South Africa’s {electrical} energy mix

CSIR Energy Centre

2nd Nuclear Regulatory Information Conference

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our future through science

Agenda

1 Global context

2 Domestic context

3 The (electrical) energy mix

4 Conclusions

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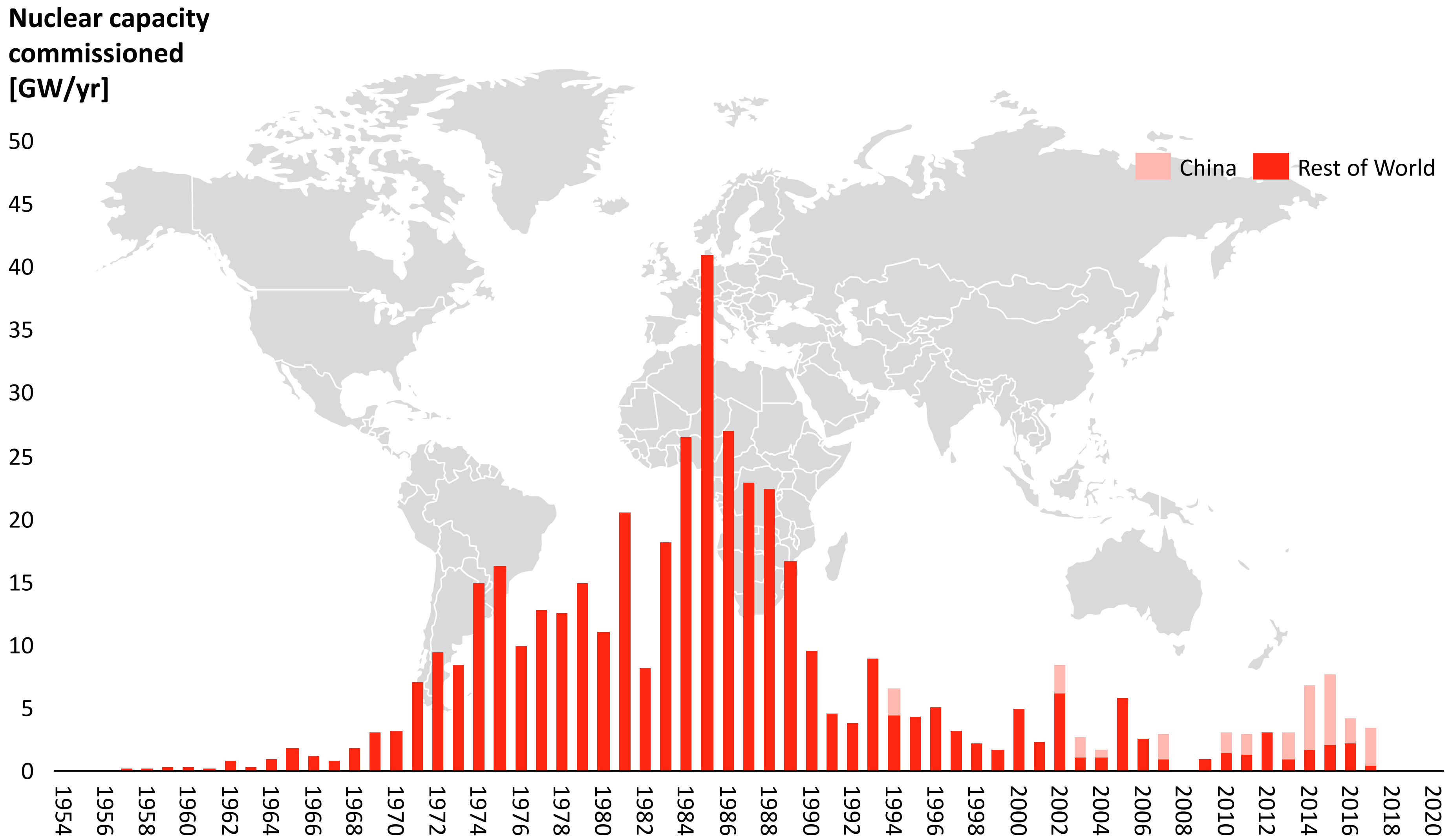
our future through science

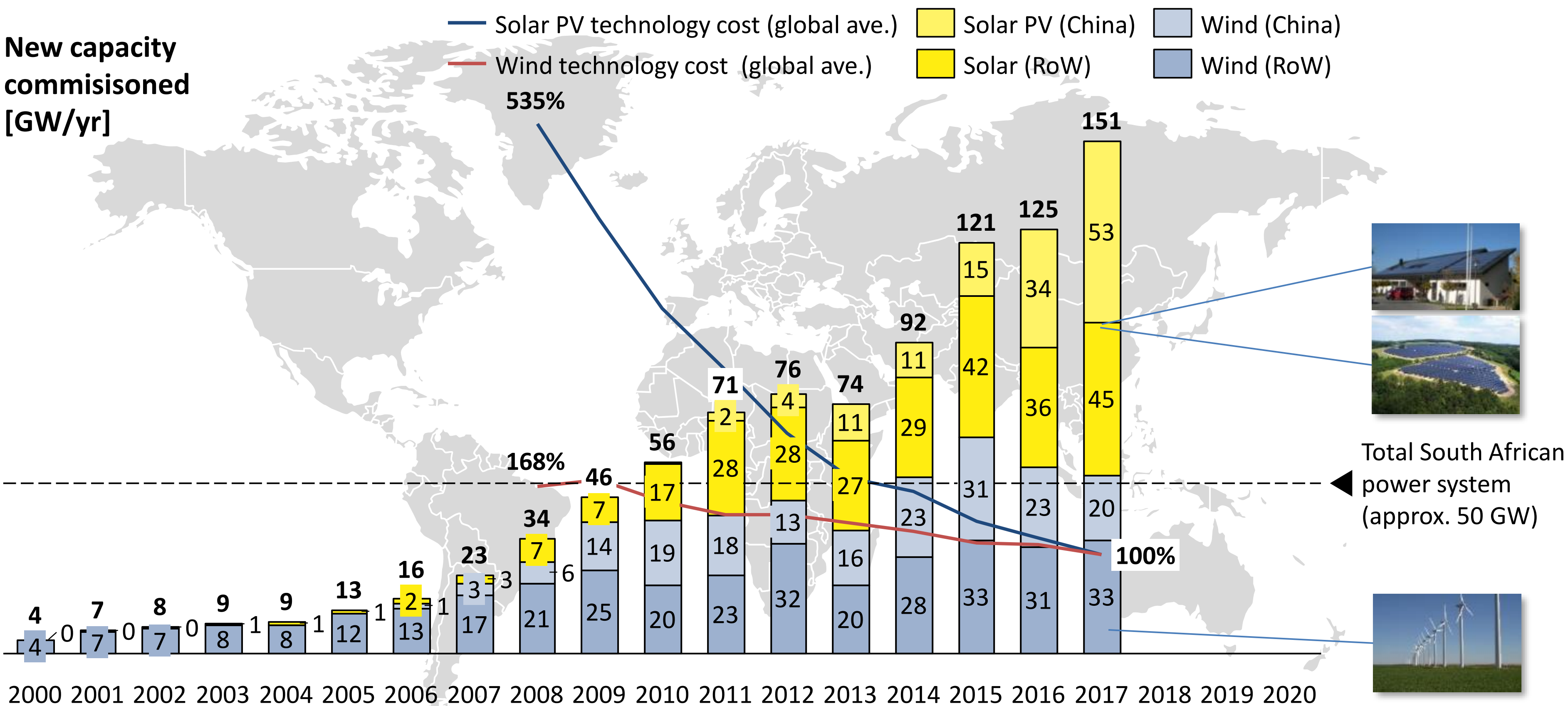
World: Last decade, more than half of new nuclear capacity came from China (likely to continue)

Nuclear capacity commissioned – China vs Rest of World (1954-2016)



Sources: World Nuclear Association - Reactor database (2016), CSIR analysis

World: Significant cost reductions materialised in the last 5-8 years with China leading in both more recently



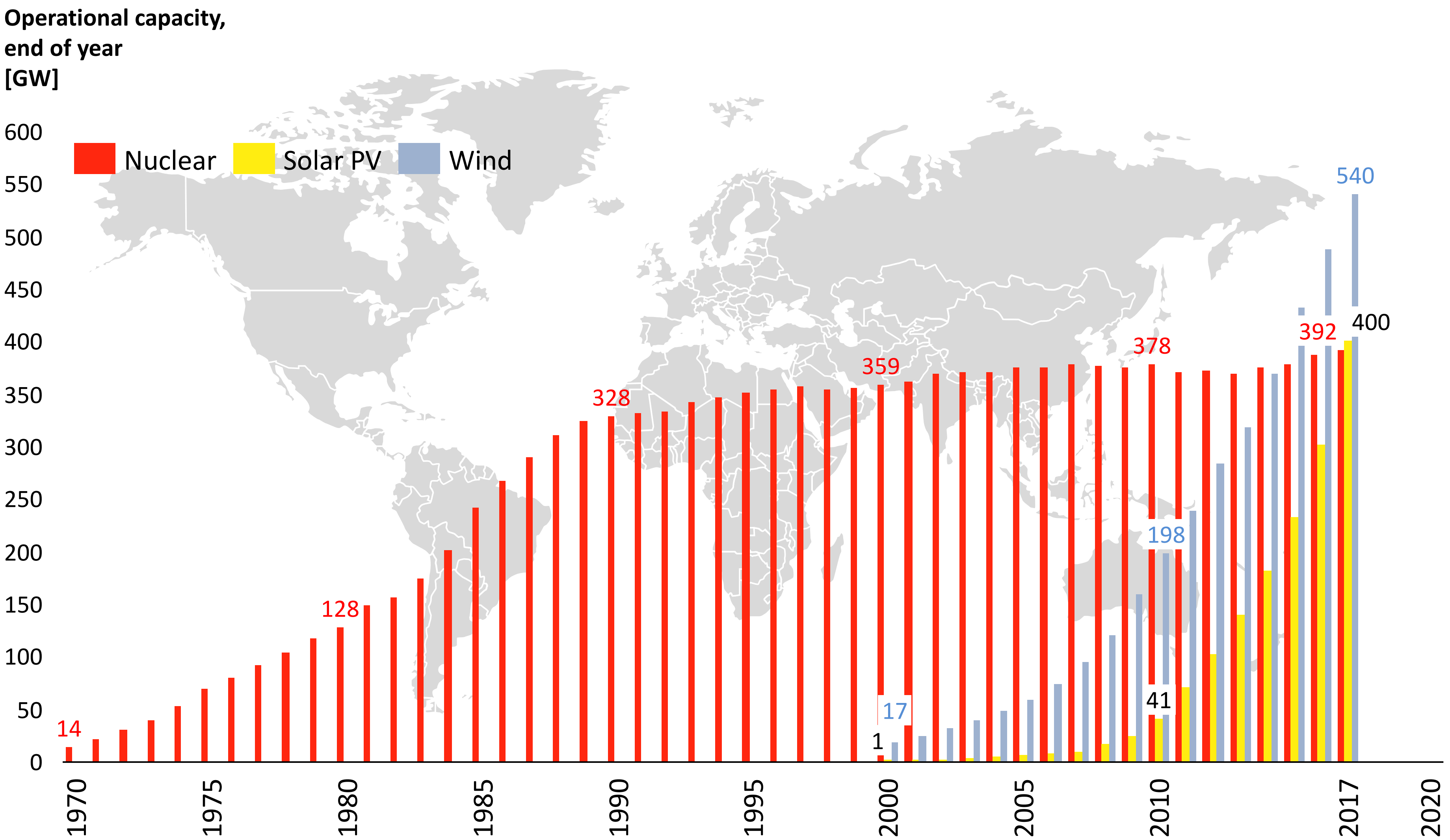
Subsidies

Cost competitive

Sources: GWEC; IRENA; IEA PVPS; CSIR analysis

After 1970-1990 ramp-up, nuclear capacity remained relatively stable whilst other technologies have grown considerably since 2000

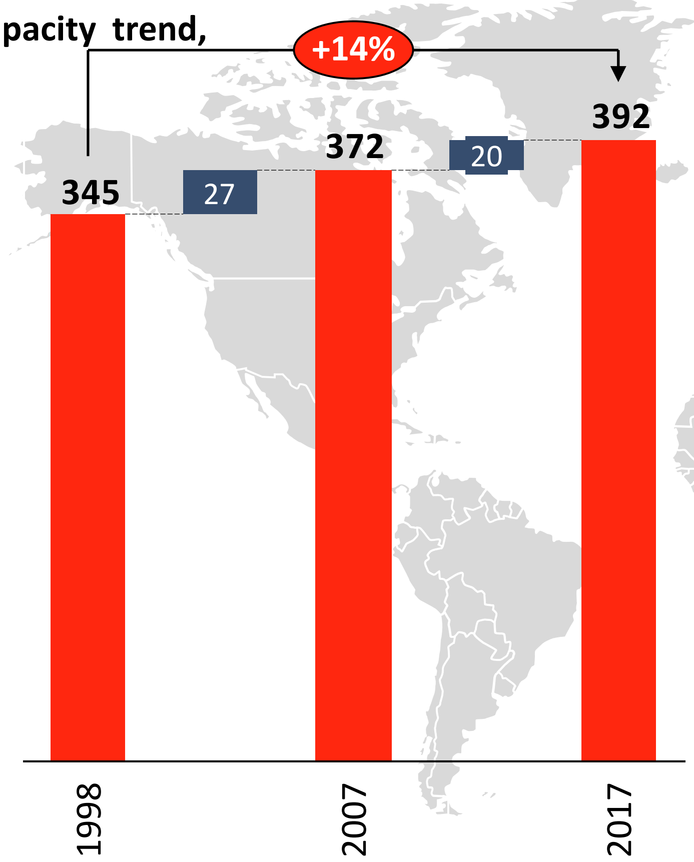
Global installed capacity end of year for nuclear, wind and solar PV (1970-2016) in GW (net)



Sources: World Nuclear Association – Reactor database; IEA PVPS; GWEC; CSIR analysis

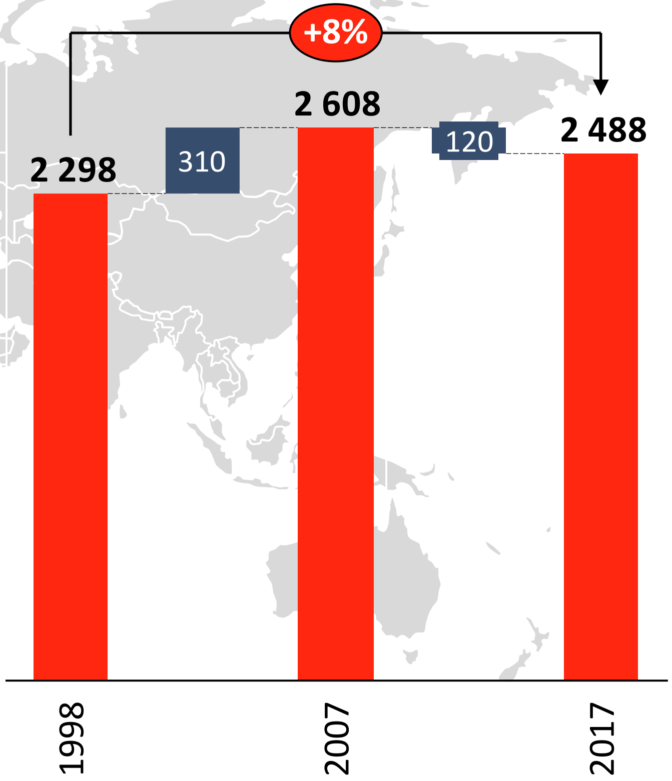
Operating nuclear capacity has grown 14% in the last two decades globally whilst electricity supplied has grown 8%

Nuclear capacity trend, [GW]



... also, ≈60 GW under construction
(22 GW in China)

Nuclear electricity supplied, [TWh]



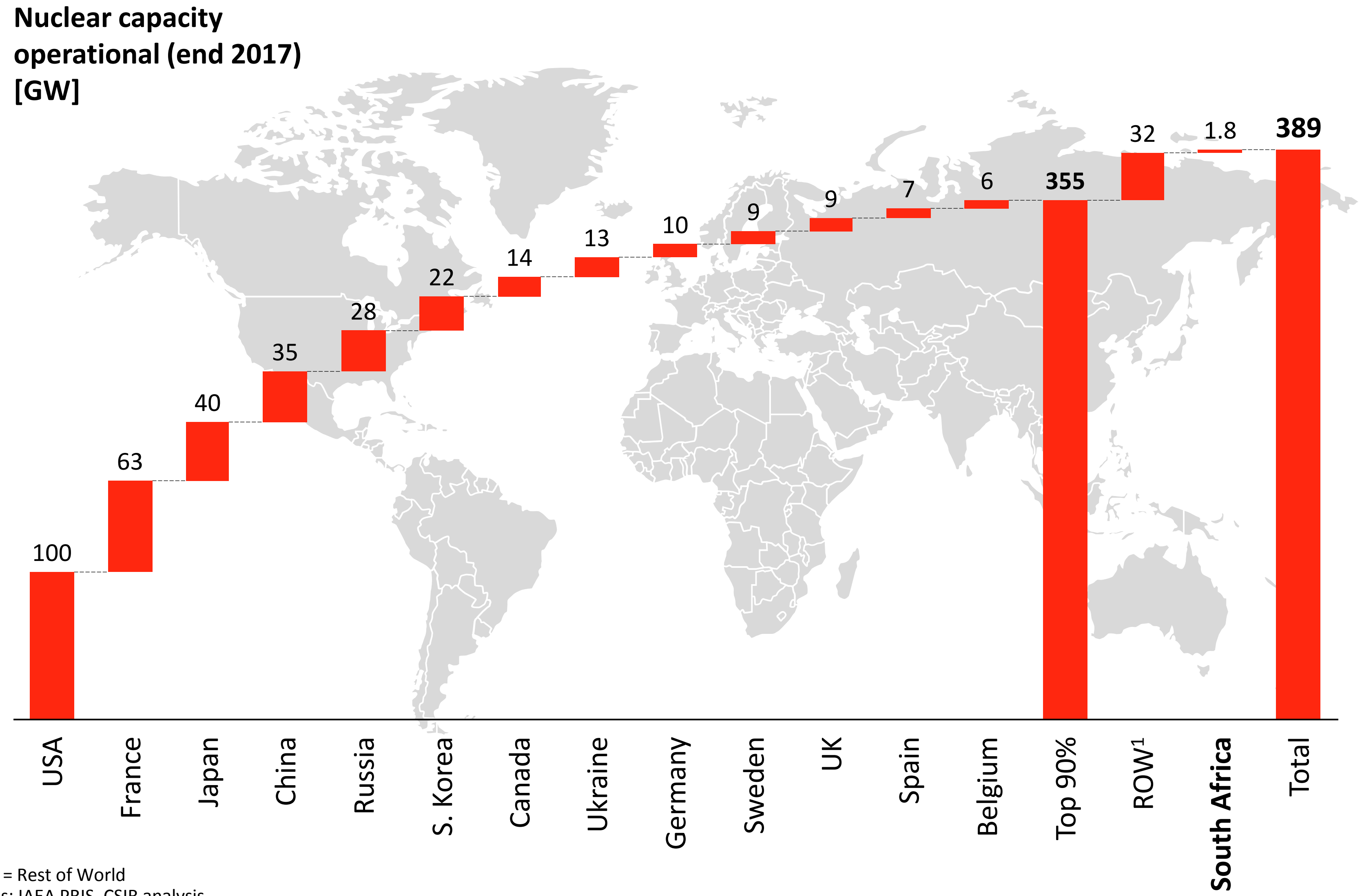
... of 17 703 TWh
(≈ 13% of global)

... of 24 345 TWh
(≈11% of global)

Sources: IAEA PRIS, IEA, CSIR analysis

13 of the 30 nuclear-power countries host 90% of all nuclear capacity coming to just under 400 GW – RSA at 1.8 GW

Operational nuclear net capacity (2017)



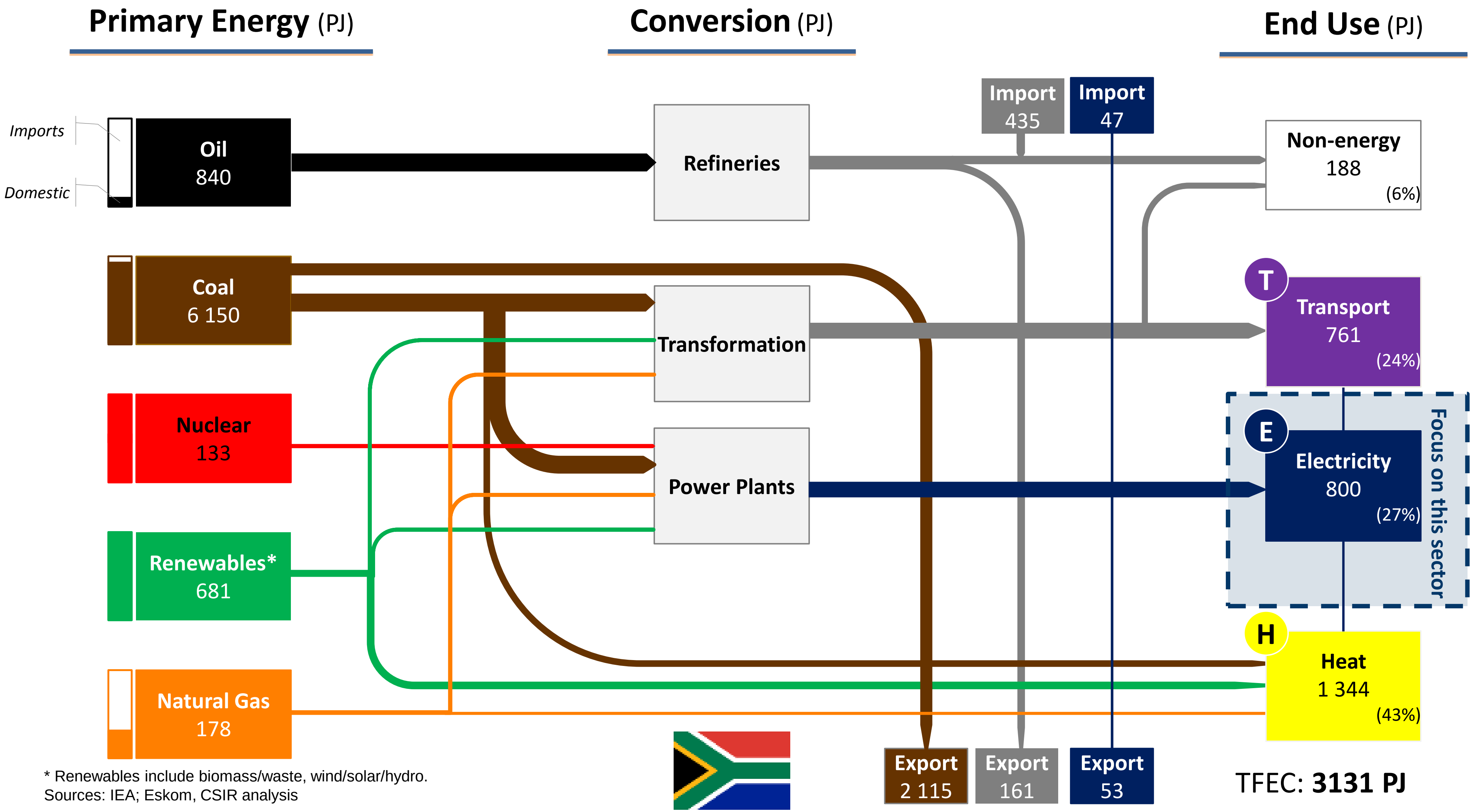
[1] ROW = Rest of World

Sources: IAEA PRIS, CSIR analysis

Agenda

Focus will be on electricity sector only – end-use is 25% transport, 25% electricity and 50% heating/cooling

Simplified energy-flow diagram (Sankey diagram) for South Africa in 2015 (PJ)



TFEC: **3131 PJ**

* Renewables include biomass/waste, wind/solar/hydro.
Sources: IEA; Eskom, CSIR analysis

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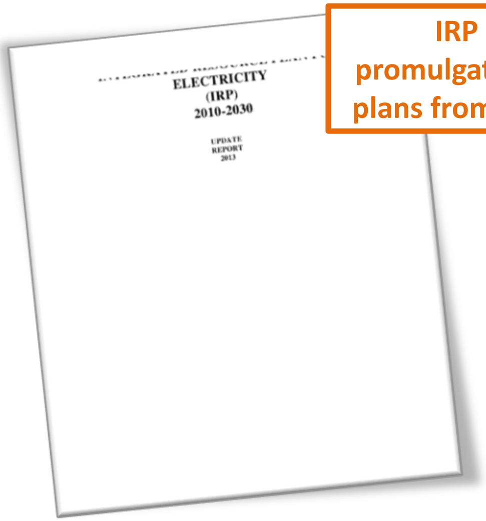
Last promulgated IRP is IRP 2010, update currently ongoing (IRP 2016) and newer version due August 2018

The enforceable IRP in South Africa is still the IRP 2010 as promulgated in 2011

A number of changes since (primarily demand forecast and confirmation of technology cost decreases)

Draft IRP 2016 the latest public update to the IRP and is the electricity system expansion plan to 2050 with public comments invited by the DoE submitted in March 2017

<u>NOW:</u> Updated version expected August 2018 following further consultations in the interim



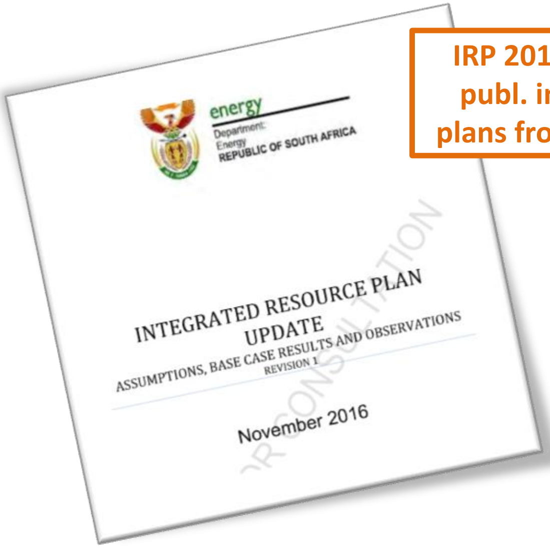
ELECTRICITY
(IRP)
2010-2030
UPDATE
REPORT
2013

IRP 2010: promulgated in 2011, plans from 2010-2030

INTEGRATED RESOURCE PLAN FOR
ELECTRICITY
(IRP)
2010-2030
UPDATE
REPORT
2013

21 NOVEMBER 2013

IRP Update 2013: Not promulgated



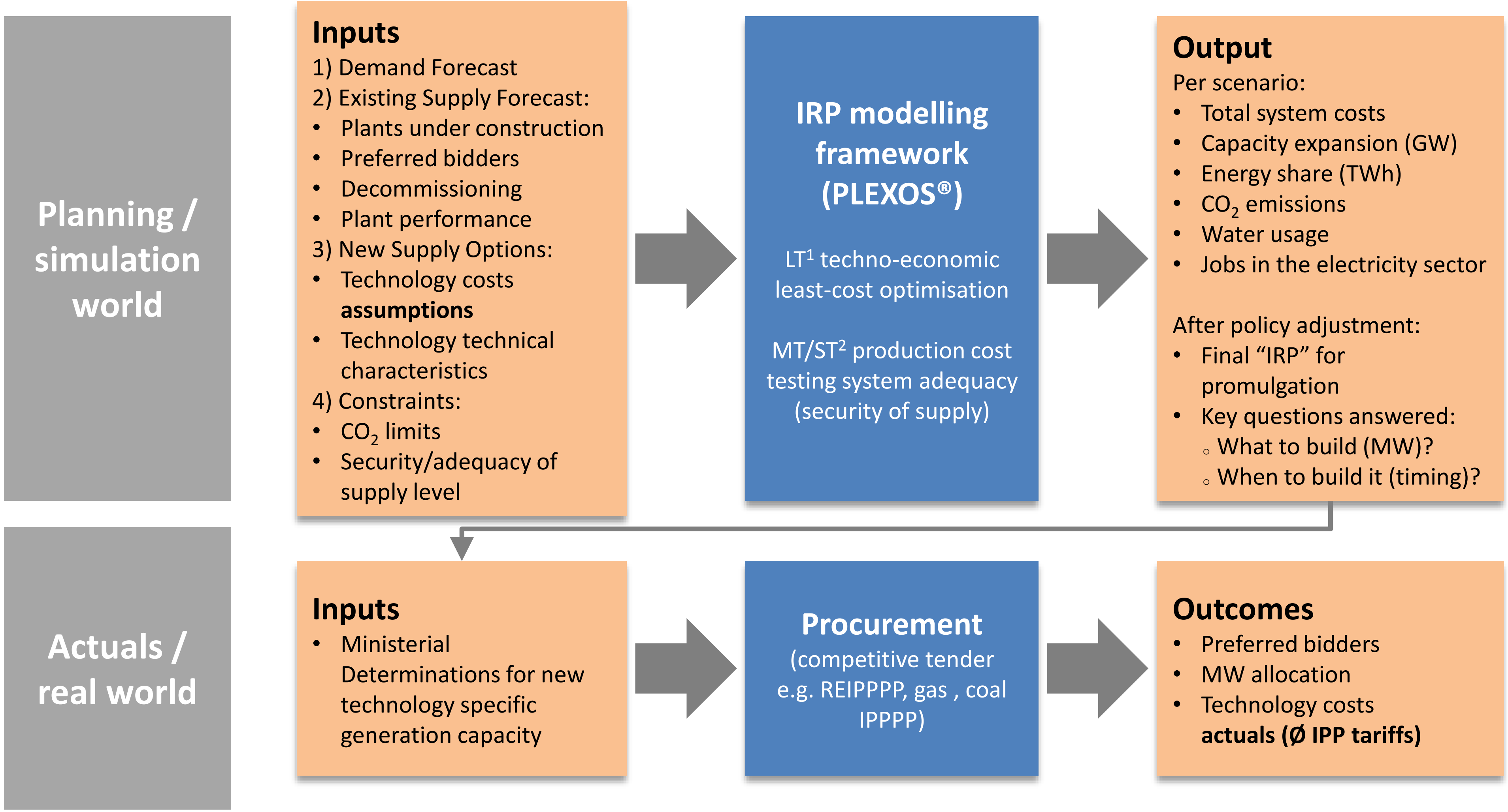
energy
Department:
Energy
REPUBLIC OF SOUTH AFRICA

INTEGRATED RESOURCE PLAN
UPDATE
ASSUMPTIONS, BASE CASE RESULTS AND OBSERVATIONS
REVISION 1

November 2016

IRP 2016: first draft publ. in Nov 2016, plans from 2016-2050

Integrated Resource Plan (IRP): Process for power generation capacity expansion in South Africa



Planning / simulation world

Inputs

1) Demand Forecast
2) Existing Supply Forecast:
- Plants under construction
- Preferred bidders
- Decommissioning
- Plant performance

3) New Supply Options:
- Technology costs **assumptions**
- Technology technical characteristics

4) Constraints:
- CO_2 limits
- Security/adequacy of supply level

IRP modelling framework (PLEXOS®)

LT[1] techno-economic least-cost optimisation

MT/ST[2] production cost testing system adequacy (security of supply)

Output

Per scenario:
- Total system costs
- Capacity expansion (GW)
- Energy share (TWh)
- CO_2 emissions
- Water usage
- Jobs in the electricity sector

After policy adjustment:
- Final “IRP” for promulgation
- Key questions answered:
  - What to build (MW)?
  - When to build it (timing)?

Actuals / real world

Inputs
- Ministerial Determinations for new technology specific generation capacity

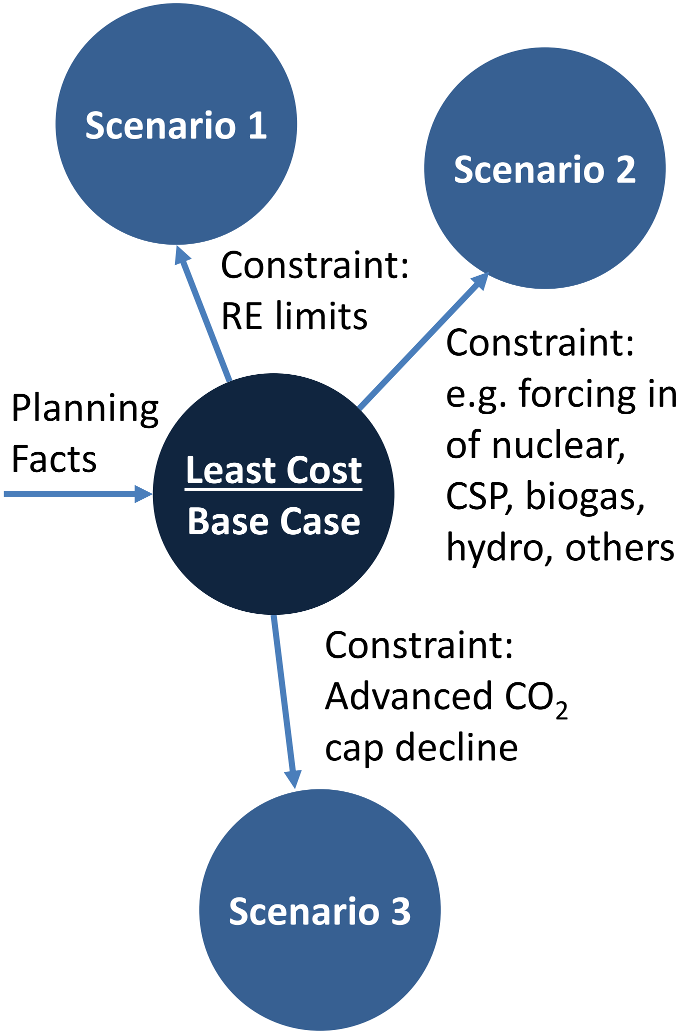
Procurement
(competitive tender e.g. REIPPPP, gas , coal IPPPP)

Outcomes
- Preferred bidders
- MW allocation
- Technology costs **actuals (Ø IPP tariffs)**

[1] LT = Long-term

[2] MT/ST = Medium-term/Short-term

IRP process as described in the Department of Energy's Draft IRP 2016: least-cost Base Case is derived from technical planning facts



Scenario 1

Scenario 2

Constraint:
RE limits

Constraint:
e.g. forcing in of nuclear, CSP, biogas, hydro, others

Planning Facts

Least Cost Base Case

Constraint:
Advanced CO_2 cap decline

Scenario 3

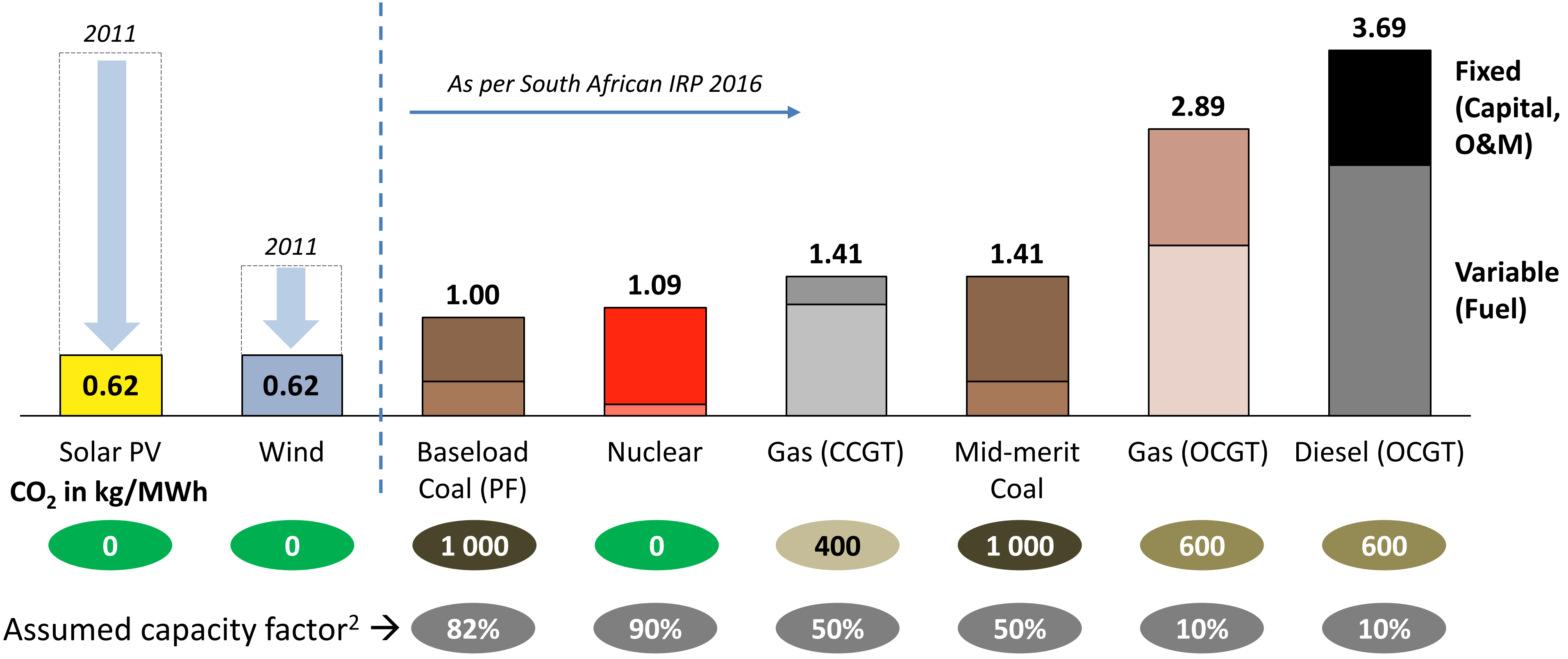
Case	**Cost**
Base Case	Base (least-cost)
Scenario 1	Base + Rxx bn/yr
Scenario 2	Base + Ryy bn/yr
Scenario 3	Base + Rzz bn/yr
…	…

1. Public consultation on costed scenarios
2. Policy adjustment of Base Case
3. Final IRP for approval and gazetting

Sources: based on Department of Energy's Draft IRP 2016, page 7; http://www.energy.gov.za/IRP/2016/Draft-IRP-2016-Assumptions-Base-Case-and-Observations-Revision1.pdf

Technology costs declines changes long-term planning outcomes considerably relative to just over 5 years ago

Today's new-build lifetime cost per energy unit[1] (LCOE) in R/kWh (April-2016-Rand)



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[1] Lifetime cost per energy unit is only presented for brevity. Modelling inherently includes the specific cost structures of each technology i.e. capex, Fixed O&M, variable O&M, fuel costs etc.

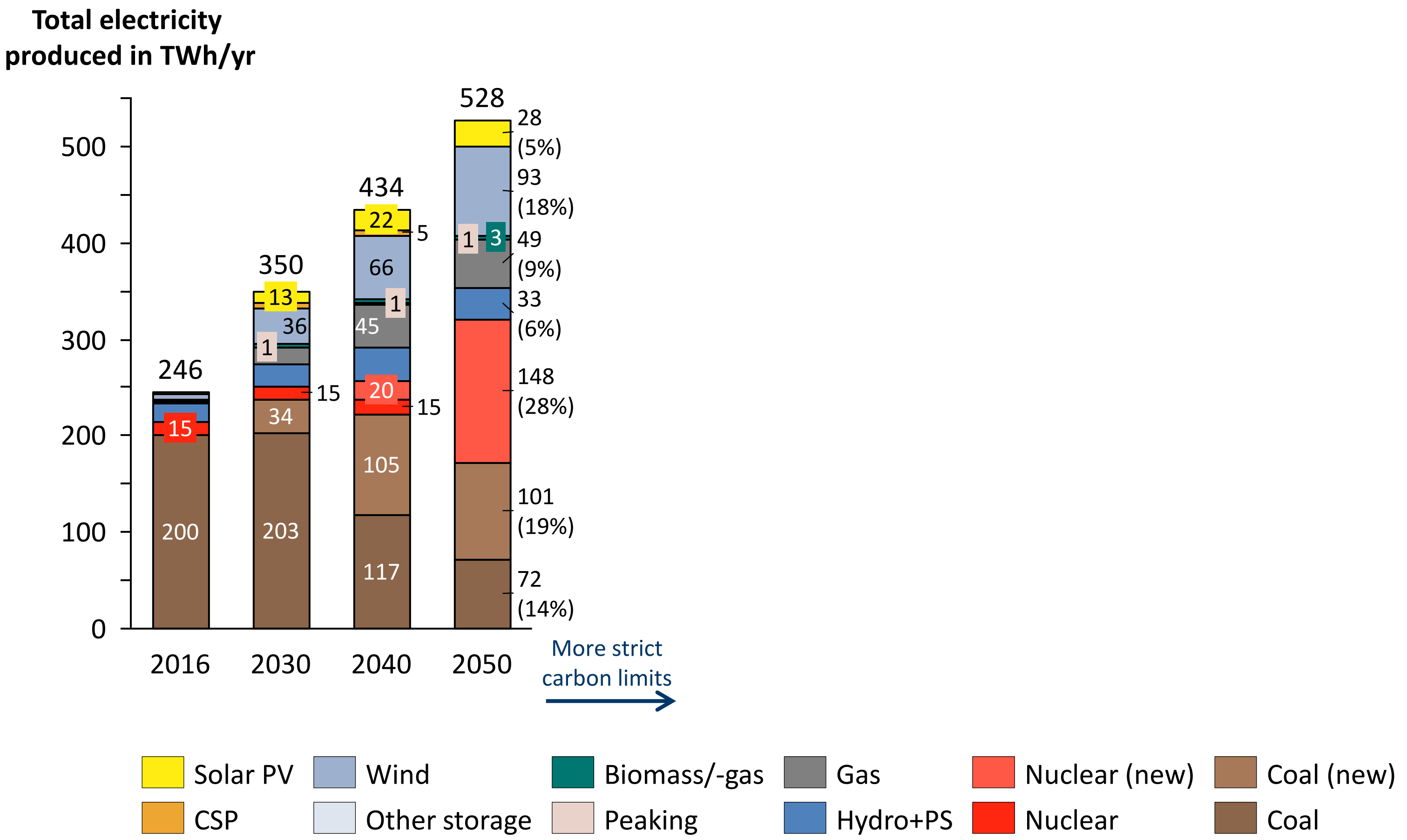
[2] Changing full-load hours for new-build options drastically changes the fixed cost components per kWh (lower full-load hours → higher capital costs and fixed O&M costs per kWh);

Assumptions: Average efficiency for CCGT = 55%, OCGT = 35%; nuclear = 33%; IRP costs from Jan-2012 escalated to May-2016 with CPI; assumed EPC CAPEX inflated by 10% to convert EPC/LCOE into tariff; Sources: IRP 2013 Update; Doe IPP Office; StatsSA for CPI; Eskom financial reports for coal/diesel fuel cost; EE Publishers for Medupi/Kusile; Rosatom for nuclear capex; CSIR analysis

Draft IRP 2016 Base Case is a mix of 1/3 coal, 1/3 nuclear, 1/3 RE

As per Draft IRP 2016

Draft IRP 2016 Base Case



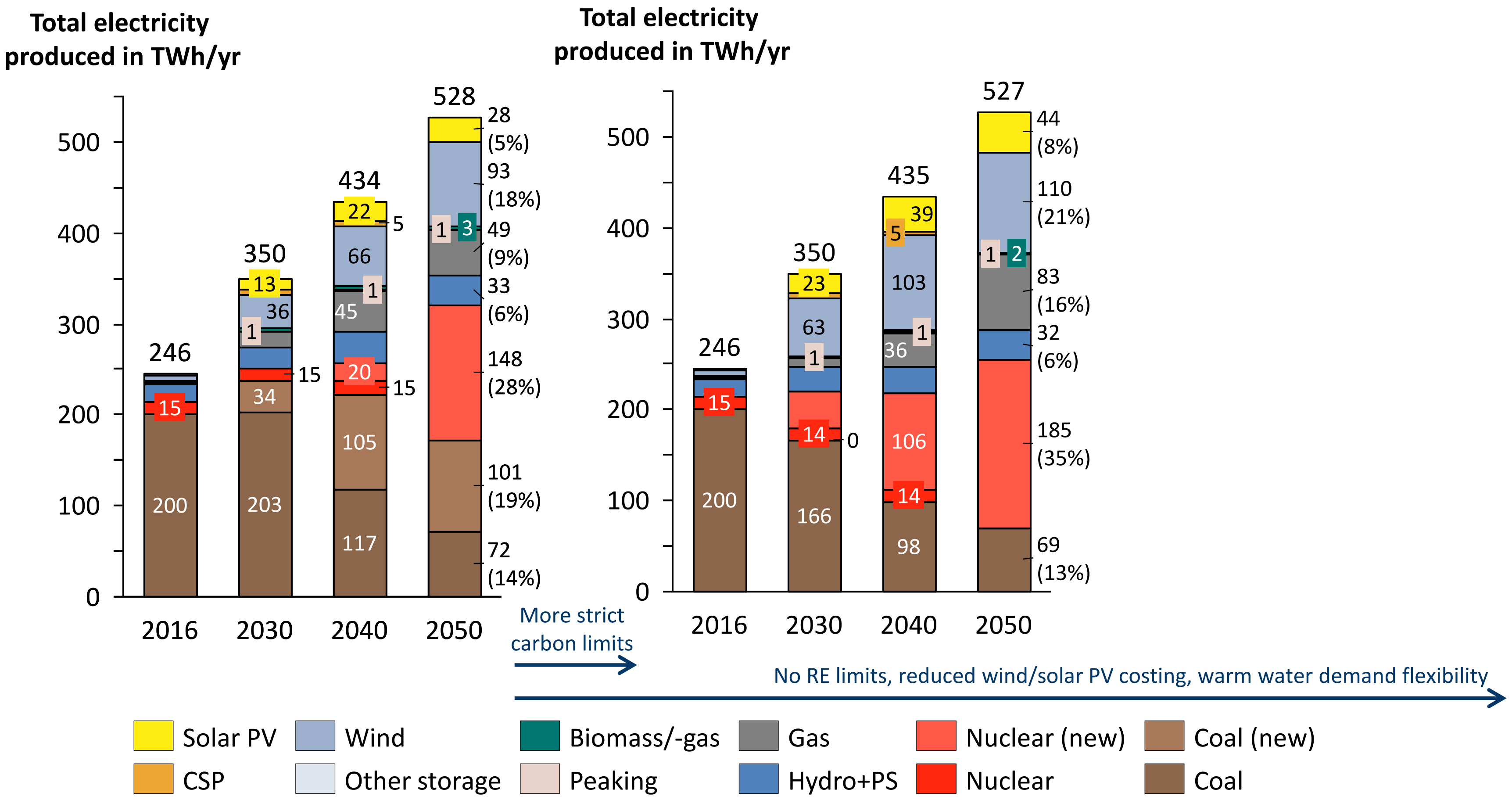
Sources: DoE Draft IRP 2016; CSIR analysis

Draft IRP 2016 Carbon Budget case: 35% nuclear energy share by 2050

As per Draft IRP 2016

Draft IRP 2016 Base Case

Draft IRP 2016 Carbon Budget



Sources: DoE Draft IRP 2016; CSIR analysis

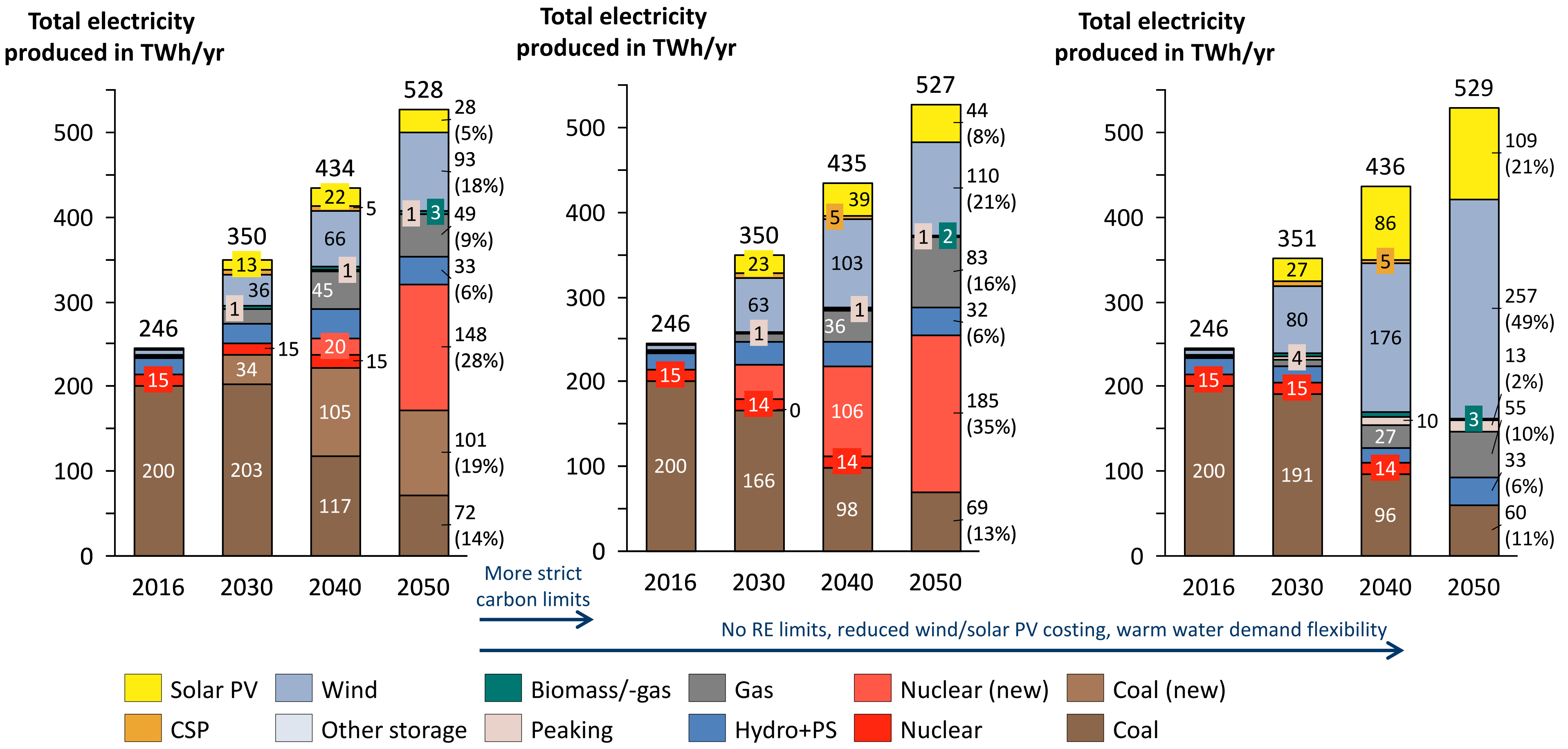
Least-cost is largely based on wind and solar PV complemented by flexibility (including existing coal, new gas, hydro and CSP)

As per Draft IRP 2016

Draft IRP 2016 Base Case

Draft IRP 2016 Carbon Budget

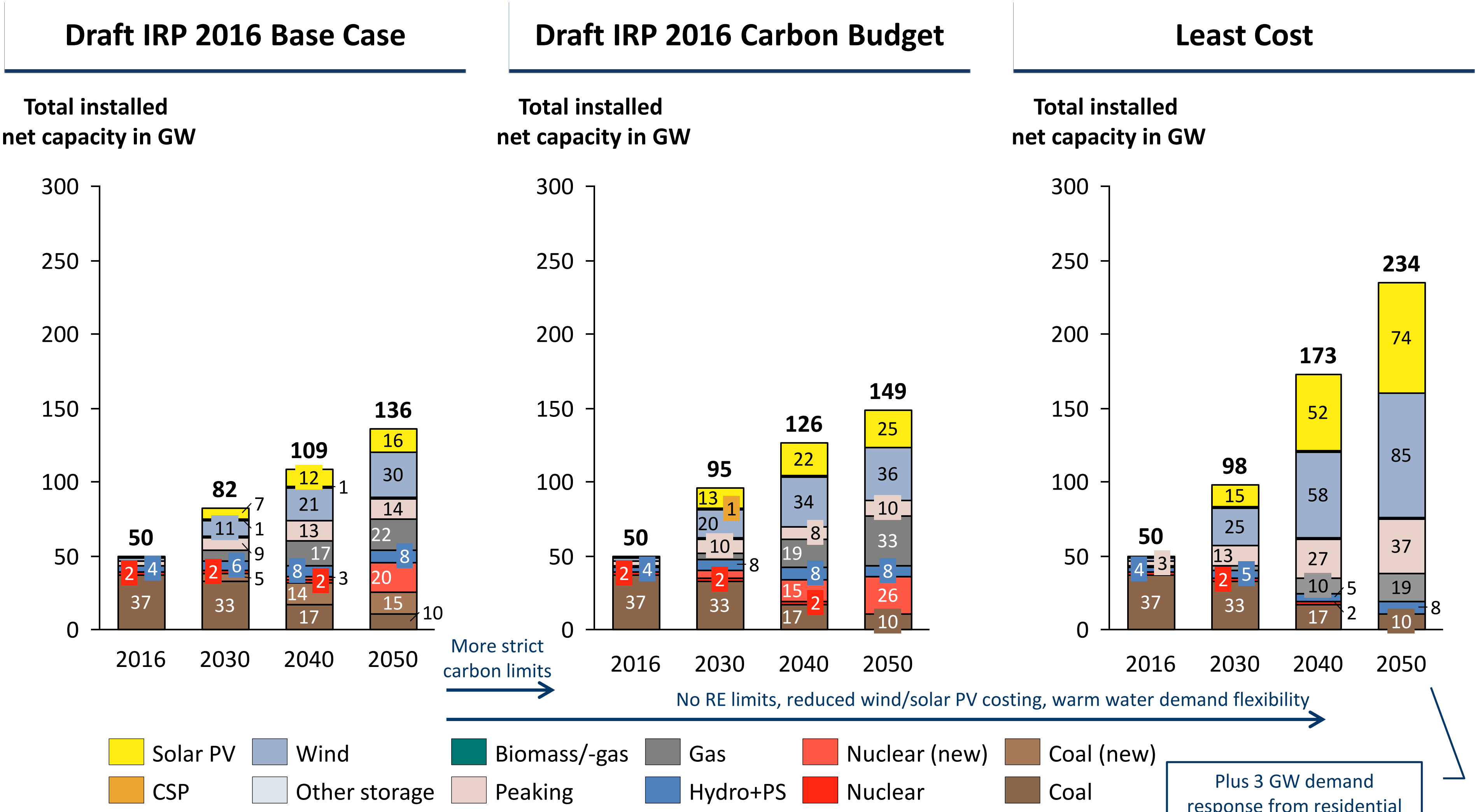
Least Cost



Sources: DoE Draft IRP 2016; CSIR analysis

Least-cost deploys significant solar PV/wind capacity with flexibility, carbon budget deploys nuclear and moderate levels of solar PV/wind

As per Draft IRP 2016

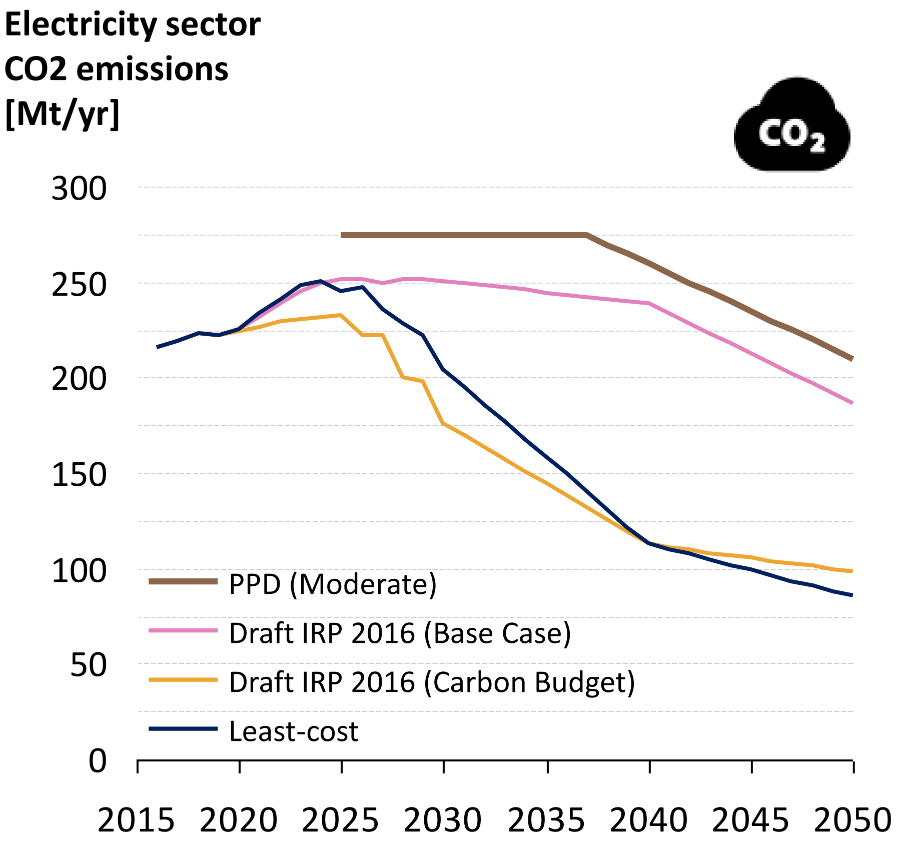


Plus 3 GW demand response from residential warm water provision

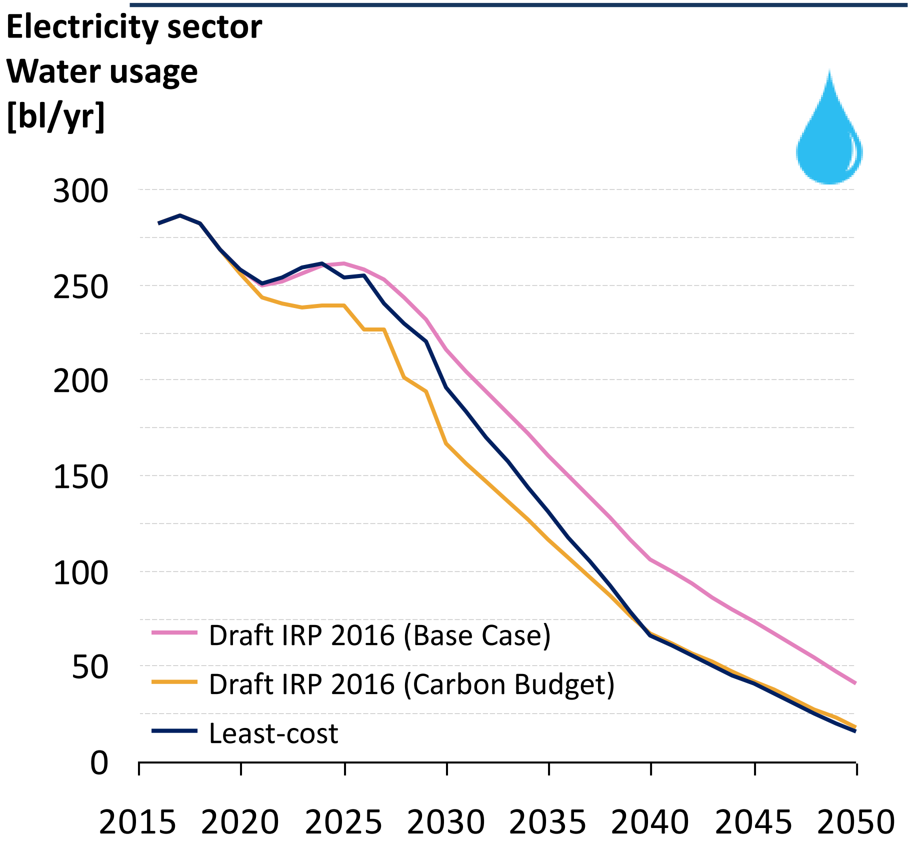
Sources: DoE Draft IRP 2016; CSIR analysis

CO_2 emissions trajectory is never binding while water use declines as coal fleet decommissions – carbon budget and least-cost perform well

CO2 emissions

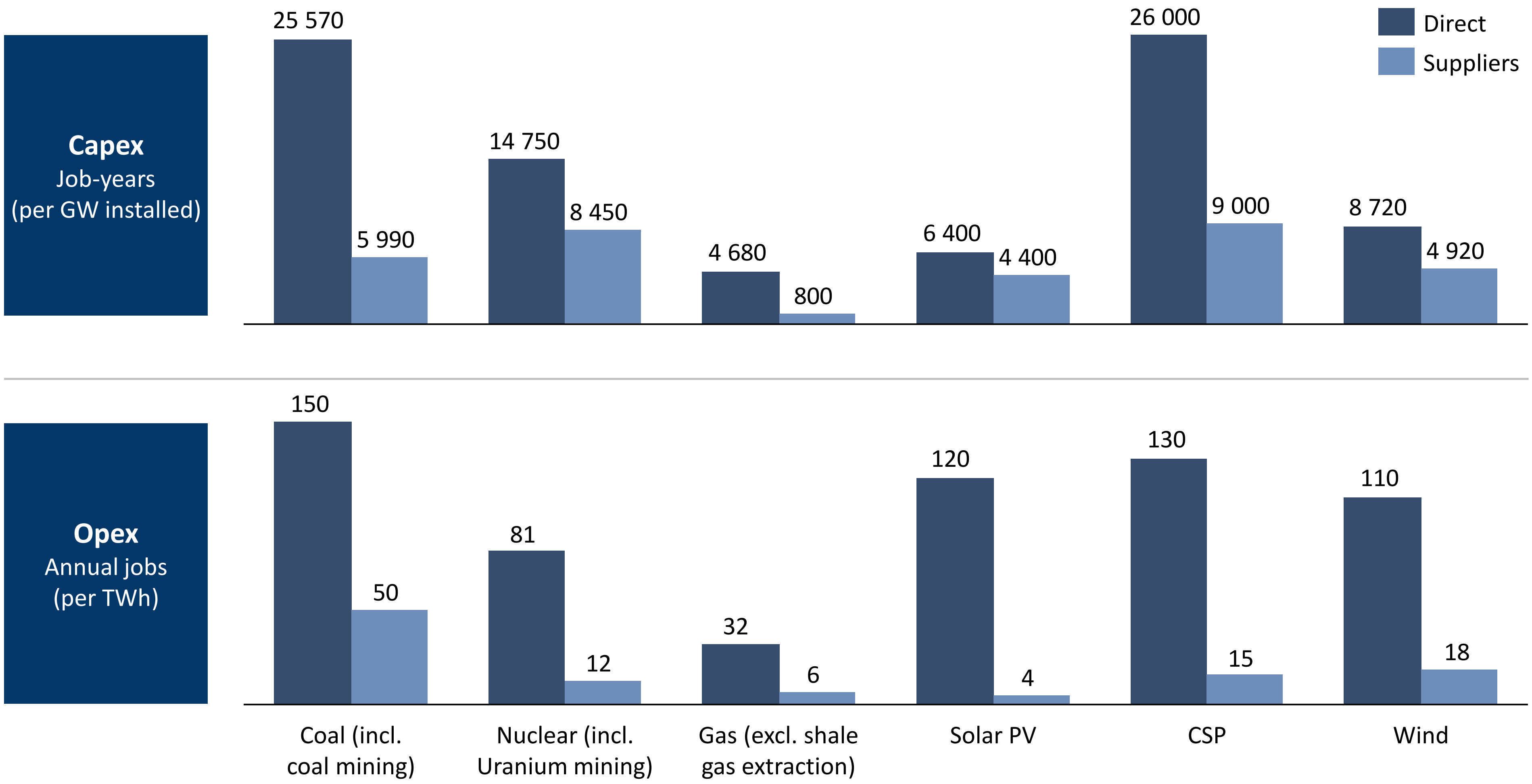


Water usage



Peak-Plateau-Decline (PPD) is not very ambitious anymore – least-cost and Carbon Budget easily below PPD

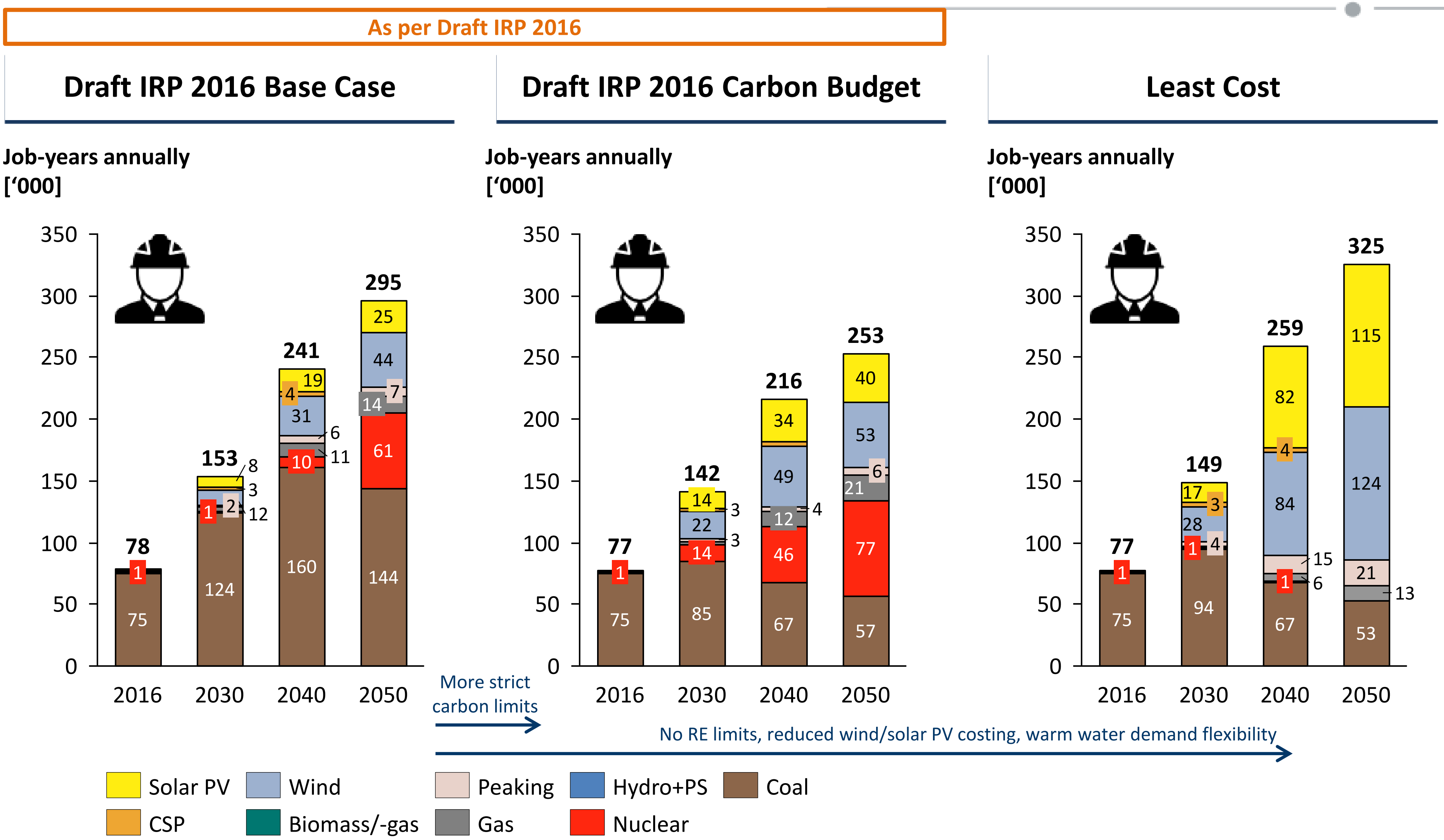
Localised job creation per technology is a function of capital (build-out) as well as operations (utilisation) for each technology



Note: It seems like McKinsey study (appendix of IEP) under-estimates direct/supply job numbers in the coal industry. Thus, CSIR have assumed more jobs in the coal industry than in the Mckinsey study.

Sources: DoE IEP 2016 Annexure B: Macroeconomic parameters

Increasing job opportunities in the electricity sector with coal-related jobs impacted in the long-term (not short-term)



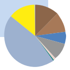
Note: Direct and supplier jobs only (jobs resulting from construction, operations and first level suppliers); Because of lack of data, zero jobs for biomass/-gas assumed; Sources: DoE; CSIR analysis

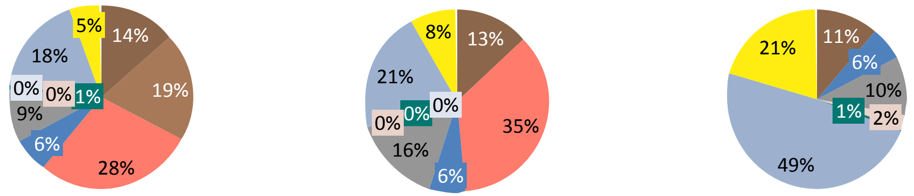
Conservatively, Least-cost is R60-75 billion/yr cheaper than the status-quo (Base Case) and Carbon Budget by 2050

As per Draft IRP 2016

Energy Mix in 2050

Demand: 522 TWh





2050		IRP 2016 Base Case	IRP 2016 Carbon Budget	Least Cost	
Cost in 2050	**Total system cost**[1] (R-billion/yr)	700	688	627	**R 60-75 bln/yr cheaper** (≈10%)
	Average tariff (R/kWh)	1.34	1.32	1.20	
Environ-ment in 2050	**CO_2 emissions** (Mt/yr)	187	99	86	**Cleaner -15% vs CB -65% vs BC**
	Water usage (billion-litres/yr)	41	18	15	
Jobs[2] in 2050	**Direct & supplier** ('000)	252-295	235-253	310-325	**10-20% more jobs**

Because of lack of data, zero jobs for biomass/-gas assumed (affects Decarbonised)

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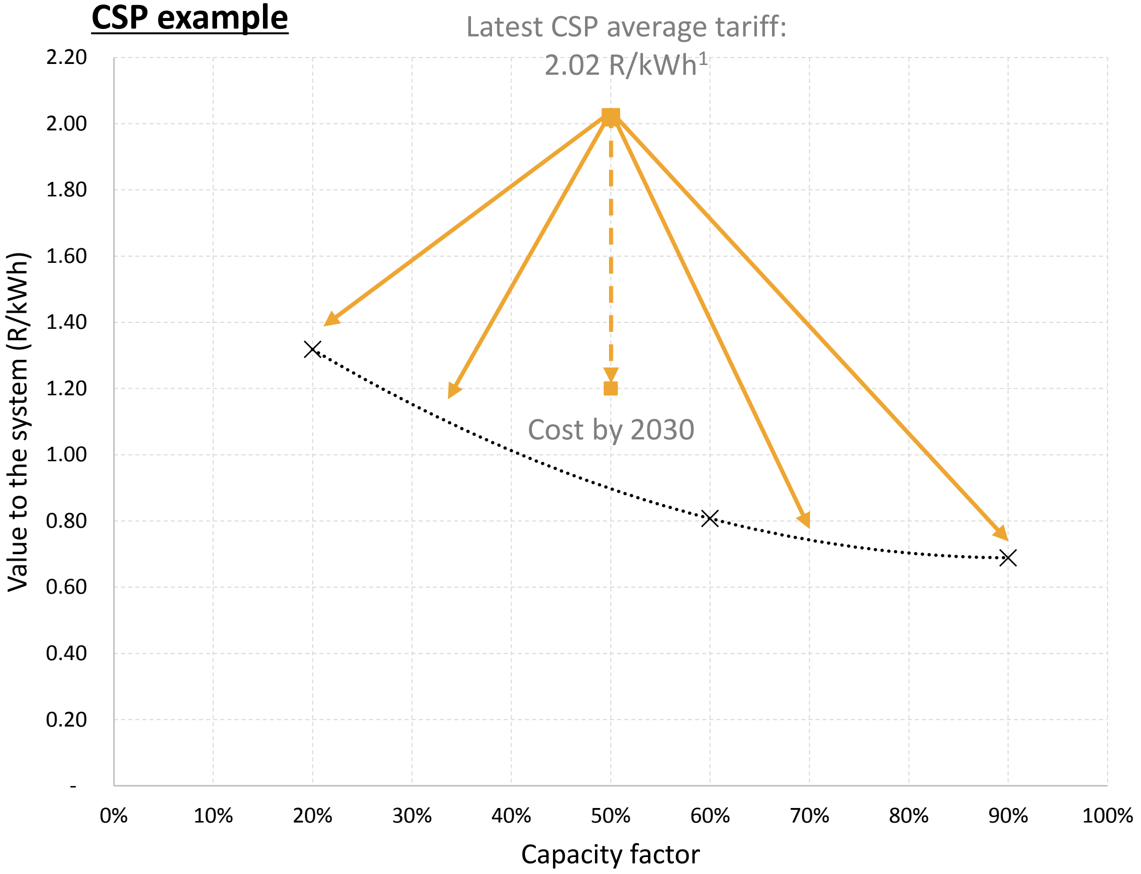
[1] Only power generation (Gx) is optimised while cost of transmission (Tx), distribution (Dx) and customer services is assumed as ≈0.30 R/kWh (today's average cost for these items)

[2] Lower value based on McKinsey study (appendix of IEP), higher value based on CSIR assumption with more jobs in the coal industry; Sources: Eskom on Tx, Dx cost; CSIR analysis; flaticon.com

Technology costs parametrised until "in the mix" for least-cost CSP: Range of cap. factors -> range of costs to get below value curve

CSP example



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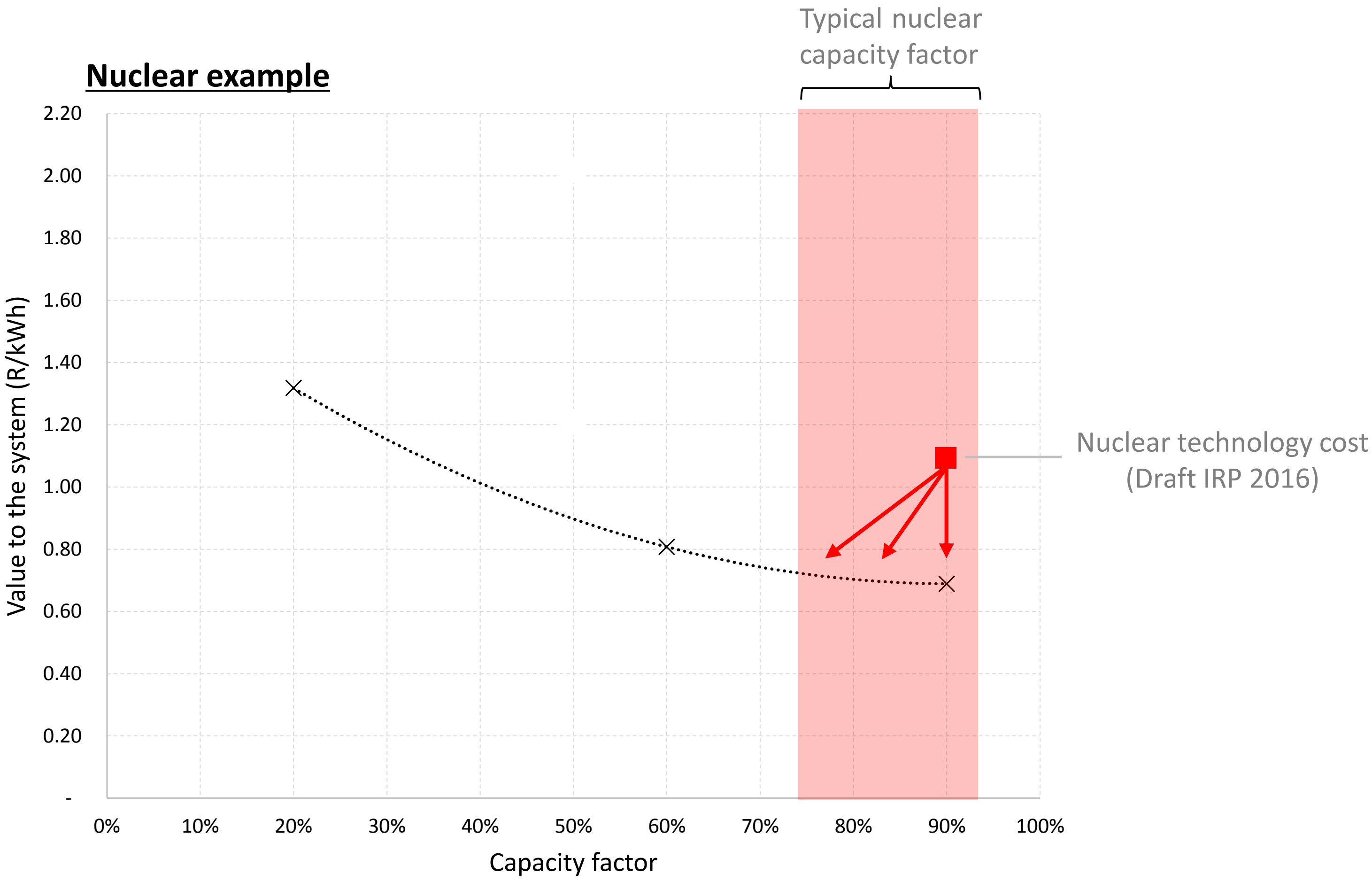
[1] Weighted average tariff for bid window 3.5 calculated on the assumption of ~50% annual load factor and full utilisation of the 5 peak-tariff hours per day

Technology costs parametrised until "in the mix" for least-cost
Nuclear: ↑ cap. factor ↓ range -> low cost to get below value curve



Nuclear would need to bring costs down to the point where it offers more value to the system than it costs

[1] Weighted average tariff for bid window 3.5 calculated on the assumption of ~50% annual load factor and full utilisation of the 5 peak-tariff hours per day

Agenda

our future through science

The energy transition is upon us but we have time – least-cost principles are key for South Africa’s future energy mix

The energy transition in South Africa’s context presents a range of transition costs and opportunities

This will take time… we have time

Least-cost principles are critical but can be augmented by other dimensions like emissions (CO_2, water) and socio-economic implications (job creation)

In electricity…

- Coal is expected to continue to play a role but existing coal fleet decommissions over time
- It is least-cost to use solar PV/wind technologies as new workhorses for RSA’s energy future
- Nuclear could play a role if cost reductions are achieved relative to alternatives

We eagerly await the latest version of the IRP…

Thank you

our future through science

BACKUP

our future through science

The CSIR:
South Africa's national, multidisciplinary research council

- The CSIR's Executive Authority is the South African Minister of Science and Technology

In numbers:

72yrs

1945 - 2017

2 668

Total staff

350

SET base with PhD

490

Publication equivalents

~ $200 m

Total operating income

1 980

Total in SET base

Based on 2015/16 forecast

CSIR

our future through science

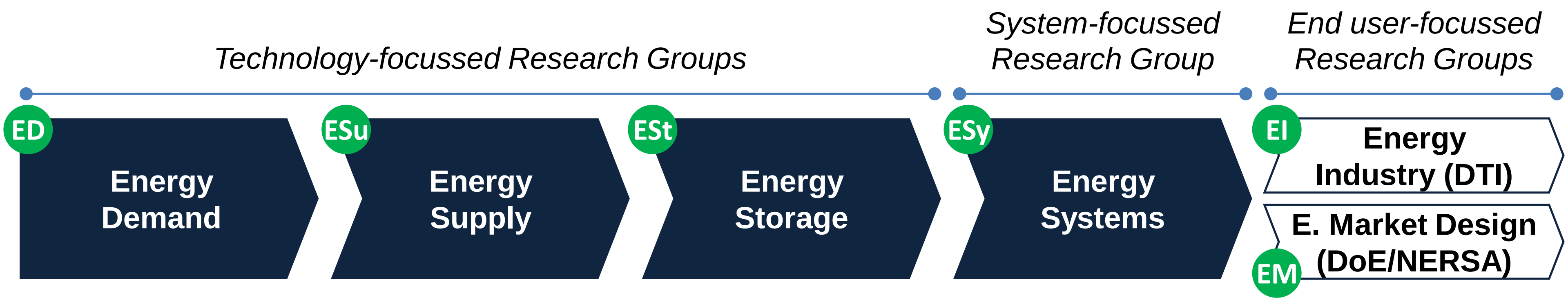
The CSIR Energy Centre’s vision

Vision

“To provide the knowledge base for the South African energy transition and beyond”

CSIR’s Energy Centre (EC) will be the first port of call for South African decision makers in politics, business and science to advise them on the energy transition. This transition is a move towards a more sustainable and cleaner energy system and will ultimately lead to energy being used more efficiently and supplied by significant share from renewables in the primary energy supply. The CSIR’s Energy Centre will also leverage the learning from the South African energy transition to support the creation of sustainable energy systems for other African countries.

Research Groups overview:
Value-chain logic, driven by end-user demand and system view



Technology-focussed Research Groups

System-focussed Research Group

End user-focussed Research Groups

ED **Energy Demand**

ESu **Energy Supply**

ESt **Energy Storage**

ESy **Energy Systems**

EI **Energy Industry (DTI)**

EM **E. Market Design (DoE/NERSA)**

Energy Demand

- Energy Efficiency Technologies
- Demand Shaping Technologies

Energy Supply

- Energy Meteorology
- Renewable Energy Technologies

Energy Storage

- Battery Technologies
- Hydrogen Technologies
- Heat Storage Technologies

Energy Systems

- Energy System Design
- Energy System Operation

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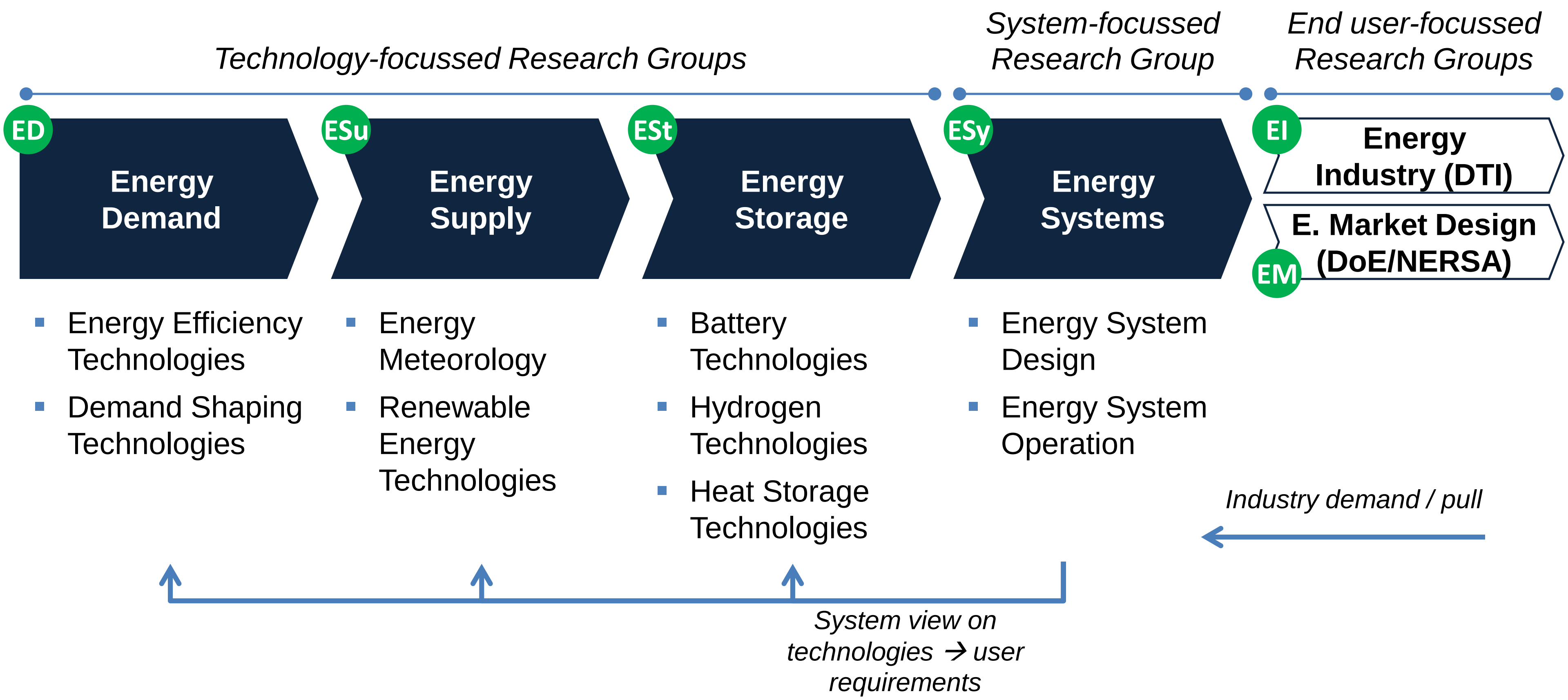

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Industry demand / pull

System view on technologies → user requirements

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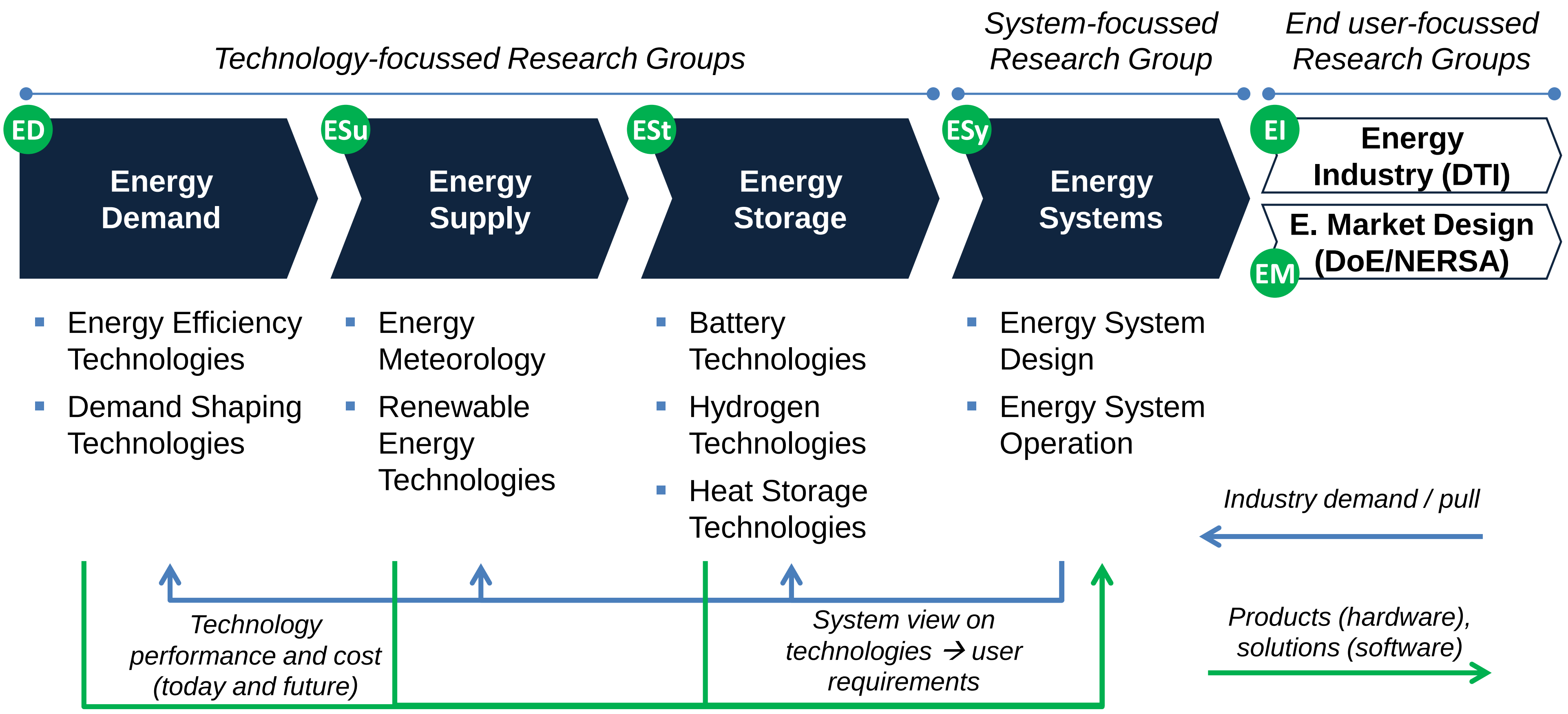

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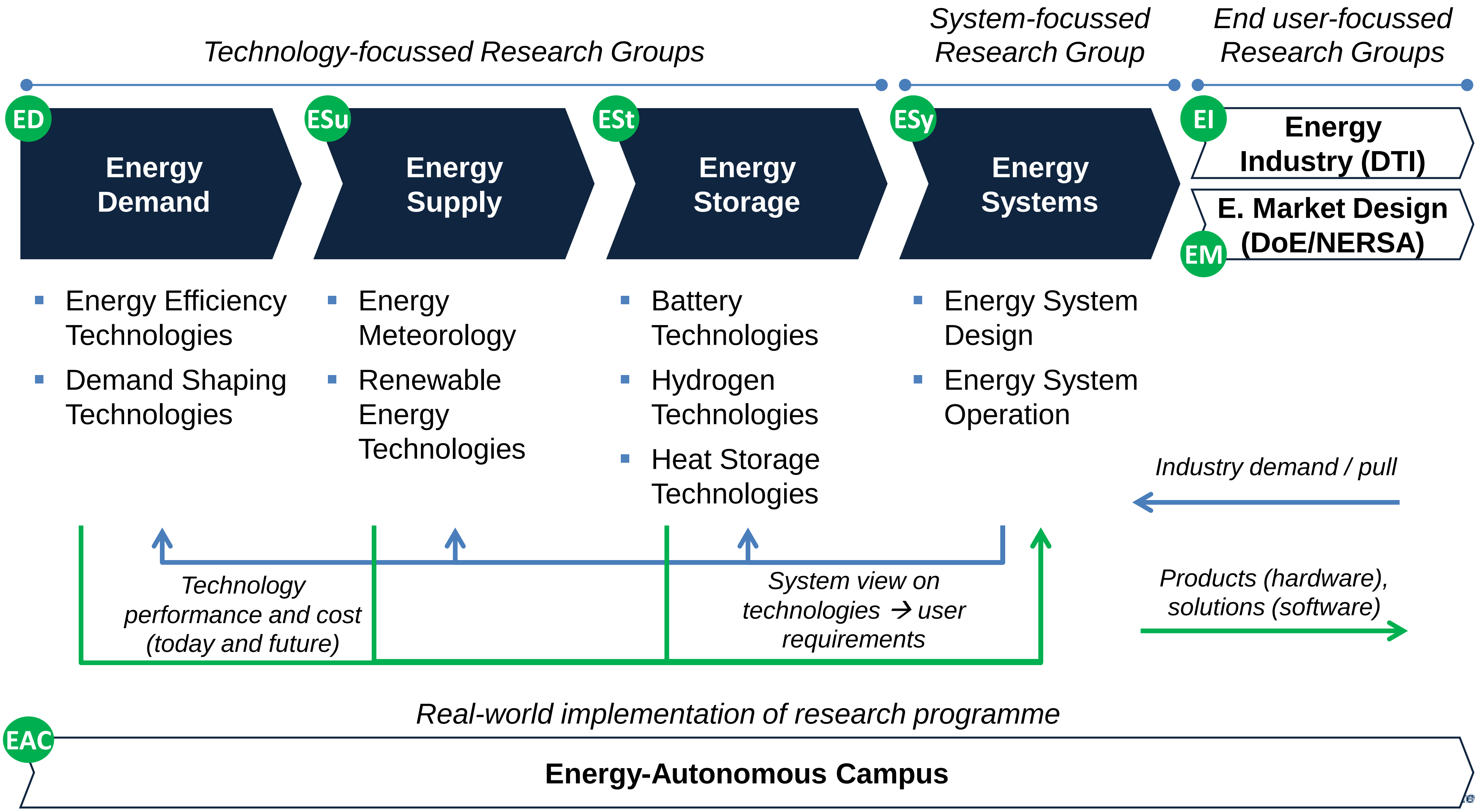
Technology performance and cost (today and future)

System view on technologies → user requirements

Industry demand / pull

Products (hardware), solutions (software)

Research Groups overview:
Value-chain logic, driven by end-user demand and system view



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Industry demand / pull

Products (hardware), solutions (software)

Technology performance and cost (today and future)

System view on technologies → user requirements

Real-world implementation of research programme

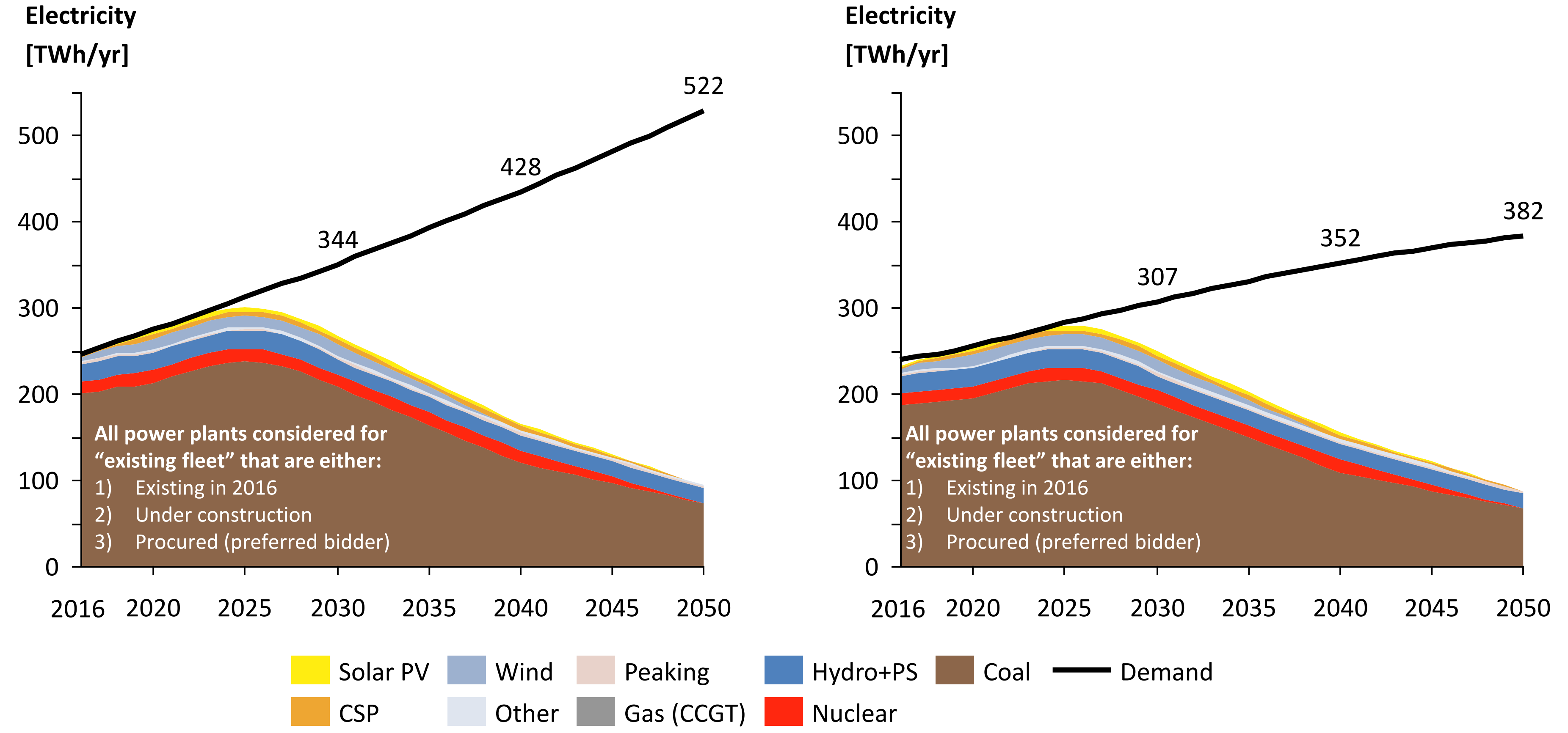
EAC **Energy-Autonomous Campus**

A need to fill the gap in the least-cost manner (subject to reliability constraints) - meeting new demand or replacing existing fleet

Energy supplied to the South African electricity system from existing plants (2016-2050)

Whether South Africa expects a high demand forecast…

… or a low demand forecast – we need electricity infrastructure investment



Note: Energy from existing generators is shown representatively; All power plants considered for “existing fleet” that are either Existing in 2016, Under construction, or Procured (preferred bidder)
Sources: DoE (IRP 2016); Eskom MTSAO 2016-2021; StatsSA; World Bank; CSIR analysis

A need to fill the gap in the least-cost manner (subject to reliability constraints) - meeting new demand or replacing existing fleet

Energy supplied to the South African electricity system from existing plants (2016-2050)

Whether a high demand forecast is expected in South Africa

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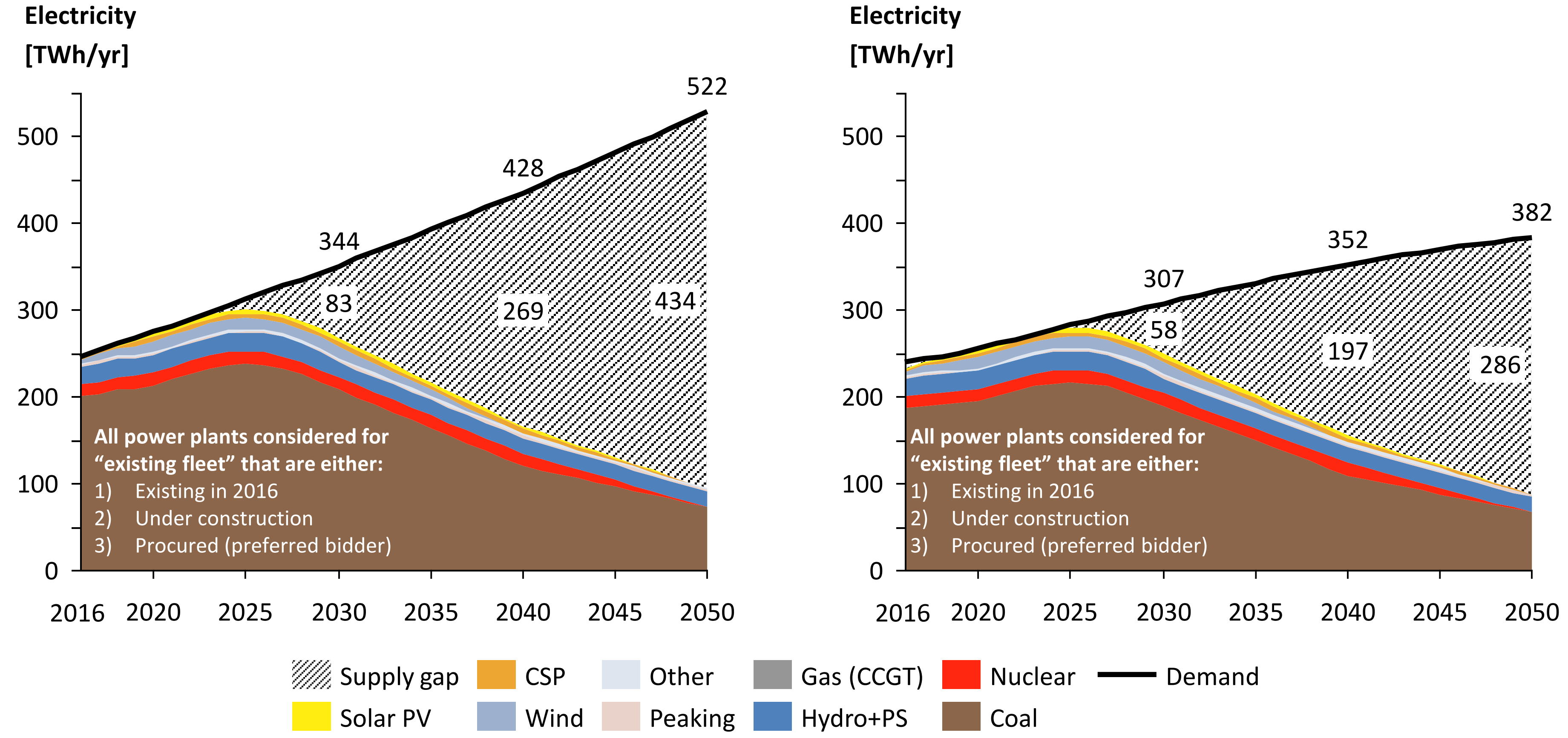

All power plants considered for "existing fleet" that are either:

1) Existing in 2016
2) Under construction
3) Procured (preferred bidder)

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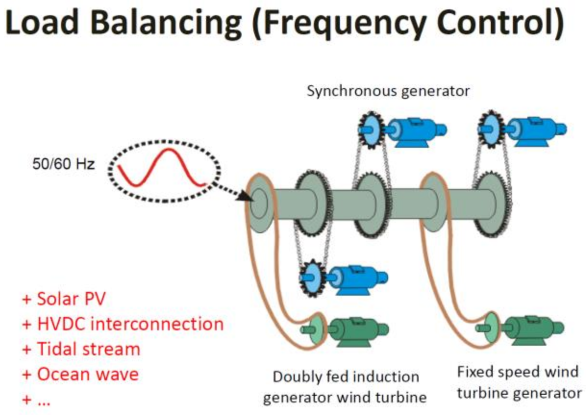
IRP model only optimises for cost of power generation (Gx) – two additional key aspects: system stability and grid costs

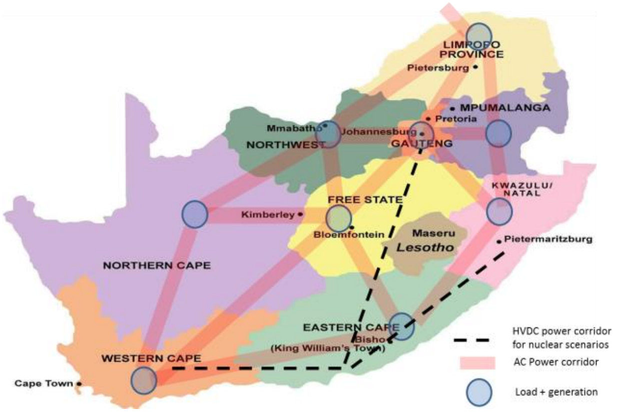
System Stability (inertia): worst case below 1% of Gx cost

- Technical solutions to operate low-inertia system exist
- “Worst case” costs
  - State-of-the-art technology (very high costs, no further tech/cost advancements)
  - Assumption: No further increase in engineering expertise of how to deal with low-inertia systems
- In all scenarios, worst-case-cost well below 1% of total cost of power generation (Gx) by 2050

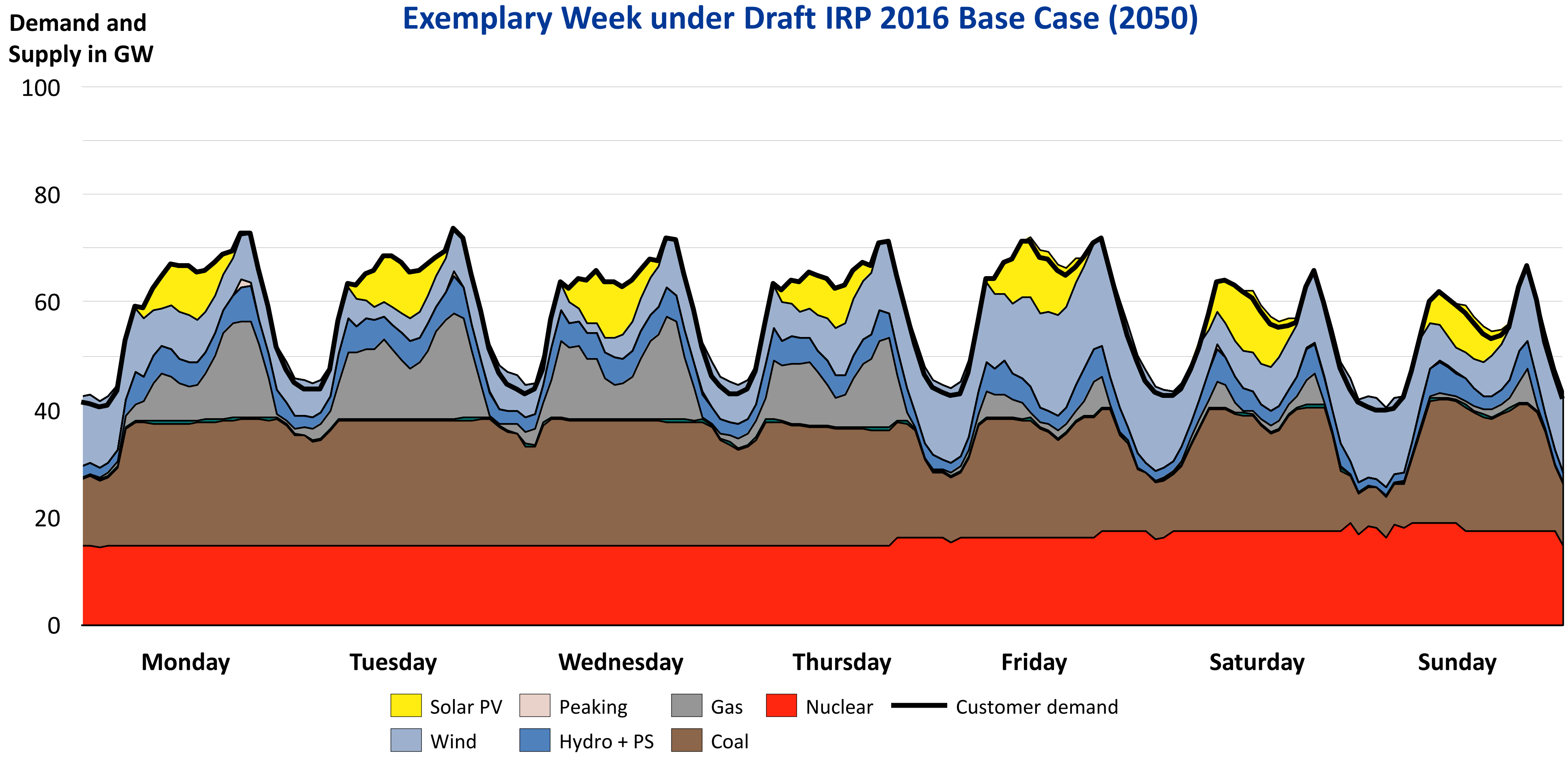


Transmission grid costs

- High-level cost estimate for shallow and deep grid connection costs for all scenarios
- Least-cost case is an additional R20-30 billion/yr cheaper relative to Draft IRP 2016 Base Case and Carbon Budget scenarios on transmission grid requirements

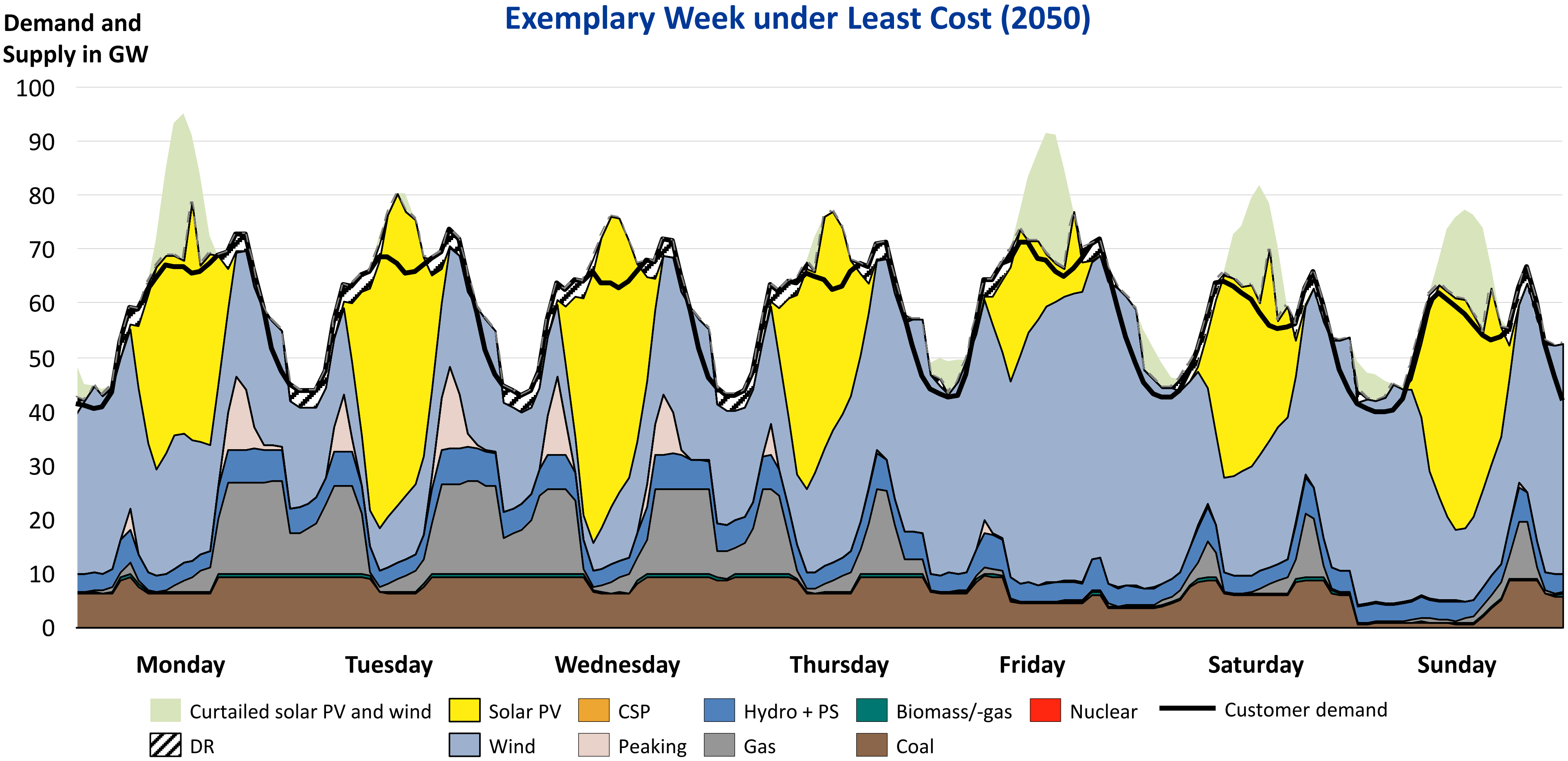


Draft IRP 2016 Base Case:
Nuclear and coal dominate the supply mix in 2050



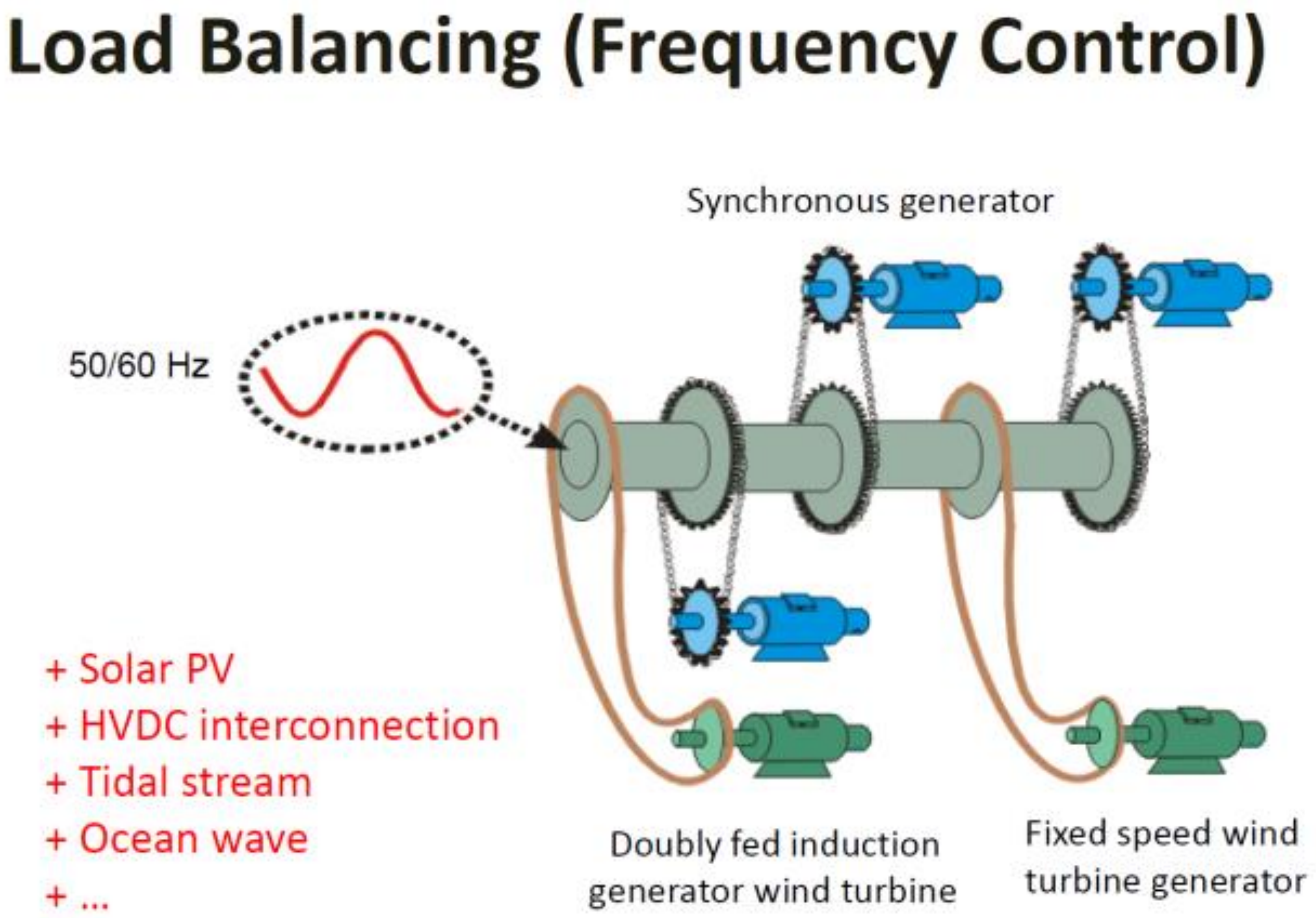
Sources: CSIR analysis, based on DoE‘s Draft IRP 2016

Scenario: Least Cost – Solar PV/wind dominate in 2050, curtailment and variability managed by flexible gas, DR, PS and hydro capacity



Sources: CSIR analysis

Synchronous generators inherently provide system stability through the direct, synchronous coupling of their physical inertia to the grid

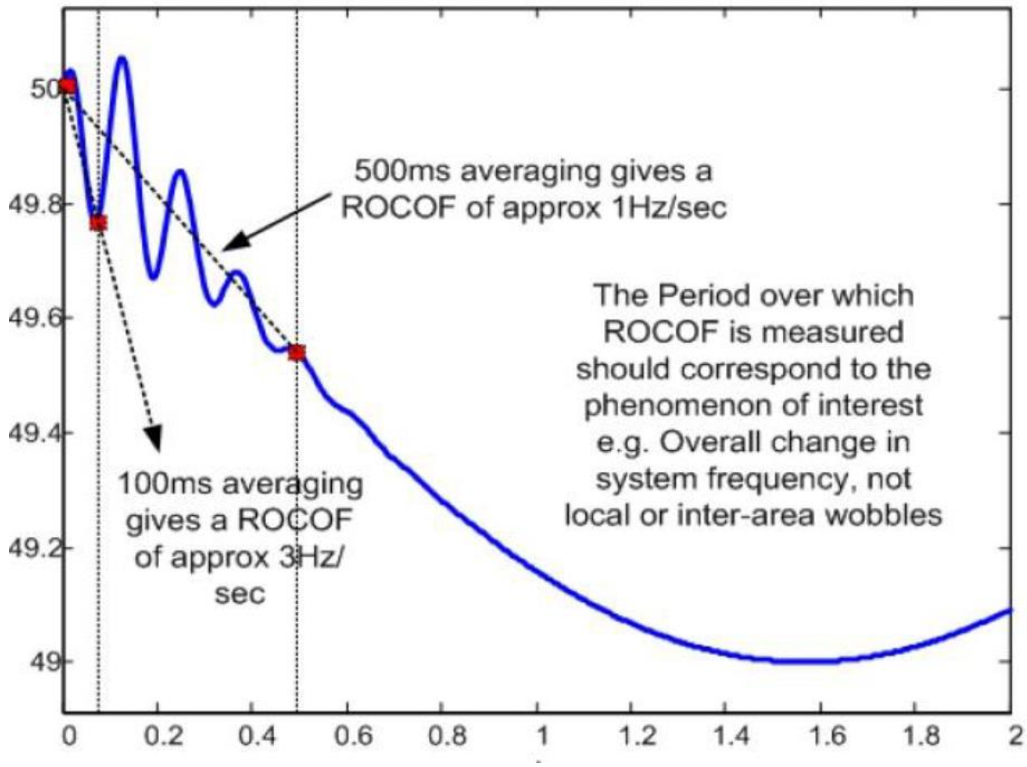


Load Balancing (Frequency Control)

- \+ Solar PV
- \+ HVDC interconnection
- \+ Tidal stream
- \+ Ocean wave
- \+ …

Sources: Damian Flynn, UC Dublin

Averaging window is important – for frequency stability typically a 500 ms averaging window for RoCoF is considered



500ms averaging gives a ROCOF of approx 1Hz/sec

The Period over which ROCOF is measured should correspond to the phenomenon of interest e.g. Overall change in system frequency, not local or inter-area wobbles

100ms averaging gives a ROCOF of approx 3Hz/ sec

The RocoF should not exceed a particular threshold within the pre-defined averaging window e.g. 500 ms

Sources: EirGrid, SONI

The demand for system inertia is driven by two assumptions: the maximum allowable RoCoF & the largest assumed system contingency

Key assumptions:

Maximum allowed $RoCoF$: 1 Hz/s

Largest contingency (P_{cont}): 2 400 MW

Kinetic energy lost in contingency event $E_{kin(cont.)}$: 5 000 MWs

$$E_{kin.(min)} = P_{cont.} \frac{f_n}{2(RoCoF)} + E_{kin(cont.)}$$

Term “inertia” is used a bit loosely to describe the amount of kinetic energy that is stored in the rotating masses of all synchronously connected power generators
(and loads to be precise)

f_n = System frequency = 50 Hz

Sources: P. Kundur, Power System Stability and Control, 1994

Demand for inertia

65 000 MWs of system inertia are required at any given point in time in order for RoCoF to stay below 1 Hz/s in the first 500 ms after the largest system contingency occurred

As a starting point – we have assessed system inertia on an hourly basis via UCED in PLEXOS and some high level assumptions

Technology	Inertia constant [MWs/MVA]
Coal (old)	4.0
Coal (new)	2.0
OCGT	6.0
CCGT	9.0
Biomass	2.0
Hydro/PS	3.0
Imports	0.0
Nuclear	5.0[1]
Wind	0.0
PV	0.0
CSP	2.5
DR	0.0
ICE	2.0

Supply of inertia

Depending on what mix of power stations is operational at any given point in time, the total actual system inertia will be different

For example, if 20 GW of old coal, 10 GW of new coal and 2 GW of nuclear are online, system inertia is:

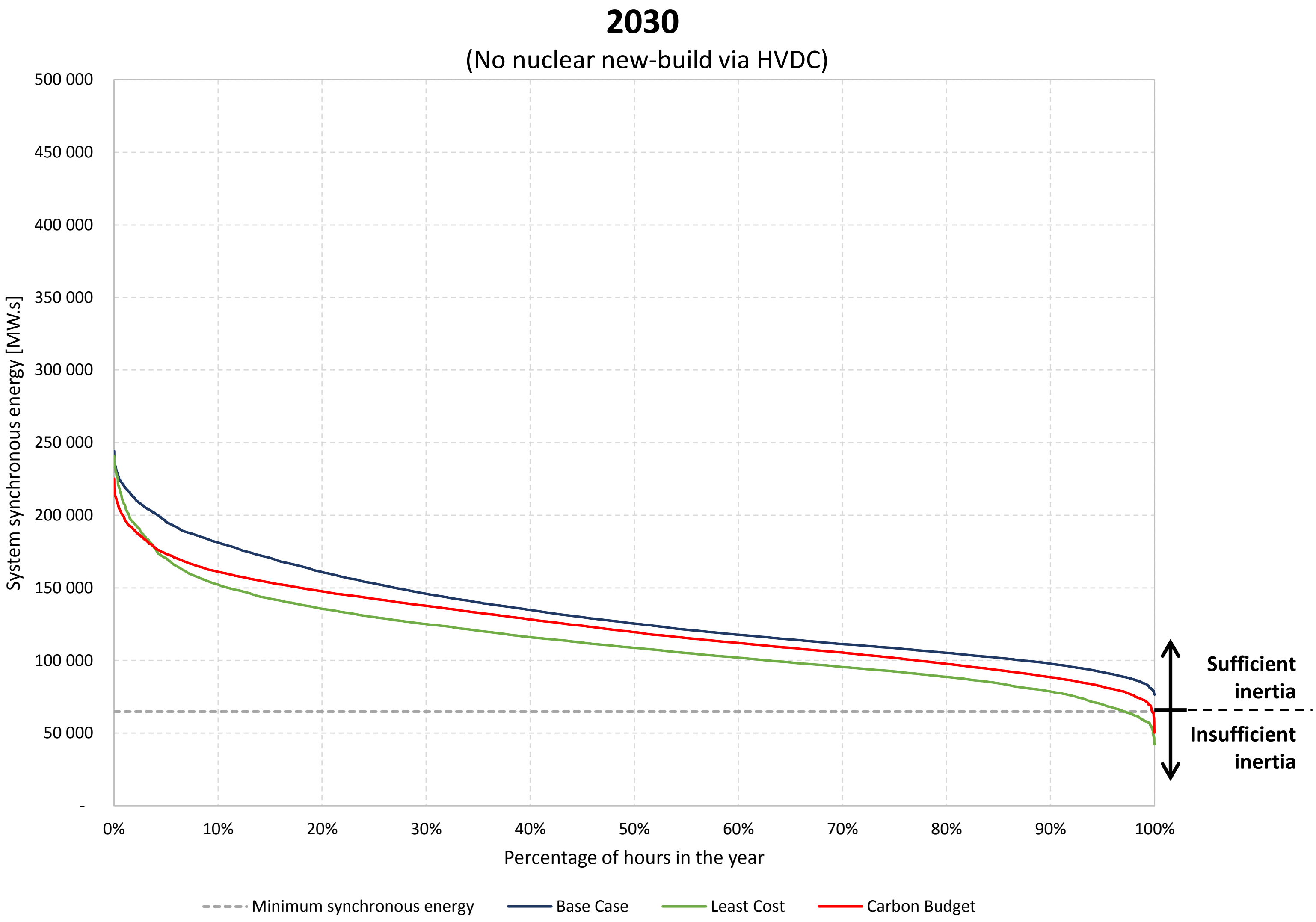
≈20 GW * 4 MWs/MVA + 10 GW * 2 MWs/MVA + 2 GW * 5 MWs/MVA

= 110 000 MWs

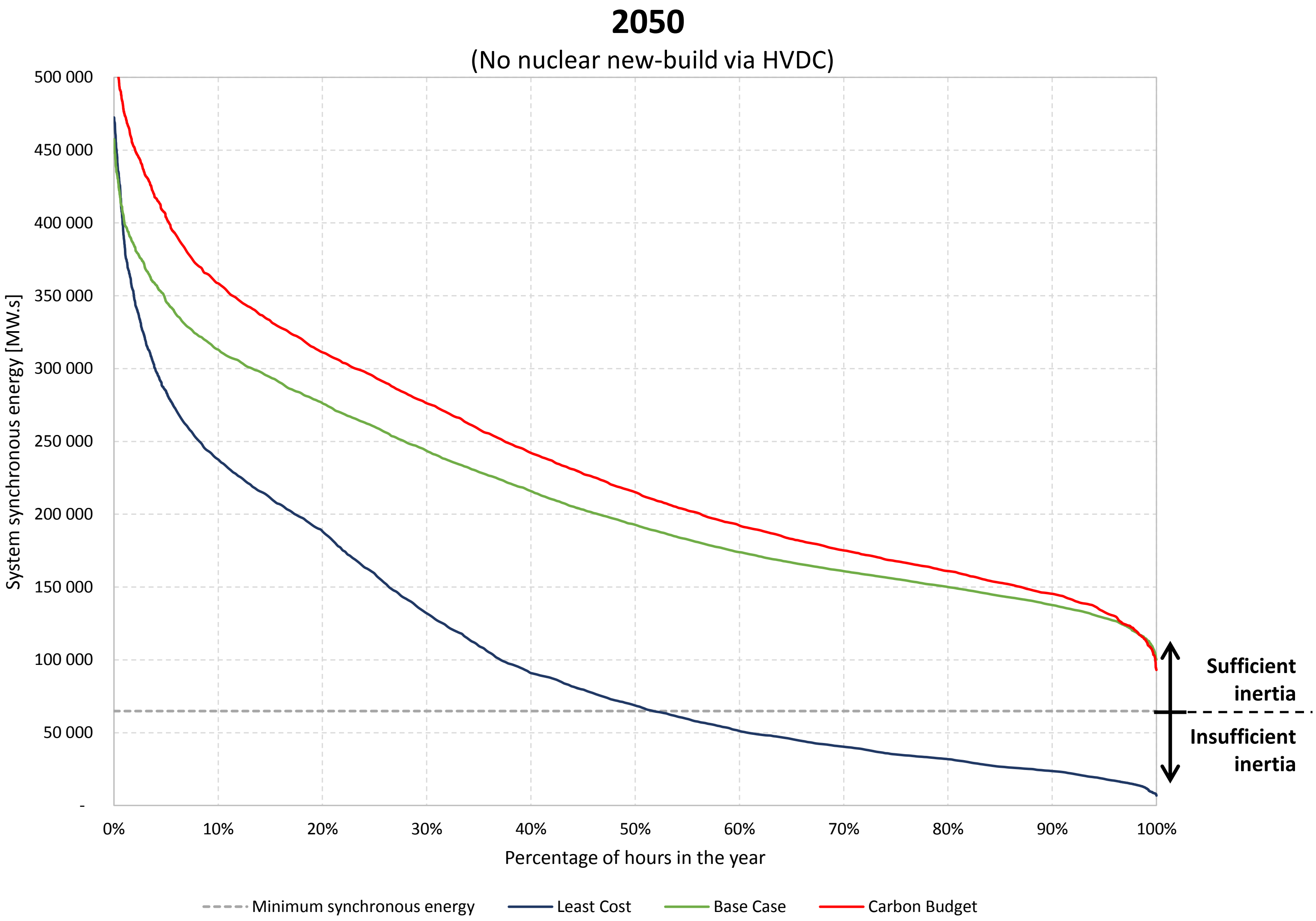
If wind, PV and 5 GW of CCGTs are online, system inertia is only 47 000 MWs

[1] Assumed in two cases:
1) At least half of the nuclear fleet is integrated via HVDC i.e. H = 2.5 MWs/MVA;
2) All of the nuclear fleet is integrated via HVDC i.e. H = 0 MW.s/MVA
Sources: P. Kundur, Power System Stability and Control, 1994

The system would likely require additional system inertia by 2030 in the Carbon Budget and Least-cost scenarios



Additional inertia will be required by 2050 for all scenarios with the most being from the Least-cost scenario



There are a number of options to increase system inertia

In principle, there are two ways to deal with lower system inertia

1) **Conservative: Introduce additional intrinsic inertia (synchronous machines) to reduce RoCoF**
2) **Progressive: Introduce reactive measures and control algorithms to deal with an increased RoCoF**

Here we will only outline the technical solutions in the conservative approach to increase intrinsic system inertia / reduce RoCoF (Option 1 above). These technical solutions are:

- Synchronous compensators (new purpose built devices and retro-fitting of decommissioned generators, with/without flywheels)
- Rotating stabiliser devices (typically a multi-pole device incorporating a flywheel, which can be based on a Doubly-Fed Induction Generator or an synchronous machine)
- Wind turbines with doubly-fed induction generator
- Pumped hydro (assuming synchronous machines are deployed)
- "Parking" of conventional generators i.e. operating generation plant at low MW output levels but with reduced/no capability to provide system services (e.g. operating reserve) at the lower output levels
- Reduction in the minimum MW generation thresholds of conventional generation while still leaving the plant with the capability to fully provide system services
- New flexible thermal power plant with high inertia constant

Sources: DNV GL, http://www.eirgridgroup.com/site-files/library/EirGrid/RoCoF-Alternative-Solutions-Technology-Assessment-Phase-1-DNV-GL-Report_.pdf

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Additional costs for rotating stabilisers to ensure sufficient system inertia by 2050 – <1% in all scenarios

Assumption: Entire nuclear and new coal fleet connected via AC

		2030			2050		
		Base Case	Carbon Budget	Least cost	Base Case	Carbon Budget	Least cost
Additional inertia needed	[MW.s]	-	14 500	22 500	-	-	58 000
Number of hours	[hrs]	-	210	440	-	-	4 320
Rotating stabilisers needed	[MW]	-	360	560	-	-	1 450
Annual cost for rotating stabilisers	[bR/yr]	-	1.1	1.7	-	-	4.5
(% of system costs)	[%]	0.0%	0.3%	0.5%	0.0%	0.0%	0.7%

Rotating stabiliser properties: CAPEX = 20 000 R/kW; FOM = 3% of CAPEX; all year operation; cost of electricity = 1 R/kWh; H = 40 MW.s/MVA