

$$\frac{1}{\alpha)^{n(t-1)}} \sum_{i \in TCH} invcost_i(t) \cdot I_i(t) + \sum_{t \in T} \frac{1}{(1 +$$

$$\sum_{i \in TCH} fixom_i(t) \cdot C_i(t) + \sum_{i \in PRC} varom_i(t).$$

$$\sum_{EEL} \sum_{z \in Z} \sum_{y \in Y} varom_i(t) \cdot P_{lzy}(t)$$

$$\sum_{EENC} \sum_s cos_{ks}(t) \cdot IMP_{ks}(t)$$

$$\sum_s \sum_{z \in Z} \sum_{y \in Y} cos_{ks}(t) \cdot IMP_{ks}(t)$$

$$\sum_s \sum_{z \in Z} \sum_{y \in Y} price_{ELCS}(t) \cdot EXP_{ELCS}(t)$$

**Long-term energy modeling for a decarbonized world:
an assessment of the Paris Agreement with an optimization bottom-up model**

Sandrine SELOSSE & Seungwoo KANG & Nadia MAIZI

MINES ParisTech, PSL Research University, CMA-Centre for Applied Mathematics

Chair Modeling for Sustainable Development

Sophia Antipolis - France



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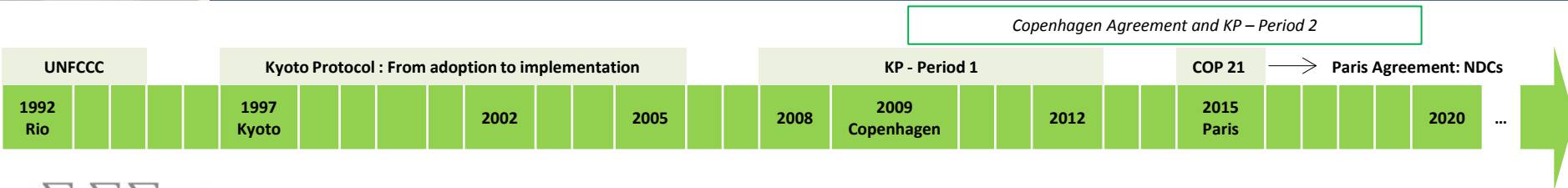
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The Paris Agreement: increasing the ambition of the long-term goal

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An historical agreement: COP 21 marked a decisive stage on the transition to a decarbonized world

A major milestone

- Higher level of **international cooperation** after decades of negotiations and regional division
- Political will to initiate a **global transition**

A new objective

- Recognition of the **1.5°C** (without formalization)
- The need for **net-zero emissions**

Article 2.1(a): “(h)olding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C”

Article 4.1: “(...) to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century”

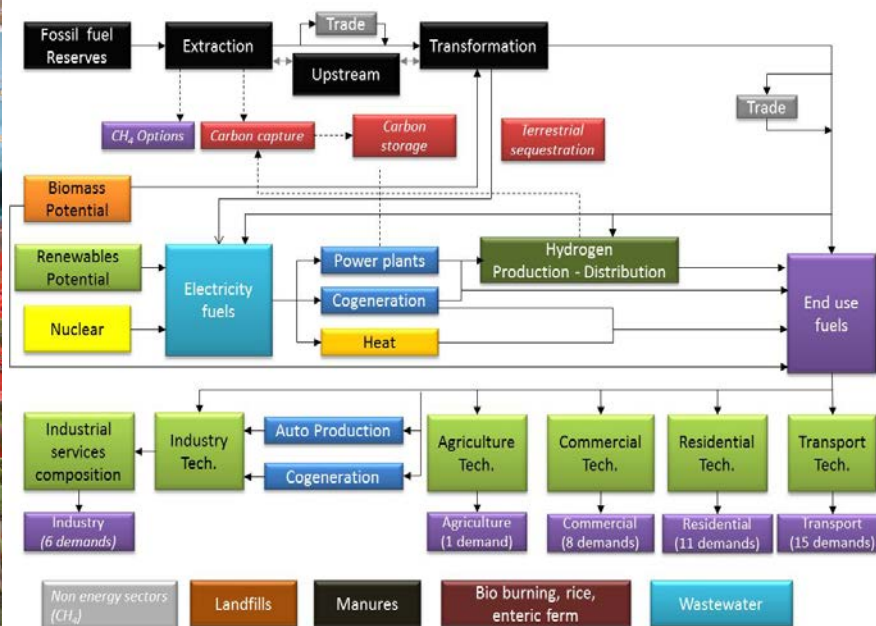
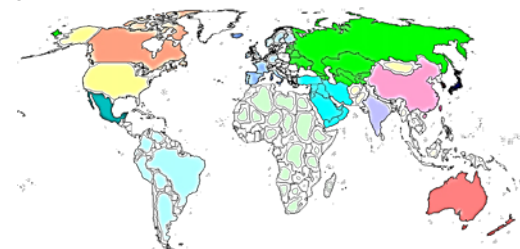
Modeling approach: TIAM-FR

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- French version of the **TIMES Integrated Assessment Model (ETSAP/IEA)**
- Optimization, linear programming, bottom-up, multiregional
 - Minimization of the total discounted cost of the system
- **Long-term possible futures of the energy system in the Post-Paris climate context**



$$NPV = \sum_{r=1}^R \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r, y)$$

Where

NPV is the net present value of the total cost for all regions over the projected period;
ANNCOST (*r*, *y*) is the total annual cost in region *r* and year *y*;
d_{r,y} is the discount rate;
REFYR is the reference year for discounting; *YEARS* is the set of years and *R* is the set of regions (15 regions)

Specification of scenario: decarbonized pathways

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$$\frac{1}{(1 + \alpha)^{n(t-1)}} \sum_{i \in TCH} in$$
$$\times \left(\sum_{i \in TCH} fixom_i(t) \right)$$
$$+ \sum_{i \in ELA} \sum_{z \in Z} \sum_{y \in Y} varu$$
$$+ \sum_{k \in ENC} \sum_s com_k(s)$$
$$+ \sum_s \sum_{z \in Z} \sum_{y \in Y} price$$
$$- \sum_{z \in Z} \sum_{y \in Y} price$$

- **A global 2050 target scenario in line with the long-term UNFCCC 2°C objective**
 - UNFCCC-40: 40%
 - UNFCCC-50: 50%
 - UNFCCC-70: 70%

⇒ GHG emissions reduction by 2050 compared to 2010
- **A regional scenario considering the Paris Agreement with NDCs**
 - NDCs scenarios according to Low and High commitments by (2025)2030 compared to reference year and regional assumptions by 2050

$$\frac{1}{(1 + \alpha)^{n(t-1)}} \sum_{i \in TCH} in$$

$$\times \left(\sum_{i \in TCH} fixom_i(t) \right)$$

$$+ \sum_{i \in EELA} \sum_{z \in Z} \sum_{y \in Y} varu$$

$$+ \sum_{k \in ENC} \sum_s com_s$$

$$+ \sum_s \sum_{z \in Z} \sum_{y \in Y} \dots$$

$$- \sum_s \sum_{z \in Z} \sum_{y \in Y} \dots$$

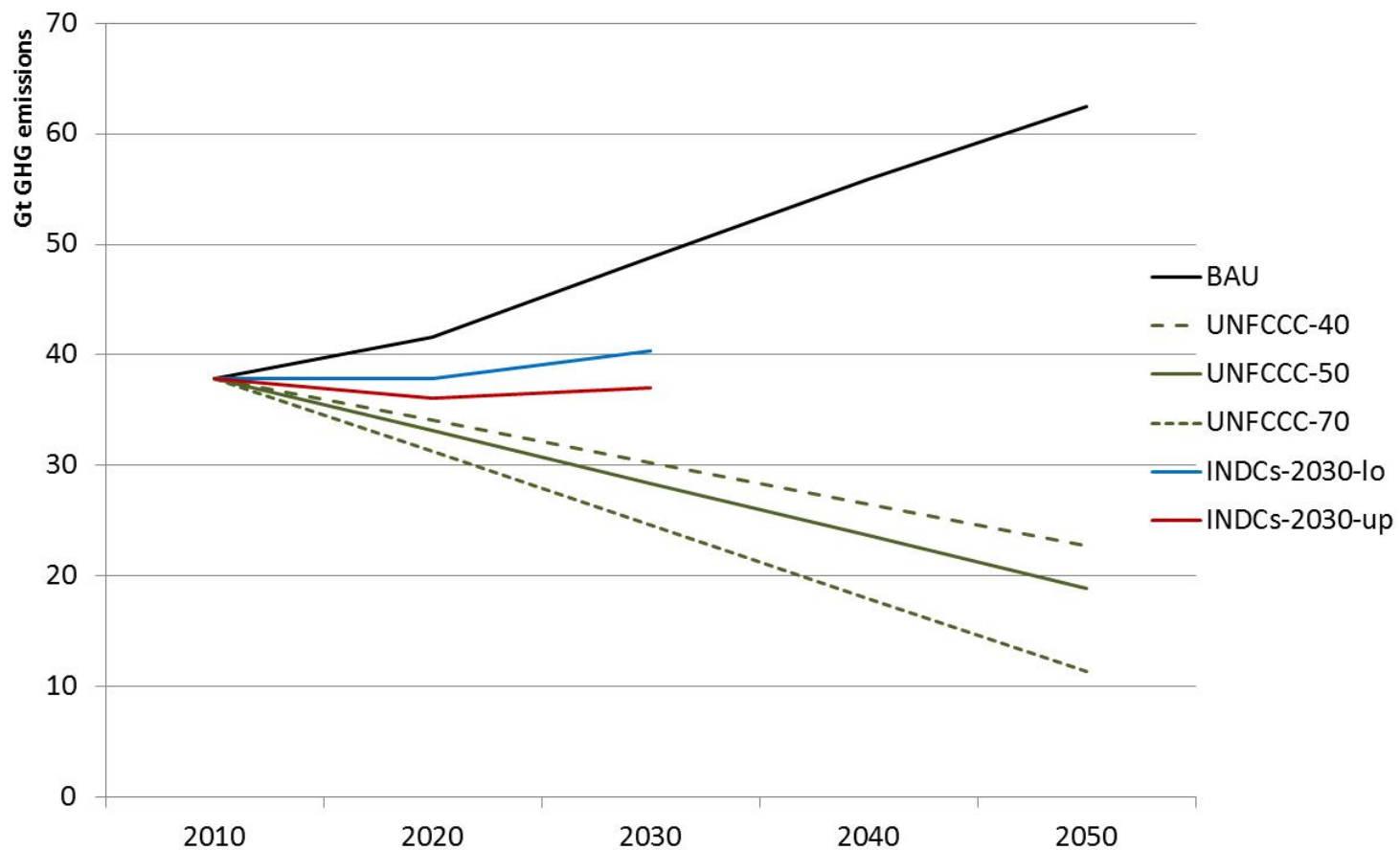
Regions	Reference year	Target year	Reduction level	Reduction type	Mitigation 2010-2030 (Low)	Mitigation 2010-2030 (High)
Industrialized countries						
Europe (WEU-EEU)	1990	2030	40%	Emission reduction	-29.5%	
The USA (USA)	2005	2025	26% - 28%		-33.3%	-35.0%
Australia and New Zeland (AUS)		2030	26% - 28%		-26.0%	-28.0%
Canada (CAN)	30%		-25.8%			
Japan (JPN)	26%		-25.5%			
Fast developing countries						
China (CHI)	2005	2030	60% - 65%	Carbon intensity	15.5%	1.1%
India (IND)			33% - 35%		133%	126.0%
Developing countries						
Russia (FSU)	1990	BAU	25% - 30%	Emission reduction	16.1%	8.4%
Mexico (MEX)			25% - 40%		-2.6%	-22.1%
South Korea (SKO)			37%		-20.8%	-20.8%
Africa (AFR)			15% - 30%		17.1%	-3.5%
Middle East (MEA)			15% - 30%		14.7%	-5.5%
Asian countries (ODA)			15% - 30%		6.5%	-12.3%
Latin America (CSA)			<i>INDCs from TIMES-ALyC</i>			

Regions	Reference year	Target year	Reduction level	Reduction type	Mitigation 2030-2050 (LowLow)	Mitigation 2030-2050 (UpUp)
Industrialized countries						
Europe (WEU-EEU)	1990	2050	60%-80%	Emission reduction	-33%	-67%
The USA (USA)	2005		83%		-73%	-72%
Australia and New Zeland (AUS)	2005		60%-80%		-46%	-72%
Canada (CAN)	2005		60%-80%		-43%	-71%
Japan (JPN)	2013		60%-80%		-46%	-73%
Fast developing countries						
China (CHI)	2030	2050	Peak emission 2030		0%	
India (IND)						
Fast developing countries						
Russia (FSU)	2030	2050	Peak emission 2030		0%	
Mexico (MEX)						
South Korea (SKO)						
Africa (AFR)						
Middle East (MEA)						
Asian countries (ODA)						
Latin America (CSA)						

Short-term GHG emissions pathways

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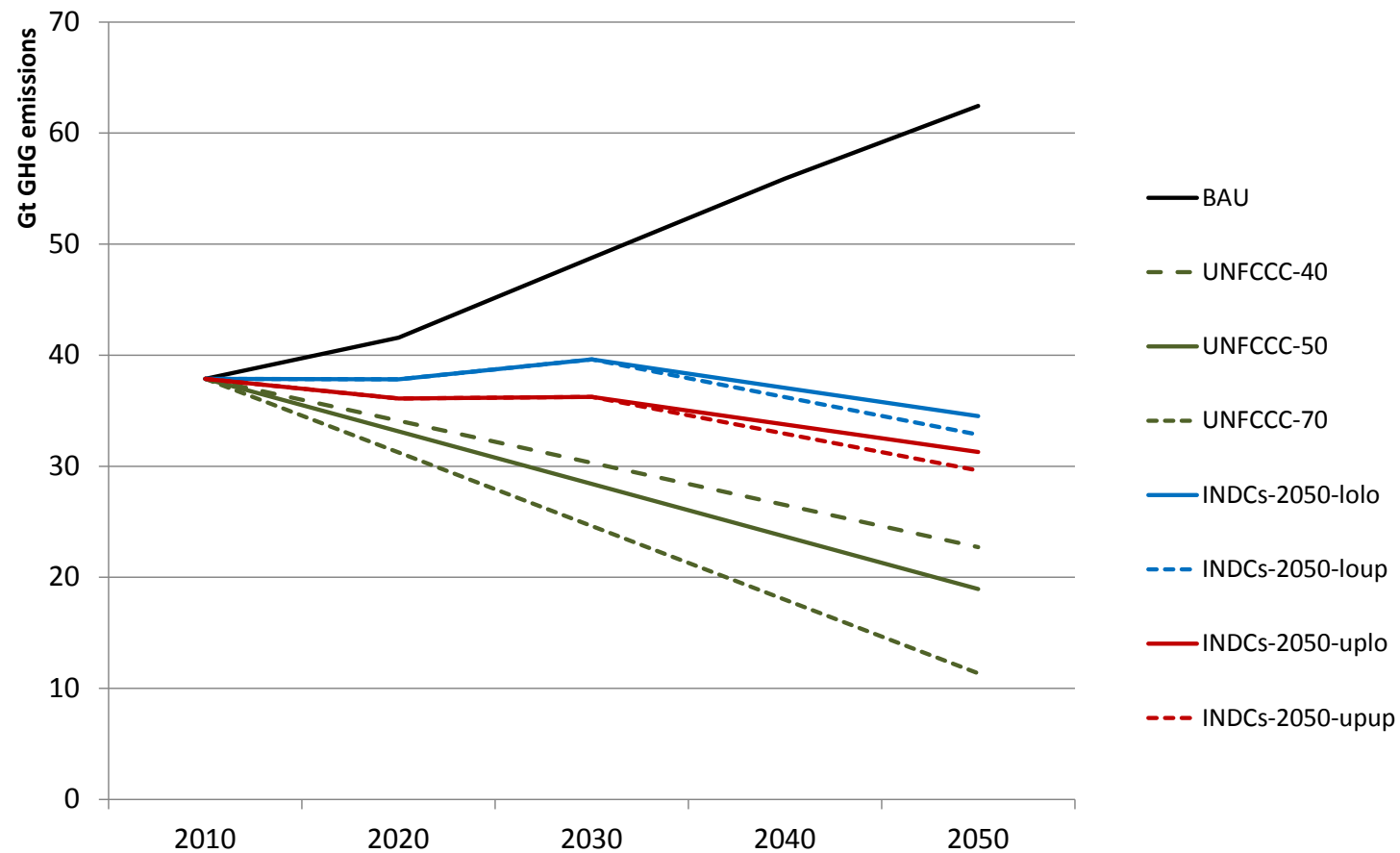
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Long-term GHG emissions pathways

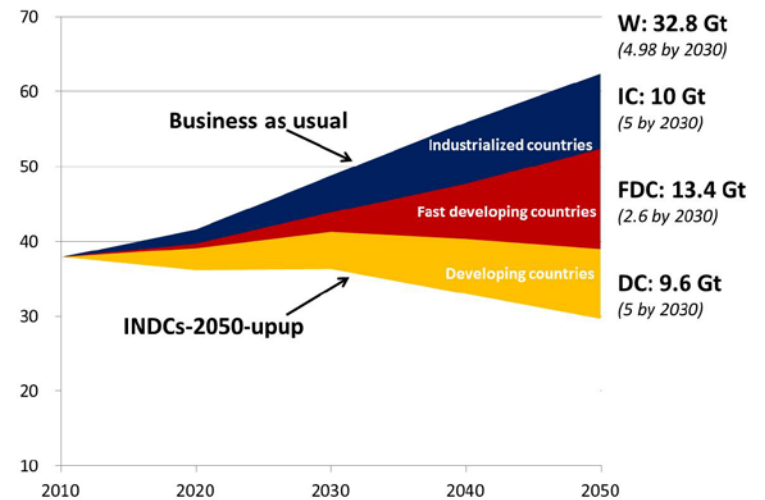
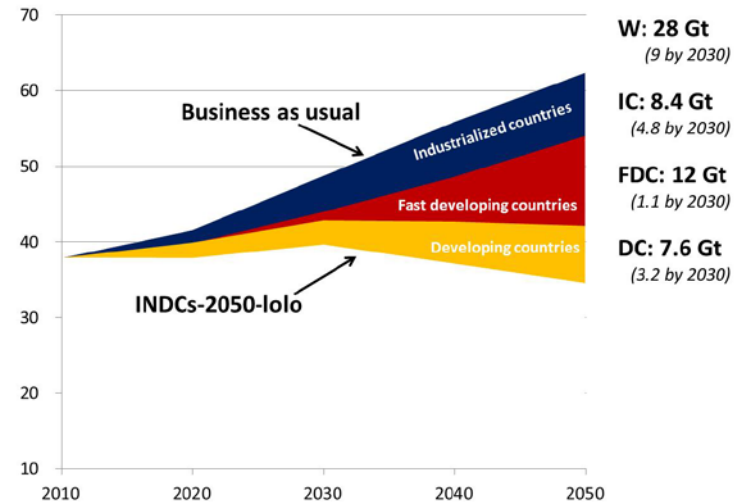
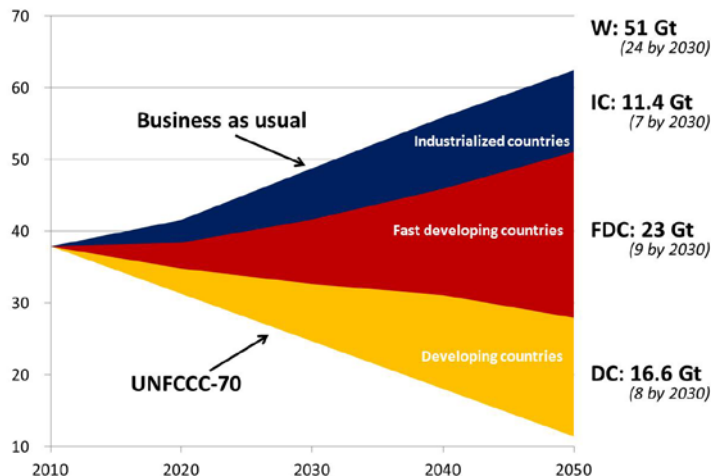
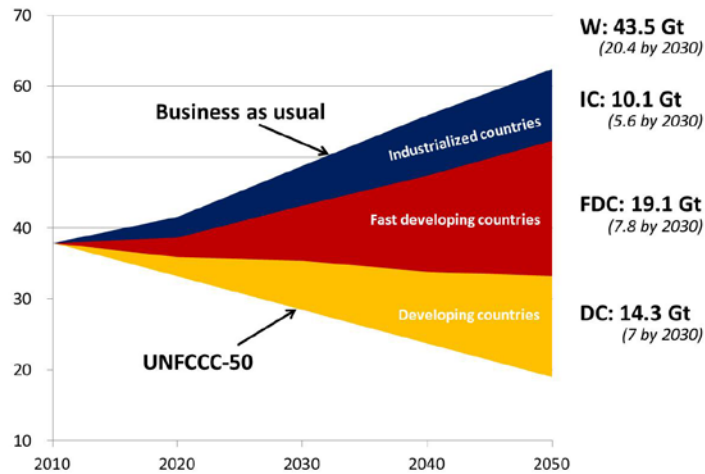
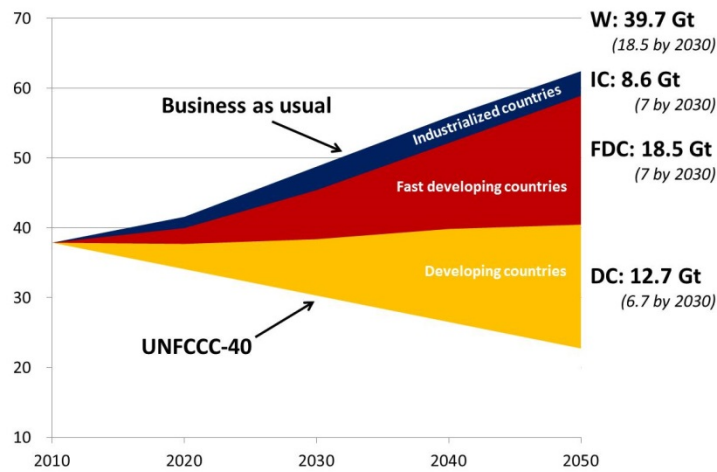
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Regional contribution to the mitigation effort

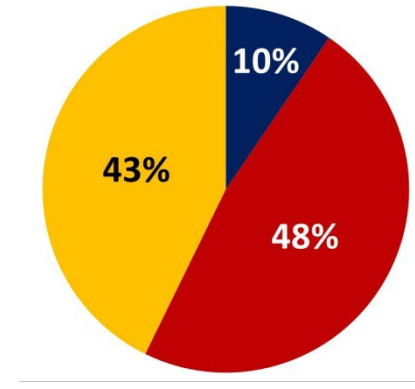
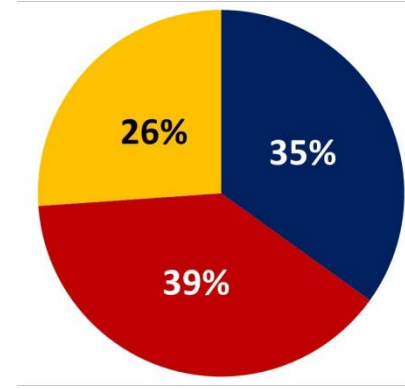
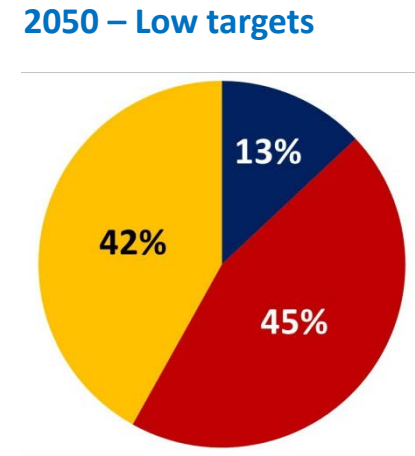
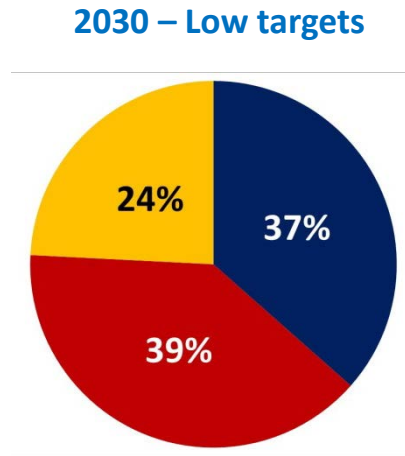
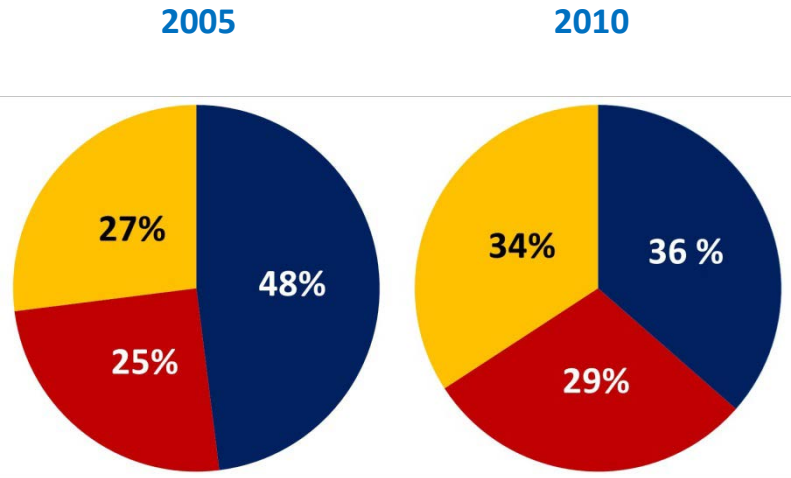
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Regional distribution of GHG emission

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- Industrialized countries
- Fast developing countries
- Developing countries

2030 – High targets

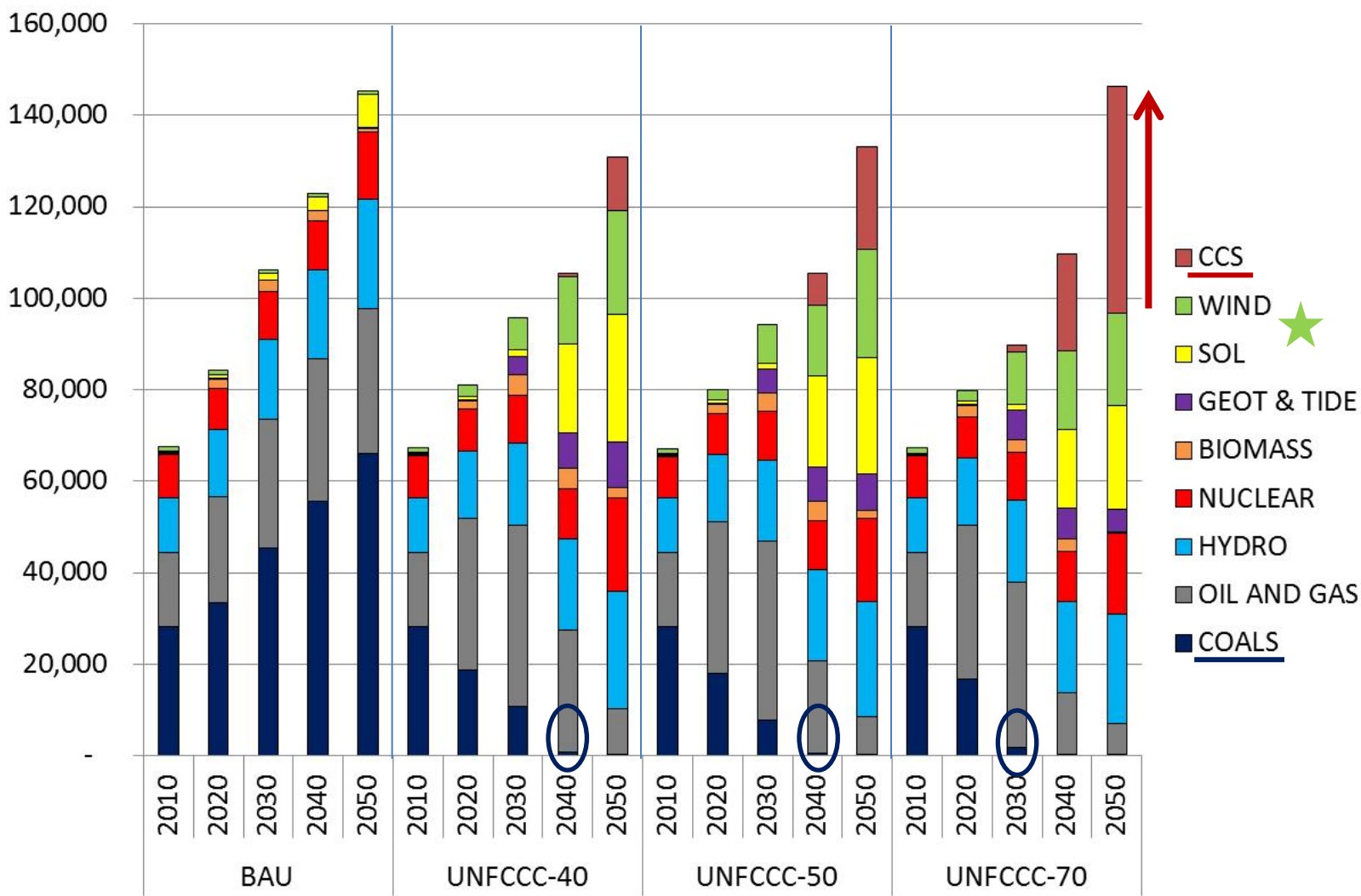
2050 – High targets

Technological choices to the mitigation effort

World electricity production (PJ)

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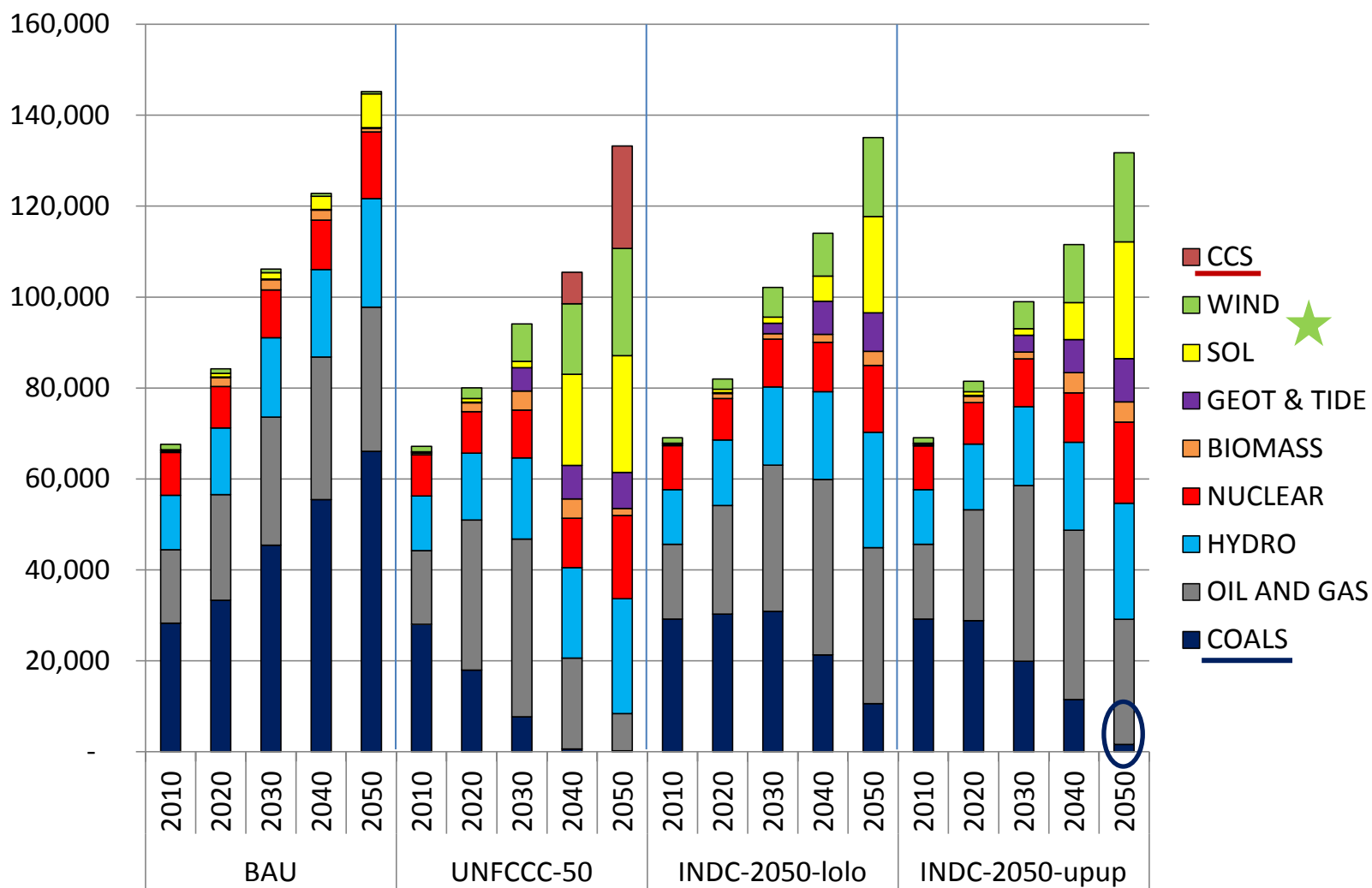


Technological choices to the mitigation effort

World electricity production (PJ)

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Regional electricity production (PJ) – Industrialized countries

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$$\frac{1}{(1 + \alpha)^{n(t-1)}} \sum_{i \in TCH} in$$

$$\times \left(\sum_{i \in TCH} fixom_i(t) \right)$$

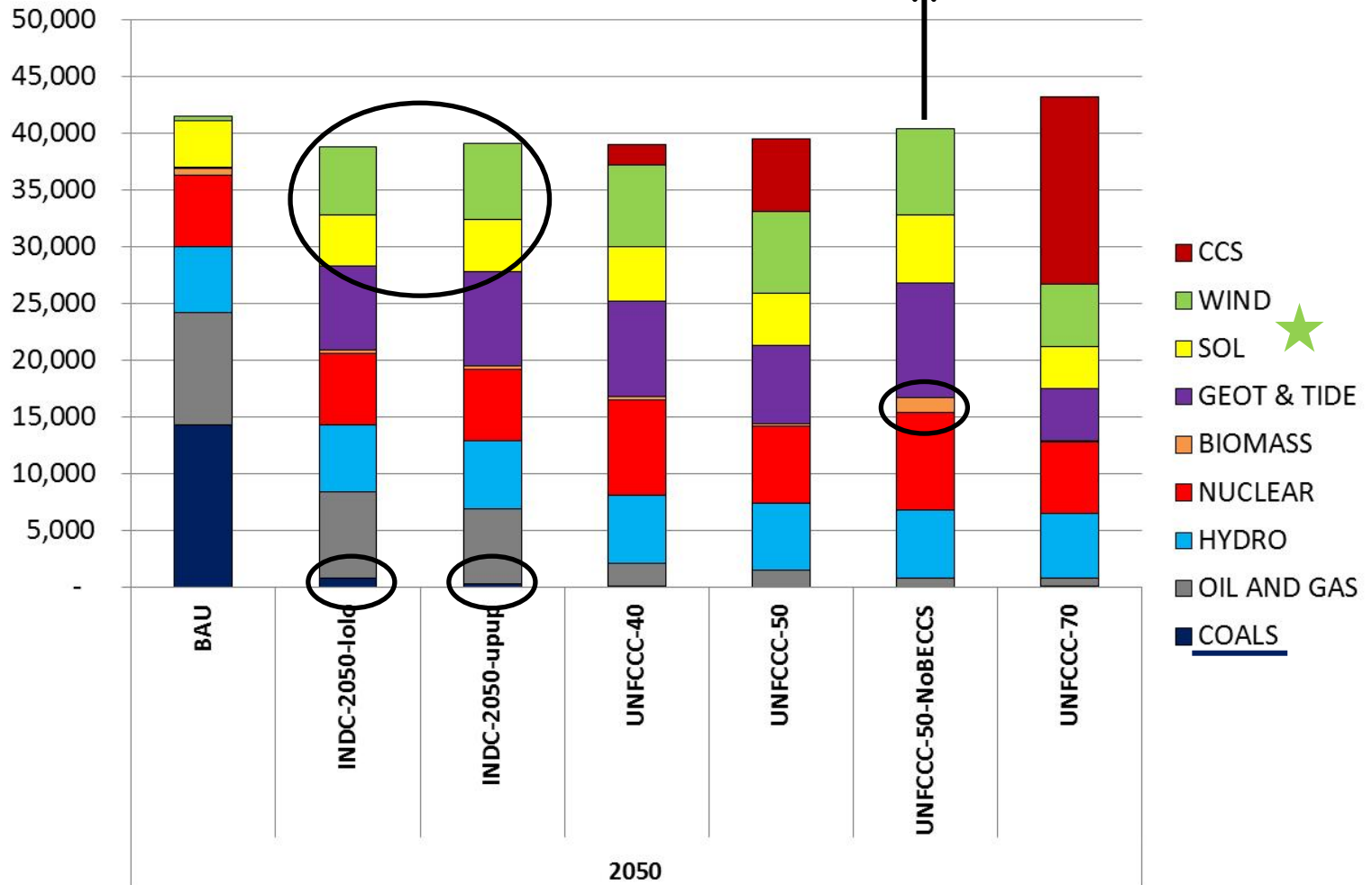
$$+ \sum_{i \in EELA} \sum_{z \in Z} \sum_{y \in Y} varu$$

$$+ \sum_{k \in ENC} \sum_s com_s$$

$$+ \sum_s \sum_{z \in Z} \sum_{y \in Y} price$$

$$- \sum_s \sum_{z \in Z} \sum_{y \in Y} price$$

No BECCS = No CCS but Investment in bioplant



Regional electricity production (PJ) – CCS Plants

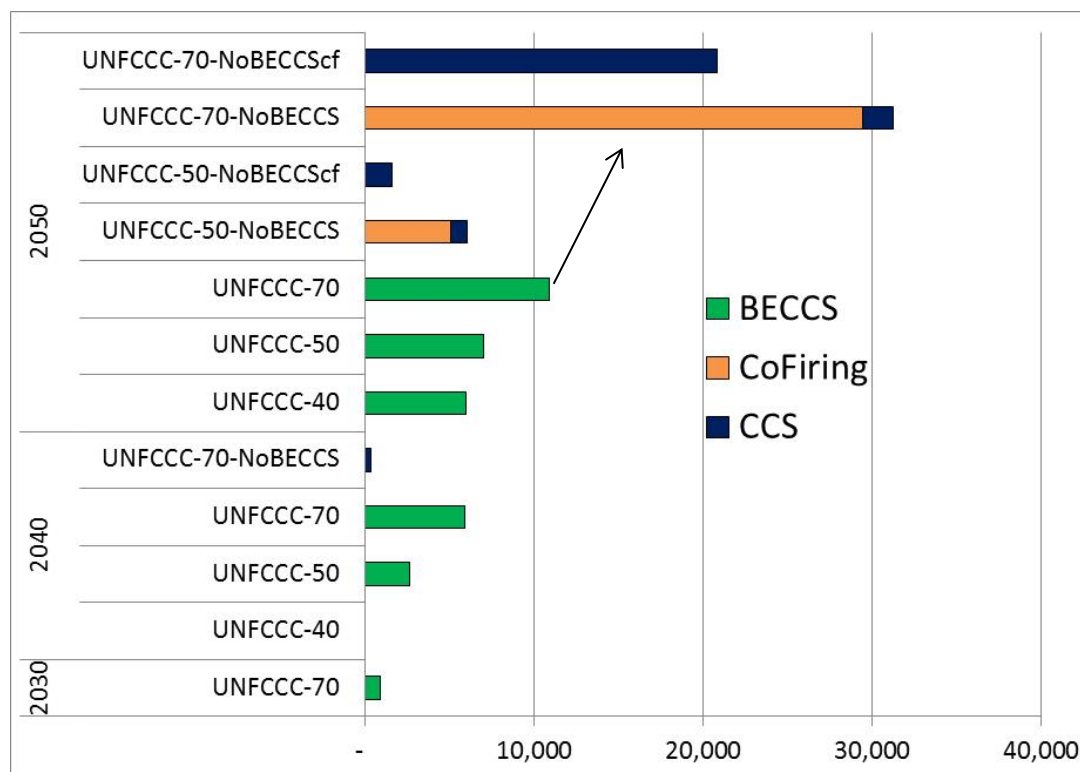
Fast developing countries

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INDCs Scenarios: no CCS but electricity from bioplant is more important

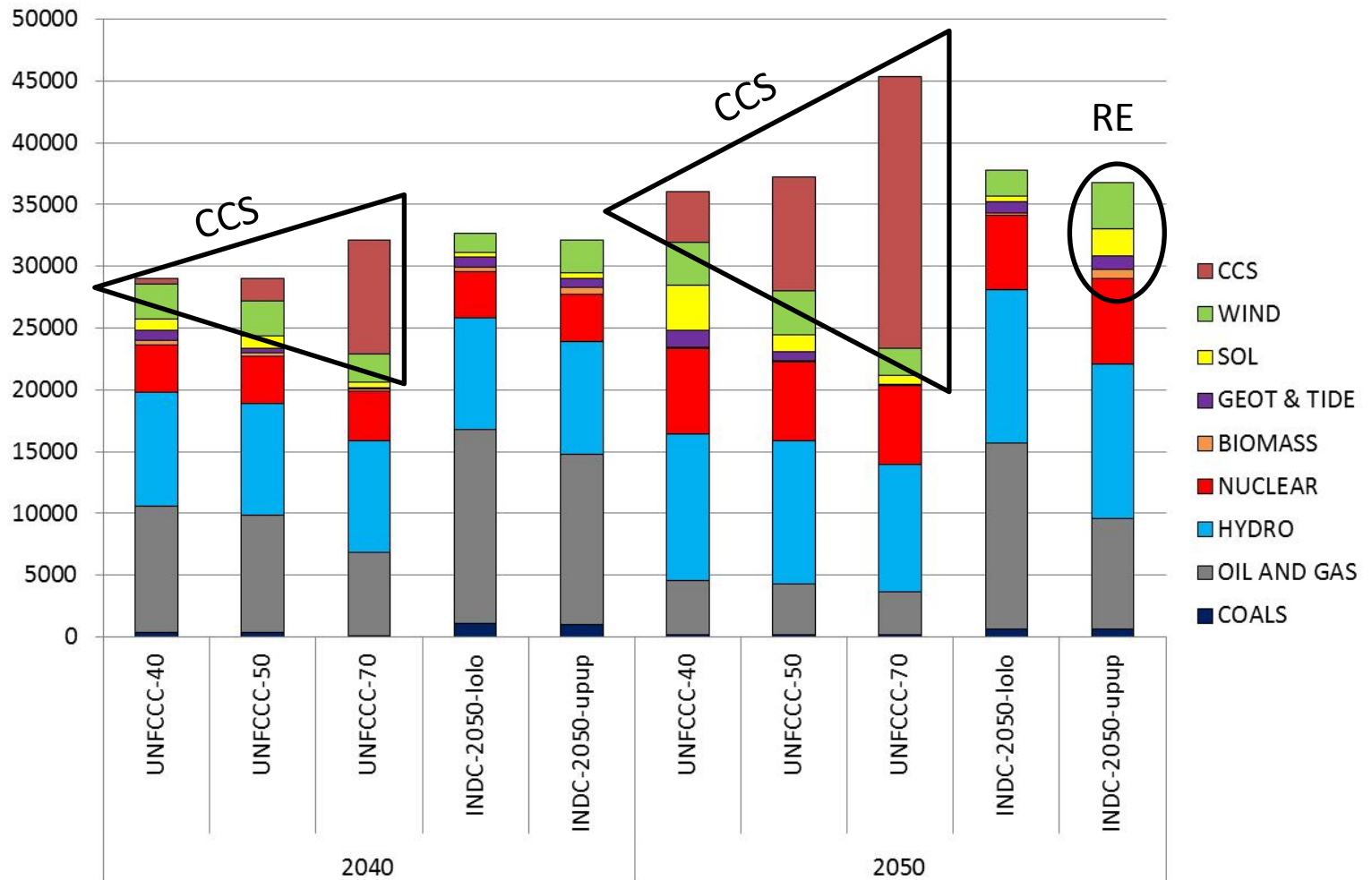
UNFCCC-70-NoBECCS: decarbonized electricity system (solar)



Regional electricity production (PJ) – Developing countries

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Carbon storage (Gt)

$$\frac{1}{(1 + \alpha)^{n(t-1)}} \sum_{i \in TCH} in$$

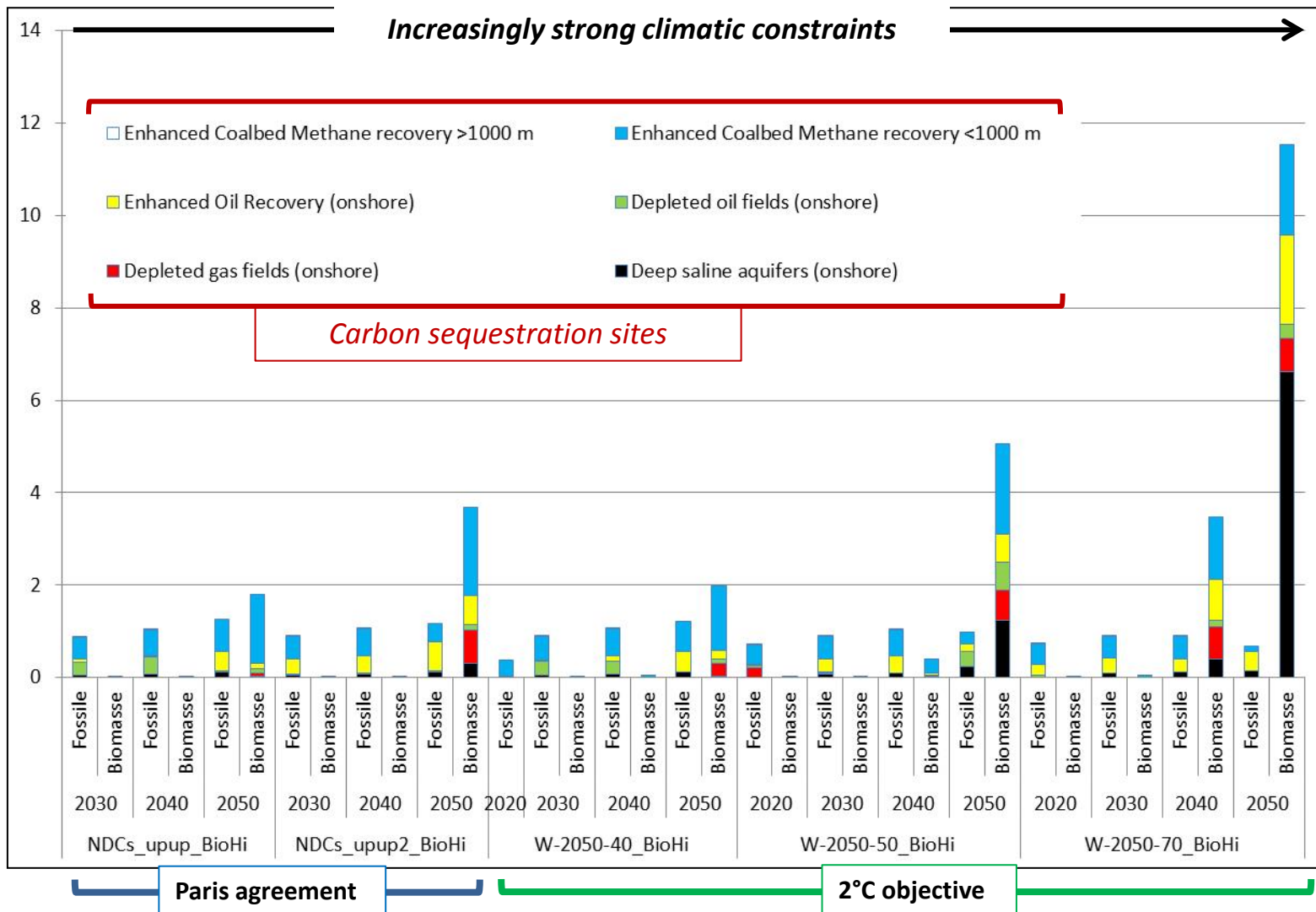
$$\times \left(\sum_{i \in TCH} fixom_i(t) \right)$$

$$+ \sum_{i \in EEA} \sum_{z \in Z} \sum_{y \in Y} varu$$

$$+ \sum_{k \in ENC} \sum_s com_s$$

$$+ \sum_s \sum_{z \in Z} \sum_{y \in Y} price$$

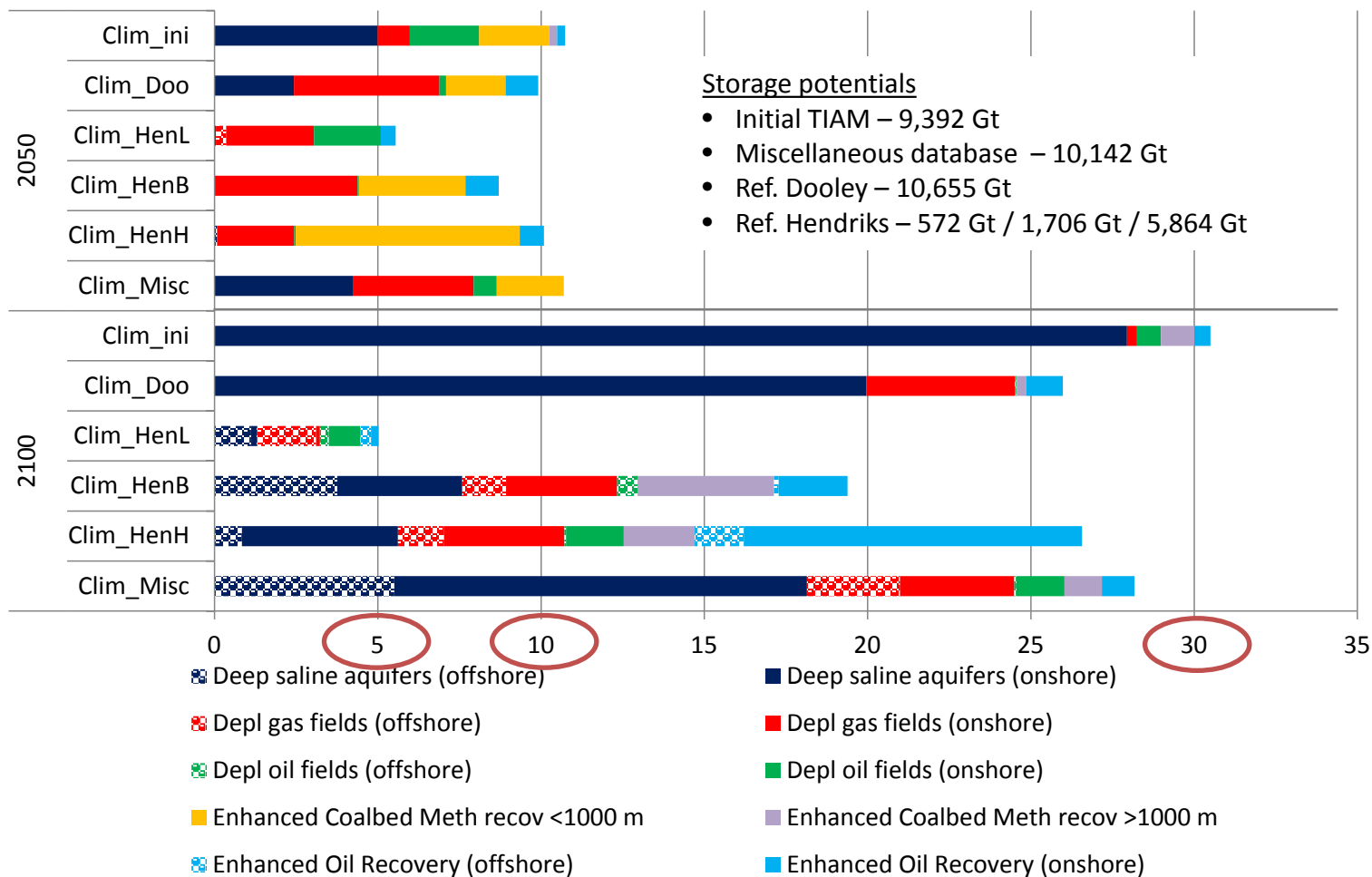
$$- \sum_s \sum_{z \in Z} \sum_{y \in Y} price$$



Carbon storage by year to achieve the 2°C objective

(radiative forcing at 2,6 W/m² by 2100)

Sensitivity analyses on carbon storage by site and scenario (Gt CO₂)



Sensitivity analysis on biomass potential and impact on storage carbon

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$$\frac{1}{(1 + \alpha)^{n(t-1)}} \sum_{i \in TCH} in$$

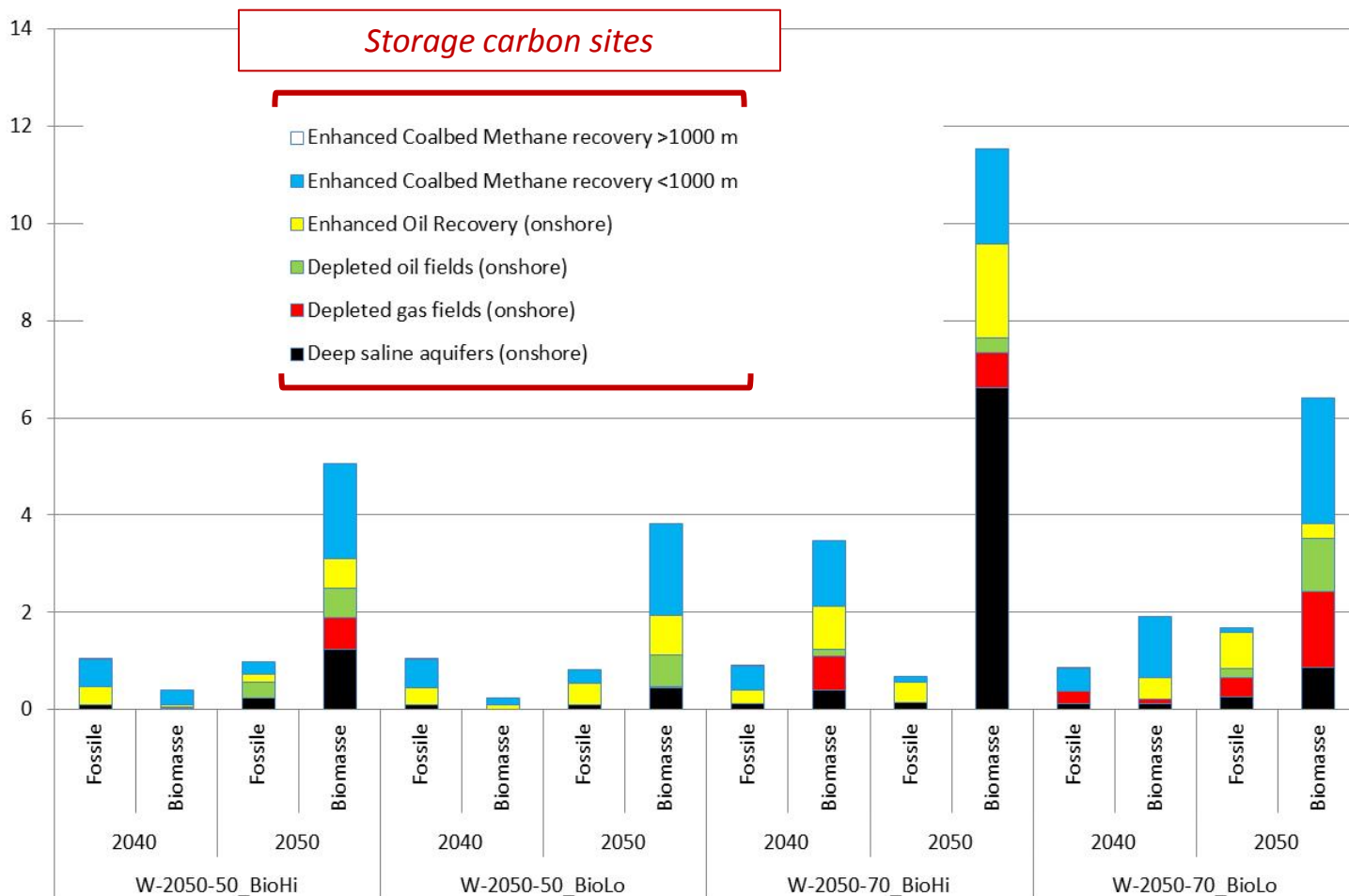
$$\times \left(\sum_{i \in TCH} fixom_i(t) \right)$$

$$+ \sum_{i \in EEA} \sum_{z \in Z} \sum_{y \in Y} varu$$

$$+ \sum_{k \in ENC} \sum_s com_k(s)$$

$$+ \sum_s \sum_{z \in Z} \sum_{y \in Y} price$$

$$- \sum_s \sum_{z \in Z} \sum_{y \in Y} price$$



Concluding remarks



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- ✓ *Contrasted regional contributions by 2030 allowing a GHG emissions stabilization (/2010 level)*
 - ✓ *2050: decarbonized pathways closer to the 2°C low targets but not enough*
 - ✓ *Industrialized: contributions closed to global mitigation pathways with an important decarbonization*
 - ✓ *Developing and fast developing: a decarbonization to increase by 2030*
 - ✓ *Important place of CCS to achieve high targets (BECCS)*
-
- One of the aims of the future UNFCCC negotiation: enhancing the climate ambition
 - Potential of decarbonization of Industrialized countries
 - The technological progress is also a significant issue
 - A clear signal for decarbonization to policy makers, investors and business community
 - Climate target: availability of technological solutions
 - To the scale of the challenge: here focus on CCS with biomass and carbon storage potential

Long-term energy modeling for a decarbonized world
July 20, 2017 – Quebec, Canada

$$\frac{1}{\alpha)^{n(t-1)}} \sum_{i \in TCH} invcost_i(t) \cdot I_i(t) + \sum_{t \in T} \frac{1}{(1 +$$

$$\sum_{i \in TCH} fixom_i(t) \cdot C_i(t) + \sum_{i \in PRC} varom_i(t).$$

$$\sum_{E \in E} \sum_{L \in L} \sum_{Z \in Z} \sum_{Y \in Y} varom_i(t) \cdot P_{lzy}$$

$$\sum_{E \in ENC} \sum_s cos_{ks}(t) \cdot IMP_{ks}(t)$$

$$\sum_s \sum_{Z \in Z} \sum_{Y \in Y} cos_{ks}(t) \cdot IMP_{ELCS}(t) \cdot IMP_{ELCS}(t)$$

$$\sum_s \sum_{Z \in Z} \sum_{Y \in Y} price_{ELCS}(t) \cdot EXP_{ELCS}(t)$$

Thank you for your attention!

sandrine.selosse@mines-paristech.fr



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Cost analysis of constraints

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$$\frac{1}{(1+\alpha)^{n(t-1)}} \sum_{i \in TCH} in$$

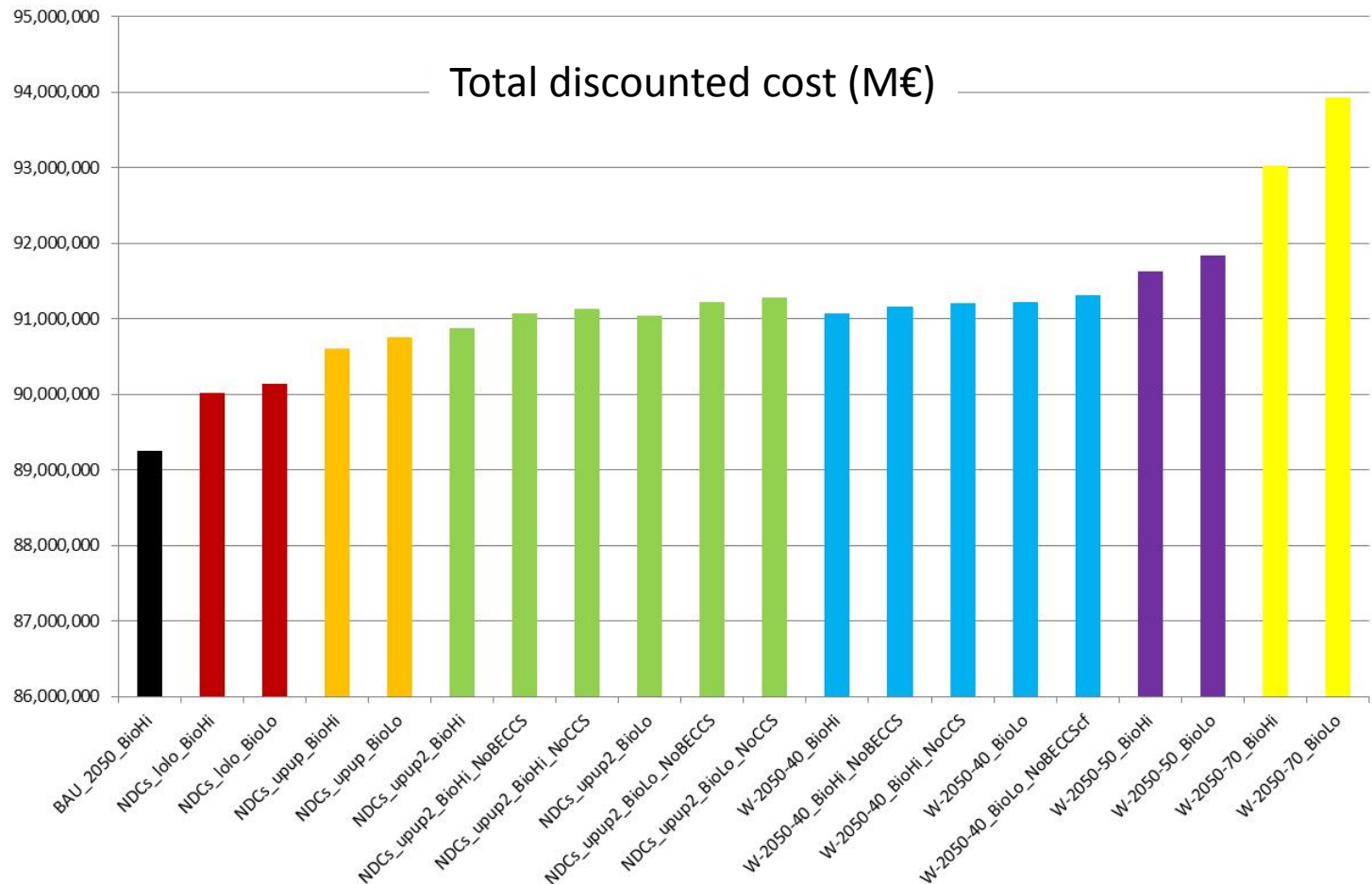
$$\times \left(\sum_{i \in TCH} fixom_i(t) \right)$$

$$+ \sum_{i \in EEA} \sum_{z \in Z} \sum_{y \in Y} varu$$

$$+ \sum_{k \in ENC} \sum_s cost_s$$

$$+ \sum_s \sum_{z \in Z} \sum_{y \in Y} price$$

$$- \sum_s \sum_{z \in Z} \sum_{y \in Y} price$$



Carbon marginal cost (\$/tCO2)

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Scenario	Période	Coût marginal du carbone
NDCs_lolo_BioHi	2030	20
NDCs_lolo_BioLo		
NDCs_upup2_BioHi	2030	25
NDCs_upup2_BioLo		
NDCs_upup_BioHi		
NDCs_upup_BioLo	2030	30
W-2050-40_BioHi		
W-2050-40_BioLo	2050	35
NDCs_lolo_BioHi		
NDCs_lolo_BioLo		
W-2050-50_BioHi	2030	40
W-2050-50_BioLo		
W-2050-70_BioLo	2030	40
W-2050-70_BioHi	2030	50
NDCs_upup_BioHi	2050	75
NDCs_upup_BioLo		
W-2050-40_BioHi	2050	90
W-2050-40_BioLo		
NDCs_upup2_BioHi	2050	95
W-2050-50_BioHi	2050	100
NDCs_upup2_BioLo	2050	120
W-2050-70_BioHi		
W-2050-50_BioLo	2050	150
W-2050-70_BioLo	2050	420

Long-term possible futures of the energy system in the post-Paris climate context

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Qualitative and quantitative variations according to inputs and data

- Energy services demands (minimizing global cost under satisfaction of demands)
- Primary resources potentials
- Technologies and characteristics
- Emissions (CO₂, CH₄, and N₂O)
- Geographic and time scales (technico-economic characteristics of technologies according to region, period, etc.)
- Political parameters (environmental, technological, resources)



Output of the model

- Primal solution
 - Technological Investments
 - Activity and capacity by technology
 - Imports/exports by tradable resource
 - Primary resource extraction
 - Input/output flow by commodity and technology
 - GGH emissions by technology, sector, region
- Dual solution
 - Marginal cost of the constraint

Perspectives

$$\frac{1}{(1 + \alpha)^{n(t-1)}} \sum_{i \in TCH} in$$

$$\times \left(\sum_{i \in TCH} fixom_i(t) \right)$$

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