CONICYT
Ministerio de Educación
Gobierno de Chile
FONDECYT
Fondo Nacional de Desarrollo Científico y Tecnológico

PONTIFICIA UNIVERSIDAD CATÓLICA DE VALPARAÍSO

A Two stage cap-and-trade model with allowance re-trading for electric capacity investment: The case of the Chilean electric sector.

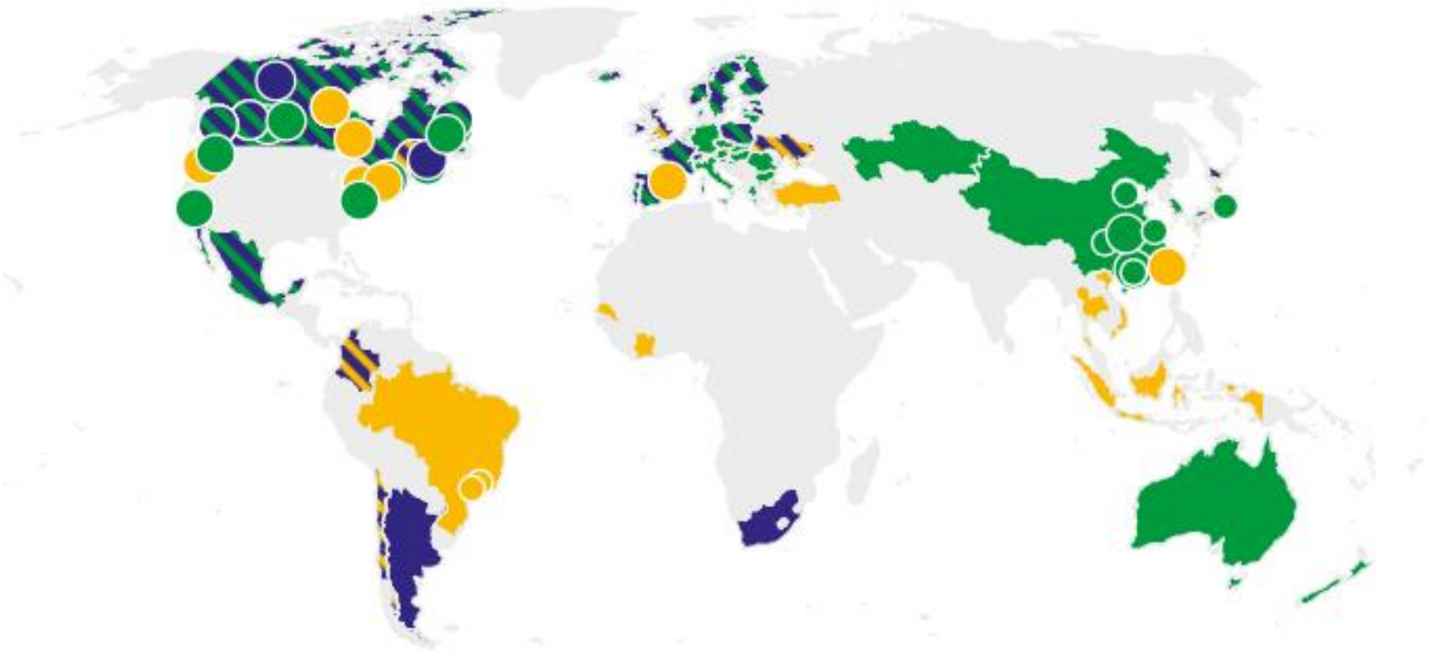
pucv.cl

Pía Amigo (UAI) y Sebastián Cea (PUCV).

Felipe Feijoo, Ph.D.
Assistant Professor
School of Industrial Engineering
PUCV

Introduction

Summary map of regional, national and subnational carbon pricing initiatives



- ETS implemented or scheduled for implementation
- ETS and carbon tax implemented or scheduled
- Carbon tax implemented or scheduled for implementation
- ETS implemented or scheduled, ETS or carbon tax under con...
- ETS or carbon tax under consideration
- Carbon tax implemented or scheduled, ETS under considera...

Case study: Chilean electricity sector and its Commitments

CHILE	Summary of pledges and targets	
PARIS AGREEMENT	Ratified	Yes
	2030 unconditional target(s)	30% below 2007 GHG intensity of GDP by 2030 [151% above 1990 emissions excl. LULUCF by 2030] [42% above 2010 emissions excl. LULUCF by 2030]
	2030 conditional target(s)	35–45% below 2007 intensity of GDP by 2030 [97–133% above 1990 emissions excl. LULUCF by 2030]
	Condition(s)	Financial support
	Coverage	Economy-wide, excl. LULUCF
	LULUCF	Separate target from rest of emissions: management and recovery of 100,000 hectares and reforestation of 100,000 hectares of forest by 2030
COPENHAGEN ACCORD	2020 target(s)	20% below BAU by 2020 [127% above 1990 GHG emissions excl. LULUCF] [29% above 2010 GHG emissions excl. LULUCF]
	Condition(s)	None
LONG-TERM GOAL(S)	Long-term goal(s)	Carbon-neutral by 2050

Climate Action Tracker

It is unclear how these pledges will be achieved

Introduction

- Several LAC studies have been presented in the past (and recent years), for instance
  - Stranded Asset Implications of the Paris Agreement in Latin America and the Caribbean (2019, environmental research letters)
    - We find that meeting the Paris goals results in stranding of $37-90 billion and investment of $1.9-2.6 trillion worth of power sector capital (2021-2050) across a range of future scenarios.
  - Energy technology roll-out for climate change mitigation: A multi-model study for Latin America (energy Economics, 2016)
    - They investigate opportunities for energy technology deployment under climate change mitigation efforts in Latin America. Cross-model comparison study
    - hydropower can be significantly expanded to meet our climate policies, typically by about 50%.

Case study: Chilean electricity sector and its Commitments

CHILE	Summary of pledges and targets	Climate Action Tracker
PARIS AGREEMENT	Ratified	Yes
	2030 unconditional target(s)	30% below 2007 GHG intensity of GDP by 2030 [151% above 1990 emissions excl. LULUCF by 2030]
	Condition(s)	None
LONG-TERM GOAL(S)	Long-term goal(s)	Carbon-neutral by 2050

Chile's NDC emission reduction targets for 2030 is rate as "Highly Insufficient"

Under currently implemented policies, Chile will not meet its NDC targets

It is unclear how these pledges will be achieved

Case study: Chilean electricity sector and its Commitments

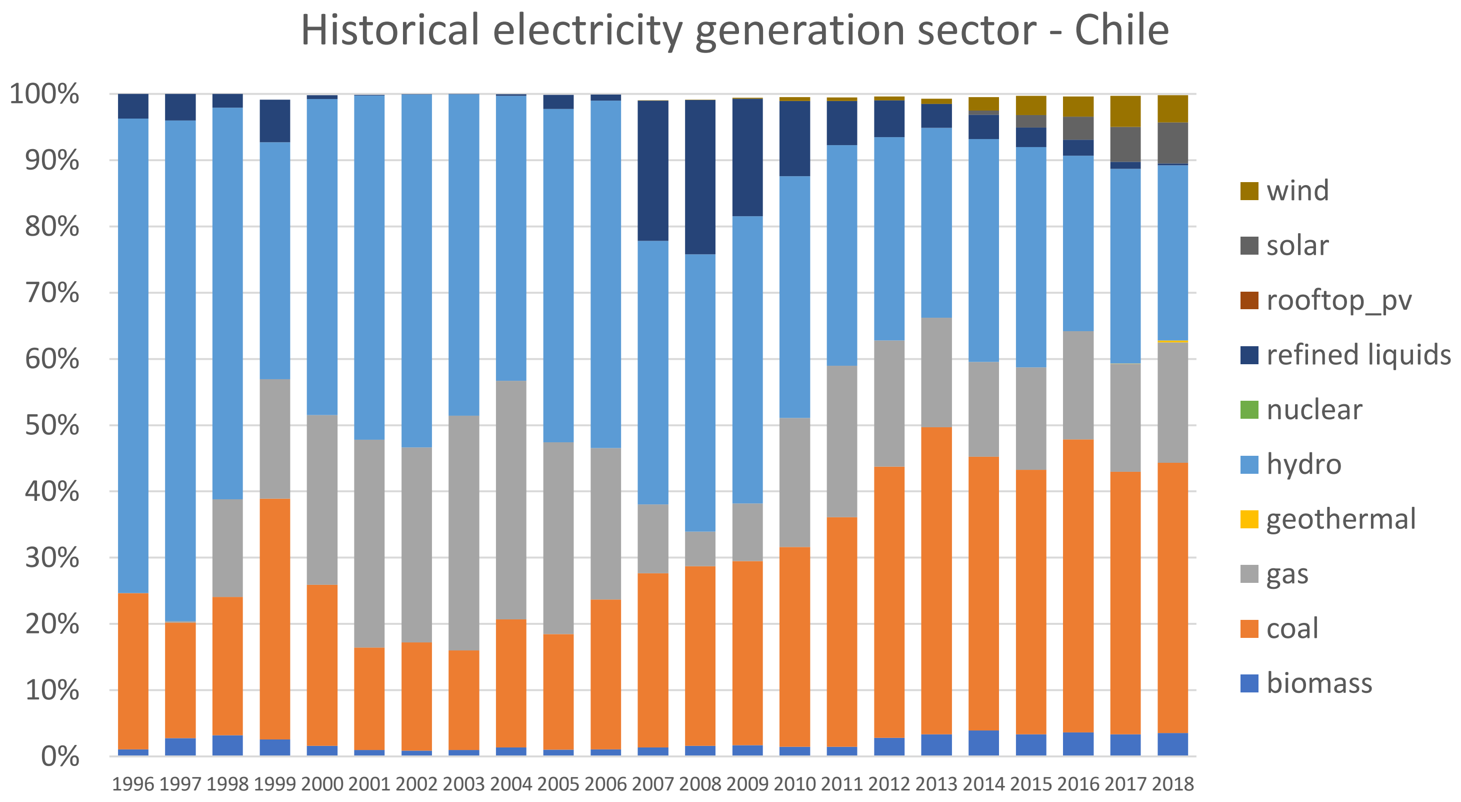
PONTIFICIA UNIVERSIDAD CATÓLICA DE VALPARAÍSO

- Chile's Energy Plan 2050 sets long-term goals for electricity generation
  - Planning to reach 60% generation from renewable sources in 2035 and,
  - 70% in 2050 (Ministerio de Energía 2015).
  - This plan builds on the Non-Conventional Renewable Energy (NCRE) Law, which aims to reach 20% of generation from non-conventional renewable energy sources by 2025.

- Current carbon tax implemented in Chile: USD$ 5/tCO_2.

- Is it sufficient? What carbon prices will be required to meet such targets?

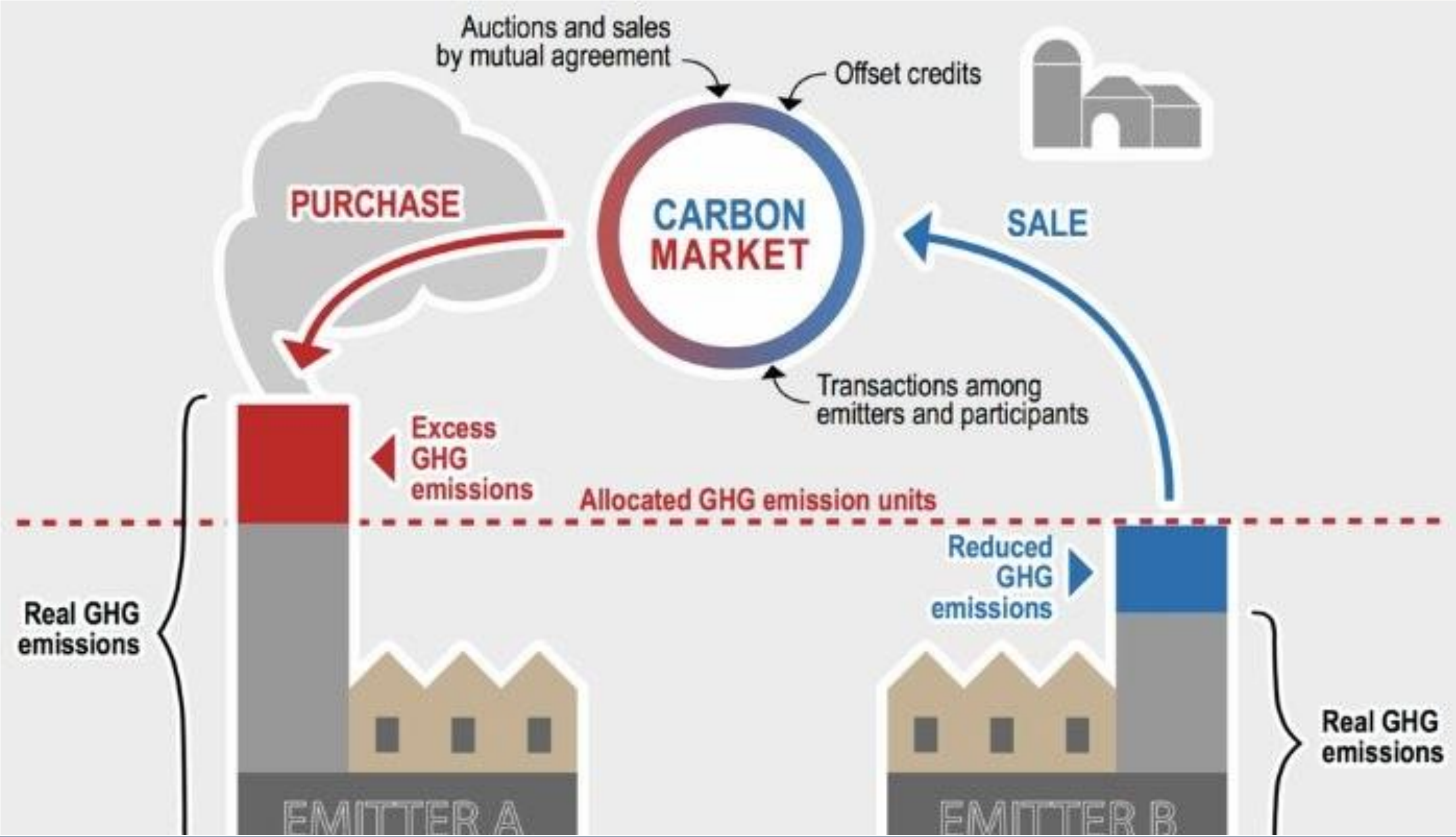
Case study: Chilean electricity sector and its Commitments



Case study: Chilean electricity sector and its Commitments

- Chile is highly vulnerable to the impacts of climate change
- The carbon tax is really not enough! (several authors have claimed this)
- An alternative strategy to cap and price carbon emissions
    - CAP and TRADE strategies
    - Adding a cap to emissions (allowances) and emitters can trade permits among themselves.

Cap and trade



Cap and trade: literature review

Literature on cap-and-trade strategies is vast, particularly that contextualized in the emissions from the electric sector.

- Authors in [1] were among the first to propose a game theoretical approach (mixed complementarity problem) to study the strategic actions when facing future emissions obligations. Their proposed deterministic model assumes a free allowance allocation approach, where generators can then65either buy or sell excess of allowances in a trading market.

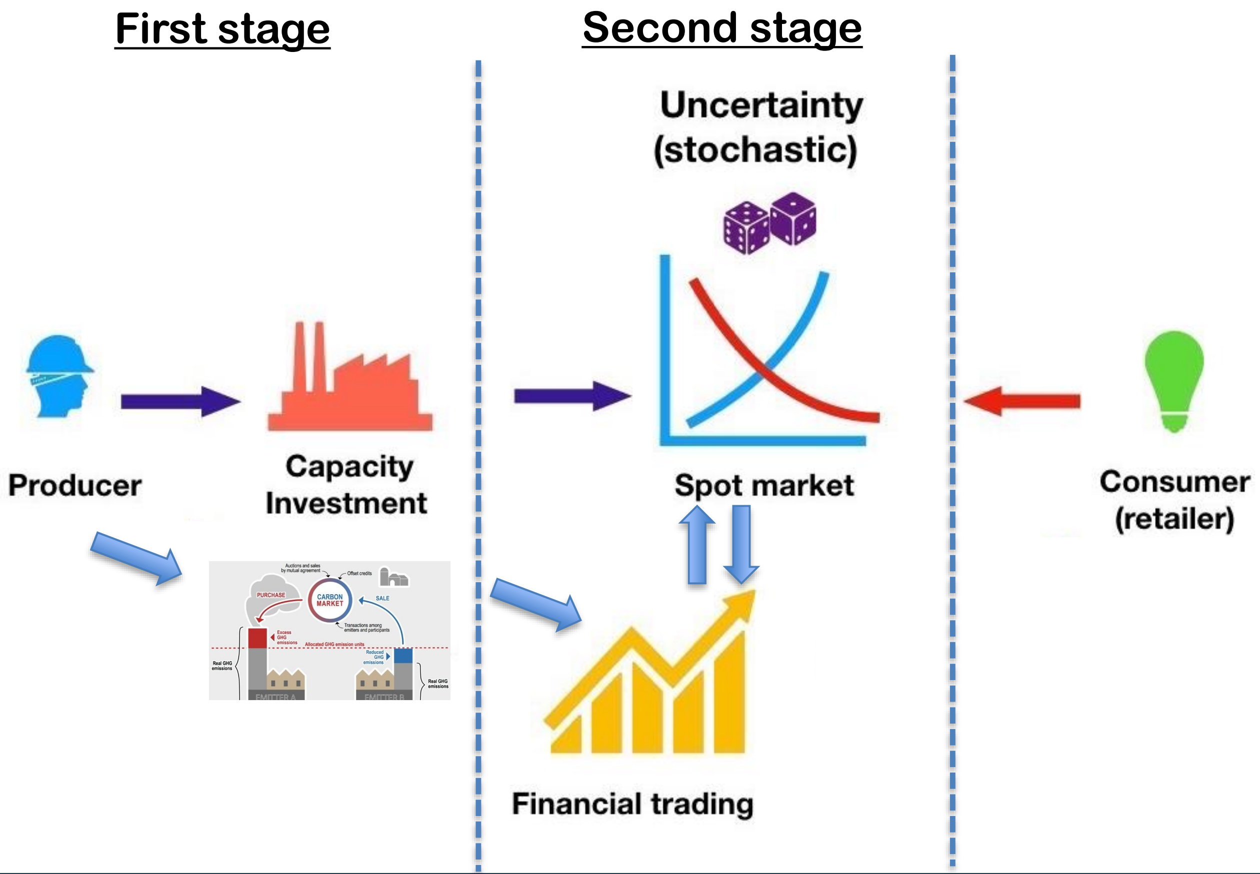
- Researchers in [2] also proposed a game theoretical approach (similar to that in [1]) where different allowance allocation strategies (free to new investment or production and either auctioned or grandfathered) were tested.

- A different modeling approach was taking by [3]. Authors proposed a model where an emissions constraint is explicitly set for the market operator agent, where its dual variable sets the price that generators face for their emissions.

- Several authors have also studied cap-and-trade systems with uncertainties at different levels, including hard and expected emissions constraints, stochastic future carbon prices, uncertain systems (such as load and renewable-supply variability), and environmental policy [4-10]. However such models do not necessarily consider a carbon market (other than a cap constraint) with an endogenous price response.

- Nevertheless, different cap-and-trade formulations have been used to study regional contexts such as China [11,12], the EU ETS [13,14], and the U.S. [15-17].

HOW DO WE MODEL THIS… a Two Stage Stochastic Model.



Two stage stochastic capacity investment model with cap and trade

Genco optimizes cost: Investing + operating with production $Y\omega$ at price $P\omega$

$$\begin{aligned} \min_{x,Y} \quad & Ix + \mathbb{E}_{\Theta}[C_\omega Y_\omega - P_\omega Y_\omega] \\ \text{s.t} \quad & x \in X \\ & 0 \leq Y_\omega \leq x \quad \forall \omega \end{aligned}$$

Demand (or allowance auctioneer) optimizes benefit (revenue) given price $P\omega$

$$\min_{Q_\omega} P_\omega Q_\omega - U_\omega Q_\omega \quad \text{s.t.} \quad Q_\omega \geq 0$$

Price $P\omega$ clears spot market

$$0 \leq Y_\omega - Q_\omega \perp P_\omega \geq 0$$

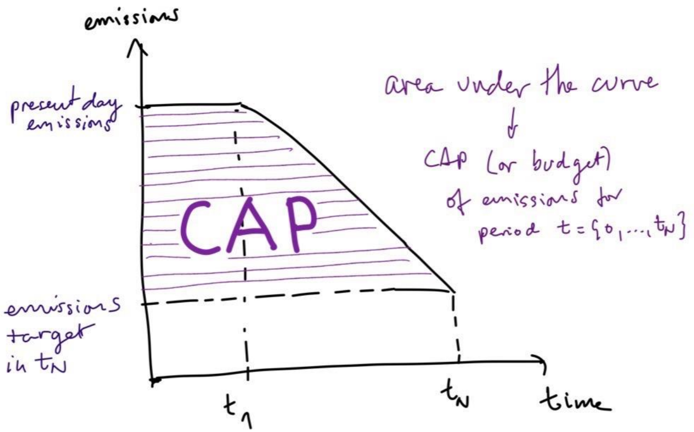
Two stage stochastic capacity investment model with cap and trade

- **First stage:**
  1. Generators have an initial installed capacity (2019 capacity)
  2. Generators do not know future demand with certainty
  3. Given possible futures
     1. Generators invest in capacity generation
     2. Generators obtained emissions permits (allowances) in a carbon market (carbon price is obtain).
     3. Generators produce electricity to meet current demand levels (known).
- **Second stage:**
  1. Demand uncertainty is cleared.
  2. Generators realize if initial allowance allocation is sufficient. If not, they can trade allowances (re-trading of allowances in a posterior market), obtaining a re-trading permit price.
  3. Generators decide on new investments and generation to meet present and future demand.

Two stage stochastic capacity investment model with cap and trade

Model assumptions and sequence: Auctioneer (permit holder):

- The permit holder, auctioneer, or government, is an agent that sells allowances to generators in the first stage of the model. Such process generates a revenue, which can then be used to finance other mitigation and adaptation strategies. The auctioneer has a maximum level of allowances that can be sold. (the cap component).



PRODUCERS or GENERATORS:

The Producer problem is

$$\begin{aligned}\min_{(x_i,Q_i,A_i,P_i,V_i)\in\mathbb{X}} & f_i\big(\pi^d(0),Q_i(0)\big) + A_i\pi^a + I_i x_i(0)\\ & + \sum_\omega Pr(\omega)\Bigg[\sum_{t>0}\frac{1}{(1+R)^t}\Big[TC_i(t)\cdot f_i\big(\pi^d(t,\omega),Q_i(t,\omega)\big)\\ & + TCR_i(t)\cdot I_i\cdot x_i(t,\omega)\Big] + \pi^v(\omega)\cdot\big(P_i(\omega)-V_i(\omega)\big)\Bigg]\end{aligned}$$

subject to

$$\begin{array}{llll}
\big(CF_i\cdot\tau\big)\Big[\overline{Q}_i + x_i(0) + \sum_{t'<t-lag_i} x_i(t',\omega)\Big] - Q_i(t,\omega) & \geq 0 & \forall \quad i,\omega,t>0 & (\alpha_{i,\omega,t})\\
\big(CF_i\cdot\tau\big)\overline{Q_i} - Q_i(0) & \geq 0 & \forall \quad i & (\kappa_i)\\
RP_i - \overline{Q}_i - x_i(0) - \sum_{t>0} x_i(t,\omega) & \geq 0 & \forall \quad i,\omega & (\psi_{i,\omega})\\
A_i - V_i(\omega) & \geq 0 & \forall \quad i,\omega & (\beta_{i,\omega})\\
A_i + (P_i(\omega)-V_i(\omega)) - \sum_{t>0} Q_i(t,\omega)\cdot\varepsilon_i - Q_i(0)\varepsilon_i & \geq 0 & \forall \quad i,\omega & (\gamma_{i,\omega})\\
Q_i(0) & \geq 0 & & (\lambda_i)\\
Q_i(t,\omega) & \geq 0 & \forall \quad \omega,t>0 & (\delta_{i,\omega,t})\\
x_i(0) & \geq 0 & & (\xi_i)\\
x_i(t,\omega) & \geq 0 & \forall \quad \omega,t>0 & (\varphi_{i,\omega,t})
\end{array}$$

PRODUCERS or GENERATORS:

Production cost/revenue $f_i(p,q) = \left(a_i \cdot q + \frac{b_i}{2} \cdot q^2\right) - p \cdot q.$

The Producer problem is

$$\min_{(x_i,Q_i,A_i,P_i,V_i)\in X} \boxed{f_i(\pi^d(0), Q_i(0))} + A_i\pi^a + I_i x_i(0)$$
$$+ \sum_{\omega} Pr(\omega) \left[\sum_{t>0} \frac{1}{(1+R)^t} \Big[TC_i(t) \cdot f_i(\pi^d(t,\omega), Q_i(t,\omega)) \right.$$
$$\left. + TCR_i(t) \cdot I_i \cdot x_i(t,\omega) \Big] + \pi^v(\omega) \cdot (P_i(\omega) - V_i(\omega)) \right]$$

subject to

$$\begin{array}{llll}
\left(CF_i \cdot \tau\right)\left[\overline{Q}_i + x_i(0) + \sum_{t'<t-lag_i} x_i(t',\omega)\right] - Q_i(t,\omega) & \geq 0 & \forall \quad i,\omega,t>0 & (\alpha_{i,\omega,t}) \\
\left(CF_i \cdot \tau\right)\overline{Q}_i - Q_i(0) & \geq 0 & \forall \quad i & (\kappa_i) \\
RP_i - \overline{Q}_i - x_i(0) - \sum_{t>0} x_i(t,\omega) & \geq 0 & \forall \quad i,\omega & (\psi_{i,\omega}) \\
A_i - V_i(\omega) & \geq 0 & \forall \quad i,\omega & (\beta_{i,\omega}) \\
A_i + (P_i(\omega) - V_i(\omega)) - \sum_{t>0} Q_i(t,\omega) \cdot \varepsilon_i - Q_i(0)\varepsilon_i & \geq 0 & \forall \quad i,\omega & (\gamma_{i,\omega}) \\
Q_i(0) & \geq 0 & & (\lambda_i) \\
Q_i(t,\omega) & \geq 0 & \forall \quad \omega,t>0 & (\delta_{i,\omega,t}) \\
x_i(0) & \geq 0 & & (\xi_i) \\
x_i(t,\omega) & \geq 0 & \forall \quad \omega,t>0 & (\varphi_{i,\omega,t})
\end{array}$$

PRODUCERS or GENERATORS:

Production cost/revenue $f_i(p,q) = \left(a_i \cdot q + \frac{b_i}{2} \cdot q^2\right) - p \cdot q.$

Allowance (Ai) cost (π is the CO2 price)

The Producer problem is

$$\min_{(x_i,Q_i,A_i,P_i,V_i)\in X} \boxed{f_i(\pi^d(0),Q_i(0))} + \boxed{A_i\pi^a} + I_i x_i(0)$$
$$+\sum_{\omega} Pr(\omega)\left[\sum_{t>0} \frac{1}{(1+R)^t}\left[TC_i(t)\cdot f_i(\pi^d(t,\omega),Q_i(t,\omega))\right.\right.$$
$$\left.\left.+TCR_i(t)\cdot I_i \cdot x_i(t,\omega)\right] + \pi^v(\omega)\cdot(P_i(\omega)-V_i(\omega))\right]$$

subject to

$$\begin{array}{llll}
(CF_i\cdot\tau)\left[\overline{Q}_i + x_i(0) + \sum_{t'<t-lag_i} x_i(t',\omega)\right] - Q_i(t,\omega) & \geq 0 & \forall\ i,\omega,t>0 & (\alpha_{i,\omega,t})\\
(CF_i\cdot\tau)\overline{Q}_i - Q_i(0) & \geq 0 & \forall\ i & (\kappa_i)\\
RP_i - \overline{Q}_i - x_i(0) - \sum_{t>0} x_i(t,\omega) & \geq 0 & \forall\ i,\omega & (\psi_{i,\omega})\\
A_i - V_i(\omega) & \geq 0 & \forall\ i,\omega & (\beta_{i,\omega})\\
A_i + (P_i(\omega)-V_i(\omega)) - \sum_{t>0} Q_i(t,\omega)\cdot\varepsilon_i - Q_i(0)\varepsilon_i & \geq 0 & \forall\ i,\omega & (\gamma_{i,\omega})\\
Q_i(0) & \geq 0 & & (\lambda_i)\\
Q_i(t,\omega) & \geq 0 & \forall\ \omega,t>0 & (\delta_{i,\omega,t})\\
x_i(0) & \geq 0 & & (\xi_i)\\
x_i(t,\omega) & \geq 0 & \forall\ \omega,t>0 & (\varphi_{i,\omega,t})
\end{array}$$

PRODUCERS or GENERATORS:

The Producer problem is

$$\min_{(x_i,Q_i,A_i,P_i,V_i)\in X} \boxed{f_i(\pi^d(0),Q_i(0))} + \boxed{A_i\pi^a} + \boxed{I_i x_i(0)}$$

$$+\sum_{\omega} Pr(\omega)\left[\sum_{t>0}\frac{1}{(1+R)^t}\left[TC_i(t)\cdot f_i(\pi^d(t,\omega),Q_i(t,\omega))\right.\right.$$

$$\left.\left.+TCR_i(t)\cdot I_i\cdot x_i(t,\omega)\right]+\pi^v(\omega)\cdot\left(P_i(\omega)-V_i(\omega)\right)\right]$$

Production cost/revenue $f_i(p,q)=\left(a_i\cdot q+\frac{b_i}{2}\cdot q^2\right)-p\cdot q.$

Allowance (Ai) cost (π is the CO2 price)

Investment cost in first stage

subject to

$$\begin{array}{llll}
\left(CF_i\cdot\tau\right)\left[\overline{Q}_i+x_i(0)+\sum_{t'<t-lag_i}x_i(t',\omega)\right]-Q_i(t,\omega) & \geq 0 & \forall\ \ i,\omega,t>0 & (\alpha_{i,\omega,t})\\
\left(CF_i\cdot\tau\right)\overline{Q}_i-Q_i(0) & \geq 0 & \forall\ \ i & (\kappa_i)\\
RP_i-\overline{Q}_i-x_i(0)-\sum_{t>0}x_i(t,\omega) & \geq 0 & \forall\ \ i,\omega & (\psi_{i,\omega})\\
A_i-V_i(\omega) & \geq 0 & \forall\ \ i,\omega & (\beta_{i,\omega})\\
A_i+(P_i(\omega)-V_i(\omega))-\sum_{t>0}Q_i(t,\omega)\cdot\varepsilon_i-Q_i(0)\varepsilon_i & \geq 0 & \forall\ \ i,\omega & (\gamma_{i,\omega})\\
Q_i(0) & \geq 0 & & (\lambda_i)\\
Q_i(t,\omega) & \geq 0 & \forall\ \ \omega,t>0 & (\delta_{i,\omega,t})\\
x_i(0) & \geq 0 & & (\xi_i)\\
x_i(t,\omega) & \geq 0 & \forall\ \ \omega,t>0 & (\varphi_{i,\omega,t})
\end{array}$$

PRODUCERS or GENERATORS:

Production cost/revenue $f_i(p,q) = \left(a_i \cdot q + \frac{b_i}{2} \cdot q^2\right) - p \cdot q.$

Allowance (Ai) cost (π is the CO2 price)

Investment cost in first stage

Second stage cost and revenue

Second stage allowance re-trading

The Producer problem is

$$\min_{(x_i,Q_i,A_i,P_i,V_i)\in X} \boxed{f_i(\pi^d(0),Q_i(0))} + \boxed{A_i\pi^a} + \boxed{I_i x_i(0)}$$

$$+\sum_{\omega} Pr(\omega)\left[\sum_{t>0}\frac{1}{(1+R)^t}\left[TC_i(t)\cdot f_i\left(\pi^d(t,\omega),Q_i(t,\omega)\right) + TCR_i(t)\cdot I_i \cdot x_i(t,\omega)\right] + \boxed{\pi^v(\omega)\cdot\left(P_i(\omega)-V_i(\omega)\right)}\right]$$

subject to

$$\begin{array}{llll}
\left(CF_i\cdot\tau\right)\left[\overline{Q}_i + x_i(0) + \sum_{t'<t-lag_i} x_i(t',\omega)\right] - Q_i(t,\omega) & \geq 0 & \forall \quad i,\omega,t>0 & (\alpha_{i,\omega,t}) \\
\left(CF_i\cdot\tau\right)\overline{Q_i} - Q_i(0) & \geq 0 & \forall \quad i & (\kappa_i) \\
RP_i - \overline{Q}_i - x_i(0) - \sum_{t>0} x_i(t,\omega) & \geq 0 & \forall \quad i,\omega & (\psi_{i,\omega}) \\
A_i - V_i(\omega) & \geq 0 & \forall \quad i,\omega & (\beta_{i,\omega}) \\
A_i + (P_i(\omega) - V_i(\omega)) - \sum_{t>0} Q_i(t,\omega)\cdot\varepsilon_i - Q_i(0)\varepsilon_i & \geq 0 & \forall \quad i,\omega & (\gamma_{i,\omega}) \\
Q_i(0) & \geq 0 & & (\lambda_i) \\
Q_i(t,\omega) & \geq 0 & \forall \quad \omega,t>0 & (\delta_{i,\omega,t}) \\
x_i(0) & \geq 0 & & (\xi_i) \\
x_i(t,\omega) & \geq 0 & \forall \quad \omega,t>0 & (\varphi_{i,\omega,t})
\end{array}$$

PRODUCERS or GENERATORS:

The Producer problem is

$$\min_{(x_i,Q_i,A_i,P_i,V_i)\in X} \boxed{f_i(\pi^d(0),Q_i(0))} + \boxed{A_i\pi^a} + \boxed{I_i x_i(0)}$$

$$+\sum_{\omega} Pr(\omega)\left[\sum_{t>0}\frac{1}{(1+R)^t}\left[TC_i(t)\cdot f_i(\pi^d(t,\omega),Q_i(t,\omega))\right.\right.$$

$$\left.\left.+TCR_i(t)\cdot I_i\cdot x_i(t,\omega)\right] + \boxed{\pi^v(\omega)\cdot(P_i(\omega)-V_i(\omega))}\right]$$

Production cost/revenue $f_i(p,q)=\left(a_i\cdot q+\frac{b_i}{2}\cdot q^2\right)-p\cdot q.$

Allowance (Ai) cost (π is the CO2 price)

Investment cost in first stage

Second stage cost and revenue

Second stage allowance re-trading

subject to

$\left(CF_i\cdot\tau\right)\left[\overline{Q}_i+x_i(0)+\sum_{t'<t-lag_i}x_i(t',\omega)\right]-Q_i(t,\omega)$	≥ 0	$\forall$	$i,\omega,t>0$	$(\alpha_{i,\omega,t})$
$\left(CF_i\cdot\tau\right)\overline{Q}_i-Q_i(0)$	≥ 0	$\forall$	i	(κ_i)
$RP_i-\overline{Q}_i-x_i(0)-\sum_{t>0}x_i(t,\omega)$	≥ 0	$\forall$	i,ω	$(\psi_{i,\omega})$
$A_i-V_i(\omega)$	≥ 0	$\forall$	i,ω	$(\beta_{i,\omega})$
$A_i+(P_i(\omega)-V_i(\omega))-\sum_{t>0}Q_i(t,\omega)\cdot\varepsilon_i-Q_i(0)\varepsilon_i$	≥ 0	$\forall$	i,ω	$(\gamma_{i,\omega})$
$Q_i(0)$	≥ 0			(λ_i)
$Q_i(t,\omega)$	≥ 0	$\forall$	$\omega,t>0$	$(\delta_{i,\omega,t})$
$x_i(0)$	≥ 0			(ξ_i)
$x_i(t,\omega)$	≥ 0	$\forall$	$\omega,t>0$	$(\varphi_{i,\omega,t})$

Production capacity/limit constraints subject to investment decisions.

Resource constraint (investment limit)

Carbon market constraints (allowances to sell and cap on emissions)

Auctioneer:

- We consider the case where the auctioneer wants to maximize the revenue obtained from selling allowances with a trade off observed for allowing such emissions to be generated (e.g., SCC).
- Also, we consider the case where the number of CO2 permits to be available over the long run is uncertain, and follows a normal distribution.
- Chance constraint problem that can be linearized using standard tricks.

Where $CAP \sim N(\mu, \sigma^2)$. and we want $Pr(\theta \geq CAP) \leq \epsilon$

$$\min_{\theta} \boxed{-\theta\pi^a} + \boxed{\mathcal{F}(\theta)}$$
$$\text{s.t } \boxed{\phi^{-1}(\epsilon)\sigma + \mu - \theta \geq 0}$$

Allowance revenue

CO2 cost (SCC)

CO2 (stochastic) cap or limit

For each producer

$$\min_{(x_i,Q_i,A_i,P_i,V_i)\in\mathbb{X}} f_i\big(\pi^d(0),Q_i(0)\big)+A_i\pi^a+I_i x_i(0) \quad +\sum_{\omega} Pr(\omega)\left[\sum_{t>0}\frac{1}{(1+R)^t}\Big[TC_i(t)\cdot f_i\big(\pi^d(t,\omega),Q_i(t,\omega)\big) \;+TCR_i(t)\cdot I_i\cdot x_i(t,\omega)\Big]+\pi^v(\omega)\cdot\big(P_i(\omega)-V_i(\omega)\big)\right]$$

subject to

$$\begin{array}{llll}
\big(CF_i\cdot\tau\big)\left[\overline{Q}_i+x_i(0)+\displaystyle\sum_{t'<t-lag_i}x_i(t',\omega)\right]-Q_i(t,\omega) & \geq 0 & \forall\;\; i,\omega,t>0 & (\alpha_{i,\omega,t})\\
\big(CF_i\cdot\tau\big)\overline{Q_i}-Q_i(0) & \geq 0 & \forall\;\; i & (\kappa_i)\\
RP_i-\overline{Q}_i-x_i(0)-\displaystyle\sum_{t>0}x_i(t,\omega) & \geq 0 & \forall\;\; i,\omega & (\psi_{i,\omega})\\
A_i-V_i(\omega) & \geq 0 & \forall\;\; i,\omega & (\beta_{i,\omega})\\
A_i+(P_i(\omega)-V_i(\omega))-\displaystyle\sum_{t>0}Q_i(t,\omega)\cdot\varepsilon_i-Q_i(0)\varepsilon_i & \geq 0 & \forall\;\; i,\omega & (\gamma_{i,\omega})\\
Q_i(0) & \geq 0 & & (\lambda_i)\\
Q_i(t,\omega) & \geq 0 & \forall\;\; \omega,t>0 & (\delta_{i,\omega,t})\\
x_i(0) & \geq 0 & & (\xi_i)\\
x_i(t,\omega) & \geq 0 & \forall\;\; \omega,t>0 & (\varphi_{i,\omega,t})
\end{array}$$

Auctioneer

$$\min_{\theta} -\theta\pi^a+\mathcal{F}(\theta)$$

$$\text{s.t}\quad \phi^{-1}(\epsilon)\sigma+\mu-\theta\geq 0$$

For each producer

$$\min_{(x_i,Q_i,A_i,P_i,V_i)\in\mathbb{X}} f_i\big(\pi^d(0),Q_i(0)\big)+A_i\pi^a+I_i x_i(0) \;+\sum_{\omega} Pr(\omega)\left[\sum_{t>0}\frac{1}{(1+R)^t}\Big[TC_i(t)\cdot f_i\big(\pi^d(t,\omega),Q_i(t,\omega)\big)\;+TCR_i(t)\cdot I_i\cdot x_i(t,\omega)\Big]+\pi^v(\omega)\cdot\big(P_i(\omega)-V_i(\omega)\big)\right]$$

subject to

$$\begin{array}{llll}
\big(CF_i\cdot\tau\big)\Big[\overline{Q}_i+x_i(0)+\sum\limits_{t'<t-lag_i}x_i(t',\omega)\Big]-Q_i(t,\omega) & \geq 0 & \forall\;\; i,\omega,t>0 & (\alpha_{i,\omega,t})\\
\big(CF_i\cdot\tau\big)\overline{Q_i}-Q_i(0) & \geq 0 & \forall\;\; i & (\kappa_i)\\
RP_i-\overline{Q}_i-x_i(0)-\sum\limits_{t>0}x_i(t,\omega) & \geq 0 & \forall\;\; i,\omega & (\psi_{i,\omega})\\
A_i-V_i(\omega) & \geq 0 & \forall\;\; i,\omega & (\beta_{i,\omega})\\
A_i+(P_i(\omega)-V_i(\omega))-\sum\limits_{t>0}Q_i(t,\omega)\cdot\varepsilon_i-Q_i(0)\varepsilon_i & \geq 0 & \forall\;\; i,\omega & (\gamma_{i,\omega})\\
Q_i(0) & \geq 0 & & (\lambda_i)\\
Q_i(t,\omega) & \geq 0 & \forall\;\; \omega,t>0 & (\delta_{i,\omega,t})\\
x_i(0) & \geq 0 & & (\xi_i)\\
x_i(t,\omega) & \geq 0 & \forall\;\; \omega,t>0 & (\varphi_{i,\omega,t})
\end{array}$$

Market Clearing Constraints (supply = demand)

$$\begin{array}{rlll}
\textit{(available allowances } t=0\textit{)}: & \sum\limits_i A_i^*=\theta & & (\pi^{a*})\\
\textit{(equilibrium in trading market } t>0\textit{)}: & \sum\limits_i P_{i,\omega}^*=\sum\limits_i V_{i,\omega}^* & \forall\;\omega & (\pi^{v*}(\omega))\\
\textit{(fulfillment of the demand –first stage)}: & \sum\limits_i Q_i(0)^*=D(0), & & (\pi^{d*}(0))\\
\textit{(fulfillment of the demand –second stage)}: & \sum\limits_i Q_i(t,\omega)^*=D(t,\omega), & \forall\;\omega,t & (\pi^{d*}(t,\omega))
\end{array}$$

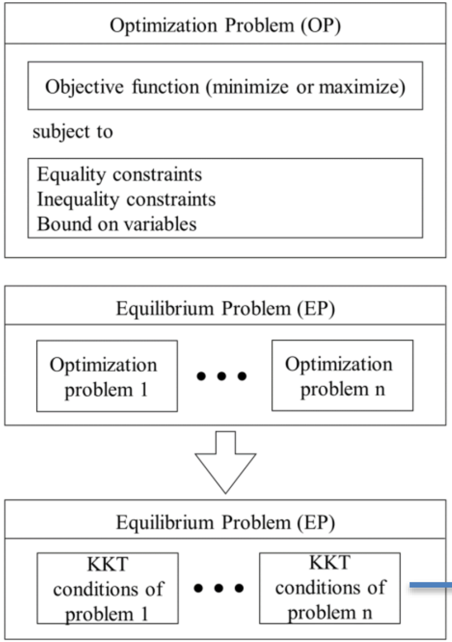
Auctioneer

$$\min_{\theta}-\theta\pi^a+\mathcal{F}(\theta)$$

$$\text{s.t}\quad \phi^{-1}(\epsilon)\sigma+\mu-\theta\geq 0$$

Solution approach

- Get the Lagrange function for each problem (for EACH producer and the auctioneer), derivate and set it to 0
- Plus some other conditions (complementarity, feasibility) we get the KKT conditions for each player
- Add the market clearing conditions to have a square system of equations.



$$\begin{aligned} \min \quad & f(x) \\ \text{s.t} \quad & h(x) = 0 \\ & g(x) \leq 0 \end{aligned}$$

$$(L) = f(x) + \lambda^T h(x) + \mu^T g(x)$$

$$\begin{gathered} \nabla_x f(x) + \lambda^T \nabla_x h(x) + \mu^T \nabla_x g(x) = 0 \\ h(x) = 0, \quad \lambda \quad \text{free} \\ g(x) \leq 0 \\ \mu^T g(x) = 0 \\ \mu \geq 0 \end{gathered}$$

Solution approach

- Get the Lagrange function for each problem (for EACH producer and the auctioneer), derivate and set it to 0
- Plus some other conditions (complementarity, feasibility) we get the KKT conditions for each player
- Add the market clearing conditions to have a square system of equations.

KKT for producers

$$0 \leq Pr(\omega)\left[\frac{1}{(1+R)^t} TCR_i(t)\cdot I_i\right] - \sum_{t>t\prime} \alpha_{i,\omega,t}(CF_i\cdot\tau) + \psi_{i,\omega} \perp x_i(t,\omega) \geq 0 \qquad \forall\, i,\omega,t>0$$

$$0 \leq (a_i + b_i Q_i(0)) - \pi^d(0) + \kappa_i + \sum_{\omega} \gamma_{i,\omega}\varepsilon_i \perp Q_i(0) \geq 0 \qquad \forall\, i$$

$$0 \leq Pr(\omega)\frac{1}{(1+R)^t}\Big(TC_i(t)\big(a_i + b_i Q_i(t,\omega)\big) - \pi^d(t,\omega)\Big) + \alpha_{i,\omega,\tau} + \gamma_{i,\omega}\varepsilon_i \perp Q_i(t,\omega) \geq 0 \qquad \forall\, i,\omega,t>0$$

$$0 \leq \pi^a - \sum_{\omega}\beta_{i,\omega} - \sum_{\omega}\gamma_{i,\omega} \perp A_i \geq 0 \qquad \forall\, i$$

$$0 \leq -Pr(\omega)\pi^v(\omega) + \beta_{i,\omega} + \gamma_{i,\omega} \perp V_i(\omega) \geq 0 \qquad \forall\, i,\omega$$

$$0 \leq Pr(\omega)\pi^v(\omega) - \gamma_{i,\omega} \perp P_{-i}(\omega) \geq 0 \qquad \forall\, -i,\omega$$

$$0 \leq (CF_i\cdot\tau)\left[\overline{Q}_i + \sum_{t\leq t\prime} x_i(t,\omega) + x_i(0)\right] - Q_i(t,\omega) \perp \alpha_{i,\omega,\tau} \geq 0 \qquad \forall\, i,\omega,t>0$$

$$0 \leq \big(CF_i\cdot\tau\big)\overline{Q}_i(0) - Q_i(0) \perp \kappa_i \geq 0 \qquad \forall\, i$$

$$0 \leq A_i - V_i(\omega) \perp \beta_{i,\omega} \geq 0 \qquad \forall\, \omega$$

$$0 \leq A_i + P_i(\omega) - V_i(\omega) - \sum_{t>0} Q_i(t,\omega)\varepsilon_i - Q_i(0)\varepsilon_i \perp \gamma_{i,\omega} \geq 0 \qquad \forall\, i,\omega$$

$$0 \leq RP_i - \overline{Q}_i - x_i(0) - \sum_{t>0} x_i(t,\omega) \perp \psi_{i,\omega} \geq 0 \qquad \forall\, i,\omega$$

KKT for auctioneer

$$0 \leq -\pi^a + \frac{\partial\mathcal{F}(\theta)}{\partial\theta} + \eta \perp \theta \geq 0$$

$$0 \leq \phi^{-1}(M)\sigma + \mu - \theta \perp \eta \geq 0$$

Market Clearing Constraints (supply = demand)

$$(\textit{available allowances } t=0): \quad \sum_i A_i^* = \theta \qquad (\pi^{a*})$$

$$(\textit{equilibrium in trading market } t>0): \quad \sum_i P_{i,\omega}^* = \sum_i V_{i,\omega}^* \qquad \forall\,\omega \quad (\pi^{v*}(\omega))$$

$$(\textit{fulfillment of the demand -first stage}): \quad \sum_i Q_i(0)^* = D(0), \qquad (\pi^{d*}(0))$$

$$(\textit{fulfillment of the demand -second stage}): \quad \sum_i Q_i(t,\omega)^* = D(t,\omega), \quad \forall\,\omega,t \quad (\pi^{d*}(t,\omega))$$

Chilean electric market

- The Sistema Eléctrico Nacional (SEN) is the main (sub) system of the Chilean electric market4, with208a total generation capacity of 24.17 GW.
- Biomass, Coal, Wind, Gas, Geothermal, Hydro (3 types), Diesel, and Solar technologies.
- Production cost, investment cost, technology change and all other parameters based on relevant literature and calibration.

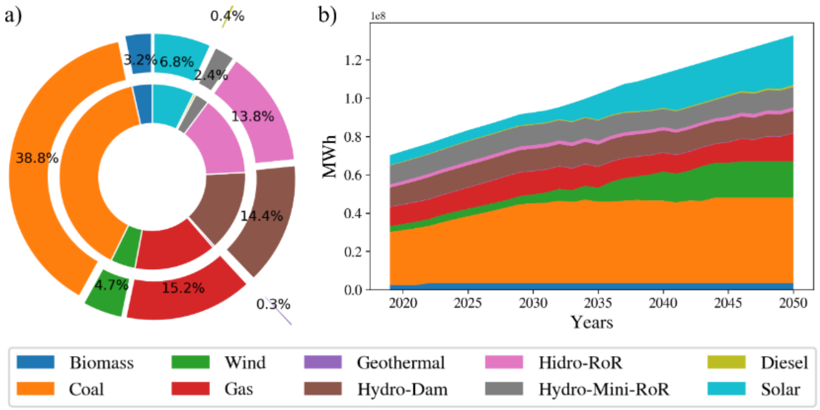


Figure 1: Panel (a): The outer ring shows the production percentage over the total electricity production in 2018 for each technology obtained from the calibration of our model. The inner ring shows the real operation data for that year. Panel (b): Production levels per technology in the period 2019-2050 for our base-case scenario in our model, that is, business-as-usual, no green policies planned or implemented.

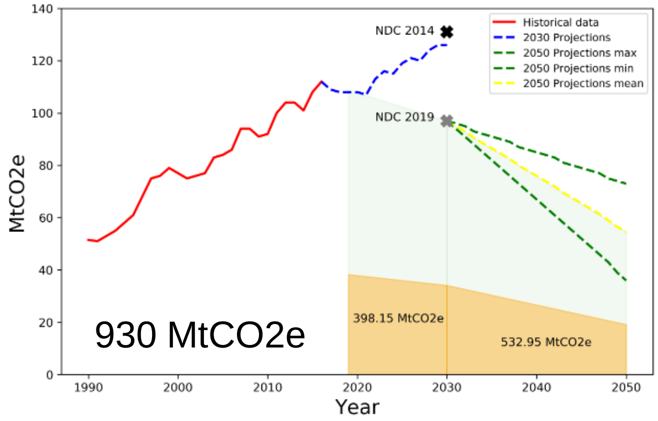
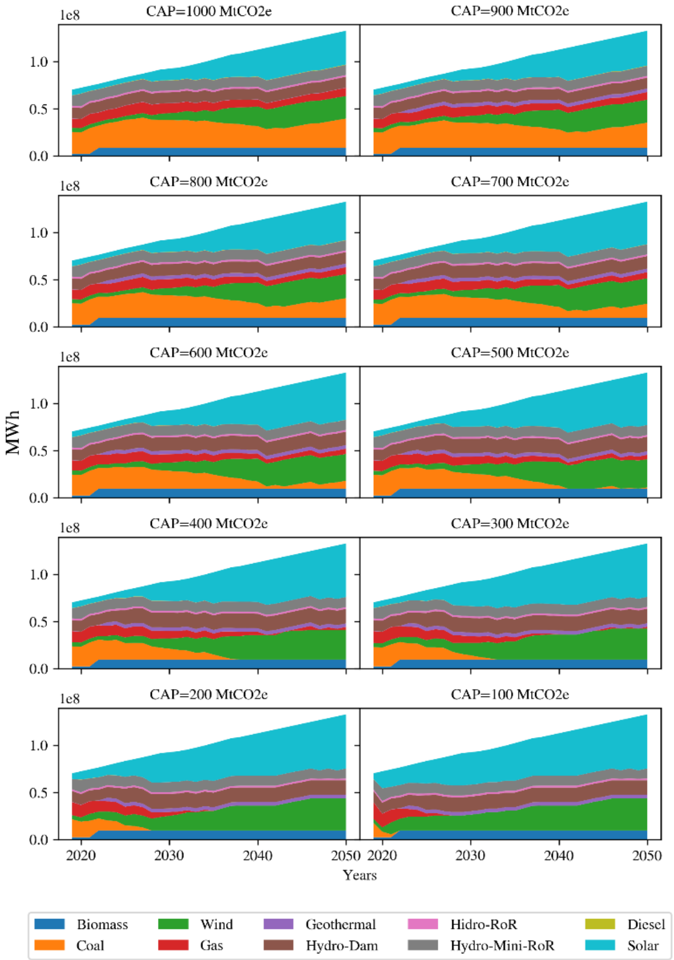


Figure 2: Emission data for Chile from Climate Action Tracker website, historical and projected. See text for details

Results: Cap-and-trade in an deterministic context (first)

- Sensitivity analysis on the cap (amount of emissions allowed) to contrast to current emissions budget.
- Mean and variance in the auctioneer problem: mean set to values between 100 and 1000 MtCO2, and no variance is considered (deterministic)
- Single demand scenario (BAU case)



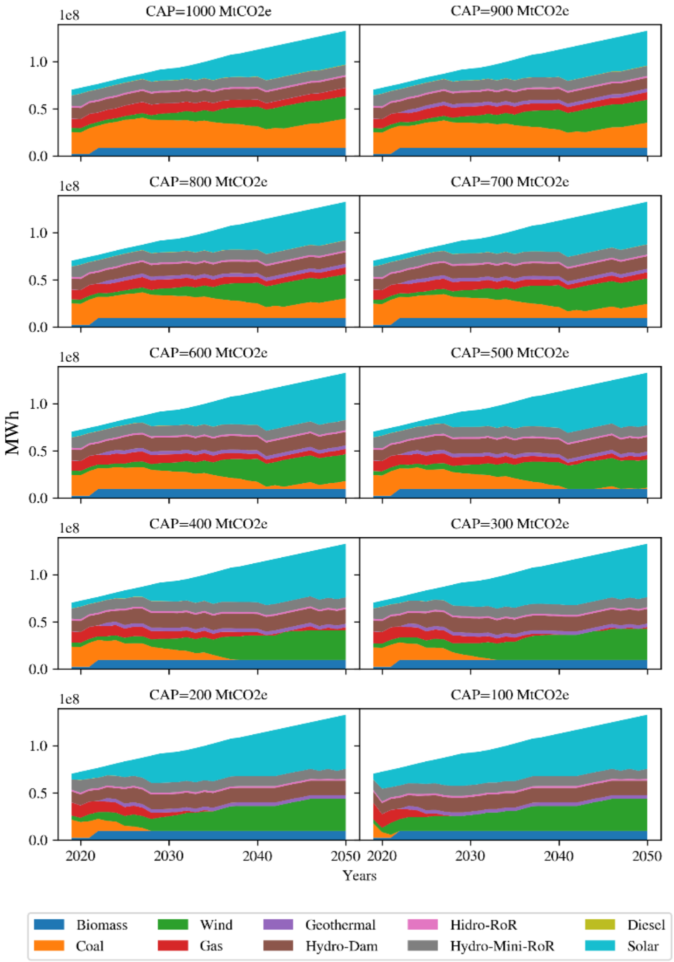
Results: Cap-and-trade in an deterministic context (first)

- Sensitivity analysis on the cap (amount of emissions allowed) to contrast to current emissions budget.
- Mean and variance in the auctioneer problem: mean set to values between 100 and 1000 MtCO2, and no variance is considered (deterministic)
- Single demand scenario (BAU case)

Results (some observations)

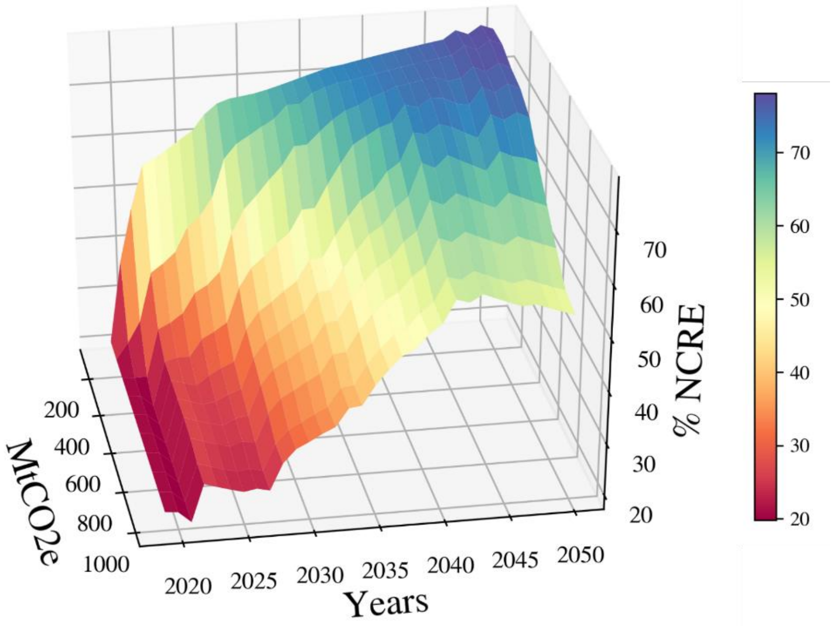
- Based carbon budget (BAU) is not even close to phase out coal. The CO2 price obtained in the less stringent case **is 24 USD/tCO2**. The highest price (budget of 100 MtCO2) is **174 USD/tCO2**. Prices of at least 45USD/tCO2 to phase out coal.

- For a high budget (1000 MtCO2e), total capacity additions increase to 25.58 GW, an increment of 47% compared to the base case (17.3 GW).
  - New solar capacity accounts to 14.41 GW (48% increase) whereas wind energy investment was of 9.91 GW (32% increase).
  - solar and wind investments account to 24.67 GW and 14.94 GW (154% and 99%3 increase), respectively, in a stringent case (100 MtCO2)



Results: Cap-and-trade in an deterministic context (first)

- Percentage of power generation from NCRE sources in the period 2019-2050 at different carbon budgets.

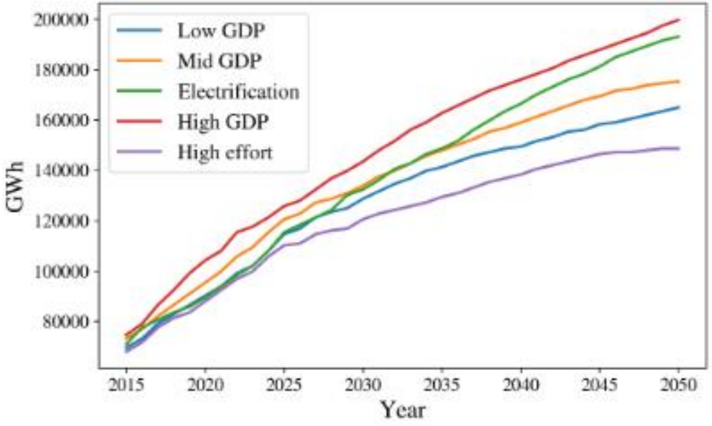


Pledge	Carbon budget ($MtCO_2e$)			
	100	500	700	1000
Year in which coal is phased-out	2022	2041	–	–
Percentage (%) of coal and gas in 2050	0	0	16	30
Year with 60% NCREs	2025	2038	2041	–
Year with 70% NCREs	2034	2041	–	–
Price of allowances (USD per tCO_2e)	174	45	35	23

Results: Cap-and-trade with **demand uncertainty**

- We now consider five different official projections (Chilean Road map towards 2050). Each scenario equally likely.
- Under uncertainty, generators must acquire carbon allowance during the first stage to guarantee they can satisfy all demand (unknown yet) levels.

- Demand Scenarios:
  - Low, Mid and High GDP, Electrification (replacement of fuels for electricity in tertiary sectors) and High Effort (energy efficiency policies)



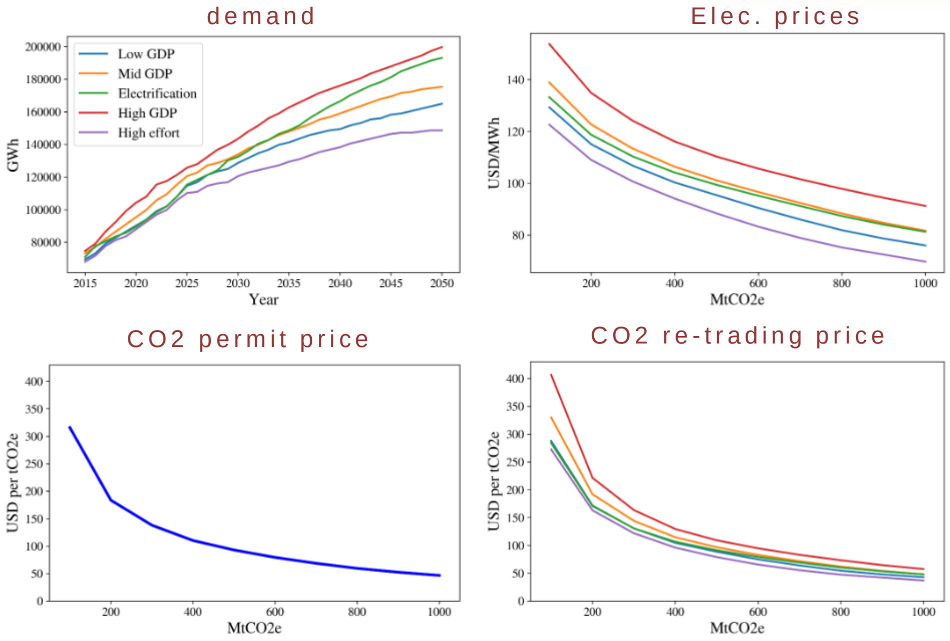
Results: Cap-and-trade with **demand uncertainty**

Electricity price:

- Higher demand scenarios result in higher mean electricity prices (31% higher for a carbon budget of 1000 MtCO2e), which are further increased with more restrictive carbon budgets
  - Reducing the carbon budget results in a price increase of 68%.
  - Offset effect for the Elect. And Mid GDP scenarios

Carbon price:

- Demand uncertainty (driven also by high demand scenarios) result in significant higher prices than the deterministic case.
- Different carbon prices observed in the re-trading market (higher and lower prices, depending on the demand scenario).



$$0 \leq \pi^a - \sum_{\omega} \beta_{i,\omega} - \sum_{\omega} \gamma_{i,\omega} \perp A_i \geq 0$$

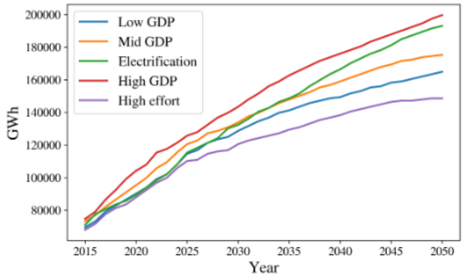
Results: Cap-and-trade with **demand uncertainty**

PONTIFICIA UNIVERSIDAD CATÓLICA DE VALPARAÍSO

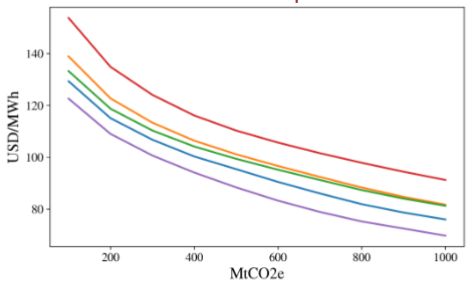
Carbon price:

- Demand uncertainty (driven also by high demand scenarios) result in significant higher prices than the deterministic case.
- Different carbon prices observed in the re-trading market (higher and lower prices, depending on the demand scenario).

demand



Elec. prices



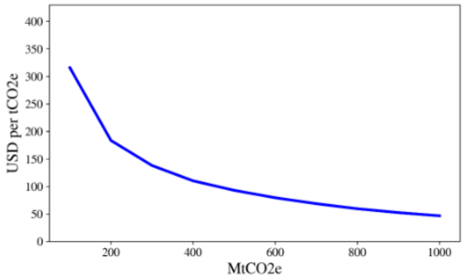
carbon prices

$$0 \leq \pi^a - \sum_{\omega} \beta_{i,\omega} - \sum_{\omega} \gamma_{i,\omega} \perp A_i \geq 0$$

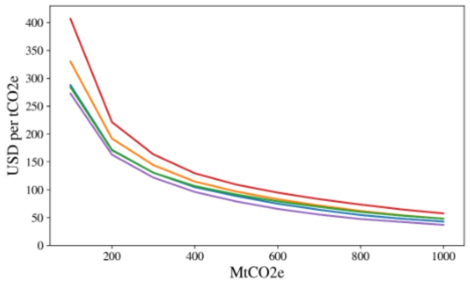
$$0 \leq A_i - V_i(\omega) \perp \beta_{i,\omega} \geq 0$$

$$0 \leq A_i + P_i(\omega) - V_i(\omega) - \sum_{t>0} Q_i(t,\omega)\varepsilon_i - Q_i(0)\varepsilon_i \perp \gamma_{i,\omega} \geq 0$$

CO2 permit price



CO2 re-trading price

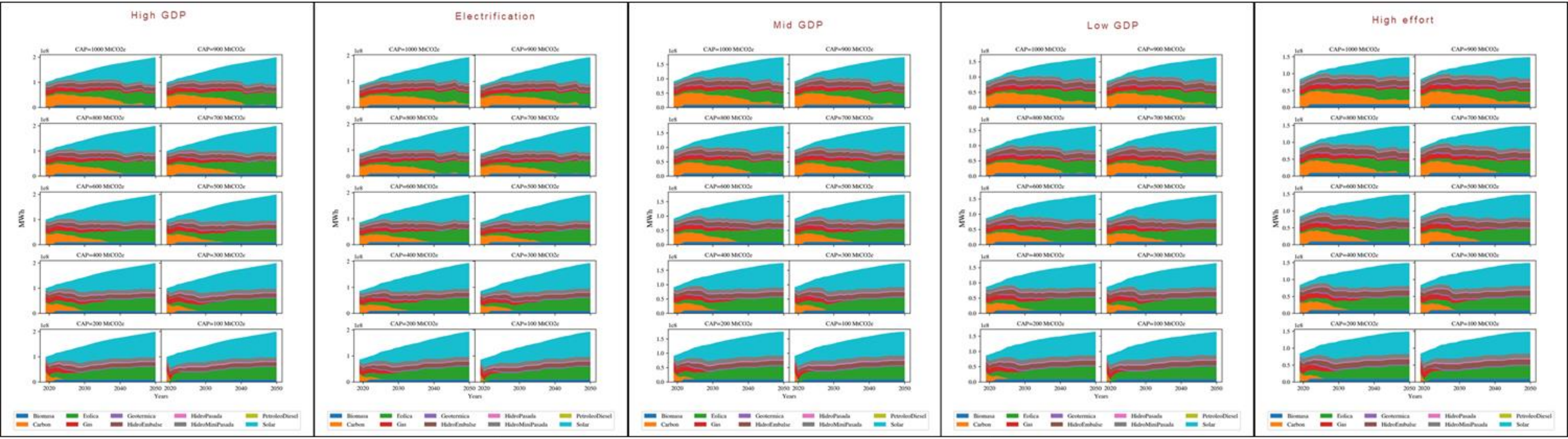


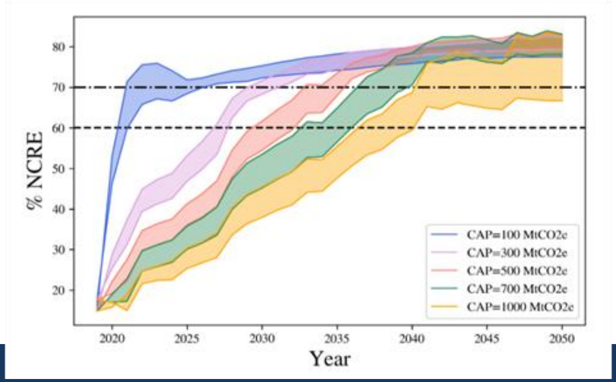
Re-trading carbon prices

$$0 \leq -Pr(\omega)\pi^v(\omega) + \beta_{i,\omega} + \gamma_{i,\omega} \perp V_i(\omega) \geq 0 \qquad \forall\ i, \omega$$

$$0 \leq Pr(\omega)\pi^v(\omega) - \gamma_{i,\omega} \perp P_{-i}(\omega) \geq 0 \qquad \forall\ -i, \omega$$

Results: Cap-and-trade with **demand uncertainty**





Conclusions:

- We propose a two stage capacity expansion model that consider a cap-and-trade system that is also modeled in two stages, an initial allocation carbon market followed by a re-trading market.
- Unlike many other studies, we model actual trade of allowances if economic incentives are present. Several studies consider just a cap component or assume that generators can sell unused allowances in a separate market (buffer).
- The model is used to study the Chilean electric system. We show that current pledges are really not sufficient to meet long-term targets.
- Higher carbon prices are needed (9-10 times higher, at least).

References

[1]C. Yihsu and B. Hobbs, "An oligopolistic power market model with tradable nox permits,"IEEE Transactions on Power Systems, vol. 20, no. 1, pp. 119–129, 2005.533
[1] J. Zhao, B. F. Hobbs, and J.-S. Pang, "Long-run equilibrium modeling of emissions allowance allocation systems in electric power markets,"Operations research, vol. 58, no. 3, pp. 529–548,5352010.536
[3] T. Limpaitoon, Y. Chen, and S. S. Oren, "The impact of carbon cap and trade regulation on congested electricity market equilibrium,"Journal of Regulatory Economics, vol. 40, no. pp. 237–260, 2011.539
[4] G. Mavromatidis, K. Orehounig, and J. Carmeliet, "Design of distributed energy systems under uncertainty: A two-stage stochastic programming approach," Applied energy, vol. 222, pp. 932–541950, 2018.542
[5] J. Liang and W. Tang, "Stochastic multistage co-planning of integrated energy systems considering power-to-gas and the cap-and-trade market,"International Journal of Electrical Power& Energy Systems, vol. 119, p. 105817, 2020.545
[6] L. Boffino, A. J. Conejo, R. Sioshansi, and G. Oggioni, "A two-stage stochastic optimization planning framework to decarbonize deeply electric power systems,"Energy Economics, vol. 84,p. 104457, 2019.548
[7] J. Cristóbal, G. Guillén-Gosálbez, A. Kraslawski, and A. Irabien, "Stochastic milp model for optimal timing of investments in co2 capture technologies under uncertainty in prices,"Energy, vol. 54, pp. 343–351, 2013.551
[8] L. Ji, X. Zhang, G. Huang, and J. Yin, "Development of an inexact risk-aversion optimization model for regional carbon constrained electricity system planning under uncertainty,"Energy conversion and management, vol. 94, pp. 353–364, 2015.554
[9] V. Gonela, "Stochastic optimization of hybrid electricity supply chain considering carbon emission schemes,"Sustainable Production and Consumption, vol. 14, pp. 136–151, 2018.556
[10] M. Li, Y. Li, and G. Huang, "An interval-fuzzy two-stage stochastic programming model for planning carbon dioxide trading under uncertainty,"Energy, vol. 36, no. 9, pp. 5677–5689,5582011.559
[11] Z. Guo, R. Cheng, Z. Xu, P. Liu, Z. Wang, Z. Li, I. Jones, and Y. Sun, "A multi-region load dispatch model for the long-term optimum planning of china's electricity sector,"Applied energy, vol. 185, pp. 556–572, 2017.562
[12] Y. Liu, N. Zhang, C. Kang, Q. Xia, H. Wu, and Z. Chen, "Impact of carbon market on china's electricity market: an equilibrium analysis," in2017 IEEE Power & Energy Society General Meeting, pp. 1–5, IEEE, 2017.565
[13] Y. Chen, W. Lise, J. Sijm, and B. F. Hobbs, "Greenhouse gas emissions trading in the electricity sector: Model formulation and case studies," inHandbook of CO2 in Power Systems, pp. 33–52, Springer, 2012.568
[14] W. Lise, J. Sijm, and B. F. Hobbs, "The impact of the eu ets on prices, profits and emissions in the power sector: simulation results with the competes eu20 model,"Environmental and Resource Economics, vol. 47, no. 1, pp. 23–44, 2010.57123
[15] P. Rocha, T. Das, V. Nanduri, and A. Botterud, "Impact of co2 cap-and-trade programs on restructured power markets with generation capacity investments,"International Journal of Electrical Power & Energy Systems, vol. 71, pp. 195–208, 2015.574
[16] Y. Chen, B. F. Hobbs, J. H. Ellis, C. Crowley, and F. Joutz, "Impacts of climate change on power sector nox emissions: A long-run analysis of the us mid-atlantic region,"Energy Policy, vol. 84, pp. 11–21, 2015