FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Sequential Contracts for Uncertain Electricity Resources

Hamidreza Tavafoghi

joint with Demosthenis Teneketzis

University of Michigan

Berkeley UNIVERSITY OF CALIFORNIA
Massachusetts Institute of Technology
NSF
MICHIGAN
VANDERBILT UNIVERSITY

Outline

- Motivation & Background

Outline

- Motivation & Background
    - Firm Contracts

Outline

- Motivation & Background
    - Firm Contracts
- Sequential model

Outline

- Motivation & Background
  - Firm Contracts
- Sequential model
- Propose two (flexible) sequential contracts with and without monitoring

Outline

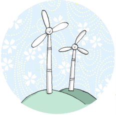
- Motivation & Background
  - Firm Contracts
- Sequential model
- Propose two (flexible) sequential contracts with and without monitoring
- Comparison of the three different contract schemes

Outline

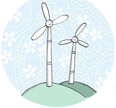
- Motivation & Background
  - Firm Contracts
- Sequential model
- Propose two (flexible) sequential contracts with and without monitoring
- Comparison of the three different contract schemes
- Conclusion & future work

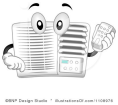
Smart Grids

- Introduction of new electricity resources into the grid
  - Renewable energy (RE) resources: wind, solar
  - Flexible/responsive demands: deferrable loads



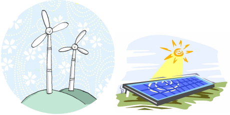
- Introduction of new electricity resources into the grid
  - Renewable energy (RE) resources: wind, solar
  - Flexible/responsive demands: deferrable loads





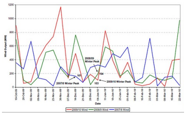
33% penetration by 2020 in California

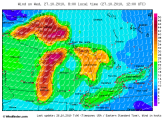
- Introduction of new electricity resources into the grid
  - Renewable energy (RE) resources: wind, solar
  - Flexible/responsive demands: deferrable loads



33% penetration by 2020 in California

- **Key characteristics:**
  - **Uncertainty**: cannot follow a predetermined schedule (non-dispatchable resources)
  - **Dynamic information**: Information arrives over time. Wind generation can be precisely predicted only 15min in advance.





Market Design

“**Develop rules for market evolution that enable system flexibility**” is listed as an area of intervention to accommodate high renewable energy penetration. **NREL**, "Integrating Variable Renewable Energy in Electric Power Markets“, 2012.

> *Actions to Support Flexibility: lead the development and innovation of market designs; encourage market operators to adopt rules to improve system efficiency; and play a leading role in negotiating a framework for integration that optimizes flexibility across regions*

Market Design

"**Develop rules for market evolution that enable system flexibility**" is listed as an area of intervention to accommodate high renewable energy penetration. **NREL**, "Integrating Variable Renewable Energy in Electric Power Markets", 2012.

Actions to Support Flexibility: lead the development and innovation of market designs; encourage market operators to adopt rules to improve system efficiency; and play a leading role in negotiating a framework for integration that optimizes flexibility across regions

Question: What is an appropriate market mechanism that addresses **uncertainty** and **dynamic varying** nature of new resources in addition to **strategic behavior** and **private information** considerations?

Current Practice (in the U.S.)

Small share of RE $\sim 4\%$ penetration

Uncertain resources (mostly wind) are integrated into the RT market

- Participating Intermittent Resource Program (PIRP) in California requires SO to accept all produced wind power
- Highly Subsidized, *e.g.* 30% subsidy for investment, guaranteed grid-access
- No (mild) imbalance penalties
- Fixed feed-in tariffs
- Costs of reserved are socialized among load serving entities (LSE)

Current Practice (in the U.S.)

Small share of RE $\sim 4\%$ penetration

Uncertain resources (mostly wind) are integrated into the RT market

- Participating Intermittent Resource Program (PIRP) in California requires SO to accept all produced wind power
- Highly Subsidized, *e.g.* 30% subsidy for investment, guaranteed grid-access
- No (mild) imbalance penalties
- Fixed feed-in tariffs
- Costs of reserved are socialized among load serving entities (LSE)

This approach cannot be sustained for higher penetration levels

- Reliability and stability concerns
- LSEs are reluctant to undertake the increased cost of reserves
- Social welfare loss
- Uncertain resources need to be exposed to market mechanisms

Alternative Practive (in the U.K.)

Firm contract : The RE generator commits to a firm quantity q in advance, upon deviation it pays penalty at marginal rate λ.

Example: wind generator $\quad C(q) := \mathbb{E}_W \{\lambda \max(q - g(W), 0)\}$

Alternative Practive (in the U.K.)

Firm contract : The RE generator commits to a firm quantity q in advance, upon deviation it pays penalty at marginal rate λ.

Example: wind generator $C(q) := \mathbb{E}_W \{\lambda \max(q - g(W), 0)\}$

- Fits to the current two-settlement market structure

Related Literature: Bitar *et al.* (2012), Goldsmith *et al.* (2014), Bitar *et al.* (2014), Nayyar *et al.* (2014), Jain *et al.* (2014)

Alternative Practive (in the U.K.)

Firm contract : The RE generator commits to a firm quantity q in advance, upon deviation it pays penalty at marginal rate λ.

Example: wind generator $C(q) := \mathbb{E}_W \{\lambda \max(q - g(W), 0)\}$

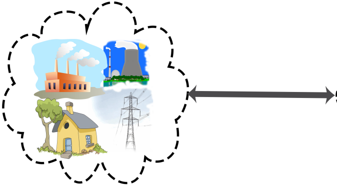
- Fits to the current two-settlement market structure
- Treats uncertain resources as conventional resources

Ignores the available information that arrives after the contract signing

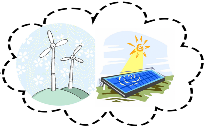
Provides no flexibility for uncertain resources

Related Literature: Bitar *et al.* (2012), Goldsmith *et al.* (2014), Bitar *et al.* (2014), Nayyar *et al.* (2014), Jain *et al.* (2014)

Model

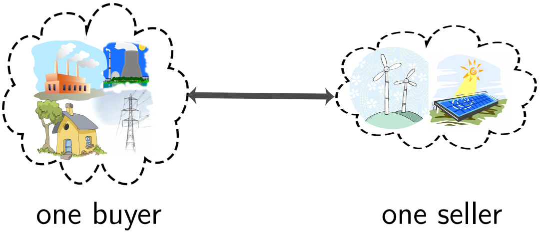


one buyer



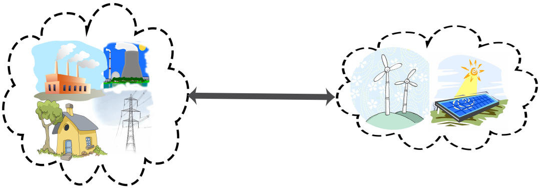
one seller

Model



- Buyer's utility $\mathcal{V}(q)$ with marginal utility $v(q)$

Model

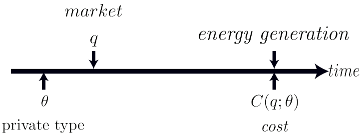


one buyer   one seller

- Buyer's utility $\mathcal{V}(q)$ with marginal utility $v(q)$
- Seller's cost $C(q;\theta)$ with marginal cost $c(q;\theta)$
  θ: seller's type

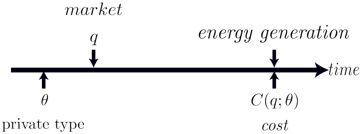
Time Diagram

- Conventional generators

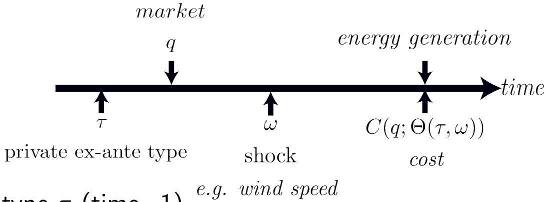


Time Diagram

- Conventional generators



- Uncertain Resources (*e.g.* wind farm)



  - Ex-ante type τ (time=1)
  - Shock ω (time=2)
  - (Ex-post) type $\theta = \Theta(\tau, \omega)$ increasing in τ and ω.

Model

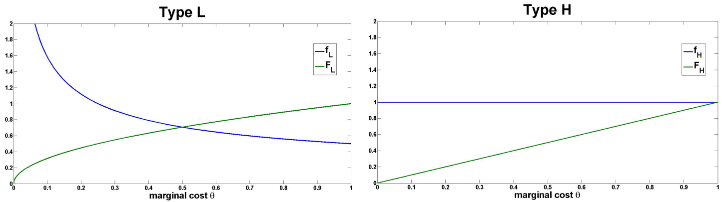
- **time** $=\mathbf{1}$, τ takes two values: H and L with prob. p_L and p_H
  $F_L(\theta)$ and $F_H(\theta)$: conditional cdf of ex-post type θ
- **time** $=\mathbf{1}^+$: buyer and seller sign a contract
  agree on quantity and payment (functions) (q, t)
- **time** $=\mathbf{2}$: ω is observed with cdf $G(\omega)$, ω is independent of τ

Model

- **time** $=$ **1**, τ takes two values: H and L with prob. p_L and p_H
  $F_L(\theta)$ and $F_H(\theta)$: conditional cdf of ex-post type θ

- **Type L has a lower cost on average** (**FSD**):

  $F_H(\theta) \leq F_L(\theta)$ for all $\theta \in [\underline{\theta}, \overline{\theta}]$ (first order stochastic dominance)



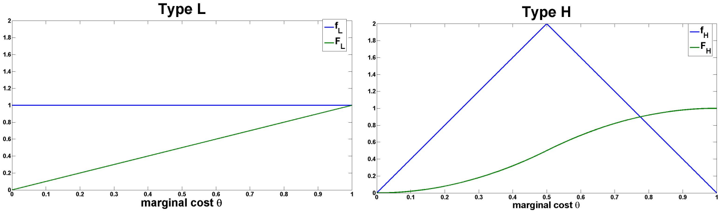
Example: wind farm $C(q; \Theta(\tau, \omega)) = \lambda \max\left\{q - \gamma_\tau \omega^3, 0\right\}, \ \gamma_L > \gamma_H$

Model

- **time** $= \mathbf{1}$, τ takes two values: H and L with prob. p_L and p_H
  $F_L(\theta)$ and $F_H(\theta)$: conditional cdf of ex-post type θ

- **Type L has higher uncertainty, same expected cost** (**MPS**):

  $\theta_L = \theta_H + \xi$ where $\mathbb{E}\{\xi|\theta_H\} = 0$ (mean preserving spread)



Model

- **time** $=\mathbf{1}$, τ takes two values: H and L with prob. p_L and p_H
  $F_L(\theta)$ and $F_H(\theta)$: conditional cdf of ex-post type θ
- **time** $=\mathbf{1}^+$: buyer and seller sign a contract
  agree on quantity and payment (functions) (q,t)
- **time** $=\mathbf{2}$: ω is observed with cdf $G(\omega)$, ω is independent of τ

The difference between ex-ante types:

(i) FSD: type L has a lower cost on average

(ii) MPS: same expected cost, type L has a higher uncertainty

Model - Assumption

Both buyer and seller are risk neutral (quasi-linear utility)

Buyer is the mechanism designer

Technical assumptions:

- *Non-shifting support*
- *Monotone cross hazard rate*

Mechanism Design Problem

Buyer's objective (from the revelation principle):

$$\underset{(q,t)}{\text{maximize}} \quad \mathbb{E}\{\mathcal{V}(q(\tau,\omega)) - t(\tau,\omega)\}$$

Mechanism Design Problem

Buyer's objective (from the revelation principle):

$$\begin{aligned} \underset{(q,t)}{\text{maximize}} \quad & \mathbb{E}\{\mathcal{V}(q(\tau,\omega)) - t(\tau,\omega)\} \\ \text{subject to} \quad & \text{incentive compatibility (IC)} \\ & \text{individual rationality (IR)} \end{aligned}$$

- **IC**: the seller has incentive to report truthfully its private information
- **IR**: the seller earns a positive expected utility

Mechanism Design Problem

Buyer's objective (from the revelation principle):

$$\underset{(q,t)}{\text{maximize}} \quad \mathbb{E}\{\mathcal{V}(q(\tau,\omega)) - t(\tau,\omega)\}$$

$$\text{subject to} \quad \text{incentive compatibility (IC)}$$

$$\text{individual rationality (IR)}$$

- **IC**: the seller has incentive to report truthfully its private information
- **IR**: the seller earns a positive expected utility

We have $\mathcal{S} - \mathcal{R} = \mathbb{E}\{\mathcal{V}(q(\tau,\omega)) - t(\tau,\omega)\}$

$\mathcal{S}$: social welfare (buyer's utility + seller's utility)

$\mathcal{R}$: seller's utility (information rent)

Mechanism Design Problem

Buyer's objective (from the revelation principle):

$$\begin{aligned} \underset{(q,t)}{\text{maximize}} \quad & \mathcal{S} - \mathcal{R} \\ \text{subject to} \quad & \text{incentive compatibility (IC)} \\ & \text{individual rationality (IR)} \end{aligned}$$

- **IC**: the seller has incentive to report truthfully its private information
- **IR**: the seller earns a positive expected utility

We have $\mathcal{S} - \mathcal{R} = \mathbb{E}\{\mathcal{V}(q(\tau,\omega)) - t(\tau,\omega)\}$

$\mathcal{S}$: social welfare (buyer's utility + seller's utility)

$\mathcal{R}$: seller's utility (information rent)

Efficient Allocation

Full information, no strategic behavior ($\mathcal{R} = 0$)

$$\underset{(q,t)}{\text{maximize}} \quad \mathcal{S}$$

Efficient allocation

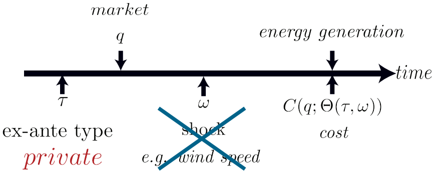
$$v(\tilde{q}^{e*}(\tau, \theta)) = c(\tilde{q}^{e*}(\tau, \theta))$$

Firm Contract

- **Firm allocation:** $q^f(\tau)$ is fixed and independent of ω
  $t^f(\tau)$ denote the expected payment.

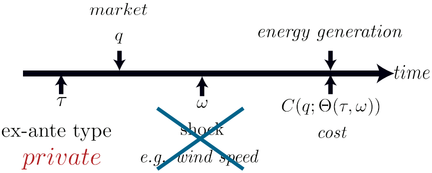
Firm Contract

- **Firm allocation:** $q^f(\tau)$ is fixed and independent of ω
  $t^f(\tau)$ denote the expected payment.



Firm Contract

- **Firm allocation:** $q^f(\tau)$ is fixed and independent of ω
  $t^f(\tau)$ denote the expected payment.



The optimal firm forward contract:

$$\begin{aligned} \underset{(q^f,t^f)}{\text{maximize}} \quad & \mathcal{S} - \mathcal{R} \\ \text{subject to} \quad & \text{IC for ex-ante type } \tau \\ & IR \end{aligned}$$

Firm Contract

Theorem

With two ex-ante types, the allocation $q^{f*}(\tau)$ of the optimal firm forward contract satisfies

$$v(\tilde{q}^{f*}(L)) = \mathbb{E}_{F_L}\left\{c(\tilde{q}^{f*}(L);\theta)\right\},$$
$$v(\tilde{q}^{f*}(H)) = \mathbb{E}_{F_H}\left\{c(\tilde{q}^{f*}(H);\theta)\right\} + \frac{p_L}{p_H}\left[\mathbb{E}_{F_H}\{c(\tilde{q}^{f*}(H);\theta)\} - \mathbb{E}_{F_L}\{c(\tilde{q}^{f*}(H);\theta)\}\right];$$

distortion due to exclusion new information (shock ω)
distortion due to strategic behavior

Firm Contract

Theorem

With two ex-ante types, the allocation $q^{f*}(\tau)$ of the optimal firm forward contract satisfies

$$v(\tilde{q}^{f*}(L)) = \mathbb{E}_{F_L}\big\{c(\tilde{q}^{f*}(L);\theta)\big\},$$
$$v(\tilde{q}^{f*}(H)) = \mathbb{E}_{F_H}\big\{c(\tilde{q}^{f*}(H);\theta)\big\} + \frac{p_L}{p_H}\big[\mathbb{E}_{F_H}\{c(\tilde{q}^{f*}(H);\theta)\} - \mathbb{E}_{F_L}\{c(\tilde{q}^{f*}(H);\theta)\}\big];$$

the associated payment function $t^{f*}(\tau)$ is given by

$$\tilde{t}^{f*}(L) = \mathbb{E}_{F_L}\big\{C(\tilde{q}^{f*}(L);\theta)\big\} + \big[\mathbb{E}_{F_H}\big\{C(\tilde{q}^{f*}(H);\theta)\big\} - \mathbb{E}_{F_L}\big\{C(\tilde{q}^{f*}(H);\theta)\big\}\big]$$
$$\tilde{t}^{f*}(H) = \mathbb{E}_{F_H}\big\{C(\tilde{q}^{f*}(H);\theta)\big\}$$

cost compensation

Firm Contract

Theorem

With two ex-ante types, the allocation $q^{f*}(\tau)$ of the optimal firm forward contract satisfies

$$v(\tilde{q}^{f*}(L)) = \mathbb{E}_{F_L}\Big\{c(\tilde{q}^{f*}(L);\theta)\Big\},$$
$$v(\tilde{q}^{f*}(H)) = \mathbb{E}_{F_H}\Big\{c(\tilde{q}^{f*}(H);\theta)\Big\} + \frac{p_L}{p_H}\Big[\mathbb{E}_{F_H}\{c(\tilde{q}^{f*}(H);\theta)\} - \mathbb{E}_{F_L}\{c(\tilde{q}^{f*}(H);\theta)\}\Big];$$

the associated payment function $t^{f*}(\tau)$ is given by

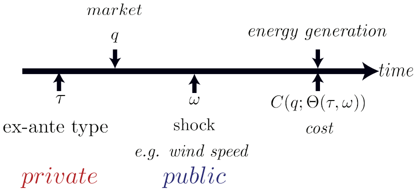
$$\tilde{t}^{f*}(L) = \mathbb{E}_{F_L}\Big\{C(\tilde{q}^{f*}(L);\theta)\Big\} + \Big[\mathbb{E}_{F_H}\Big\{C(\tilde{q}^{f*}(H);\theta)\Big\} - \mathbb{E}_{F_L}\Big\{C(\tilde{q}^{f*}(H);\theta)\Big\}\Big]$$
$$\tilde{t}^{f*}(H) = \mathbb{E}_{F_H}\Big\{C(\tilde{q}^{f*}(H);\theta)\Big\}$$

cost compensation

incentive for truth-telling of ex-ante type L

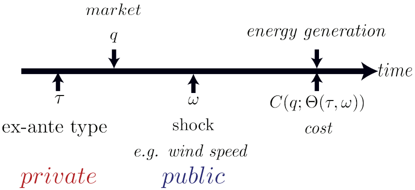
Flexible Contract with Public Shock

- **Flexible contract with public shock:** ex-ante type τ is private and shock ω is publicly observed (*e.g.* wind speed).



Flexible Contract with Public Shock

- **Flexible contract with public shock:** ex-ante type τ is private and shock ω is publicly observed (*e.g.* wind speed).



$q^c(\tau,\omega)$: allocation function $\qquad$ $t^c(\tau,\omega)$: payment function

The optimal flexible contract with public shock

$$\begin{aligned} \underset{(q^c,t^c)}{\text{maximize}} \quad & \mathcal{S} - \mathcal{R} \\ \text{subject to} \quad & \text{IC for ex-ante type } \tau \\ & IR \end{aligned}$$

Flexible Contract with Public Shock

Theorem

With two ex-ante types, the allocation $q^{c*}(\tau, \omega)$ of the optimal flexible contract with public shock satisfies

$$v(q^{c*}(L,\omega)) = c(q^{c*}(L,\omega); \Theta(L,\omega)),$$

$$v(q^{c*}(H,\omega)) = c(q^{c*}(H,\omega); \Theta(H,\omega)) + \frac{p_L}{p_H}[c(q^{c*}(H,\omega);\Theta(H,\omega)) - c(q^{c*}(H,\omega);\Theta(L,\omega))];$$

distortion due to strategic behavior

Flexible Contract with Public Shock

Theorem

With two ex-ante types, the allocation $q^{c*}(\tau,\omega)$ of the optimal flexible contract with public shock satisfies

$$v(q^{c*}(L,\omega)) = c(q^{c*}(L,\omega);\Theta(L,\omega)),$$

$$v(q^{c*}(H,\omega)) = c(q^{c*}(H,\omega);\Theta(H,\omega)) + \frac{p_L}{p_H}[c(q^{c*}(H,\omega);\Theta(H,\omega)) - c(q^{c*}(H,\omega);\Theta(L,\omega))];$$

the associated payment function $t^{c*}(\tau,\omega)$ is given by

$$t^{c*}(L,\omega) = C(q^{c*}(L);\Theta(L,\omega)) + [C(q^{c*}(H);\Theta(H,\omega)) - C(q^{c*}(H);\Theta(L,\omega))],$$

$$t^{c*}(H,\omega) = C(q^{c*}(H);\Theta(H,\omega))$$

cost compensation

Flexible Contract with Public Shock

Theorem

With two ex-ante types, the allocation $q^{c*}(\tau,\omega)$ of the optimal flexible contract with public shock satisfies

$$v(q^{c*}(L,\omega)) = c(q^{c*}(L,\omega);\Theta(L,\omega)),$$
$$v(q^{c*}(H,\omega)) = c(q^{c*}(H,\omega);\Theta(H,\omega)) + \frac{p_L}{p_H}[c(q^{c*}(H,\omega);\Theta(H,\omega)) - c(q^{c*}(H,\omega);\Theta(L,\omega))];$$

the associated payment function $t^{c*}(\tau,\omega)$ is given by

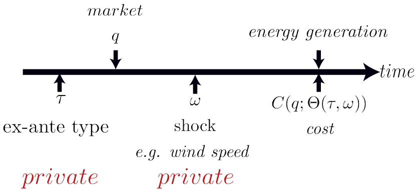
$$t^{c*}(L,\omega) = C(q^{c*}(L);\Theta(L,\omega)) + [C(q^{c*}(H);\Theta(H,\omega)) - C(q^{c*}(H);\Theta(L,\omega))],$$
$$t^{c*}(H,\omega) = C(q^{c*}(H);\Theta(H,\omega))$$

cost compensation

incentive for truth-telling of ex-ante type L

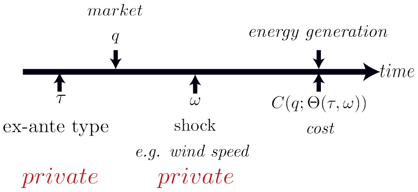
Flexible Contract with Private Shock

- **Flexible contract with private shock:** ex-ante type τ and shock ω are private information (no monitoring of wind speed).



Flexible Contract with Private Shock

- **Flexible contract with private shock:** ex-ante type τ and shock ω are private information (no monitoring of wind speed).



$q^p(\tau, \omega)$: allocation function $t^p(\tau, \omega)$: payment function

The optimal flexible contract with public shock

$$\begin{aligned} \underset{(q^p, t^p)}{\text{maximize}} \quad & \mathcal{S} - \mathcal{R} \\ \text{subject to} \quad & \text{IC for ex-ante type } \tau\text{, IC for shock } \omega \\ & IR \end{aligned}$$

Flexible Contract with Private Shock

Theorem

With two ex-ante types, the allocation $\tilde{q}^{p*}(\tau,\theta)$ of the optimal flexible contract with private shock satisfies

$$v\left(\tilde{q}^{p*}(L,\theta);\theta\right) = c(\tilde{q}^{p*}(L,\theta);\theta),$$

$$v\left(\tilde{q}^{p*}(H,\theta);\theta\right) = c(\tilde{q}^{p*}(H,\theta);\theta) + \frac{p_L}{p_H}\left[\frac{F_L(\theta) - F_H(\theta)}{f_H(\theta)}\right] c_\theta(\tilde{q}^{p*}(H,\theta);\theta);$$

distortion due to strategic behavior

Flexible Contract with Private Shock

Theorem

With two ex-ante types, the allocation $\tilde{q}^{p*}(\tau,\theta)$ of the optimal flexible contract with private shock satisfies

$$v\left(\tilde{q}^{p*}(L,\theta);\theta\right) = c(\tilde{q}^{p*}(L,\theta);\theta),$$

$$v\left(\tilde{q}^{p*}(H,\theta);\theta\right) = c(\tilde{q}^{p*}(H,\theta);\theta) + \frac{p_L}{p_H}\left[\frac{F_L(\theta)-F_H(\theta)}{f_H(\theta)}\right] c_\theta(\tilde{q}^{p*}(H,\theta);\theta);$$

the associated payment function $\tilde{t}^{p*}(\tau,\theta)$ is given by

$$\tilde{t}^{p*}(L,\theta) = C(\tilde{q}^{p*}(L,\theta);\theta) + \int\left[F_L(\hat{\theta})-F_H(\hat{\theta})\right] C_\theta(\tilde{q}^{p*}(H,\hat{\theta});\hat{\theta})d\hat{\theta}$$

$$+\left[\int_{\theta}^{\overline{\theta}} C_\theta(\tilde{q}^{p*}(L,\hat{\theta});\hat{\theta})d\hat{\theta} - \int F_L(\hat{\theta})C_\theta(\tilde{q}^{p*}(L,\hat{\theta});\hat{\theta})d\hat{\theta}\right]$$

cost compensation

$$\tilde{t}^{p*}(H,\theta) = C(\tilde{q}^{p*}(H,\theta);\theta)$$

$$+\left[\int_{\theta}^{\overline{\theta}} C_\theta(\tilde{q}^{p*}(H,\hat{\theta});\hat{\theta})d\hat{\theta} - \int F_H(\hat{\theta})C_\theta(\tilde{q}^{p*}(H,\hat{\theta});\hat{\theta})d\hat{\theta}\right]$$

Flexible Contract with Private Shock

Theorem

With two ex-ante types, the allocation $\tilde{q}^{p*}(\tau,\theta)$ of the optimal flexible contract with private shock satisfies

$$v\left(\tilde{q}^{p*}(L,\theta);\theta\right) = c(\tilde{q}^{p*}(L,\theta);\theta),$$

$$v\left(\tilde{q}^{p*}(H,\theta);\theta\right) = c(\tilde{q}^{p*}(H,\theta);\theta) + \frac{p_L}{p_H}\left[\frac{F_L(\theta)-F_H(\theta)}{f_H(\theta)}\right] c_\theta(\tilde{q}^{p*}(H,\theta);\theta);$$

the associated payment function $\tilde{t}^{p*}(\tau,\theta)$ is given by

$$\tilde{t}^{p*}(L,\theta) = C(\tilde{q}^{p*}(L,\theta);\theta) + \int\left[F_L(\hat{\theta})-F_H(\hat{\theta})\right] C_\theta(\tilde{q}^{p*}(H,\hat{\theta});\hat{\theta})d\hat{\theta}$$

$$+\left[\int_{\theta}^{\overline{\theta}} C_\theta(\tilde{q}^{p*}(L,\hat{\theta});\hat{\theta})d\hat{\theta} - \int F_L(\hat{\theta}) C_\theta(\tilde{q}^{p*}(L,\hat{\theta});\hat{\theta})d\hat{\theta}\right]$$

$$\tilde{t}^{p*}(H,\theta) = C(\tilde{q}^{p*}(H,\theta);\theta)$$

$$+\left[\int_{\theta}^{\overline{\theta}} C_\theta(\tilde{q}^{p*}(H,\hat{\theta});\hat{\theta})d\hat{\theta} - \int F_H(\hat{\theta}) C_\theta(\tilde{q}^{p*}(H,\hat{\theta});\hat{\theta})d\hat{\theta}\right]$$

cost compensation

incentive for ex-ante type L

Flexible Contract with Private Shock

Theorem

With two ex-ante types, the allocation $\tilde{q}^{p*}(\tau,\theta)$ of the optimal flexible contract with private shock satisfies

$$v\left(\tilde{q}^{p*}(L,\theta);\theta\right) = c(\tilde{q}^{p*}(L,\theta);\theta),$$

$$v\left(\tilde{q}^{p*}(H,\theta);\theta\right) = c(\tilde{q}^{p*}(H,\theta);\theta) + \frac{p_L}{p_H}\left[\frac{F_L(\theta)-F_H(\theta)}{f_H(\theta)}\right] c_\theta(\tilde{q}^{p*}(H,\theta);\theta);$$

the associated payment function $\tilde{t}^{p*}(\tau,\theta)$ is given by

$$\tilde{t}^{p*}(L,\theta) = C(\tilde{q}^{p*}(L,\theta);\theta) + \int \left[F_L(\hat{\theta}) - F_H(\hat{\theta})\right] C_\theta(\tilde{q}^{p*}(H,\hat{\theta});\hat{\theta}) d\hat{\theta}$$

$$+ \left[\int_\theta^{\overline{\theta}} C_\theta(\tilde{q}^{p*}(L,\hat{\theta});\hat{\theta}) d\hat{\theta} - \int F_L(\hat{\theta}) C_\theta(\tilde{q}^{p*}(L,\hat{\theta});\hat{\theta}) d\hat{\theta}\right]$$

$$\tilde{t}^{p*}(H,\theta) = C(\tilde{q}^{p*}(H,\theta);\theta)$$

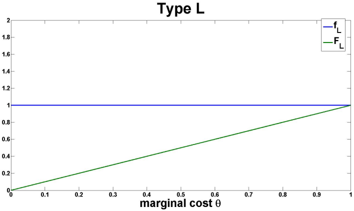
$$+ \left[\int_\theta^{\overline{\theta}} C_\theta(\tilde{q}^{p*}(H,\hat{\theta});\hat{\theta}) d\hat{\theta} - \int F_H(\hat{\theta}) C_\theta(\tilde{q}^{p*}(H,\hat{\theta});\hat{\theta}) d\hat{\theta}\right]$$

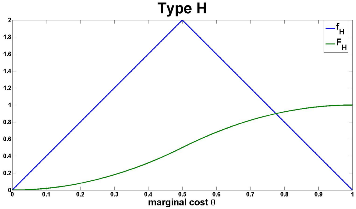
cost compensation

incentive for ex-ante type L

incentive for shock ω

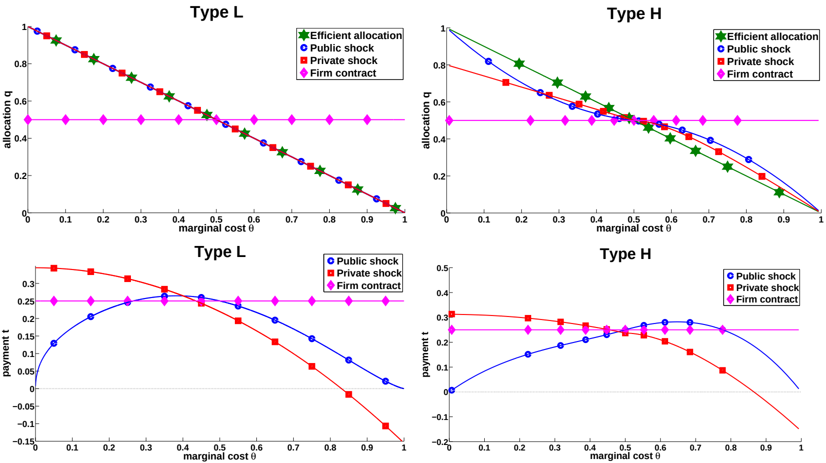
MPS case





Example

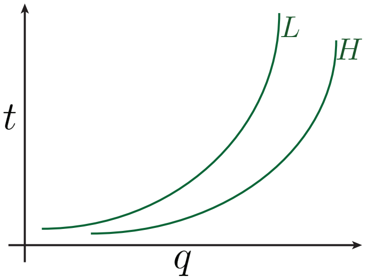
MPS case



Sequential Contracts as Menus of Contracts

Flexible contracts:

- At $t = 1^+$, seller chooses curve L or H
  curve τ is parameterized by ω as $\{q(\tau, \omega), t(\tau, \omega)\}$
- At $t = 2$, seller chooses one point from the selected curve

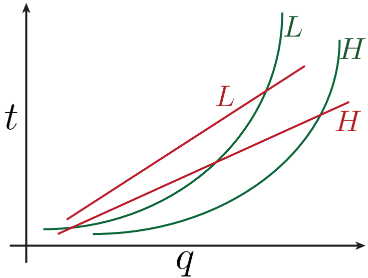


Sequential Contracts as Menus of Contracts

Flexible contracts:

- At $t = 1^+$, seller chooses curve L or H
  curve τ is parameterized by ω as $\{q(\tau, \omega), t(\tau, \omega)\}$

- At $t = 2$, seller chooses one point from the selected curve



Firm contracts:

- At $t = 1^+$, seller chooses $\{q(L), t(L)\}$ or $\{q(H), t(H)\}$

- At $t = 2$, seller is penalized at fixed rate λ

Comparison

Theorem

Among the three different optimal contract schemes, the buyer's total utility is the highest from the forward contract under uncertainty with public shock and is the lowest from the firm forward contract. That is,

$$\mathcal{S}_c^* - \mathcal{R}_c^* \;\geq\; \mathcal{S}_p^* - \mathcal{R}_p^* \;\geq\; \mathcal{S}_f^* - \mathcal{R}_f^*.$$ [a]

flexible with public shock	flexible with private shock	firm contract

[a] The result holds for any finite number of ex-ante type τ.

Comparison

Theorem

Among the three different optimal contract schemes, the buyer's total utility is the highest from the forward contract under uncertainty with public shock and is the lowest from the firm forward contract. That is,

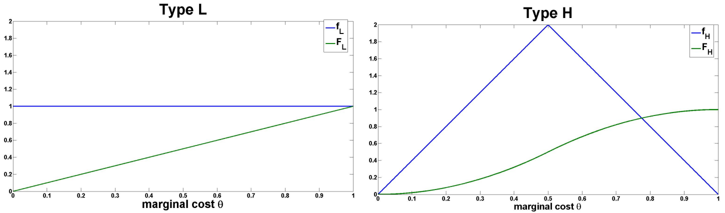
$$\underbrace{\mathcal{S}_c^* - \mathcal{R}_c^*}_{\text{flexible with public shock}} \;\geq\; \underbrace{\mathcal{S}_p^* - \mathcal{R}_p^*}_{\text{flexible with private shock}} \;\geq\; \underbrace{\mathcal{S}_f^* - \mathcal{R}_f^*}_{\text{firm contract}}.^{a}$$

[a] The result holds for any finite number of ex-ante type τ.

Theorem does not imply a similar ranking for social welfare or information rent!

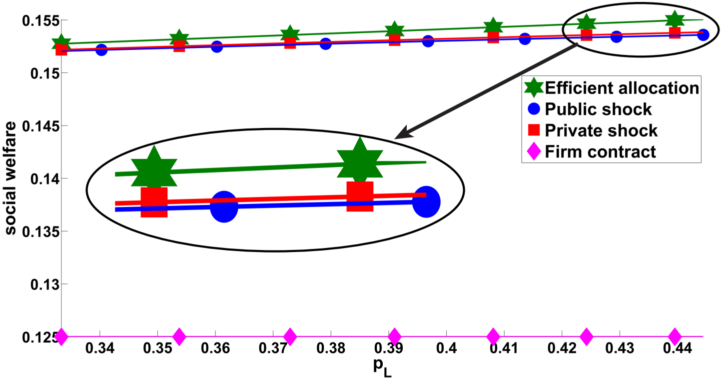
Monitoring May Hurt!

Example: MPS case



Monitoring May Hurt!

Example: MPS case



Conclusion

- We proposed a model that captures the uncertain and the dynamic varying nature of RE

Conclusion

- We proposed a model that captures the uncertain and the dynamic varying nature of RE
- We proposed two flexible contracts that take into account the new information (shock ω) that arrives after contract signing

Conclusion

- We proposed a model that captures the uncertain and the dynamic varying nature of RE
- We proposed two flexible contracts that take into account the new information (shock ω) that arrives after contract signing
- All three contract schemes can be interpreted as menus of contracts that seller sequentially chooses from them

Conclusion

- We proposed a model that captures the uncertain and the dynamic varying nature of RE
- We proposed two flexible contracts that take into account the new information (shock ω) that arrives after contract signing
- All three contract schemes can be interpreted as menus of contracts that seller sequentially chooses from them
- With inclusion of new information (shock), one can enrich the space of allocation functions

Conclusion

- We proposed a model that captures the uncertain and the dynamic varying nature of RE
- We proposed two flexible contracts that take into account the new information (shock ω) that arrives after contract signing
- All three contract schemes can be interpreted as menus of contracts that seller sequentially chooses from them
- With inclusion of new information (shock), one can enrich the space of allocation functions
- The proposed two flexible contracts outperform the equivalent firm contract

Conclusion

- We proposed a model that captures the uncertain and the dynamic varying nature of RE
- We proposed two flexible contracts that take into account the new information (shock ω) that arrives after contract signing
- All three contract schemes can be interpreted as menus of contracts that seller sequentially chooses from them
- With inclusion of new information (shock), one can enrich the space of allocation functions
- The proposed two flexible contracts outperform the equivalent firm contract
- With flexible contracts one can distinguish between sellers with different uncertainty levels, while firm contracts treat them the same

Conclusion

- We proposed a model that captures the uncertain and the dynamic varying nature of RE
- We proposed two flexible contracts that take into account the new information (shock ω) that arrives after contract signing
- All three contract schemes can be interpreted as menus of contracts that seller sequentially chooses from them
- With inclusion of new information (shock), one can enrich the space of allocation functions
- The proposed two flexible contracts outperform the equivalent firm contract
- With flexible contracts one can distinguish between sellers with different uncertainty levels, while firm contracts treat them the same
- We showed that monitoring does not necessarily improve the social welfare

Ongoing & Future Work

- Investigate the value of penalty instrument and risk exposure
- Extension to multiple buyers/sellers

Reference:

H. Tavafoghi and D. Teneketzis, "Sequential Contracts for Uncertain Electricity Resources", NetEcon, 2015.