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UNECE Pathways to Sustainable Energy: GCAM Results

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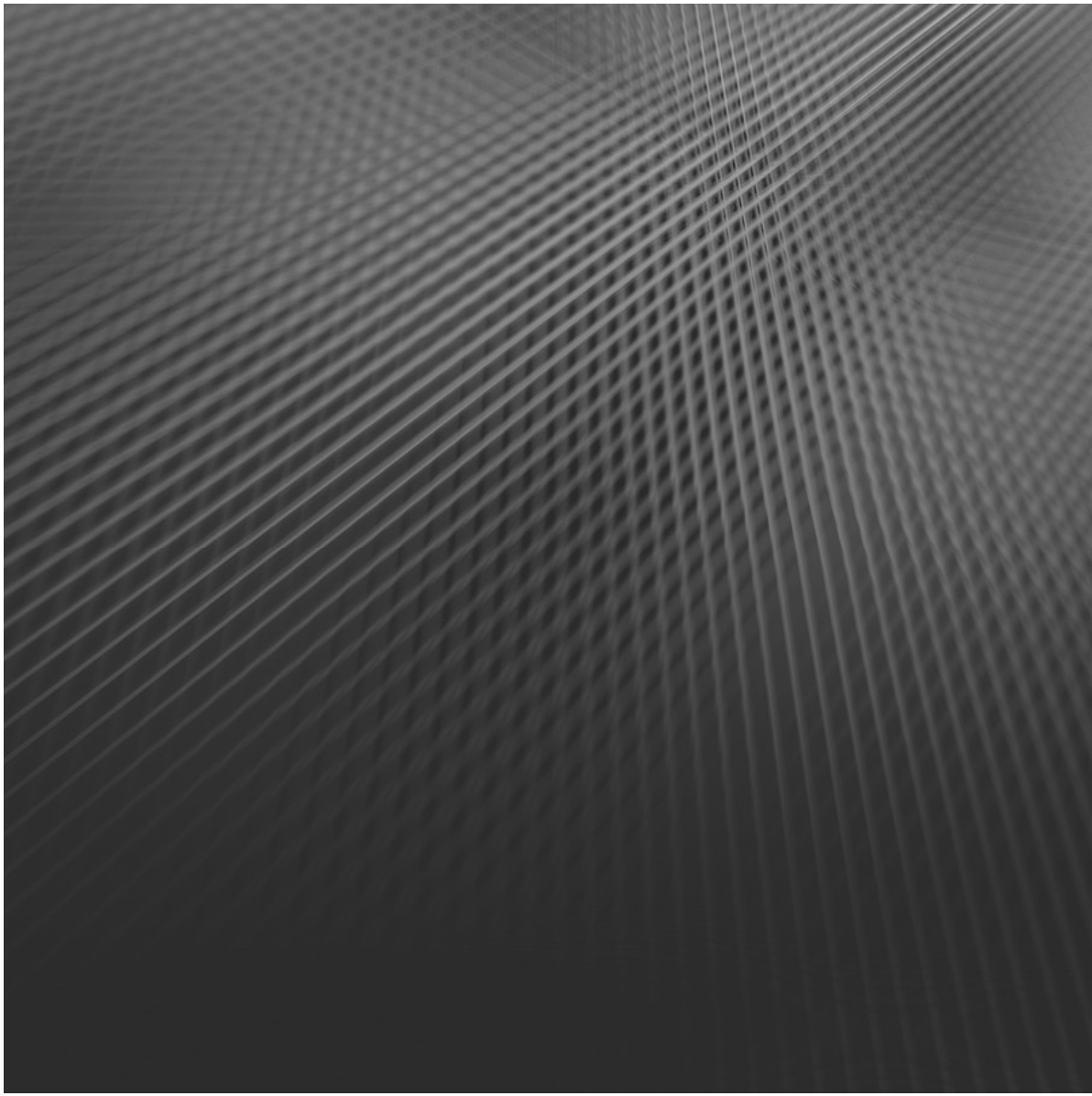

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Scenario design

- Population and GDP trajectories taken from the Shared Socioeconomic Pathway 2 (SSP2)
- Policy scenarios are paired with technology sensitivities for a total of 15 runs
  - Policy scenarios reflect various levels of emissions constraints based on explicit policy decisions
  - Technology sensitivities are intended to represent different potential technological development pathways in which specific technologies develop more quickly or slowly than in our reference assumptions
  - Technology sensitivities do not include explicit representation of R&D costs or incentives that could be used to instill more rapid development of a specific technology
  - Each technology's policy scenario should be compared to its own reference scenario to address how measures of sustainable energy would differ with climate policies under alternate technology development pathways
- Policy scenarios
  - Ref (no climate policy)
  - NDC (regional CO_2 constraints consistent with country-level NDCs through 2030 with "continued ambition" through 2100*)
  - NDC-G (global CO_2 constraint equal to the sum of regional NDC constraints, model allocates across regions based on economic efficiency)
  - P2C (regional CO_2 constraints consistent with country-level NDC pledges through 2030 then continued reductions to achieve a 2ºC target in 2100)
  - P2C-G (global CO_2 constraint equal to the sum of regional P2C constraints, model allocates across regions based on economic efficiency)
- Technology sensitivities
  - RefTech (model's reference energy technology assumptions)
  - AdvRE (RefTech + reduced capital costs for geothermal, solar, and win
  - AdvNuc (RefTech + reduced capital costs for nuclear)
  - noCCS (RefTech – CCS technology)

* Fawcett AA *et al.* (2015) Can Paris pledges avert severe climate change? *Science (80)*

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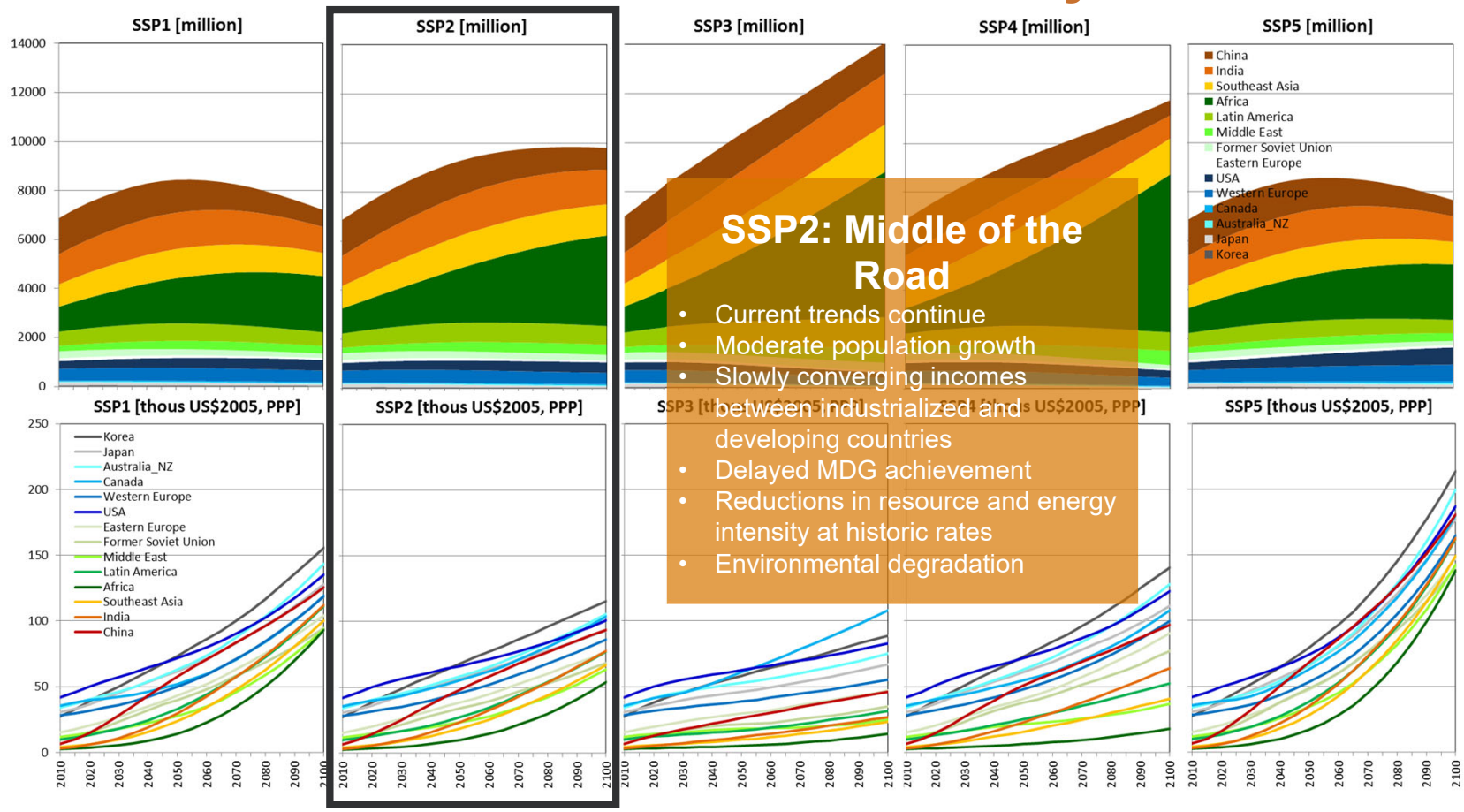
Shared Socioeconomic Pathways



SSP2: Middle of the Road

- Current trends continue
- Moderate population growth
- Slowly converging incomes between industrialized and developing countries
- Delayed MDG achievement
- Reductions in resource and energy intensity at historic rates
- Environmental degradation

O'Neill et al (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122:3.

GCAM scenario review

Technology

- **Reference**: SSP2 assumptions (next slide)
- **Advanced renewables**: Reduced capital costs for solar, wind, and geothermal
- **Low-cost nuclear**: Lower capital costs reflective of small modular reactors
- **No CCS**: No carbon capture and storage technology

Policy

- **Reference:** No mitigation action
- **Paris NDC continued ambition:** regional CO_2 emissions caps based on national Paris pledges plus continued actions post-2030
- **Paris NDC continued ambition, global cooperation:** CO_2 mitigation as in NDC, implemented using a global carbon market
- **Paris to 2ºC:** regional CO_2 emissions caps based on national Paris pledges plus enhanced ambitions post-2030 to reach the 2ºC goal
- **Paris to 2ºC, global cooperation:** CO_2 mitigation as in P2C, implemented with a global carbon market

Technology	Reference	Paris NDC continued ambition*	Paris NDC cont. ambition, global cooperation	Paris to 2°C	Paris to 2°C, global cooperation
Reference Technology	Ref_RefTech	NDC_RefTech	NDC-G_RefTech	P2C_RefTech	P2C-G_RefTech
Advanced Renewables	Ref_REAdv	NDC_REAdv		P2C_REAdv	
Low-cost Nuclear (SMR)	Ref_NucAdv	NDC_NucAdv		P2C_NucAdv	
No CCS	Ref_noCCS		NDC-G_noCCS		P2_noCCS

Measuring change in metrics

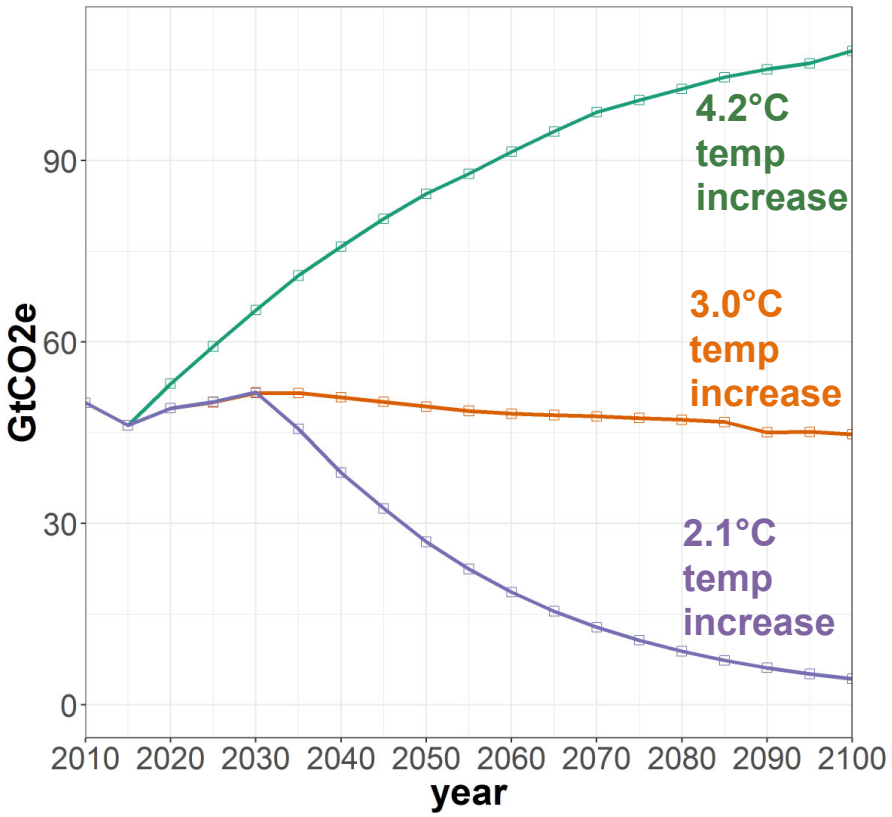
- Each technology scenario is viewed as a "what if" change
  - The reference technology suite is the modelers' best guess about future changes in technology efficiencies and costs
  - The alternate technology scenarios represent scenarios in which these change differently (e.g., more rapid cost reduction)
  - These changes are assumed to be costless, they do not reflect any needed R&D or government investment that might by required to realize these improvements
- Metrics for the NDC and P2C policy scenarios are compared to each technology's own "Reference" (no policy) scenario

Technology	[illegible]	Paris NDC continued ambition*	Paris NDC cont. ambition, global cooperation	Paris to 2°C	Paris to 2°C, global cooperation
Reference Technology	[illegible]ech	[illegible]C_RefTech	NDC-G_RefTech	P2C_RefTech	P2C-G_RefTech
Advanced Renewables	[illegible]EAdv	[illegible]C_REAdv		P2C_REAdv	
Low-cost Nuclear (SMR)	Ref_NucAdv	NDC_NucAdv		P2C_NucAdv	
No CCS	Ref_noCCS		NDC-G_noCCS		P2_noCCS

Detailed technology assumptions

Technology		Reference assumptions	Technology assumptions
Renewables	Solar	• Capital costs decline about 25% by 2050	• Capital costs decline more than 60% by 2050
	Wind	• Capital costs decline about 20% by 2050	• Capital costs decline more than 60% by 2050
	Geothermal	• Capital costs less than 10% by 2050 • Only hydrothermal resources	• Capital costs decline about 20% by 2050 • New enhanced geothermal system (EGS) resources (regional specific supply curves)
Nuclear		• 2010 $5,501/kW • 2030 $5,307/kW • 2050 $5,094/kW	• Lower capital costs that reflect the small module reactors (SMR) • Advanced assumption is about 35% lower than the reference assumption
CCS		• CO2 capture rate: 85% in 2020, increase to 95% by 2100	• No available CCS technology

Global annual GHG emissions, by policy scenario



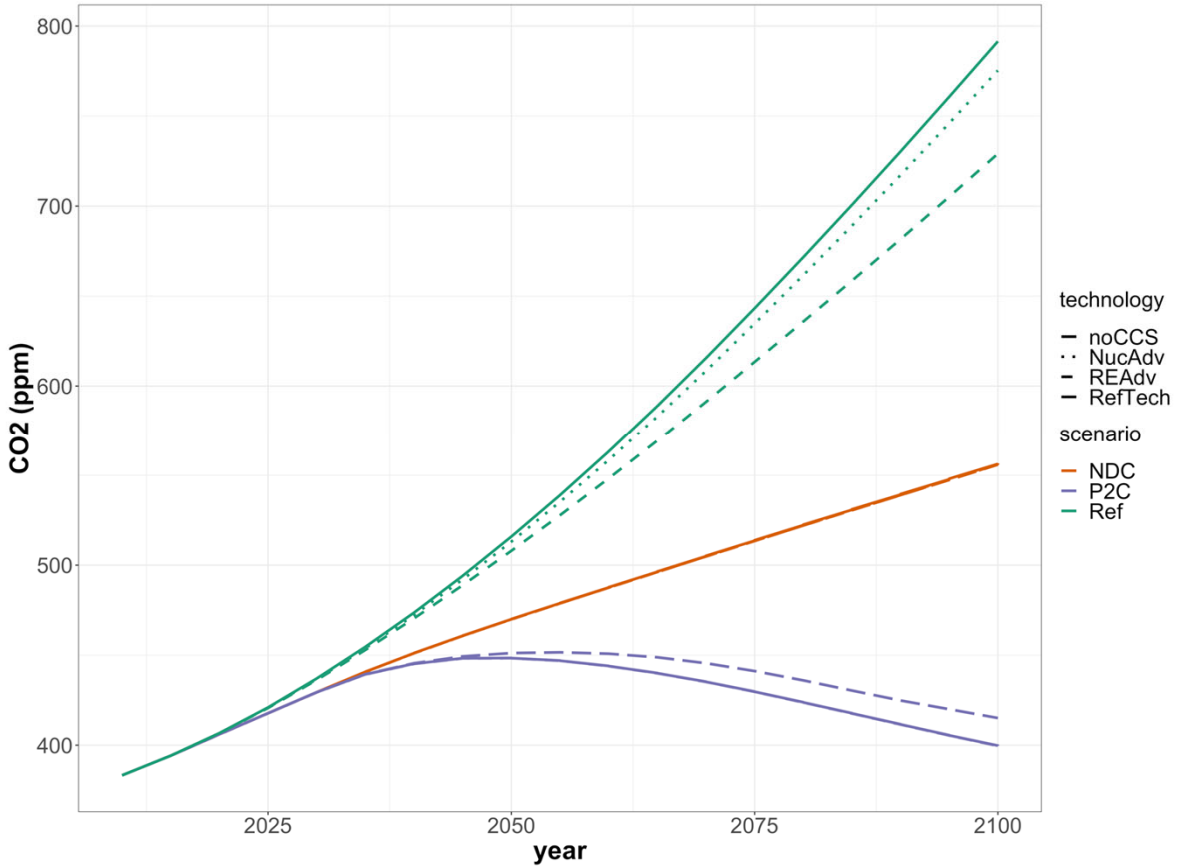
- **Reference**: SSP2 assumptions
  - Reference technology
- **NDCs***
  - Regional GHG emissions caps based on national Paris pledges
  - Continued ambition post-2030
- **Paris to 2C:**
  - Regional GHG emissions caps based on national Paris pledges
  - Enhanced ambitions post-2030 to achieve 2ºC goal

ALTERNATIVE AMBITIONS

* Fawcett AA *et al.* (2015) Can Paris pledges avert severe climate change? *Science (80)*

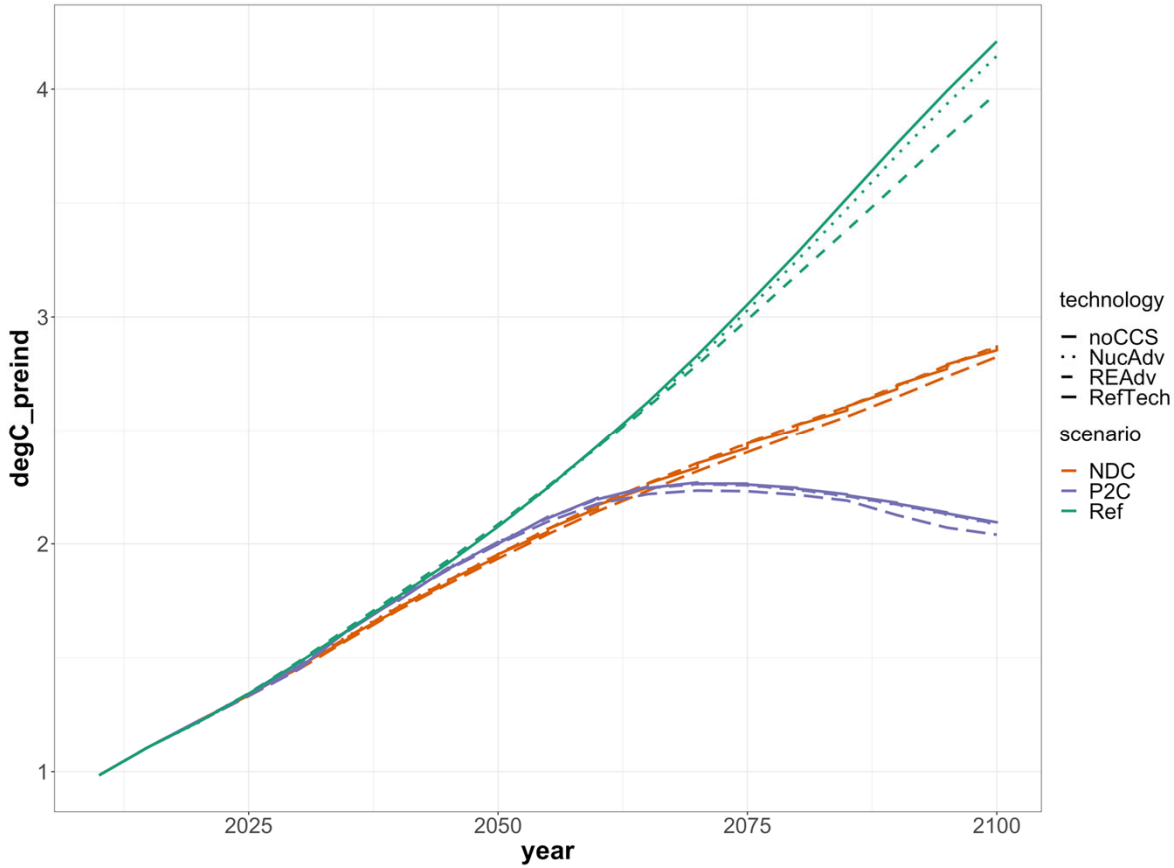
CO_2 concentrations

- Reference scenarios
  - Reference technology ~ 800 ppm
  - REAdv technology ~ 725 ppm
- NDC scenarios ~ 550 ppm
- P2C scenarios
  - Peak in ~2050 at 450 ppm
  - Decline to 400 ppm in 2100
  - Slightly higher concentrations in noCCS technology



Global mean temperature change

- Reference scenarios (no emissions constraints) result in ~ 4ºC in 2100
  - Advanced energy technologies result in a small decrease in temperature (~0.25ºC)
- NDC scenarios reduce temperature increase by ~ 1ºC compared to reference
- P2C emissions constraints achieve ~ 2.1ºC increase



Regional CO_2 constraints by policy scenario

Reference:

- Unconstrained emissions, driven by GDP; technology costs/efficiencies

NDC:

- CO_2 emissions constraints by region, consistent with NDC pledges and continued ambition*
- Regional carbon markets (tax)

NDC Global:

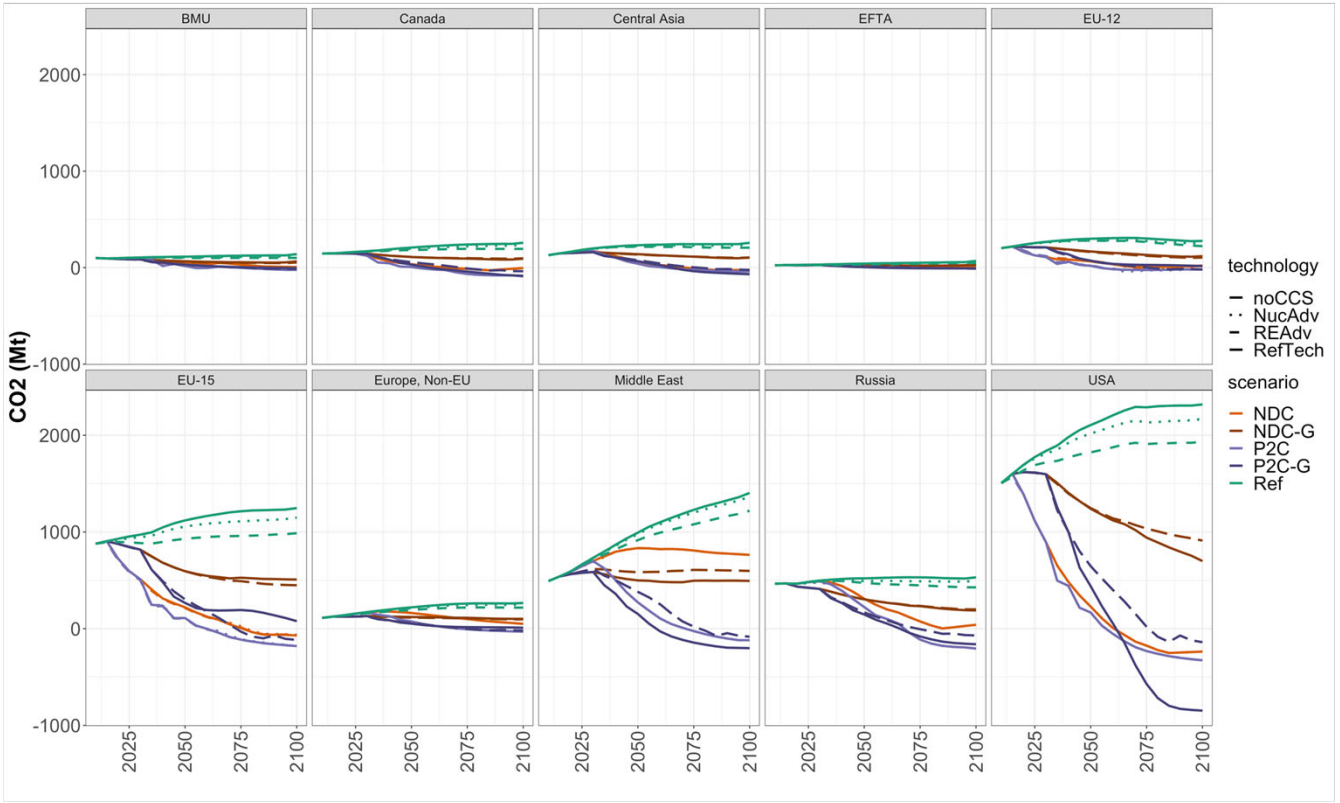
- ***Global*** CO_2 emissions consistent with the sum of all regional NDC constraints
- Global carbon market

P2C:

- NDC constraints through 2030, regional markets thereafter to achieve 2ºC
- Regional carbon markets

P2C Global:

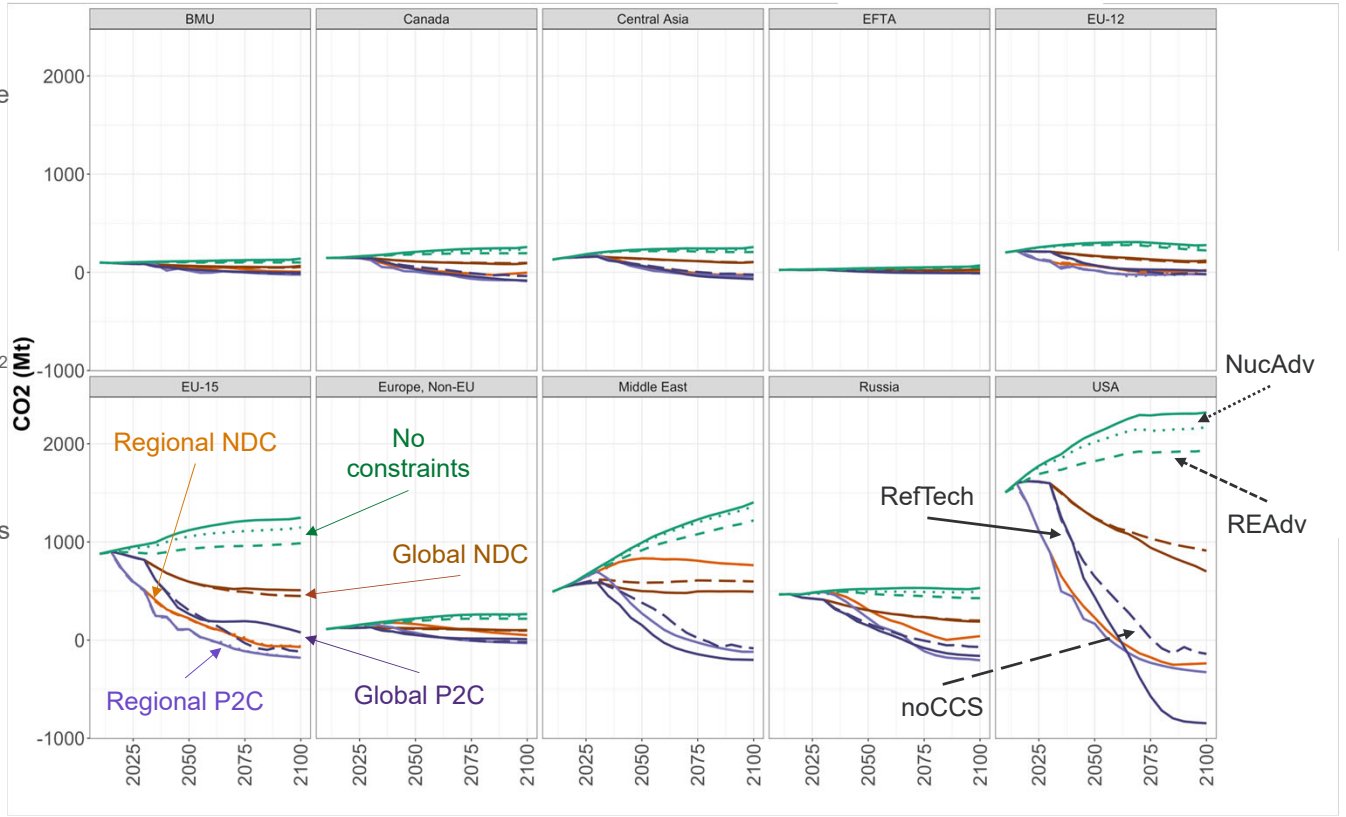
- ***Global*** CO_2 emissions consistent with the sum of all regional P2C constraints
- Global carbon market



* Fawcett AA *et al.* (2015) Can Paris pledges avert severe climate change? *Science (80)*

Regional CO_2 emissions

- Reference scenarios do not have any constraints on CO_2 emissions
  - Differences in reference emissions are a result of emissions intensities of technologies, prices, and resulting demand
- *Regional* constraints
  - NDC scenarios constrain CO_2 emissions for each region based on commitments through 2030 and continued ambition through 2100; CO_2 emissions will be identical across all technologies for all NDC scenarios
  - P2C scenarios further reduce emissions from 2030-2100 to achieve 2ºC; CO_2 emissions will be identical across technologies for P2C scenarios
- *Global* constraints
  - Global emissions are constrained based on the sum of all the regional constraints (either NDC or P2C)
  - Regional mitigation depends on the relative cost of mitigation (least cost)
  - Emissions will vary within a region compared to the regional constraints and across technologies



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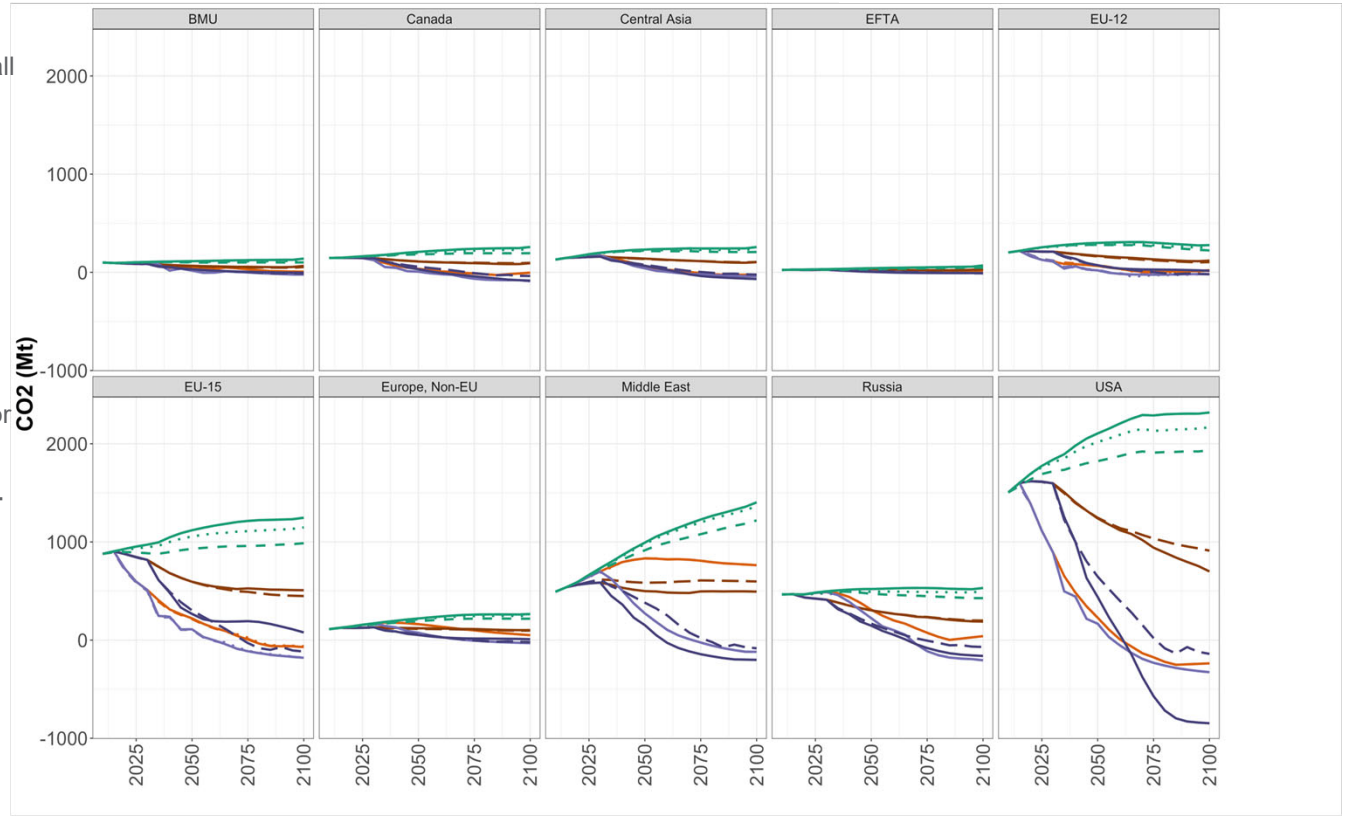
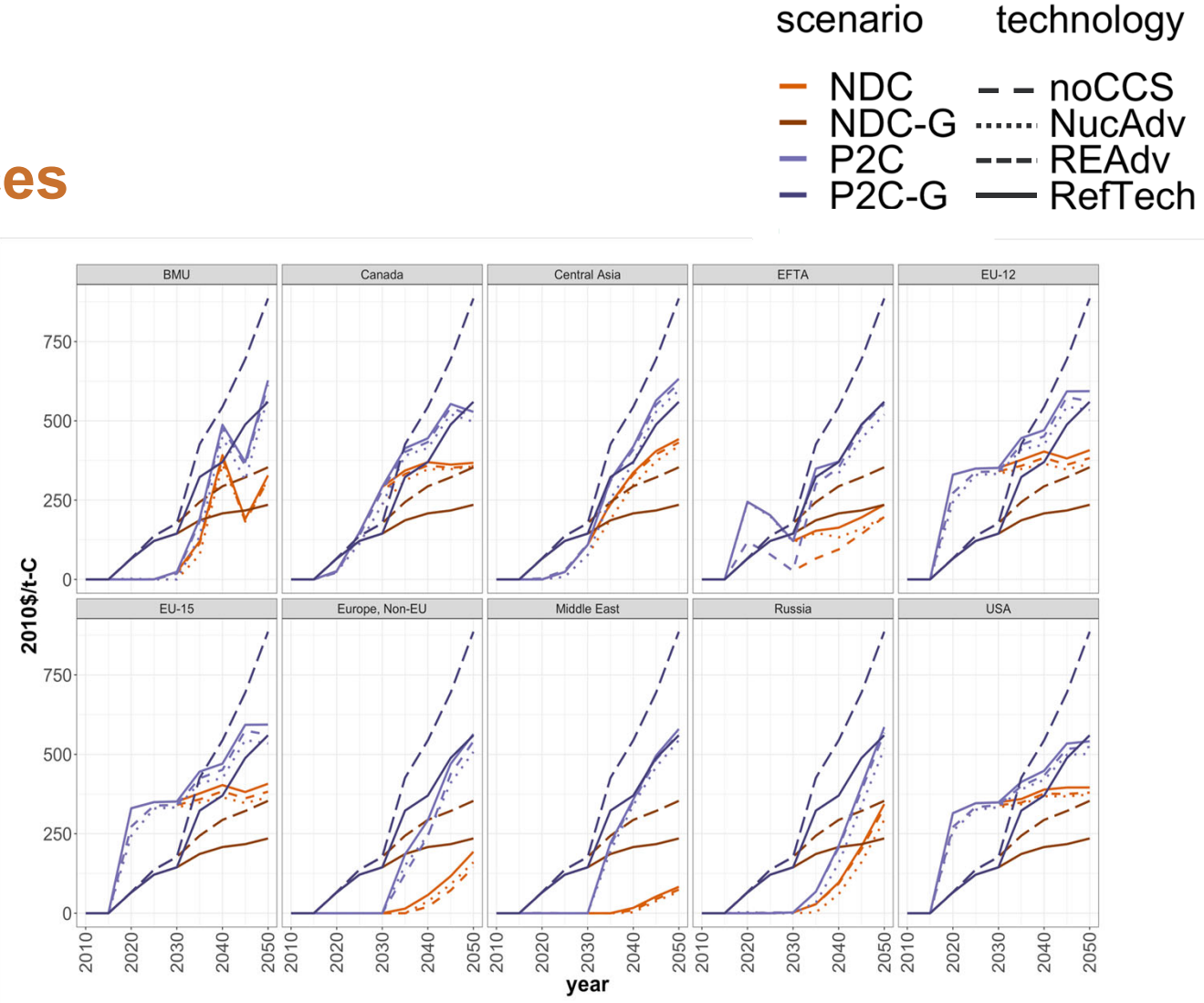
Regional CO_2 emissions

- No emissions constraints (Ref)
  - Emissions increase through 2100 in all regions and scenarios
  - Increases are smaller in NucAdv and REAdv technology scenarios
- Regional emissions constraints (NDC and P2C)
  - Reference emissions are identical to NDC and P2C emissions through 2030 for BMU, Europe Non-EU, Middle East, Russia
  - NDCs are ***non-binding*** constraints for these regions
- Global emissions constraint (NDC-G and P2C-G)
  - Emissions reductions are generally ***lower*** under global constraints for regions with ***binding NDCs***
  - Regions with ***non-binding NDCs*** show increased levels of mitigation with a global carbon constraint



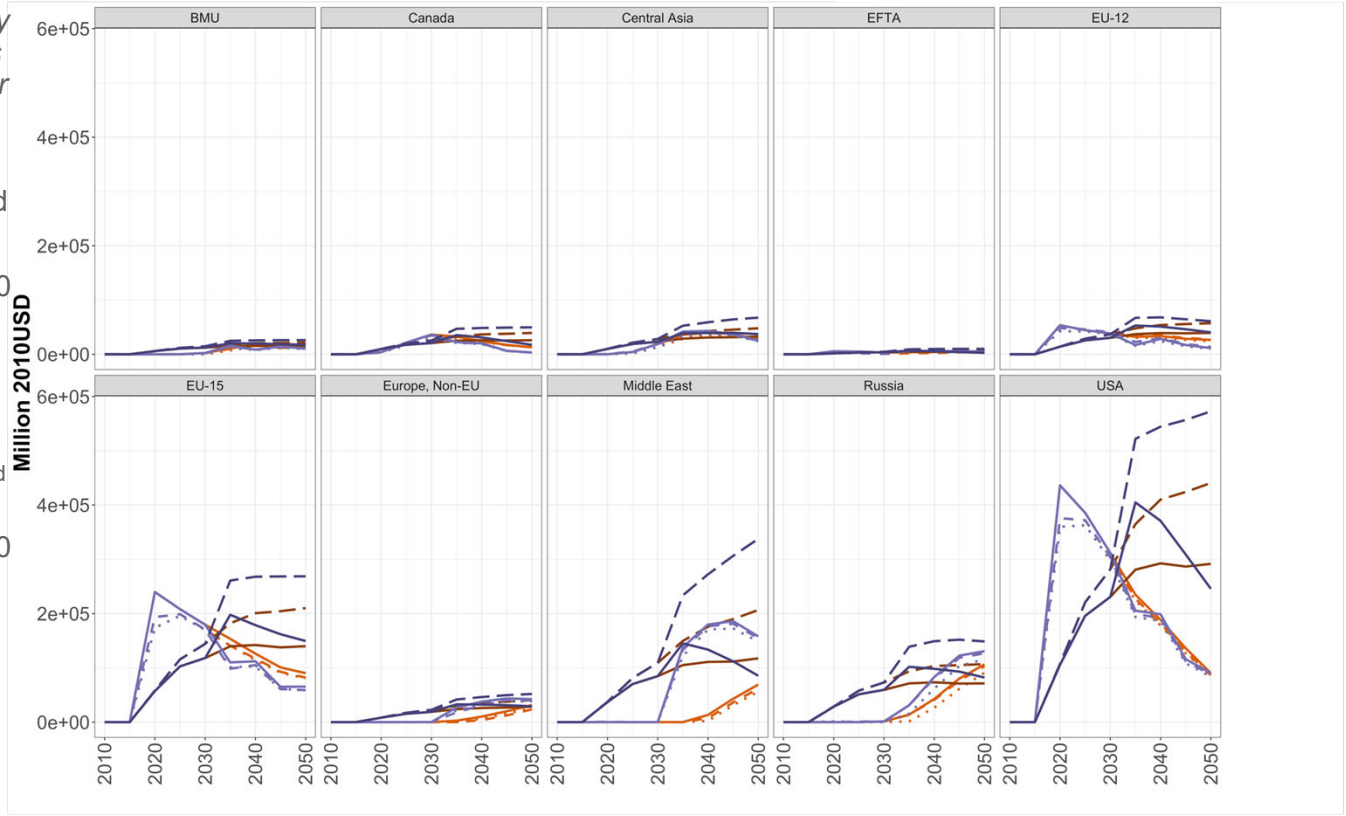
Carbon prices

- Regional carbon markets
  - No carbon prices through 2030 are required to achieve NDC or P2C constraints in four UNECE regions (BMU, Europe Non-EU, Middle East, Russia)
  - Consistent with CO_2 emissions, which do not vary from Reference through 2030 (NDCs are *non-binding* constraints)
- Global carbon markets (NDC-G and P2C-G)
  - Through 2030 global carbon markets generally result in ***lower*** carbon prices for regions with ***binding NDCs***
  - Global market prices are ***higher*** than regional market prices for regions with ***non-binding NDCs***
  - ***2050 carbon prices are ~50% greater in the noCCS scenario compared to the RefTech scenario***



Carbon expenditures

- *Higher carbon prices do not necessarily result in larger carbon expenditures, as carbon emissions **decrease** with higher carbon prices*
- Relative changes in global, compared to regional markets, across regions and policy scenarios
- Total carbon expenditures through 2050 in NDC-G compared to NDC (RefTech)
  - Lower or equal for Canada, Central Asia, EFTA, EU-12, EU-15, USA
  - Roughly 1.5-2 times greater for BMU, and Russia
  - Greater than 2 times for non-EU Europe and Middle East
- Total carbon expenditures through 2050 in P2C-G compared to P2C (RefTech)
  - Lower or equal for EFTA, EU-15, Middle East, USA
  - Less than 1.5 times grater for Canada, Central Asia, EU-12, non-EU Europe, and Russia
  - 2 times larger for BMU



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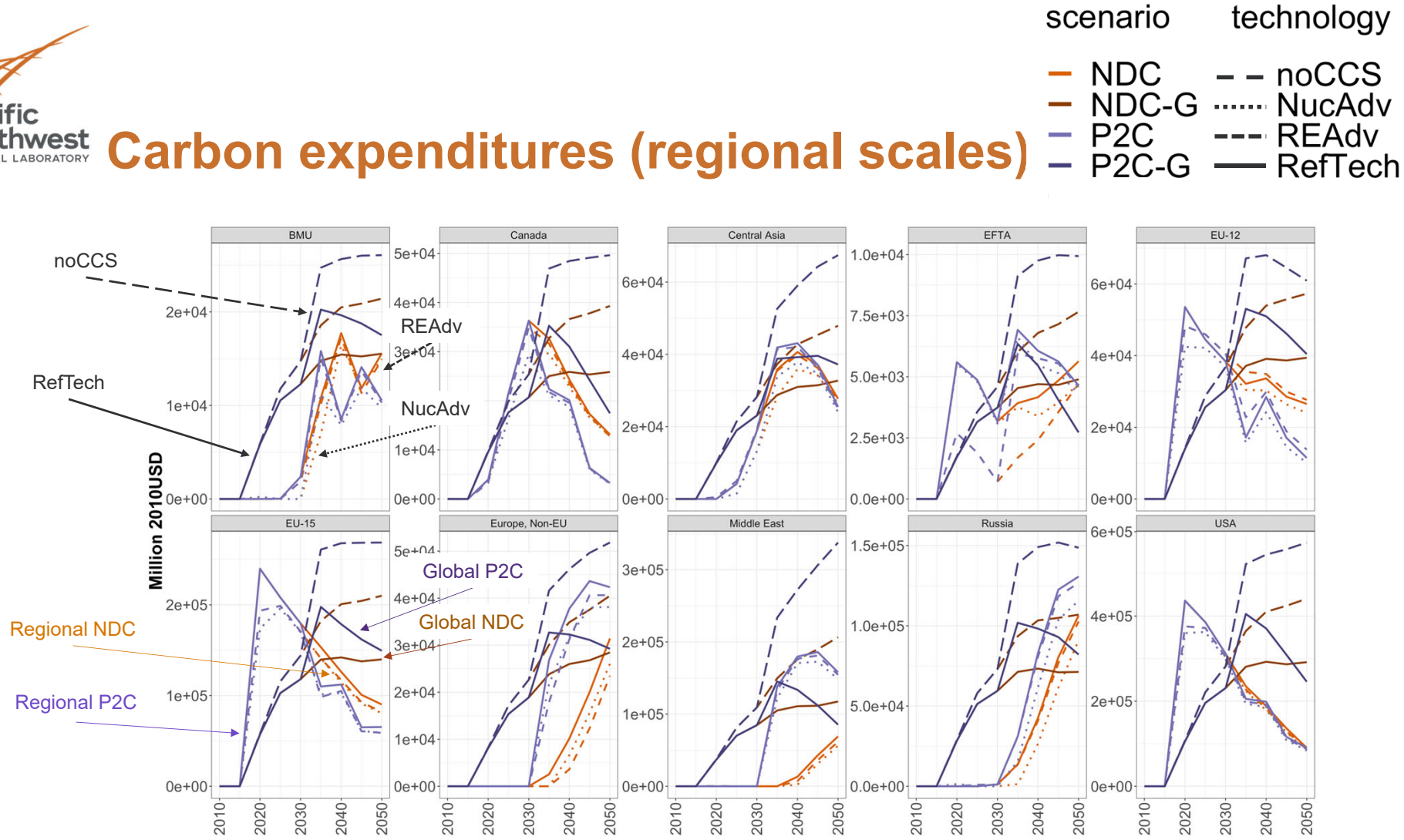
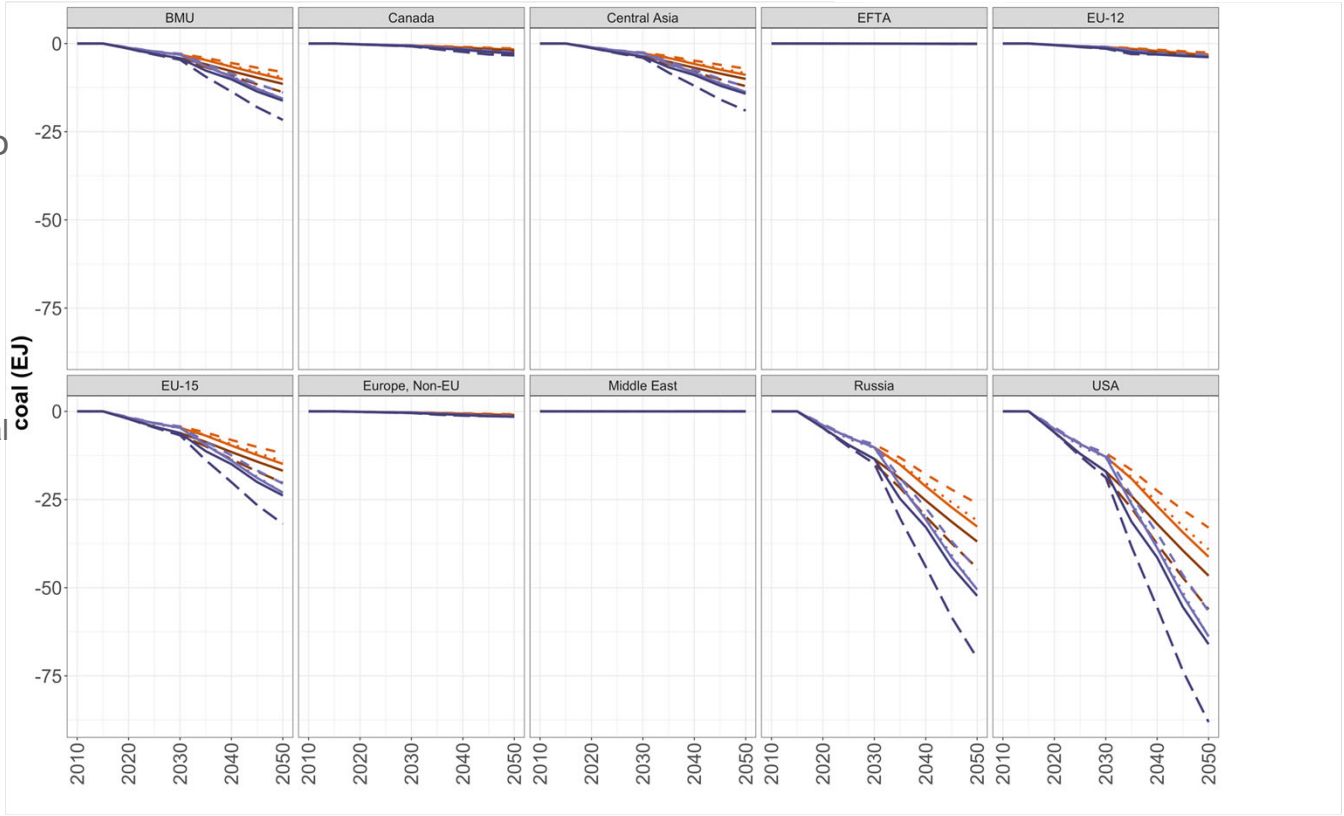
Carbon expenditures (regional scales)



Policy-induced changes in resource production: Coal

- Relative to each technology's own Ref scenario, the largest reductions in coal production are seen under *P2C-G* scenario with *noCCS* technology
  - Highest coal production under Ref with RefTech/noCCS* technologies, large reductions required under RefTech
  - Reductions even larger with noCCS technology, as system must move toward carbon-neutral fuels to achieve policy targets
- Smallest decreases in coal production in *NDC* with *AdvRE* technology, followed by NDC with AdvNuc
  - Less coal is produced in Ref scenario with AdvRE technology, so decrease required to achieve NDC targets is lower



* The RefTech and noCCS scenarios are identical without GHG mitigation policy.

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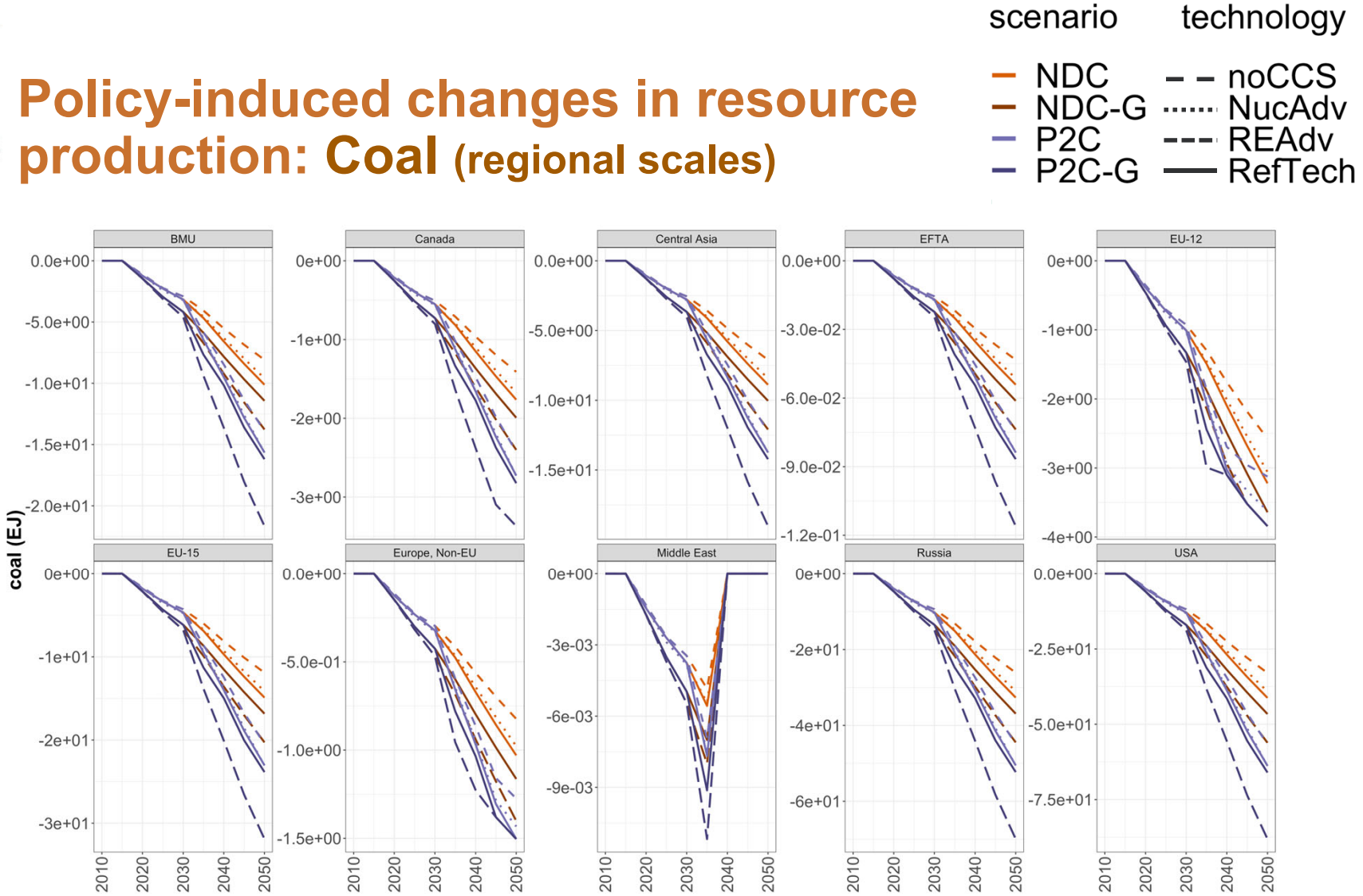
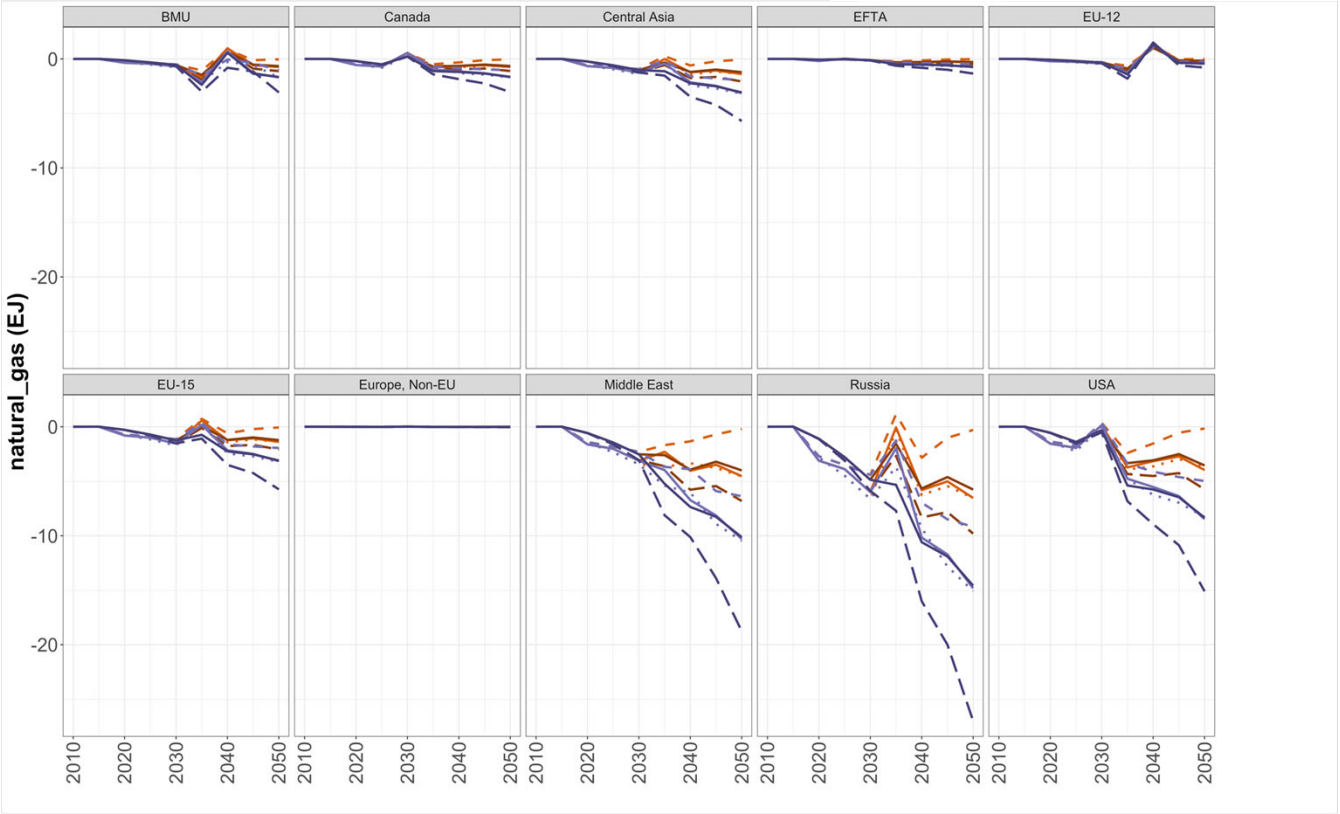
Policy-induced changes in resource production: Coal (regional scales)

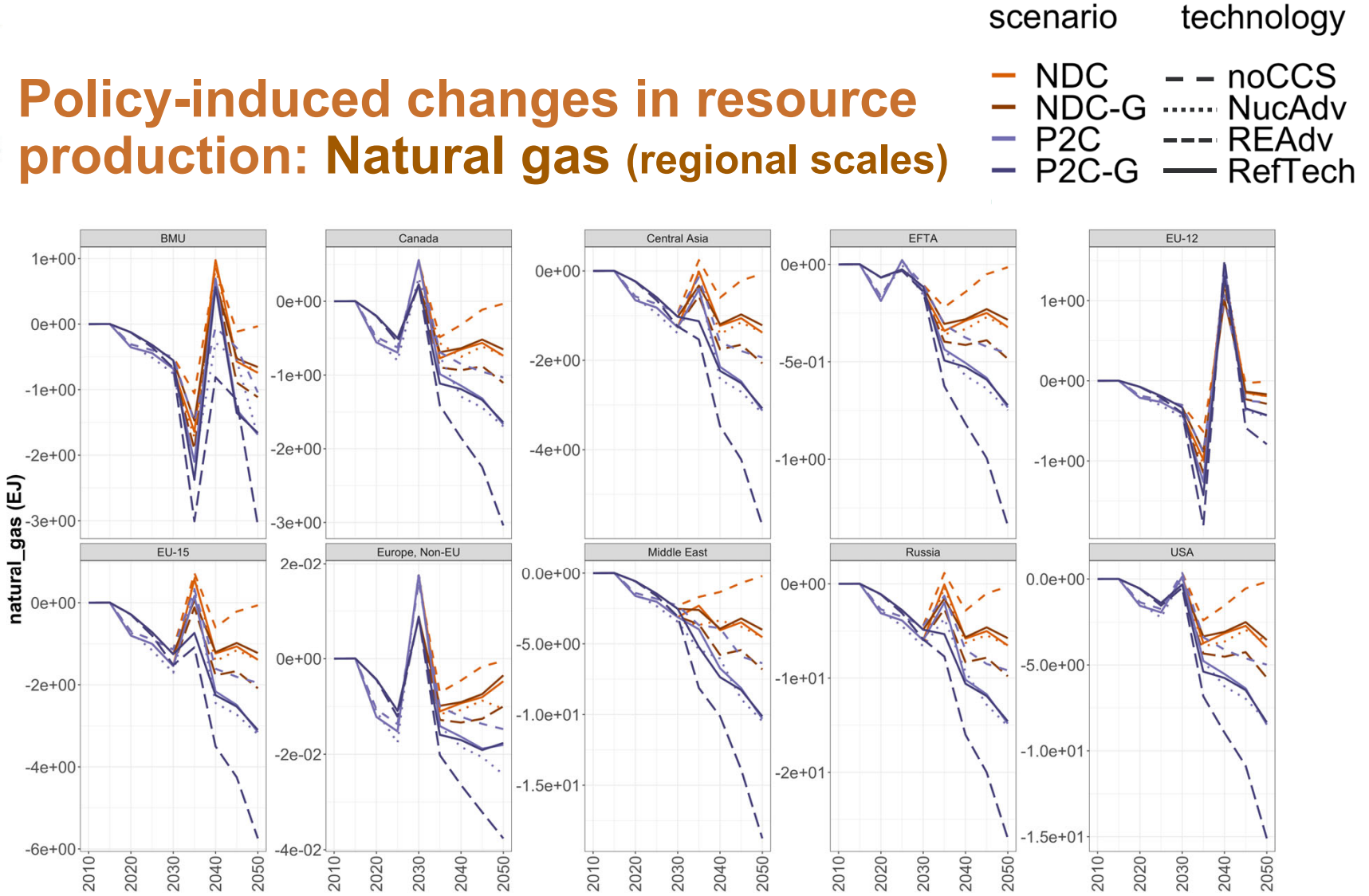


Policy-induced changes in resource production: Natural gas

- As with coal, relative to each technology's own Ref scenario, the *P2C-G* with *noCCS* technology has the largest reductions in natural gas production
  - Russia, Middle East, and USA see the largest reductions
- *NDC* with *AdvRE* shows some initial decrease in natural gas production, followed by a near neutral (zero) change by 2050, relative to AdvRE Ref scenario
  - Natural gas production in the Ref scenarios is lowest with AdvRE technology

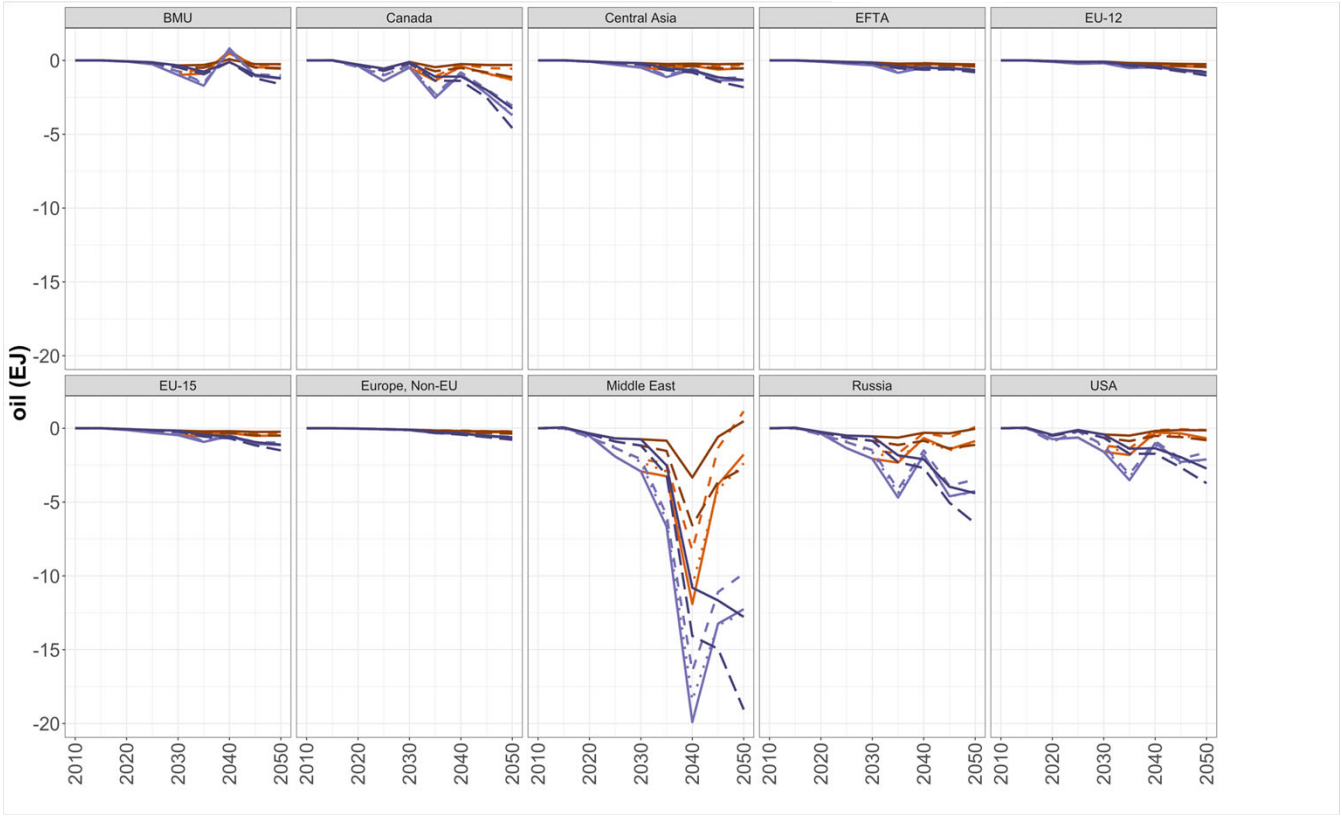


Policy-induced changes in resource production: Natural gas (regional scales)

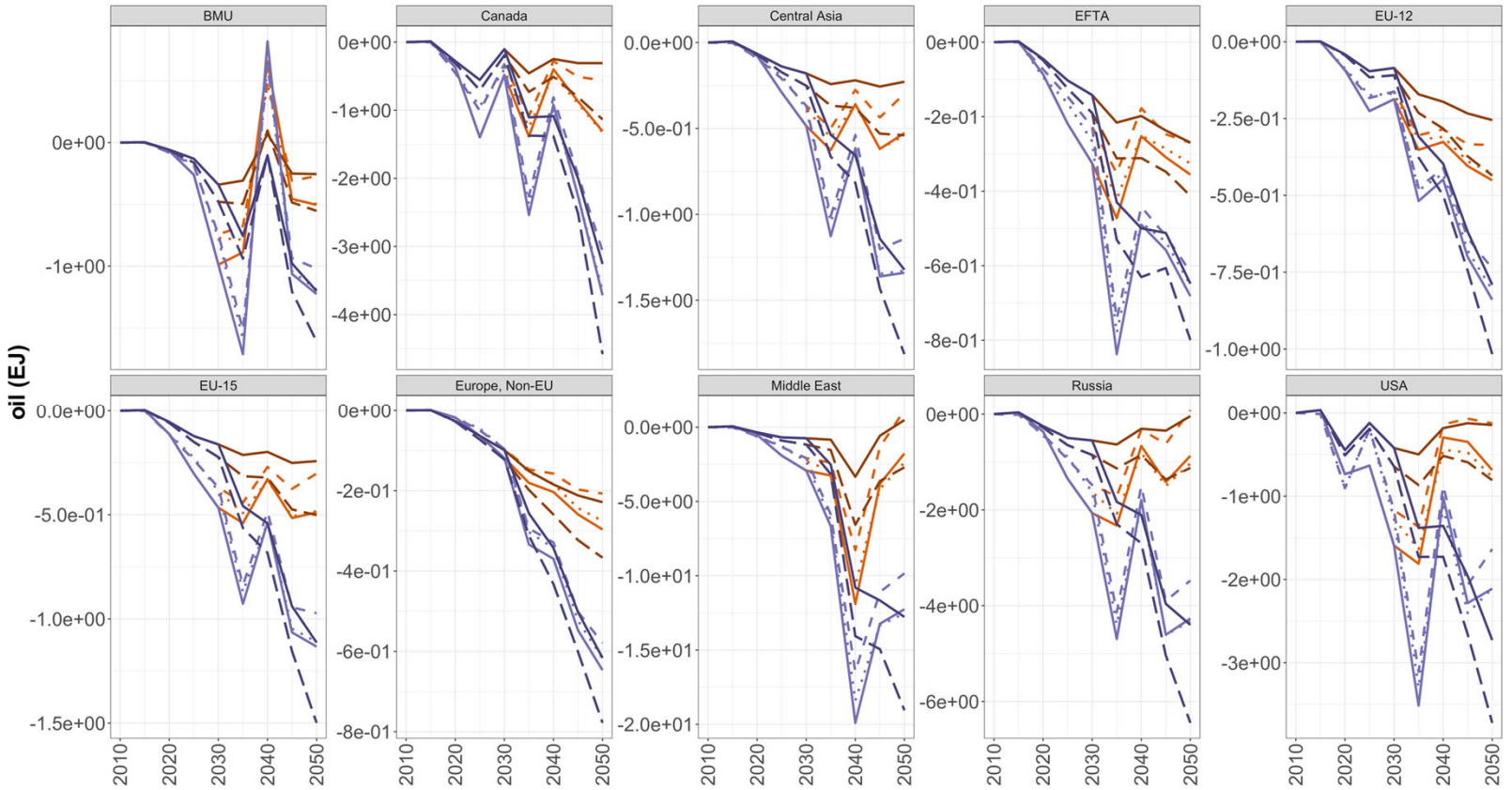


Policy-induced changes in resource production: Oil

- Oil production decreases relative to Ref in most policy scenarios and regions
  - Small decreases through 2030 in most regions
  - In P2C-G with RefTech, production is nearly equal, or slightly higher, than in Ref
- Spikes in production related to non-smooth carbon price paths



Policy-induced changes in resource production: Oil (regional scales)



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Key insights

- Current NDC mitigation commitments are insufficient to achieve a 2ºC target
- Several regions have *non-binding* NDCs: with regional carbon markets these regions'
  - emissions through 2030 do not deviate from reference (no policy) levels
  - carbon prices are zero
- A global carbon market with a single C-tax in all regions redistributes emissions mitigation and relative carbon prices compared to NDC regional markets
  - Carbon prices are lower in a global market for regions with stringent NDCs
  - Regions with non-binding NDCs have higher carbon prices under a global carbon market
- In a world without CCS technology, GCAM results show
  - There are no market-clearing taxes that could achieve *either* the NDC or P2C constraints with *regional* carbon markets
  - A single *global* carbon market that allocated emissions based on least cost is required to achieve either the NDC or P2C targets
  - Compared to the RefTech scenarios, the noCCS *global* carbon market scenarios (NDC-G, P2C-G) result in *large increases in carbon prices and expenditures* and *reductions in fossil production*

Key insights (figures not shown here)

- Advanced renewable technology generally increases share of renewables in total primary energy
  - High share of renewables does not generally result in improved values for Energy Security and Quality of Life metrics, depending on scenario and region, small or negative impact on these metrics
  - Improved Environmental Sustainability metrics, particularly GHG and CO_2 emissions
- Advanced nuclear sensitivity has small effects on most outcome variables
  - Lowers carbon prices and expenditures somewhat more than AdvRE
- Effects from policy constraints (NDC, P2C), carbon market type (regional, global) are larger than across technology sensitivities
  - Largest effects from technology sensitivities are on emissions and electricity consumption metrics
- Despite general trends, the role of policy design and technology sensitivity differs across regions

UNECE	GCAM region	Country
	Africa, Eastern	Burundi
		Comoros
		Djibouti
		Eritrea
		Ethiopia
		Kenya
		Madagascar
		Mauritius
		Reunion
		Rwanda
		Sudan
		Somalia
		Uganda
	Africa, Northern	Algeria
		Egypt
		Western Sahara
		Libyan Arab Jamahiriya
		Morocco
		Tunisia
	Africa, Southern	Angola
		Botswana
		Lesotho
		Mozambique
		Malawi
		Namibia
		Swaziland
		Tanzania, United Republic of
		Zambia
		Zimbabwe
	Africa, Western	Benin
		Burkina Faso
		Central African Republic
		Cote dIvoire
		Cameroon
		Congo, the Democratic Republic of the
		Congo
		Cape Verde
		Gabon
		Ghana
		Guinea
		Gambia
		Guinea-Bissau
		Equatorial Guinea
		Liberia
		Mali
		Mauritania
		Niger
		Nigeria
		Senegal
		Sierra Leone
		Sao Tome and Principe
		Chad
		Togo
	Argentina	Argentina
	Australia & New Zealand	Australia
		New Zealand
	Brazil	Brazil
☐	**Canada**	Canada

UNECE	GCAM region	Country
	Central America and Caribbean	Aruba
		Anguilla
		Netherlands Antilles
		Antigua & Barbuda
		Bahamas
		Belize
		Bermuda
		Barbados
		Costa Rica
		Cuba
		Cayman Islands
		Dominica
		Dominican Republic
		Guadeloupe
		Grenada
		Guatemala
		Honduras
		Haiti
		Jamaica
		Saint Kitts and Nevis
		Saint Lucia
		Montserrat
		Martinique
		Nicaragua
		Panama
		El Salvador
		Trinidad and Tobago
		Saint Vincent and the Grenadines
☐	**Central Asia**	Armenia
		Azerbaijan
		Georgia
		Kazakhstan
		Kyrgyzstan
		Mongolia
		Tajikistan
		Turkmenistan
		Uzbekistan
	China	China
		Hong Kong
		Macau
	Colombia	Colombia
☐	**EFTA**	Switzerland
		Iceland
		Liechtenstein
		Norway
		Svalbard and Jan Mayen Islands
☐	**EU-12**	Bulgaria
		Cyprus
		Czech Republic
		Estonia
		Hungary
		Lithuania
		Latvia
		Malta
		Poland
		Romania
		Slovakia
		Slovenia

UNECE	GCAM region	Country
☐	**EU-15**	Andorra
		Austria
		Belgium
		Channel Islands
		Germany
		Denmark
		Spain
		Finland
		Falkland Islands (Malvinas)
		France
		Faroe Islands
		United Kingdom
		Gibraltar
		Greece
		Greenland
		Isle of Man
		Ireland
		Italy
		Luxembourg
		Monaco
		Netherlands
		Portugal
		Saint Helena
		San Marino
		Saint Pierre and Miquelon
		Sweden
		Turks and Caicos
		Vatican
		Virgin Islands, British
		Wallis and Futuna
☐	**Europe, Eastern (BMU)**	Belarus
		Moldova, Republic of
		Ukraine
☐	**Europe, non-EU**	Albania
		Bosnia and Herzegovina
		Croatia*
		Macedonia, the former Yugoslav Republic of
		Montenegro
		Serbia
		Turkey
		Yugoslavia, Federal Republic of
	India	India
	Indonesia	Indonesia
	Japan	Japan
	Mexico	Mexico
☐	Middle East	United Arab Emirates
		Bahrain
		Iran, Islamic Republic of
		Iraq
		Israel
		Jordan
		Kuwait
		Lebanon
		Oman
		Palestinian Territory, Occupied
		Qatar
		Saudi Arabia
		Syrian Arab Republic
		Yemen
	Pakistan	Pakistan

* Croatia joined the EU after the GCAM model base year (2010).

UNECE	GCAM region	Country
☐	**Russia**	Russian Federation
	South Africa	South Africa
	South America, Northern	French Guiana
		Guyana
		Suriname
		Venezuela
	South America, Southern	Bolivia
		Chile
		Ecuador
		Peru
		Paraguay
		Uruguay
	South Asia	Afghanistan
		Bangladesh
		Bhutan
		Sri Lanka
		Maldives
		Nepal
	South Korea	Korea, Republic of
	Southeast Asia	American Samoa
		Brunei Darussalam
		Cocos (Keeling) Islands
		Cook Islands
		Christmas Island
		Fiji
		Micronesia, Federated States of
		Guam
		Cambodia
		Kiribati
		Lao Peoples Democratic Republic
		Marshall Islands
		Myanmar
		Northern Mariana Islands
		Malaysia
		Mayotte
		New Caledonia
		Norfolk Island
		Niue
		Nauru
		Pacific Islands Trust Territory
		Pitcairn Islands
		Philippines
		Palau
		Papua New Guinea
		Korea, Democratic Peoples Republic of
		French Polynesia
		Singapore
		Solomon Islands
		Seychelles
		Thailand
		Tokelau
		Timor Leste
		Tonga
		Tuvalu
		Viet Nam
		Vanuatu
		Samoa
	Taiwan	Taiwan
☐	**USA**	Puerto Rico
		United States of America
		Virgin Islands, U.S.

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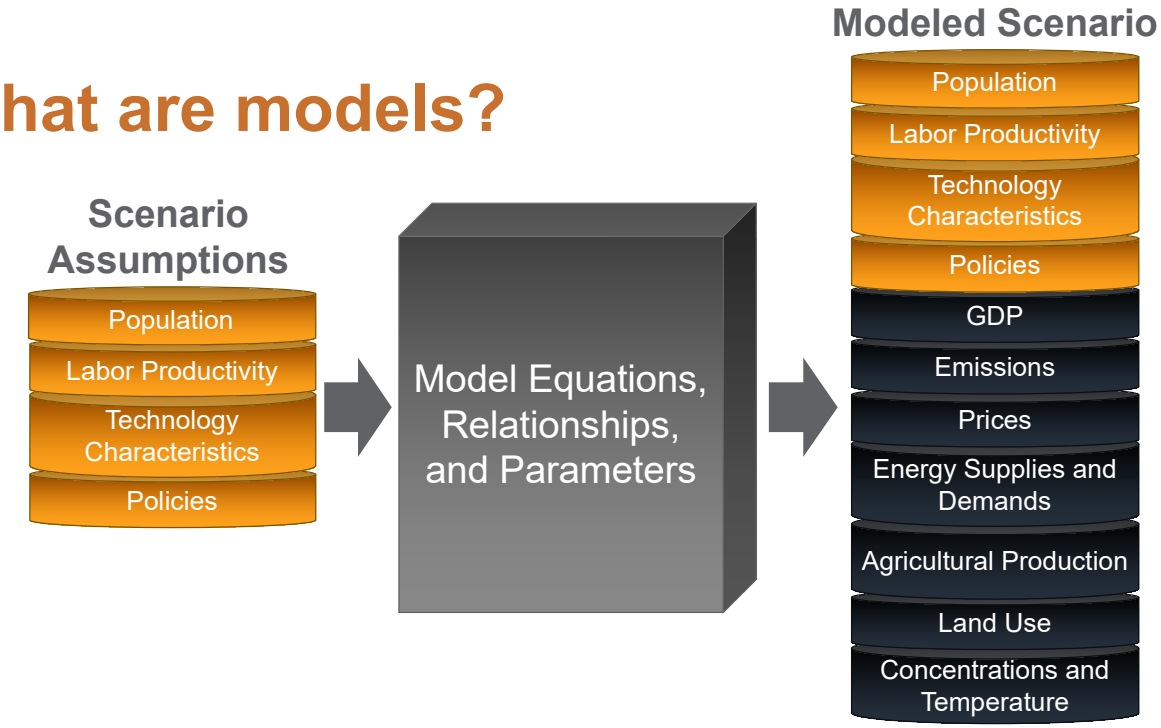
Model Background

Research: What are models?

- Models are mathematical representations of real world relationships, calibrated with historical data
- Assumptions required to parameterize models
  - Future rates of technological development
  - Socioeconomics
  - Policy changes
- The model solves the mathematical relationships, given the input assumptions
- Scenarios explore different assumptions about inputs
- Policies can be defined through changes to model assumptions ***or*** specific policy goals



Using models

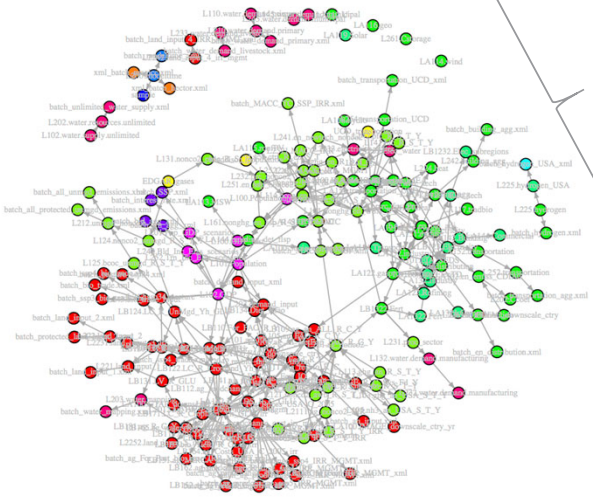
Models **can** inform policy makers on the implications of proposed domestic or international policies

Models **cannot** determine the "best" technology or policy options

Overview of the Global Change Assessment Model (GCAM)

Flexible Time Scale:
GCAM Core runs at 5 years; capability to run at one year

GCAM data calibration



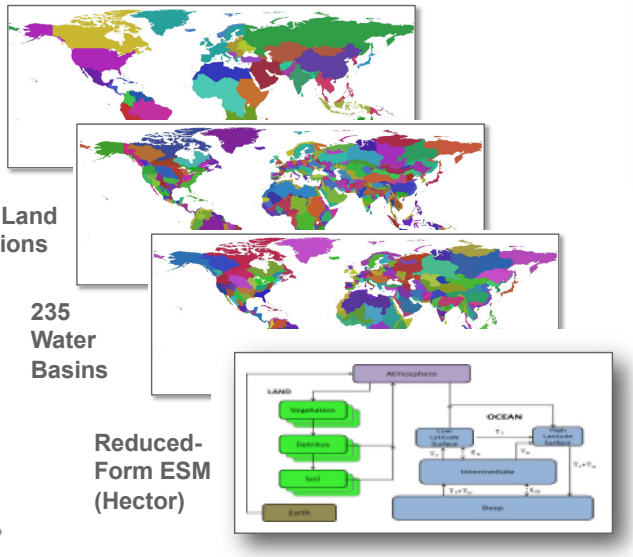
Global Coverage

32 Energy & Economy Regions

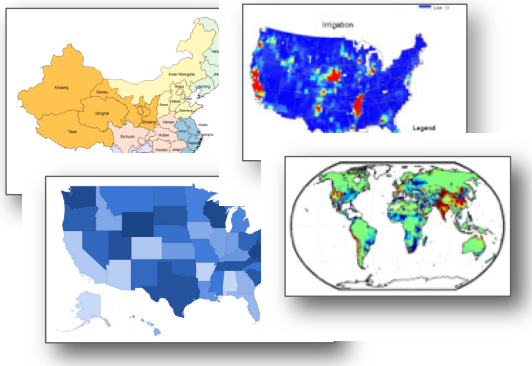
384 Land Regions

235 Water Basins

Reduced-Form ESM (Hector)



Flexible Scale



Market Equilibrium Solution

Data sources include:

- Agriculture and Land Use
  - FAO
  - USDA
  - GTAP
  - SAGE
- Energy
  - US EIA
  - IEA
  - OECD
  - Rogner
- Socioeconomics
  - UN
  - SSP
  - Maddisson
- Emissions
  - CDIAC
  - EDGAR
  - GAINS
  - US EPA

Community Model http://jgcri.github.io/gcam-doc/toc.html

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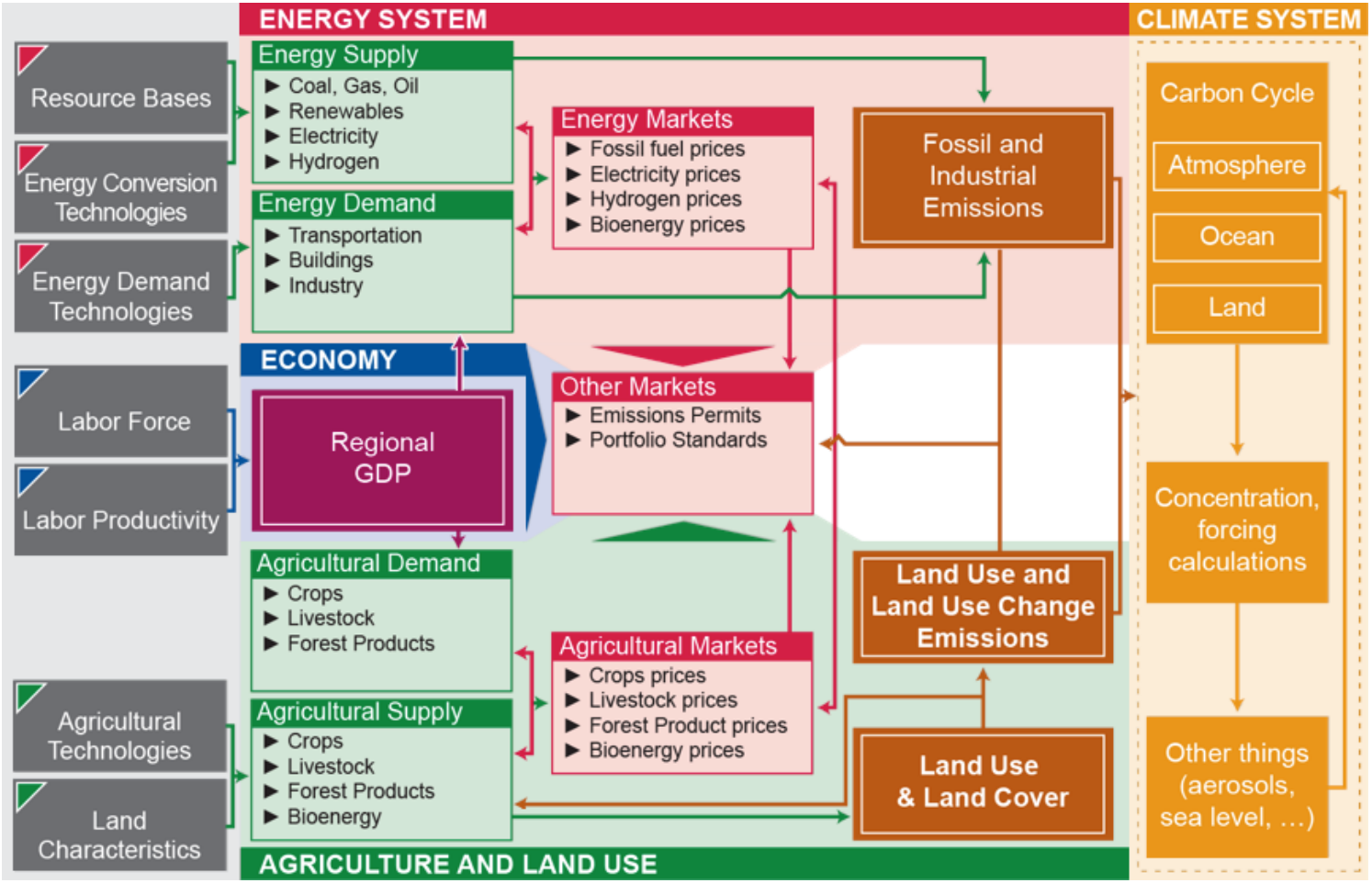
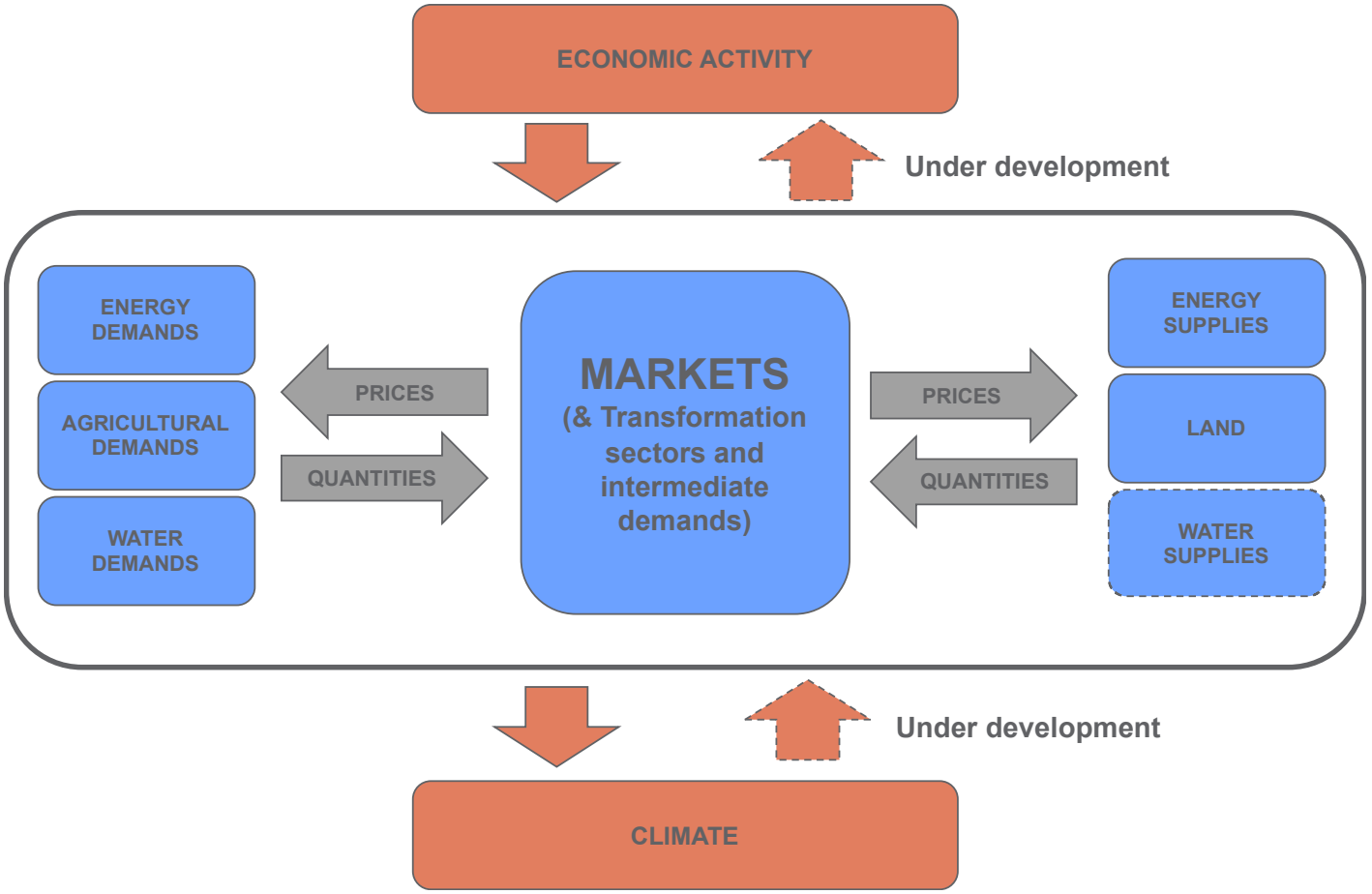
Basic GCAM structure (excludes water)

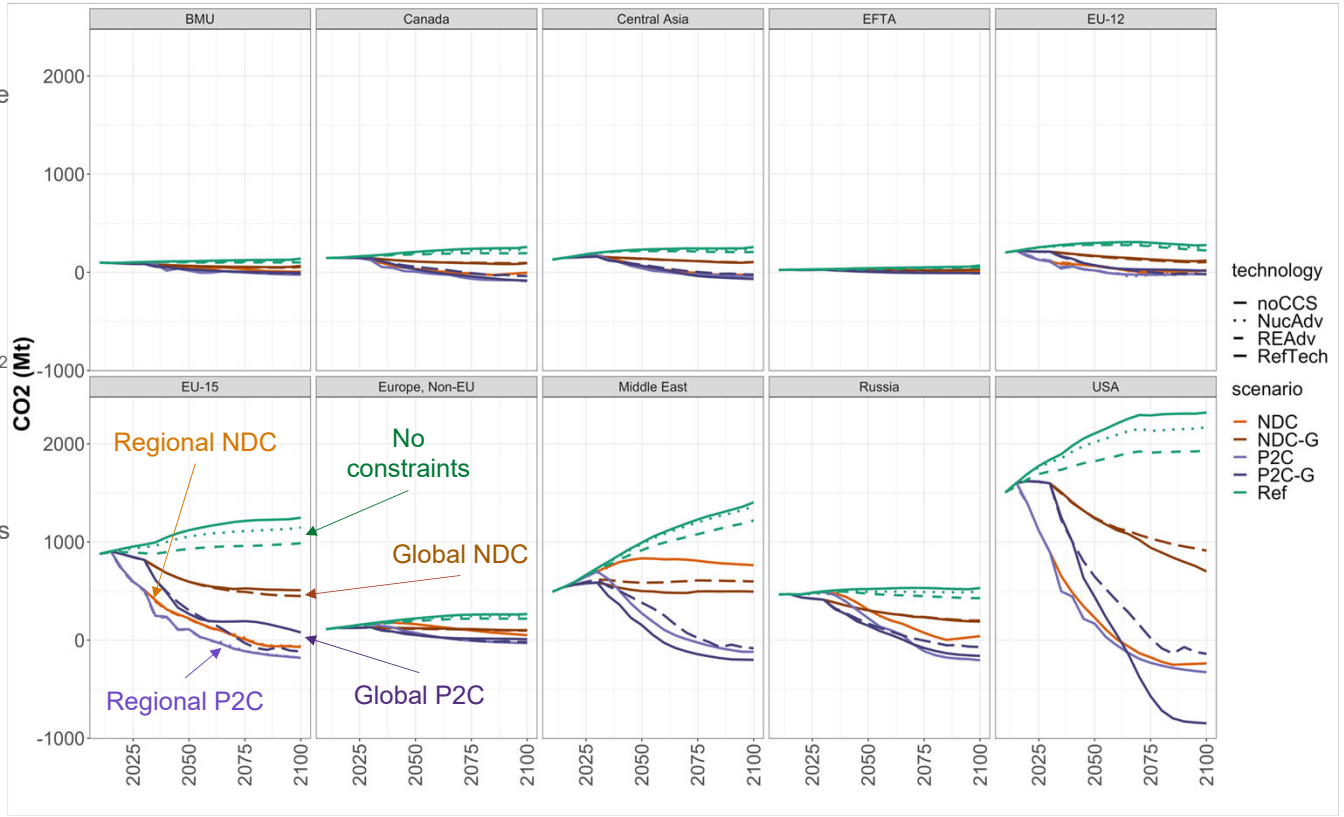


GCAM solves for market equilibrium in each model period (100s of markets)



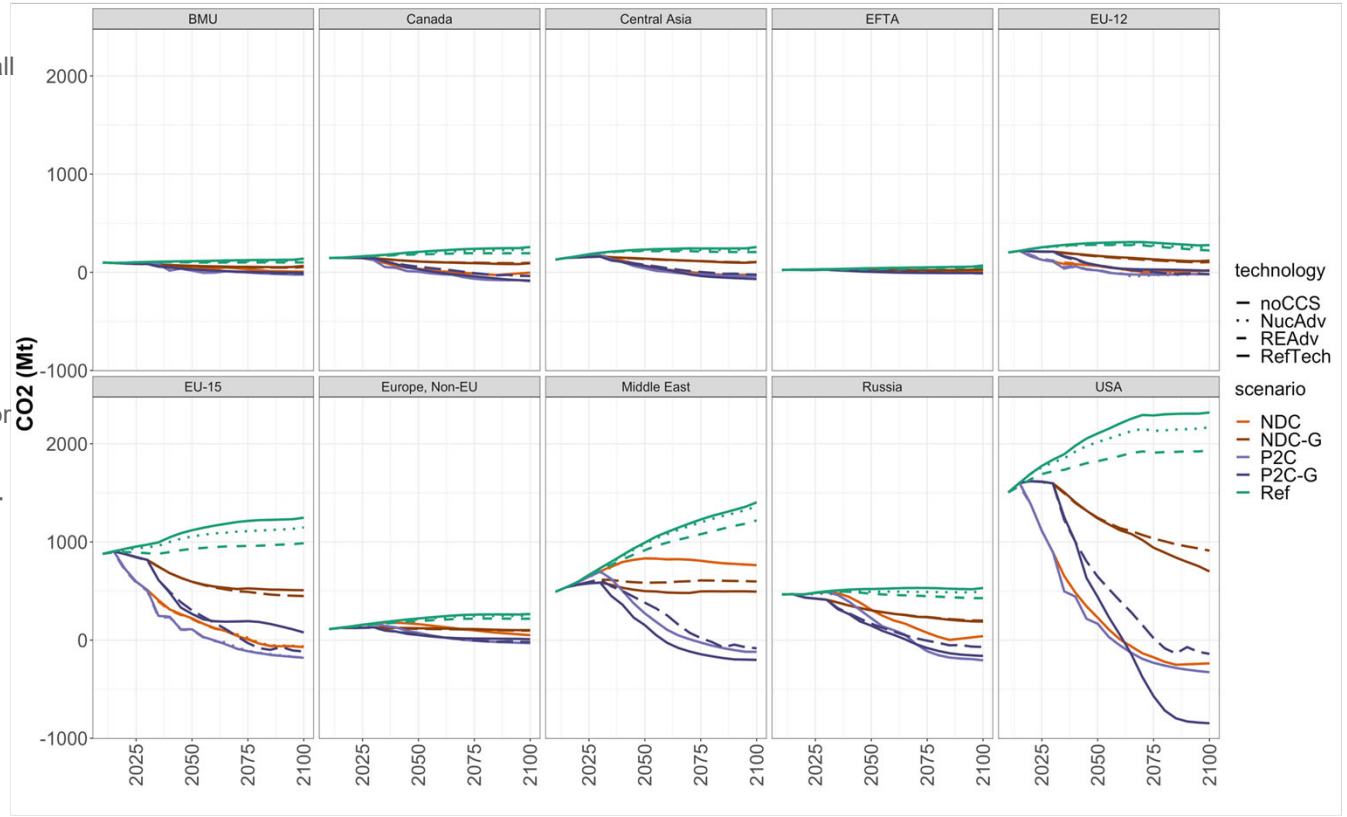
Regional CO_2 emissions

- Reference scenarios do not have any constraints on CO_2 emissions
  - Differences in reference emissions are a result of emissions intensities of technologies, prices, and resulting demand
- *Regional* constraints
  - NDC scenarios constrain CO_2 emissions for each region based on commitments through 2030 and continued ambition through 2100; CO_2 emissions will be identical across all technologies for all NDC scenarios
  - P2C scenarios further reduce emissions from 2030-2100 to achieve 2ºC; CO_2 emissions will be identical across technologies for P2C scenarios
- *Global* constraints
  - Global emissions are constrained based on the sum of all the regional constraints (either NDC or P2C)
  - Regional mitigation depends on the relative cost of mitigation (least cost)
  - Emissions will vary within a region compared to the regional constraints and across technologies



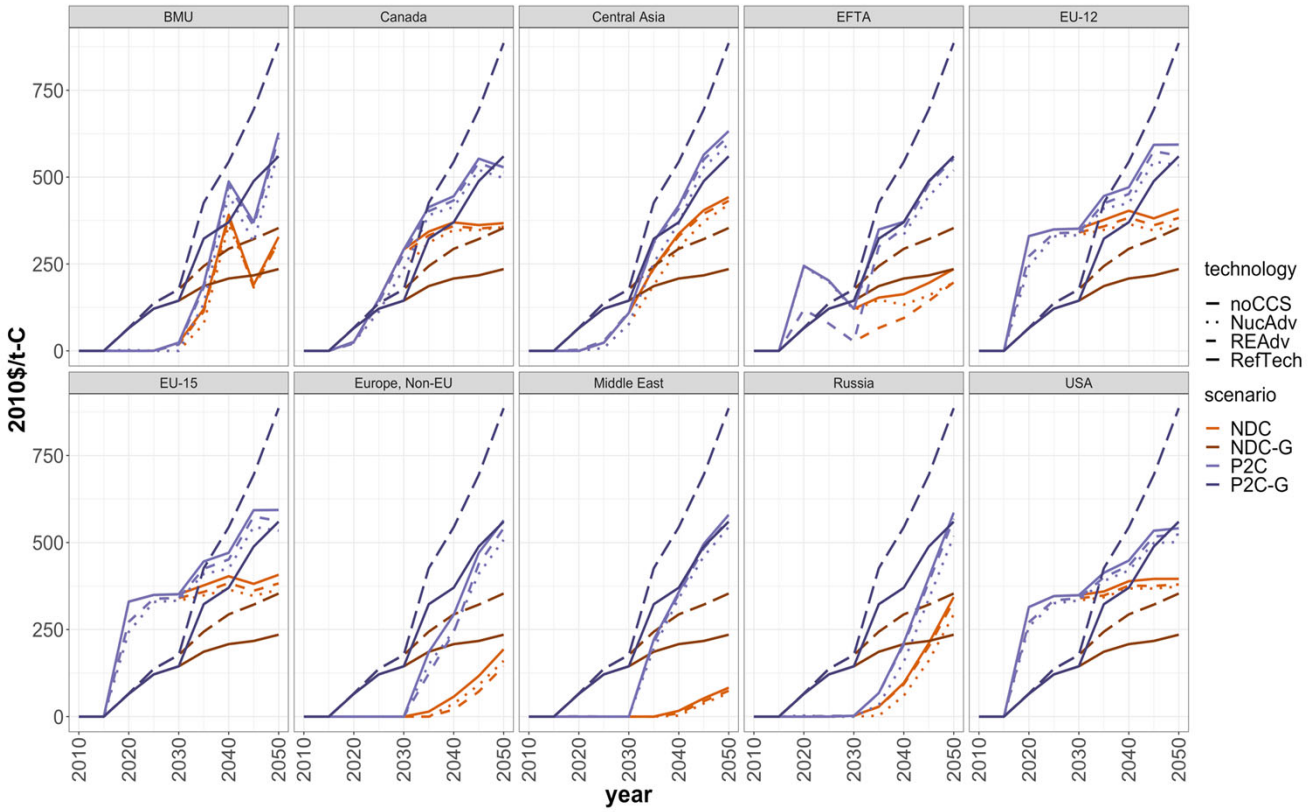
Regional CO_2 emissions

- No emissions constraints (Ref)
  - Emissions increase through 2100 in all regions and scenarios
  - Increases are smaller in NucAdv and REAdv technology scenarios
- Regional emissions constraints (NDC and P2C)
  - Reference emissions are identical to NDC and P2C emissions through 2030 for BMU, Europe Non-EU, Middle East, Russia
  - NDCs are ***non-binding*** constraints for these regions
- Global emissions constraint (NDC-G and P2C-G)
  - Emissions reductions are generally ***lower*** under global constraints for regions with ***binding NDCs***
  - Regions with ***non-binding NDCs*** show increased levels of mitigation with a global carbon constraint



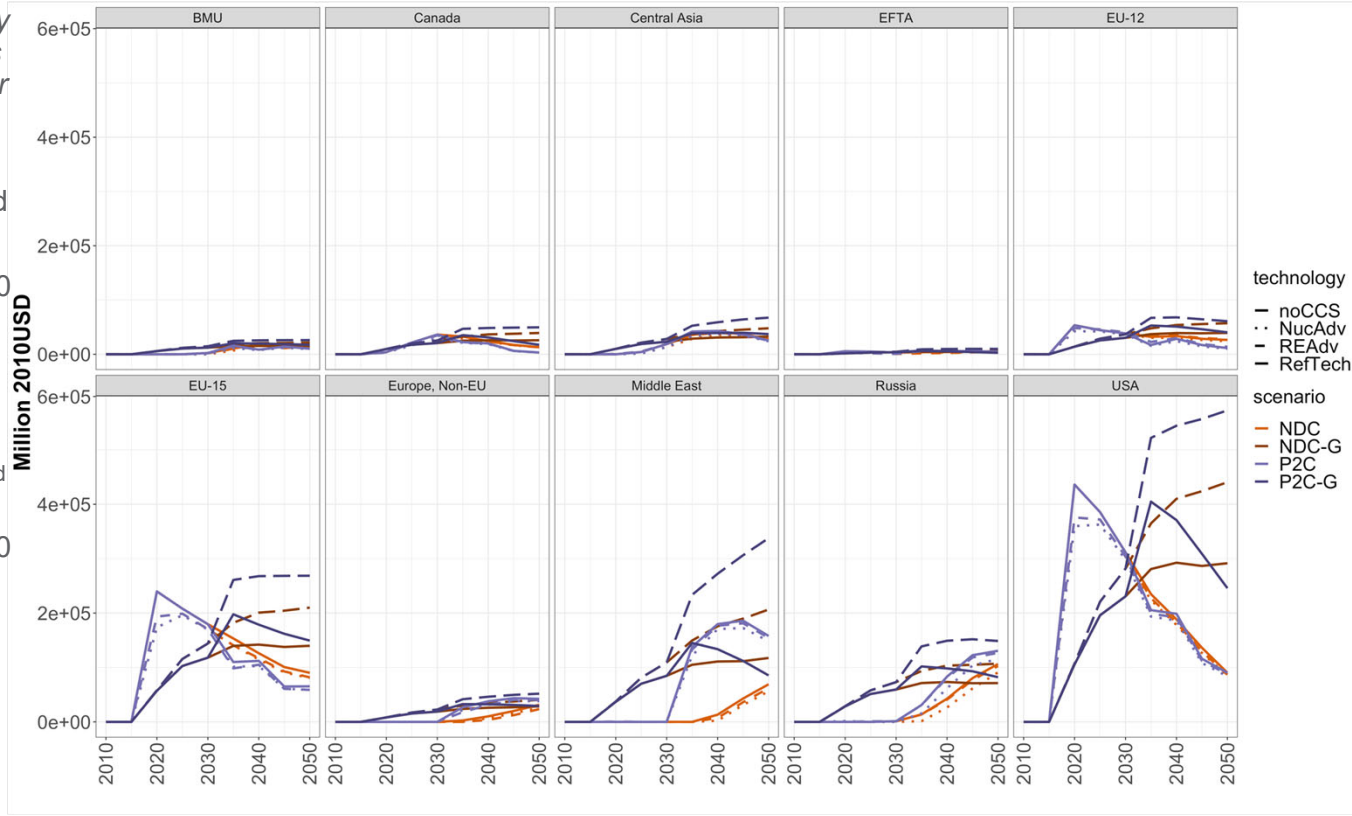
Carbon prices

- Regional carbon markets
  - No carbon prices through 2030 are required to achieve NDC or P2C constraints in four UNECE regions (BMU, Europe Non-EU, Middle East, Russia)
  - Consistent with CO_2 emissions, which do not vary from Reference through 2030 (NDCs are *non-binding* constraints)
- Global carbon markets (NDC-G and P2C-G)
  - Through 2030 global carbon markets generally result in ***lower*** carbon prices for regions with ***binding NDCs***
  - Global market prices are ***higher*** than regional market prices for regions with ***non-binding NDCs***
  - ***2050 carbon prices are ~50% greater in the noCCS scenario compared to the RefTech scenario***



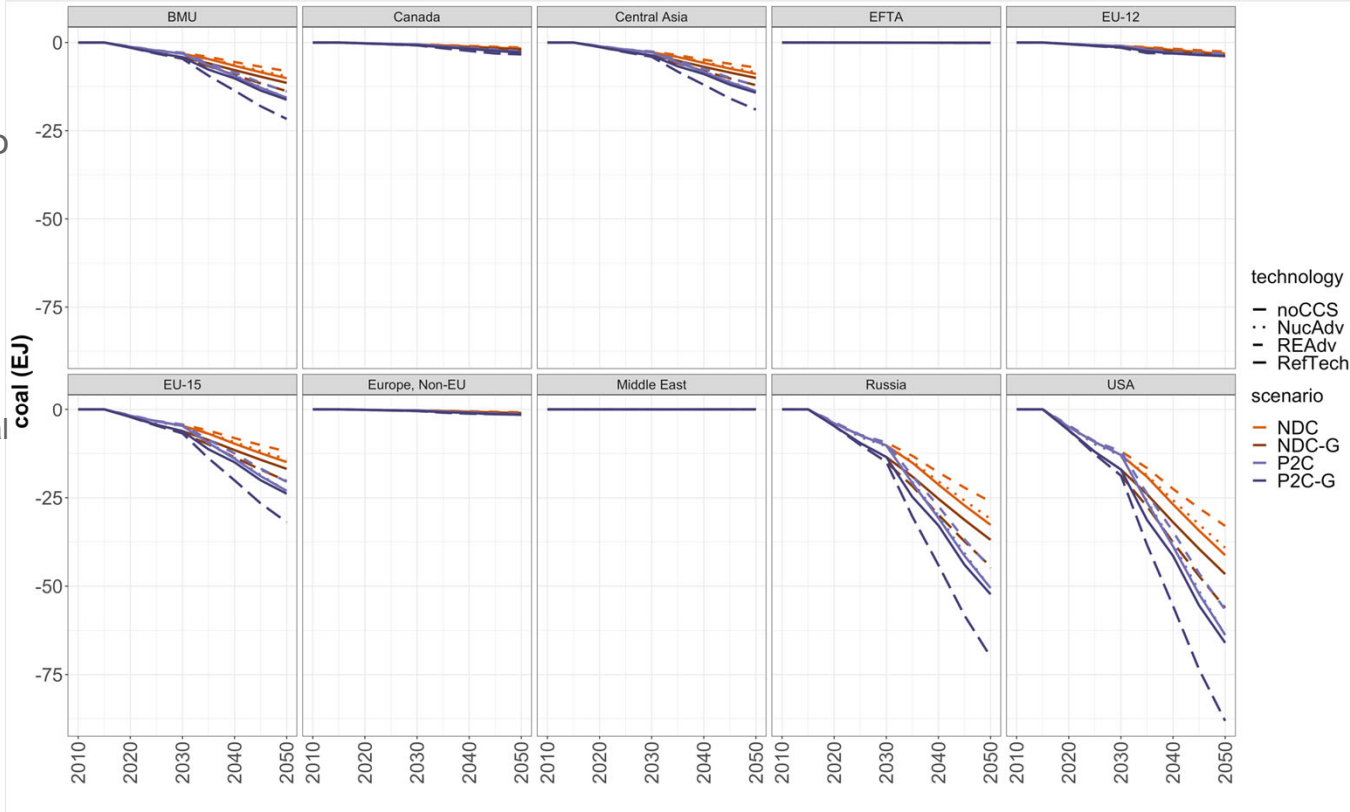
Carbon expenditures

- *Higher carbon prices do not necessarily result in larger carbon expenditures, as carbon emissions **decrease** with higher carbon prices*
- Relative changes in global, compared to regional markets, across regions and policy scenarios
- Total carbon expenditures through 2050 in NDC-G compared to NDC (RefTech)
  - Lower or equal for Canada, Central Asia, EFTA, EU-12, EU-15, USA
  - Roughly 1.5-2 times greater for BMU, and Russia
  - Greater than 2 times for non-EU Europe and Middle East
- Total carbon expenditures through 2050 in P2C-G compared to P2C (RefTech)
  - Lower or equal for EFTA, EU-15, Middle East, USA
  - Less than 1.5 times grater for Canada, Central Asia, EU-12, non-EU Europe, and Russia
  - 2 times larger for BMU



Policy-induced changes in resource production: Coal

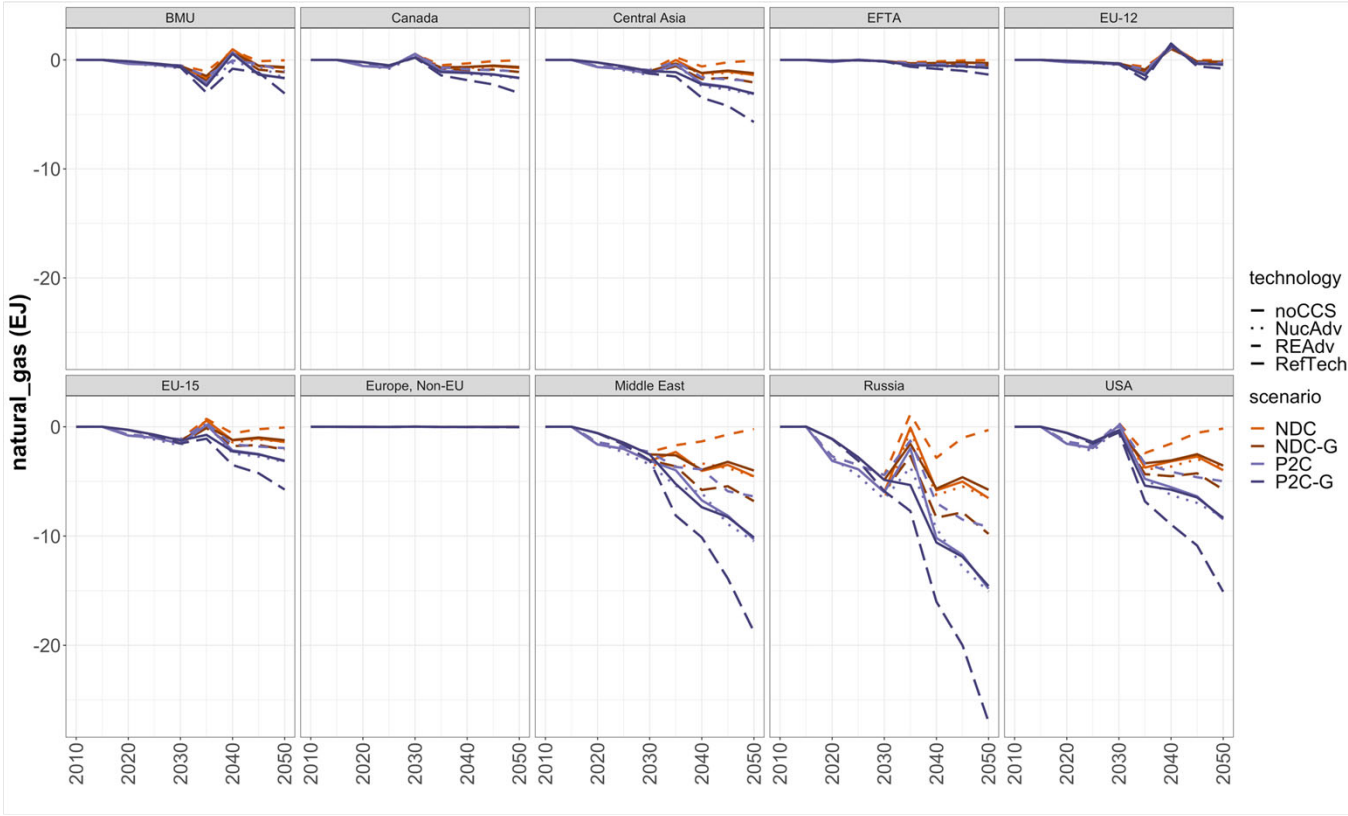
- Relative to each technology's own Ref scenario, the largest reductions in coal production are seen under *P2C-G* scenario with *noCCS* technology
  - Highest coal production under Ref with RefTech/noCCS* technologies, large reductions required under RefTech
  - Reductions even larger with noCCS technology, as system must move toward carbon-neutral fuels to achieve policy targets
- Smallest decreases in coal production in *NDC* with *AdvRE* technology, followed by NDC with AdvNuc
  - Less coal is produced in Ref scenario with AdvRE technology, so decrease required to achieve NDC targets is lower



* The RefTech and noCCS scenarios are identical without GHG mitigation policy.

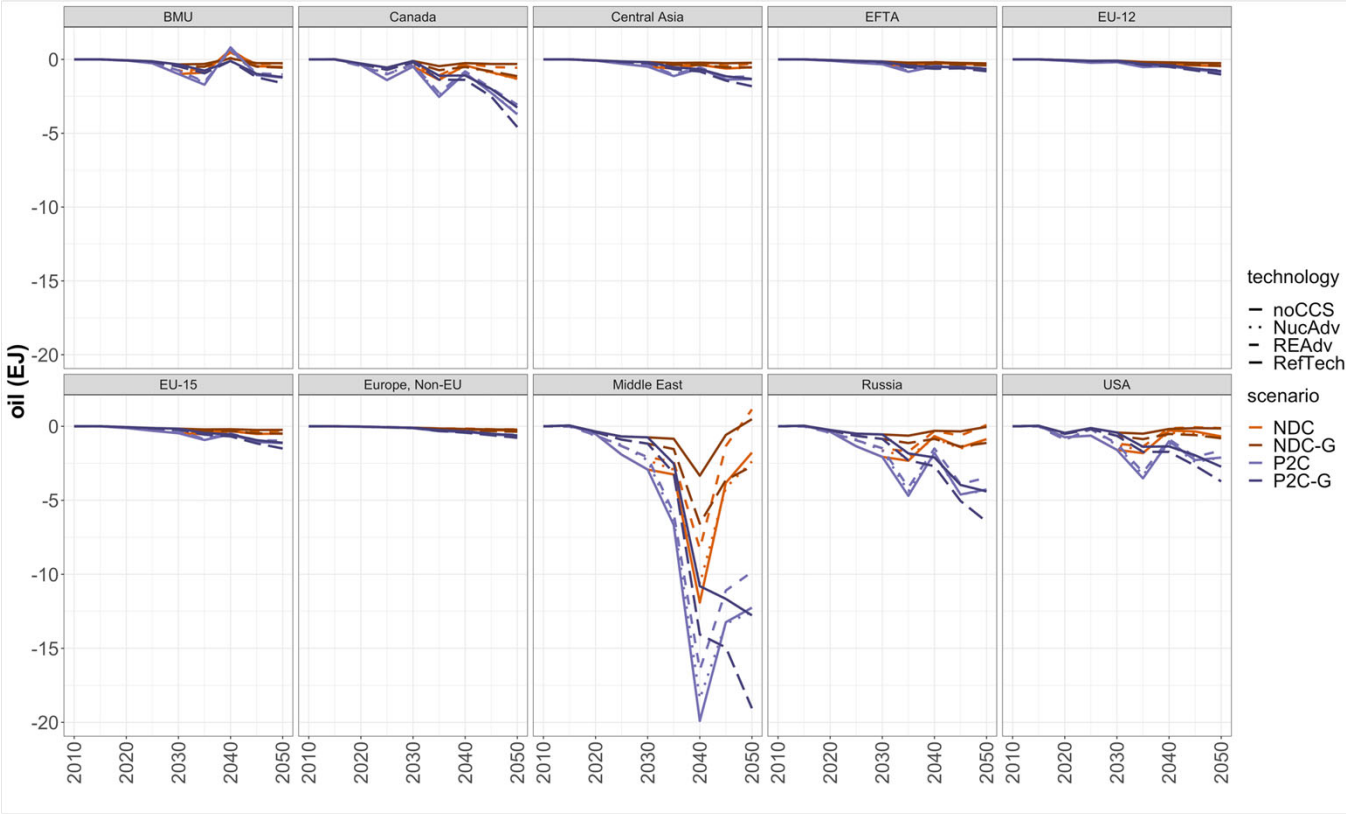
Policy-induced changes in resource production: Natural gas

- As with coal, relative to each technology's own Ref scenario, the *P2C-G* with *noCCS* technology has the largest reductions in natural gas production
  - Russia, Middle East, and USA see the largest reductions
- *NDC* with *AdvRE* shows some initial decrease in natural gas production, followed by a near neutral (zero) change by 2050, relative to AdvRE Ref scenario
  - Natural gas production in the Ref scenarios is lowest with AdvRE technology



Policy-induced changes in resource production: Oil

- Oil production decreases relative to Ref in most policy scenarios and regions
  - Small decreases through 2030 in most regions
  - In P2C-G with RefTech, production is nearly equal, or slightly higher, than in Ref
- Spikes in production related to non-smooth carbon price paths



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Carbon expenditures (regional scales)