wind, solar) and stationary batteries

bn € p.a. (incl. repowering)



Total investments (w/o capital cost, incl. re-powering) from 2015 to 2050: 515 bn $€_{2014}$

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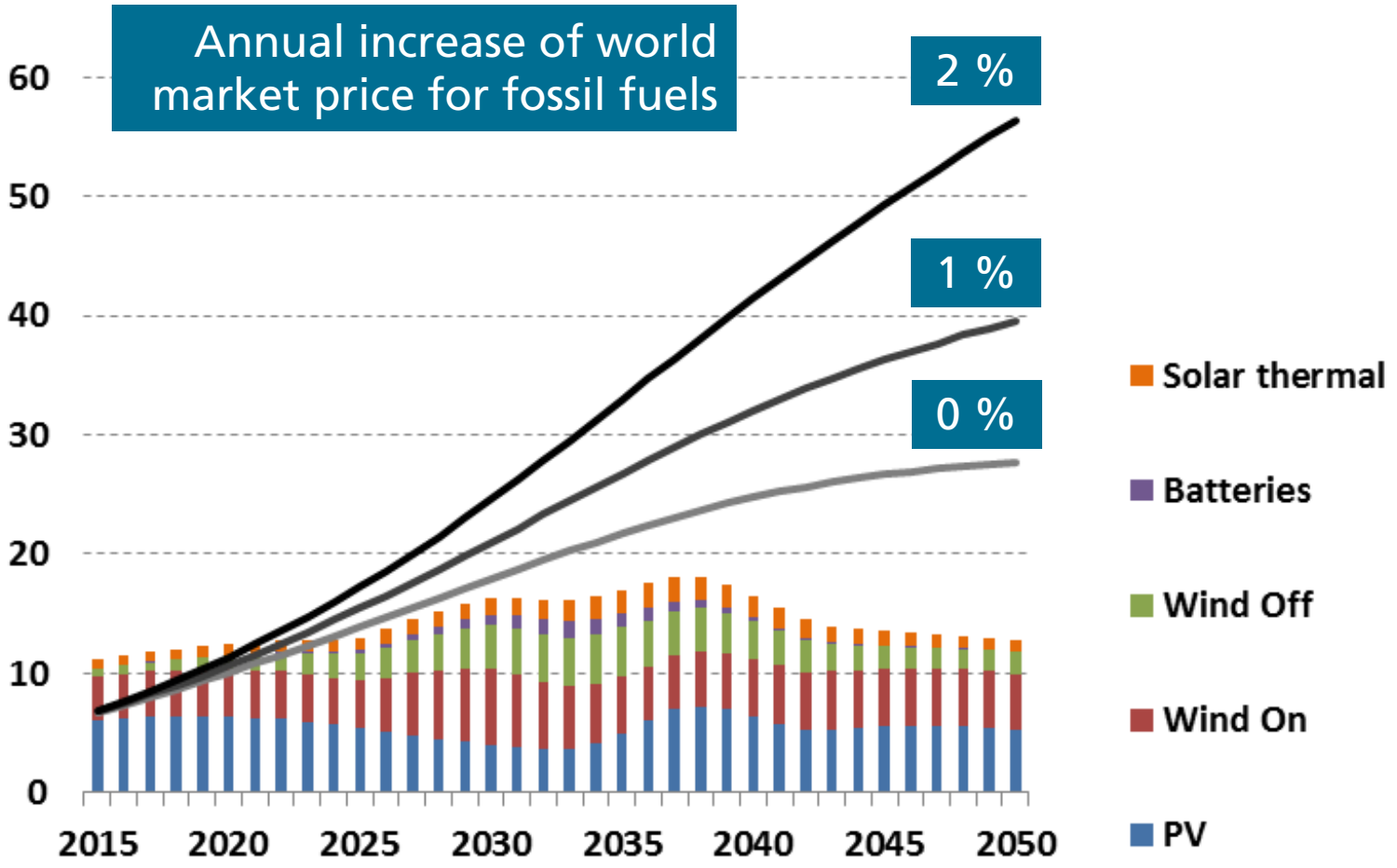
Investments vs. saved fuel cost in bn € p.a.



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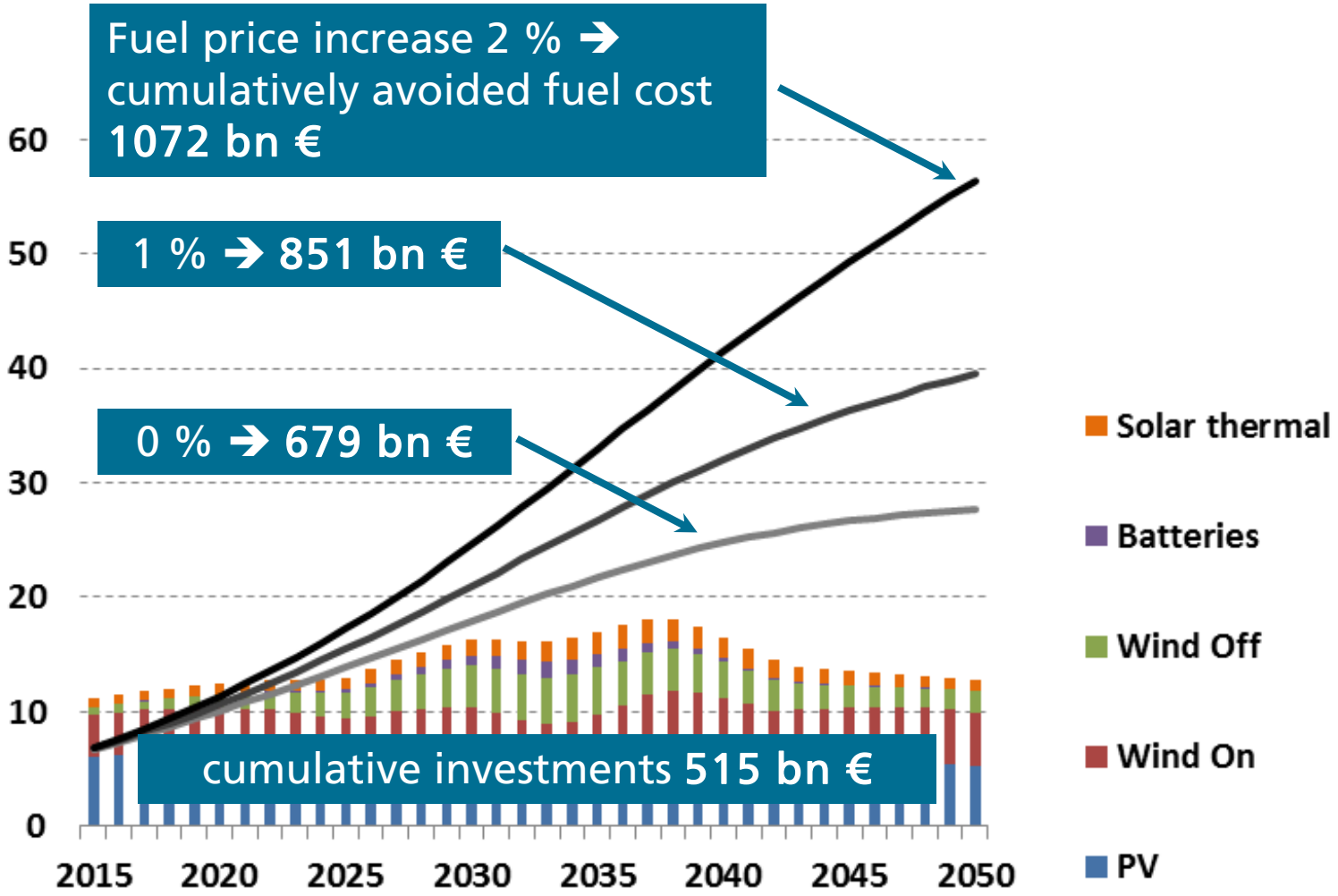
Investments vs. saved fuel cost in bn € p.a.



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Phases of the energy system transformation

Phase 1 „RE development“	Phase 2 „system integration“	Phase 3 „synthetic fuels“	Phase 4 „RE import“
CO_2-reduction ~ 0-20%	CO_2-reduction ~ 20-60%	CO_2-reduction ~ 60-80%	CO_2-reduction ~ 80-100 %
■ Development of basic RE technologies (wind, solar) ■ Significant cost reductions ■ Market introduction and extension without significant implications for the overall system	■ Activation of flexibilities: residual electricity generation and electricity use ■ Convergence of electricity and heat sector ■ Demand side management ■ Short term storage	■ Significant negative residual loads ■ Use of renewable electricity for production of synthetic fuels ■ Increased use of synthetic fuels for mobility sector	■ Final displacement of fossil fuels in all end-use sectors ■ Import of renewable fuels, e.g. from regions in the sun belt (e.g. north africa)

- Continuous increase of efficiency in end-use sectors
  - Energetic refurbishment (building stock)
  - Reduction of electricity use in classical end-use applications (e.g. artificial lighting, pumps and drives, …)
- Continuous extension of renewable energy converters (solar, wind, geothermal)

Source: Hans-Martin Henning, Andreas Palzer, Carsten Pape, Frieder Borggrefe, Henning Jachmann und Manfred Fischedick: Phasen der Transformation des Energiesystems. Energiewirtschaftliche Tagesfragen, Heft 1-2/2015, Februar 2015

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Summary and outlook

- Reduction of energy-related CO_2 emissions by 80 % and above possible
- Lower cost on long term (once major transformation completed)
- Flucutuaing renewable energies (wind, solar PV) become backbone of electricity generation and dominate the overall system
- Intersectorial integration and flexibilization highly important: electricity, heat, transportation, industry processes
- Significant local value and employment creation and investment opportunities for many stakeholders
- Powerful models can help to develop optimized systems and roadmaps on different levels: countries, regions, cities
- Ongoing further model development: optimization of transformation pathway (minimizing overall transformation cost)

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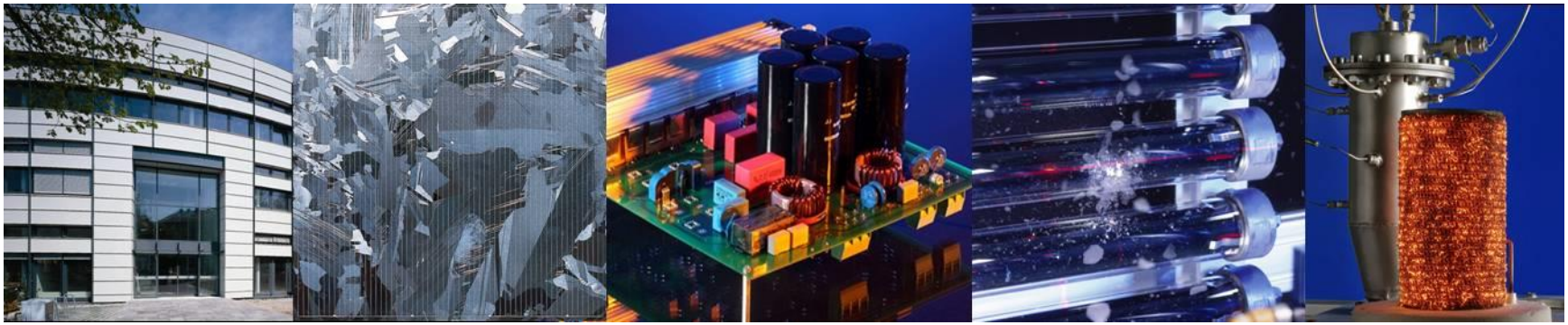

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