Robust Decarbonization Policies

Nicolas Schlegel – Niels Montanari – Michel De Lara

Citepa, Paris, France
Cermics, École des Ponts ParisTech, France

Data Driven Decision Making School
Centrale Casablanca, Maroc
8-12 mai 2023

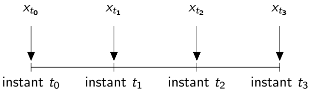
Introduction

- Suppose you want to decarbonize
  an economic sector, a firm, an industrial process
- With 100 visions of the next decades
  (about markets, technologies. . .),
  you can build 100 optimal decarbonization paths
- Each path is perfectly adapted to one vision
- Yet, what happens if the future is different from the vision?
- We propose a method to design
  a single robust decarbonization policy
  that takes into account those 100 scenarios altogether

Plan versus policy

Plan

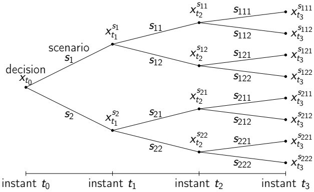
The decisions are function of time



Synonyms
programme, planning, roadmap

Policy

The decisions are function of time and information



Synonyms
strategy, adaptative plan

Application case: decarbonization of a taxi fleet

Outline of the presentation

The classic anticipative approach for decarbonization

The stochastic nonanticipative approach (risk neutral)

The stochastic nonanticipative approach with risk

Conclusion and perspectives

Outline of the presentation

Outline of the presentation

Decarbonization of a taxi fleet

- A taxi company aims at achieving CO_2 emission reductions at least cost
- Emission reductions are assessed with respect to a reference trajectory (business as usual)
- In the reference trajectory, the fleet is made up of 100% of diesel-vehicles
- Set of decarbonization actions

$$\mathcal{A} = \{\text{gasoline, hybrid-gasoline, hybrid-diesel}\}$$

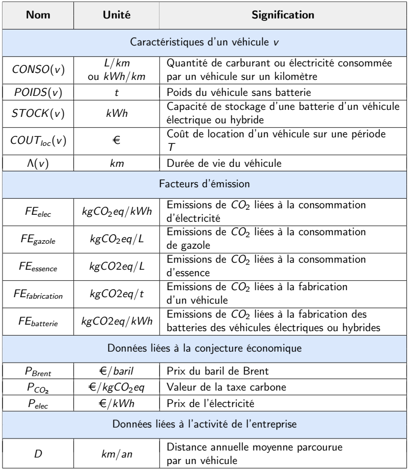
- What actions should be implemented? In which quantities?

Modeling and data

- Decarbonization problems require
  - unitary emission reductions factors
  - unitary costs factors

- Their assessment mobilize experts

- The data are uncertain
  - depends on expert
  - vary between bounds



Nom	Unité	Signification
Caractéristiques d'un véhicule v		
$CONSO(v)$	L/km ou kWh/km	Quantité de carburant ou électricité consommée par un véhicule sur un kilomètre
$POIDS(v)$	t	Poids du véhicule sans batterie
$STOCK(v)$	kWh	Capacité de stockage d'une batterie d'un véhicule électrique ou hybride
$COUT_{loc}(v)$	€	Coût de location d'un véhicule sur une période T
$\Lambda(v)$	km	Durée de vie du véhicule
Facteurs d'émission		
FE_{elec}	$kgCO_2eq/kWh$	Emissions de CO_2 liées à la consommation d'électricité
FE_{gazole}	$kgCO_2eq/L$	Emissions de CO_2 liées à la consommation de gazole
$FE_{essence}$	$kgCO2eq/L$	Emissions de CO_2 liées à la consommation d'essence
$FE_{fabrication}$	$kgCO2eq/t$	Emissions de CO_2 liées à la fabrication d'un véhicule
$FE_{batterie}$	$kgCO2eq/kWh$	Emissions de CO_2 liées à la fabrication des batteries des véhicules électriques ou hybrides
Données liées à la conjecture économique		
P_{Brent}	€$/baril$	Prix du baril de Brent
P_{CO_2}	€$/kgCO_2eq$	Valeur de la taxe carbone
P_{elec}	€$/kWh$	Prix de l'électricité
Données liées à l'activité de l'entreprise		
D	km/an	Distance annuelle moyenne parcourue par un véhicule

Outline of the presentation

A linear problem in an anticipative framework

- Admissible decisions are quantities of actions of decarbonization

$$(x_a)_{a\in\mathcal{A}} \in \mathcal{X} = \left\{ (x_a)_{a\in\mathcal{A}} \in \mathbb{R}_+^{\mathcal{A}} \;\middle|\; \sum_{a\in\mathcal{A}} x_a \leq \text{number of vehicles} \right\}$$

- unitary costs $(c_a)_{a\in\mathcal{A}}$
- unitary emission reductions $(e_a)_{a\in\mathcal{A}}$
- emission reductions target $e^{\#}$

$$\begin{aligned} \min_{x\in\mathcal{X}} \quad & \overbrace{\sum_{a\in\mathcal{A}} c_a x_a}^{\text{total cost}} \\ \text{subject to} \quad & \underbrace{\sum_{a\in\mathcal{A}} e_a x_a}_{\text{emission reductions}} \geq e^{\#} \end{aligned}$$

Solutions (extreme) of the anticipative approach

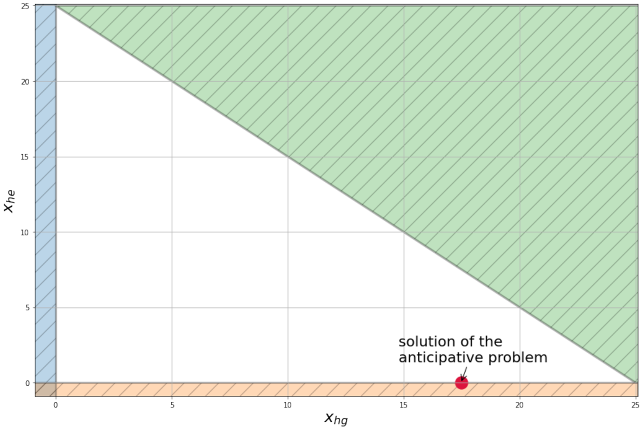


Figure: Variables domain (in white) and solution of the anticipative approach

What happens if we change the data?

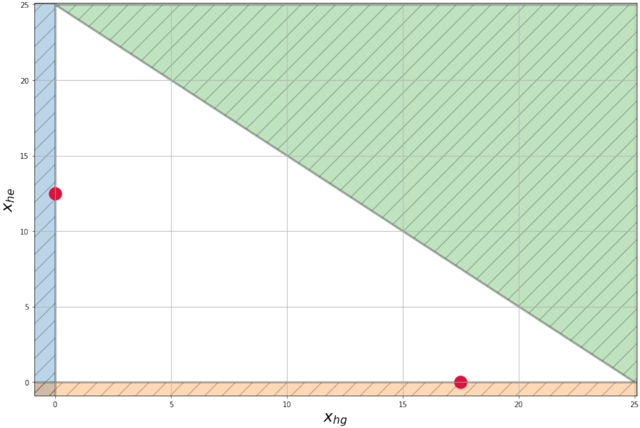


Figure: Variables domain (in white) and two solutions (extreme) of the anticipative approach

The more visions, the more extreme solutions

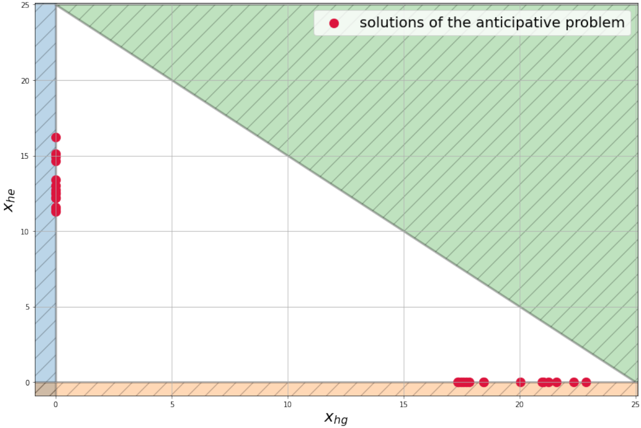


Figure: Variables domain (in white) and solutions (extreme) of the anticipative approach

Outline of the presentation

Discussion

- We have presented the structure of the optimal decarbonization problem
- The formulation is anticipative as it involves single values for the future costs and unitary emissions
- Yet, emissions and costs depend on future uncertainties (mileage, fuel prices. . .)
- We now turn to a stochastic nonanticipative formulation

Outline of the presentation

Outline of the presentation

Data for the stochastic nonanticipative approach

The stochastic nonanticipative approach requires

- a finite set $\mathcal{S}$ of scenarios (future uncertainties)
- a family $\Big\{\big(\pi^s, p^s, (c_a^s)_{a\in\mathcal{A}}, (e_a^s)_{a\in\mathcal{A}}\big),\ s \in \mathcal{S}\Big\}$ of possible data associated with the scenarios where
  - π^s is the probability of the scenario s
  - unitary costs and emissions now depend on the scenario
  - p^s is the carbon compensation price (in $€/tCO_2eq$)

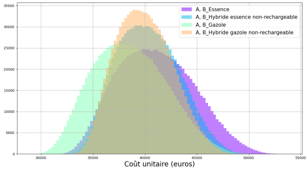


Figure: Histogram of unitary costs of actions

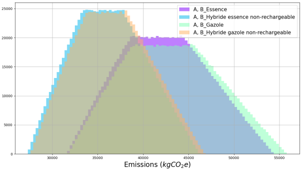


Figure: Histogram of unitary emission reductions of actions

Linear formulation of the stochastic nonanticipative approach

We set the stochastic optimization problem,
with a new recourse decision variable q^s,
representing carbon compensation after uncertainty is resolved

$$\min_{x \in \mathcal{X},\ (q^s)_{s \in \mathcal{S}} \in \mathbb{R}^{\mathcal{S}}} \quad \overbrace{\sum_{s \in \mathcal{S}} \pi^s \Big(\sum_{a \in \mathcal{A}} c_a^s x_a \ + \ \underbrace{q^s p^s}_{\text{compensation cost}} \Big)}^{\text{Mean cost on scenarios}}$$

$$s.t. \quad \sum_{a \in \mathcal{A}} e_a^s x_a + \underbrace{q^s}_{\text{compensation}} \geq e^{\#} \ , \qquad \forall s \in \mathcal{S}$$

$$q^s \geq 0 \ , \qquad \forall s \in \mathcal{S}$$

Equivalent convex formulation of the stochastic nonanticipative approach

$$\min_{x \in \mathcal{X}} \quad \overbrace{\sum_{a \in \mathcal{A}} \bar{c}_a x_a}^{\text{cost of actions}} + \overbrace{\sum_{s \in \mathcal{S}} \pi^s \underbrace{p^s \left[e^{\#} - \sum_{a \in \mathcal{A}} e_a^s x_a \right]_+}_{\text{convex term}}}^{\text{mean compensation cost}}$$

- We minimize a convex function of x so that, in contrast with the solutions of the anticipative approach, the solutions of the stochastic approach can be inner solutions (mixed solutions)
- The convex term can be interpreted as an economic penalty when the decision-maker falls short of the emission reductions target

Solution (inner) of the stochastic approach

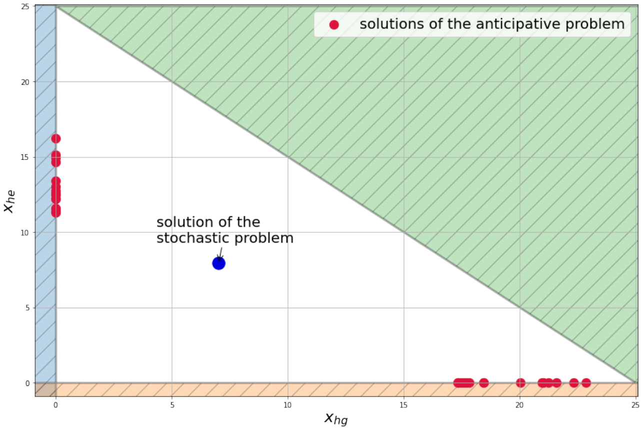


Figure: Solution of the stochastic approach inside the optimization domain

Now for a numerical application

- We have set up a stochastic nonanticipative approach to make solutions more robust to uncertainty

- We are going to perform a numerical application

- We will observe that solutions are not systematically inner. . .

Outline of the presentation

Anticipative versus nonanticipative solutions

- The solution of the stochastic problem
  has been fitted on 10,000 scenarios,
  for a carbon price of 750€$/tCO_2eq$ (discussed later)

- The solution of the anticipative problem
  has been fitted on the mean scenario (over the $10,000$ scenarios)

Problem	**Gasoline**	**Hybrid-Diesel**	**Hybrid-Gasoline**
Anticipative	0	31	0
Stochastic	0	34	0

- We do not observe mixed solutions ☹

Assessment of solutions

- We have generated 1,000,000 test scenarios for emissions and costs
- Solutions of the anticipative and stochastic approaches
  have been assessed on each scenario
- As in the stochastic nonanticipative approach,
  the solution of the anticipative problem is penalized
  when it falls short of the emission reductions target
  (at the same carbon compensation price)
- Costs and emission reductions of the solutions
  are represented on histograms
  (x-axis=value of the parameter, y-axis=frequency of the value)

Nonanticipative approach makes for thinner tail cost distributions

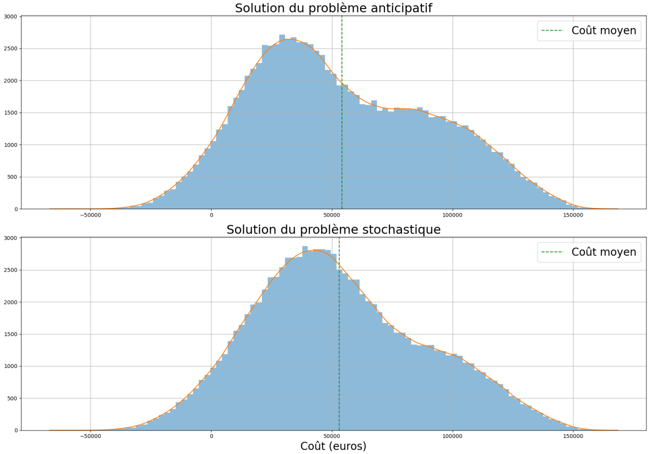


Figure: Histograms of the costs of the solutions of the anticipative and stochatic nonanticipative problems (the more to the left, the better)

Nonanticipative approach with high compensation prices leads to more emission reductions

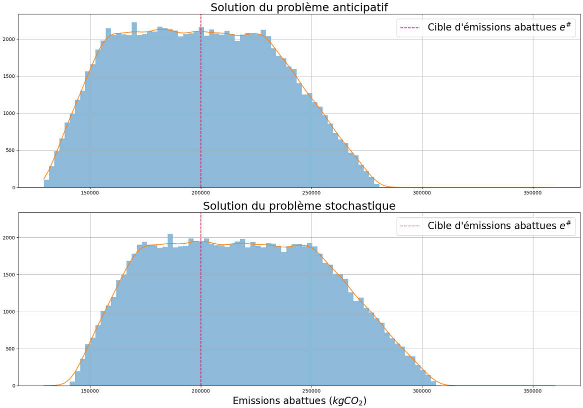


Figure: Histograms of the emission reductions in the solutions of the anticipative and stochatic nonanticipative problems (the more to the right, the better)

With the anticipative solution, compensation costs are higher

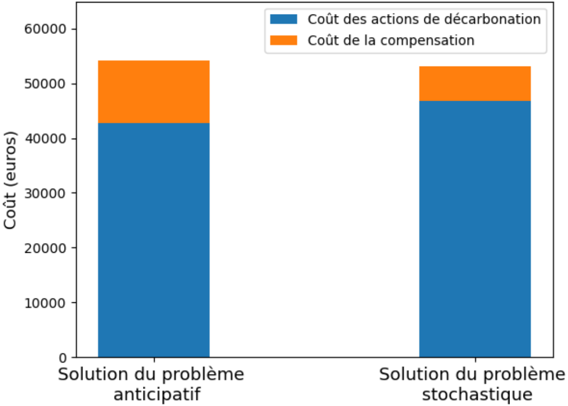


Figure: Part of carbon compensation in each solution

Outline of the presentation

Discussion about the compensation price of carbon

$$\min_{x \in \mathcal{X}} \quad \sum_{a \in \mathcal{A}} \bar{c}_a x_a + \sum_{s \in \mathcal{S}} \pi^s p^s \left[e^{\#} - \sum_{a \in \mathcal{A}} e_a^s x_a \right]_+$$

- What is the impact of the carbon compensation price?
- Even if carbon compensation price p^s should be uncertain (depends on the scenario s),
  we have fixed its value to p to facilitate interpretations

Influence of the compensation price on the solution of the stochastic nonanticipative problem

CO_2 **compensation price** (**€**$/tCO_2eq$)	**Gasoline**	**Hybrid-diesel**	**Hybrid-gasoline**
44.6 (carbon tax)	0	0	0
100	0	0	0
200	0	0	0
250 (SVC2030)	0	25	0
350	0	28	0
500 (SVC2040)	0	31	0
775 (SVC2050)	0	34	0
1,000	0	36	0

Table: Solution of the stochastic problem according to the carbon compensation price
(SVC2030 means "shadow value of carbon in 2030 in France")

Outline of the presentation

The classic anticipative approach for decarbonization
  - Decarbonization of a taxi fleet
  - The anticipative approach
  - Discussion

The stochastic nonanticipative approach (risk neutral)
  - Mathematical formulation
  - Numerical application to the taxi fleet decarbonization problem
  - Sensitivity of solutions to the carbon compensation price
  - Discussion

The stochastic nonanticipative approach with risk
  - Value at risk and Tail value at risk
  - Formulation of the risk-averse optimization problem
  - Numerical application to the taxi fleet decarbonization problem
  - Sensitivity of the solution to risk parameters
  - Discussion

Conclusion and perspectives

Discussion

- The stochastic nonanticipative optimization framework
    - highlights the possible gap between targeted and observed emissions
    - introduces recourse variables penalizing this gap
- High carbon compensation value
  calls for more decarbonization commitment
- We obtain a single solution for 10,000 scenarios ☺
  yet we do not observe mixed solutions ☹
- We now turn to a formulation with risk

Outline of the presentation

The classic anticipative approach for decarbonization
- Decarbonization of a taxi fleet
- The anticipative approach
- Discussion

The stochastic nonanticipative approach (risk neutral)
- Mathematical formulation
- Numerical application to the taxi fleet decarbonization problem
- Sensitivity of solutions to the carbon compensation price
- Discussion

The stochastic nonanticipative approach with risk
- Value at risk and Tail value at risk
- Formulation of the risk-averse optimization problem
- Numerical application to the taxi fleet decarbonization problem
- Sensitivity of the solution to risk parameters
- Discussion

Conclusion and perspectives

Outline of the presentation

Motivation for the risk-averse approach

- In the (risk-neutral) stochastic nonanticipative approach, high costs are balanced by low costs in the mean cost

- What happens if we put more weight on high costs?

Value at risk = quantile

Once chosen the risk level $\lambda \in [0,1]$ (probability), we define

$$\mathrm{VaR}_\lambda(X) = \inf\left\{x \in \mathbb{R},\ \mathbb{P}\big(X \geq x\big) \leq \lambda\right\}$$

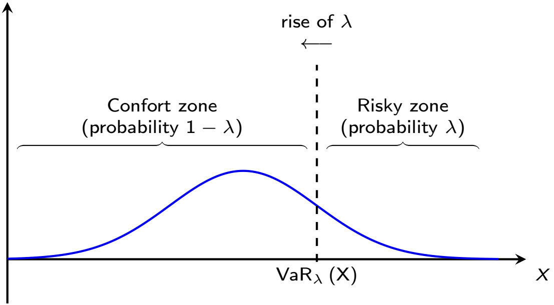


Figure: Illustration of value at risk, risky zone and confort zone

Tail value at risk = expectation above value at risk

$$\mathrm{TVaR}_\lambda\left(X\right) = \mathbb{E}\left[X \middle| X \geq \mathrm{VaR}_\lambda\left(X\right)\right] \left(\geq \mathrm{VaR}_\lambda\left(X\right)\right)$$

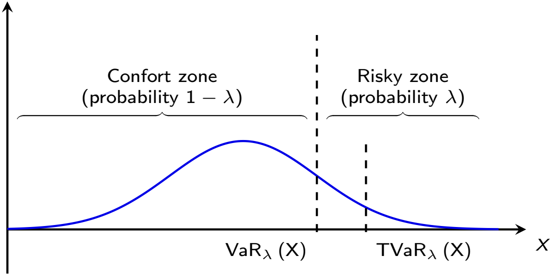


Figure: Illustration of tail value at risk

Outline of the presentation

The classic anticipative approach for decarbonization
  - Decarbonization of a taxi fleet
  - The anticipative approach
  - Discussion

The stochastic nonanticipative approach (risk neutral)
  - Mathematical formulation
  - Numerical application to the taxi fleet decarbonization problem
  - Sensitivity of solutions to the carbon compensation price
  - Discussion

The stochastic nonanticipative approach with risk
  - Value at risk and Tail value at risk
  - Formulation of the risk-averse optimization problem
  - Numerical application to the taxi fleet decarbonization problem
  - Sensitivity of the solution to risk parameters
  - Discussion

Conclusion and perspectives

The risk-averse problem and its parameters

$$\min \quad (1-\theta)\,\mathbb{E}\left[COSTS\right] + \theta\ \mathrm{TVaR}_{\lambda}\left(COSTS\right)$$

- λ is a probability defining the size of the risky zone

Worst cost minimization — Stochastic problem (risk-neutral)

$\lambda \to 0$ — $\lambda = 1$

- θ is a coefficient of weight on the risk measure

Stochastic problem (risk-neutral) — Totally risk-averse problem

$\theta = 0$ — $\theta = 1$

Linear formulation of the risk-averse problem

$$\mathrm{TVaR}_{\lambda}\left(\mathrm{X}\right) = \inf\left\{ \frac{\mathbb{E}\left[[\mathrm{X}-u]_{+}\right]}{\lambda} + u,\ u \in \mathbb{R} \right\}$$

Hence the linear formulation of the risk-averse problem

$$\begin{aligned}
\min_{\substack{x\in\mathcal{X},\ (q^s)_{s\in\mathcal{S}},\\ (v^s)_{s\in\mathcal{S}},\ u}} \quad & (1-\theta)\Big(\sum_{a\in\mathcal{A}} \bar{c}_a x_a + \sum_{s\in\mathcal{S}} \pi^s q^s p^s\Big) + \theta\Big(\frac{1}{\lambda}\sum_{s\in\mathcal{S}} \pi^s v^s + u\Big) \\
s.t. \quad & \sum_{a\in\mathcal{A}} e_a^s x_a + q^s \geq e^{\#}\ , && \forall s\in\mathcal{S} \\
& v^s \geq \sum_{a\in\mathcal{A}} c_a^s x_a + q^s p^s - u\ , && \forall s\in\mathcal{S} \\
& v^s \geq 0\ , && \forall s\in\mathcal{S} \\
& q^s \geq 0\ , && \forall s\in\mathcal{S}
\end{aligned}$$

Intermediate solutions between risk-neutral problem and minimization of the worst case

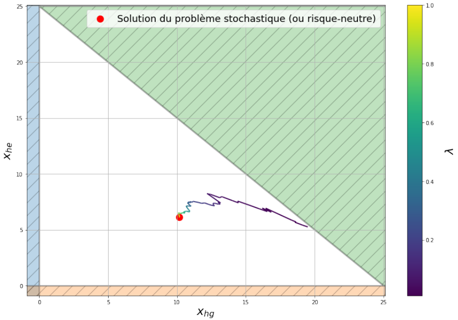


Figure: Evolution of the solutions of the risk-averse problem for $\theta = 1$ when λ varies between 1 (red point on the graph, risk-neutral) and 0 (other side of the path on the graph, worst case scenario)

- Reducing the risky zone ($\lambda \searrow$) calls for more decarbonization actions

Intermediate solutions between risk-neutral and totally risk-averse problems

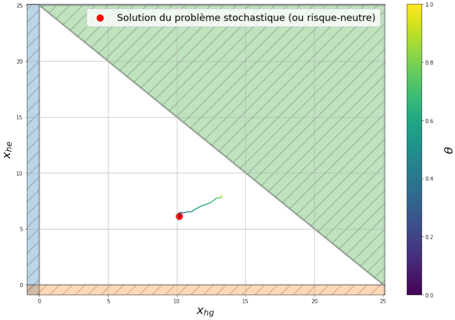


Figure: Evolution of the solutions of the risk-averse problem for $\lambda = 0.05$ when θ varies between 0 (red point on the graph, risk-neutral) and 1 (other side of the path on the graph, totally risk averse)

- Increasing risk weight ($\theta \nearrow$) calls for more decarbonization actions

Outline of the presentation

Comparison of the solutions of the three methods

Problem	**Gasoline**	**Hybrid-Diesel**	**Hybrid-Gasoline**
Anticipative	0	31	0
Stochastic (risk-neutral)	0	34	0
Risk-averse ($\lambda = 0.05$, $\theta = 0.8$)	0	25	14

Table: Solutions of the three approaches for a carbon compensation price of 750€/TCO_2eq

- The risk-averse approach yields mixed solutions ☺

Comparison of costs histograms

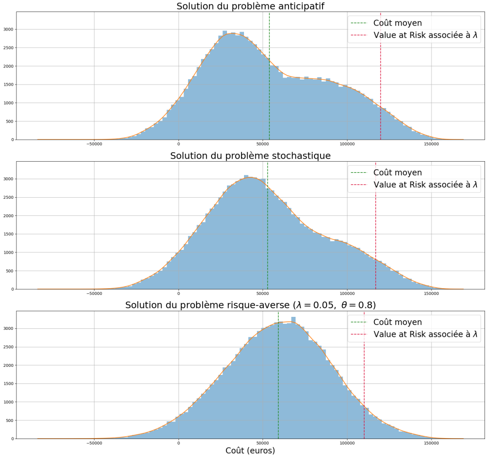


Figure: Cost histograms induced by the solutions of the three approaches (the more to the left, the better)

Comparison of emissions histograms

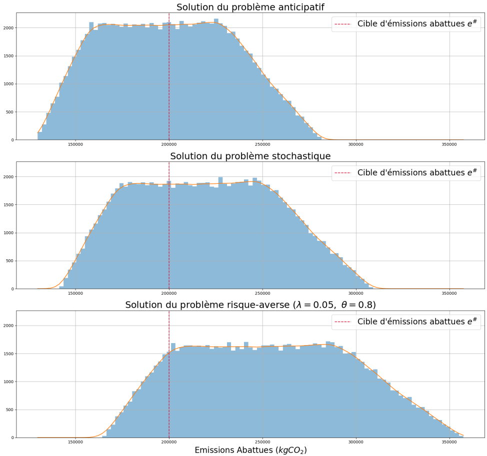


Figure: Emissions histograms induced by the solutions of the three approaches (the more to the right, the better)

With the risk-averse approach, compensation costs are even lower

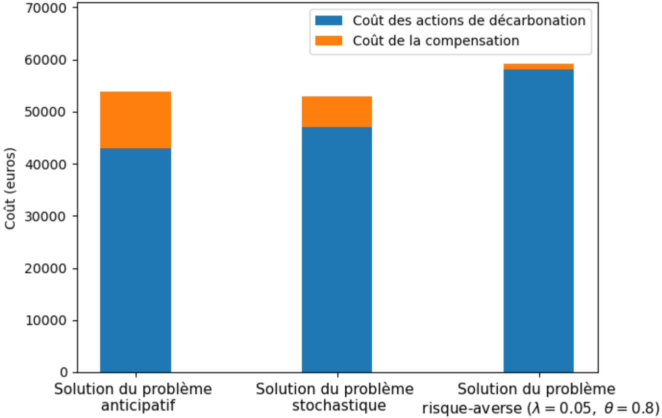


Figure: Part of carbon compensation in each solution

Outline of the presentation

Mixed solutions appear as risk aversion increases ($\lambda \to 0$ and $\theta \to 1$)

risk-neutral → worst case

risk-neutral ↓ totally risk-averse

		$\lambda = 1$			$\lambda = 0.5$			$\lambda = 0.2$			$\lambda = 0.01$		
		E	HG	HE	E	HG	HE	E	HG	HE	E	HG	HE
θ	0	0	34	0	0	34	0	0	34	0	0	34	0
	0.2	0	34	0	0	35	0	0	35	0	0	34	0
	0.4	0	34	0	0	35	0	0	37	0	0	35	0
	0.6	0	34	0	0	35	0	0	38	0	0	25	11
	0.8	0	34	0	0	36	0	0	30	8	0	23	16
	1	0	34	0	0	36	0	0	26	12	0	23	17

Table: Solutions of the risk-averse problem for several values θ and λ and a carbon compensation price of 750€$/tCO_2eq$

The tail of the cost distribution becomes thiner as one gets more risk-averse

risk-neutral

totally risk-averse

toward the minimization of the worts cost

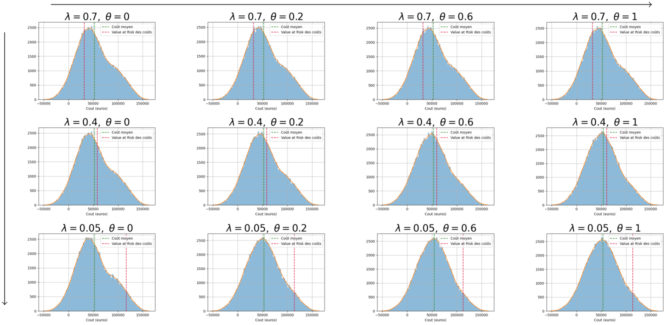


Figure: Histograms of the costs of solutions of the risk-averse problem for different values of λ and θ

The more risk averse, the less compensation

totally
risk-averse

risk-neutral

toward the
minimization
of the
worts cost

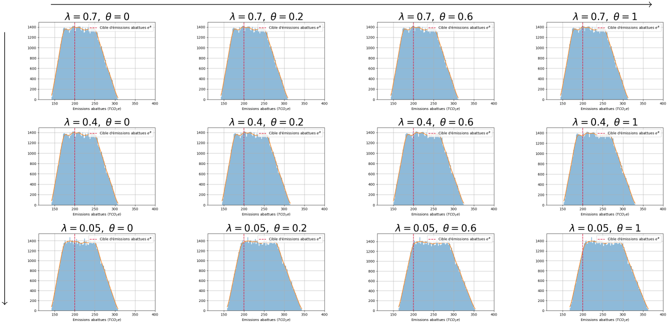


Figure: Histograms of the emission reduction obtained without compensation of solutions of the risk-averse problem for diferent values of λ and θ

Outline of the presentation

Discussion

- Including risk-aversion into the stochastic approach makes for cost distributions with thiner right tails

- High risk aversion encourages mixed solutions

- Risk-averse formulations require a trade-off between mean cost and thin-tail distribution

Outline of the presentation

Conclusion

- We have formulated optimal decarbonization problems, in which emissions and costs are observed after the decisions and are subject to future uncertainties

- The stochastic framework
  - produces a single solution that takes into account a range of plausible futures altogether
  - enables the anticipation and the penalization of the gap between observed and targeted emission reductions

- In our numerical experiments, we have observed that
  - extreme solutions exist even in the stochastic case
  - as the carbon compensation price increases, more actions are taken
  - as risk-aversion increases, mixed solutions are favoured and tails of cost distributions get thiner

Perspectives

This project would benefit from

- applications to other case studies
- an in-depth economic work about the meaning and the value of the carbon compensation cost
- the development of multistage approaches, allowing decisions at several timesteps

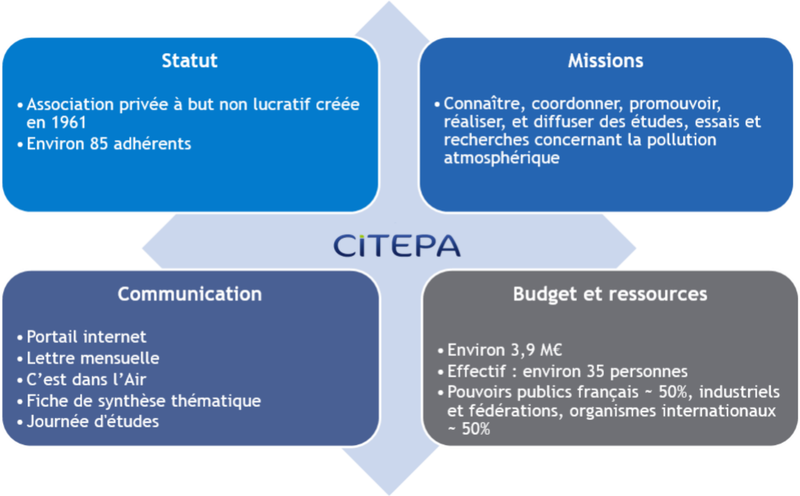
Thanks for your attention!

École des Ponts
ParisTech

CITEPA

le cnam

Présentation du Citepa



Statut

- Association privée à but non lucratif créée en 1961
- Environ 85 adhérents

Missions

- Connaître, coordonner, promouvoir, réaliser, et diffuser des études, essais et recherches concernant la pollution atmosphérique

CITEPA

Communication

- Portail internet
- Lettre mensuelle
- C'est dans l'Air
- Fiche de synthèse thématique
- Journée d'études

Budget et ressources

- Environ 3,9 M€
- Effectif : environ 35 personnes
- Pouvoirs publics français ~ 50%, industriels et fédérations, organismes internationaux ~ 50%

The decarbonization problem

Data
- emission reductions target $e^{\#}$
- action set $\mathcal{A}$
- unitary costs of actions $(c_a)_{a\in\mathcal{A}}$
- unitary emission factors $(e_a)_{a\in\mathcal{A}}$

Objective
- We want fulfill the emission reductions commitment at least cost

Question
- What actions should be implemented?
- In which quantities?

Introduction of risk measures

- Two cost distributions can have the same mean value, but can be looked at differently by the decision-maker
- Thin-tail costs distribution are perceived as less risky than fat-tail costs distribution

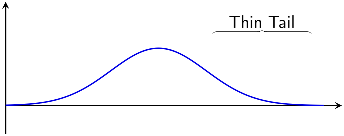


Figure: Thin-tail cost distribution

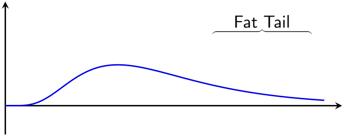
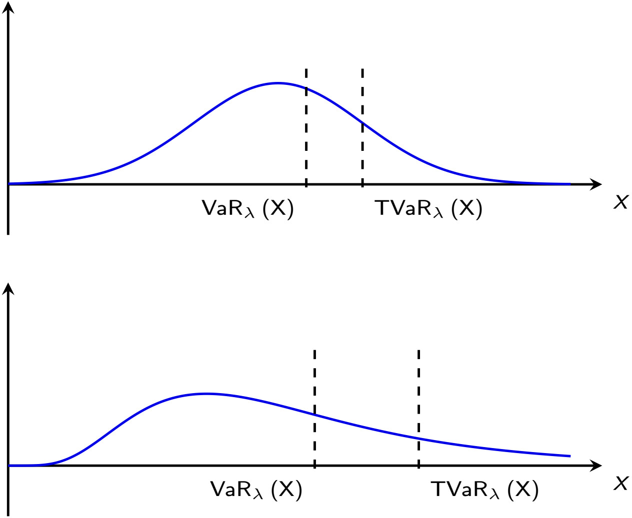


Figure: Fat-tail cost distribution

Tail value at risk on thin-tail and fat-tail distributions



Influence of the carbon compensation price on the solution

risk-neutral → worst case

CO_2 compensation price (€/$TCO2eq$)	$\lambda = 1$			$\lambda = 0.5$			$\lambda = 0.2$			$\lambda = 0.01$		
	G	**HE**	**HG**	**G**	**HE**	**HG**	**G**	**HE**	**HG**	**G**	**HE**	**HG**
44.6 (carbon tax)	0	0	0	0	0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
200	0	0	0	0	0	0	0	0	0	0	0	0
250 (SPC2030)	0	25	0	0	0	0	0	0	0	0	0	0
300	0	26	0	0	0	0	0	0	0	0	0	0
350	0	28	0	0	27	2	0	0	0	0	0	0
400	0	29	0	0	29	2	0	0	0	0	0	0
450	0	30	0	0	32	1	0	0	0	0	0	0
500 (SPC2040)	0	31	0	0	33	1	0	18	14	0	0	0
550	0	32	0	0	34	1	0	21	13	0	0	0
600	0	32	0	0	34	1	0	23	12	0	0	0
700	0	33	0	0	35	1	0	25	12	0	25	15
775 (SPC2050)	0	34	0	0	36	1	0	26	11	0	27	14
900	0	35	0	0	37	1	0	27	11	0	30	12
1000	0	36	0	0	41	1	0	28	11	0	31	11

Table: Solutions of the risk-averse problem for different values of λ and of the carbon compensation price, when $\theta = 1$
(SVC2030 means "shadow value of carbon in 2030 in France")