Optimization and Data Sciences in Energy Networks

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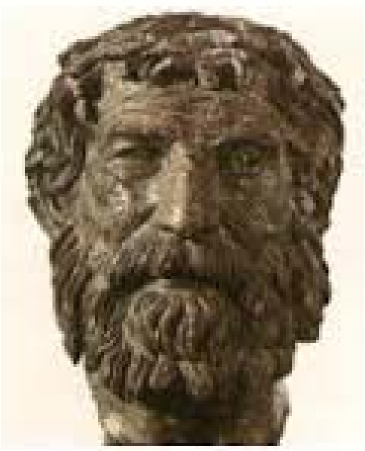
http://www.ise.ufl.edu/pardalos/

https://nnov.hse.ru/en/latna/.

'activity, operation'

ἐνέργεια: *energeia*

“Air, earth, water and fire are ever existing elements beginning and end of the Universe.”



Empedocles, pre - Socratic philosopher (c. 490 BC - 430 BC

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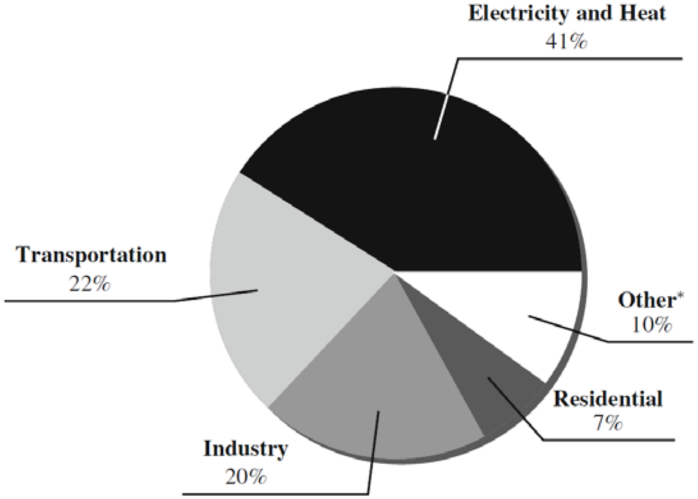
Dynamics of global energy systems

- Changes in oil and gas production and trade flows (shale gas and oil, new fields in USA / Canada, oil production in Iraq, changes in global economy and geopolitical balance)
- Reconciling the goals of energy security and environmental protection is needed
- Renewable energy (solar, wind, biofuels etc.)
- Focus on energy efficiency / sustainable energy systems (climate changes)
- Issues with Fossil Fuel Subsidies
- Around 1.6 billion people have no access to electricity
- Energy/Water/Environmental issues
- Advances in Technology/Modeling/Optimization

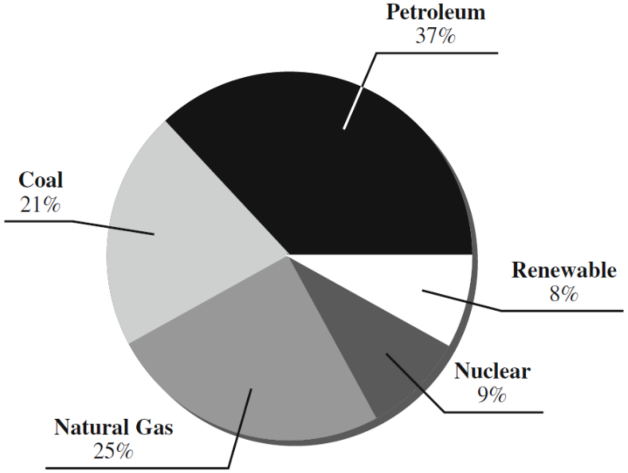
Introduction

World CO_2 emissions by sector



- Electricity and heat generation accounted for 41%
- Transport produced 22%

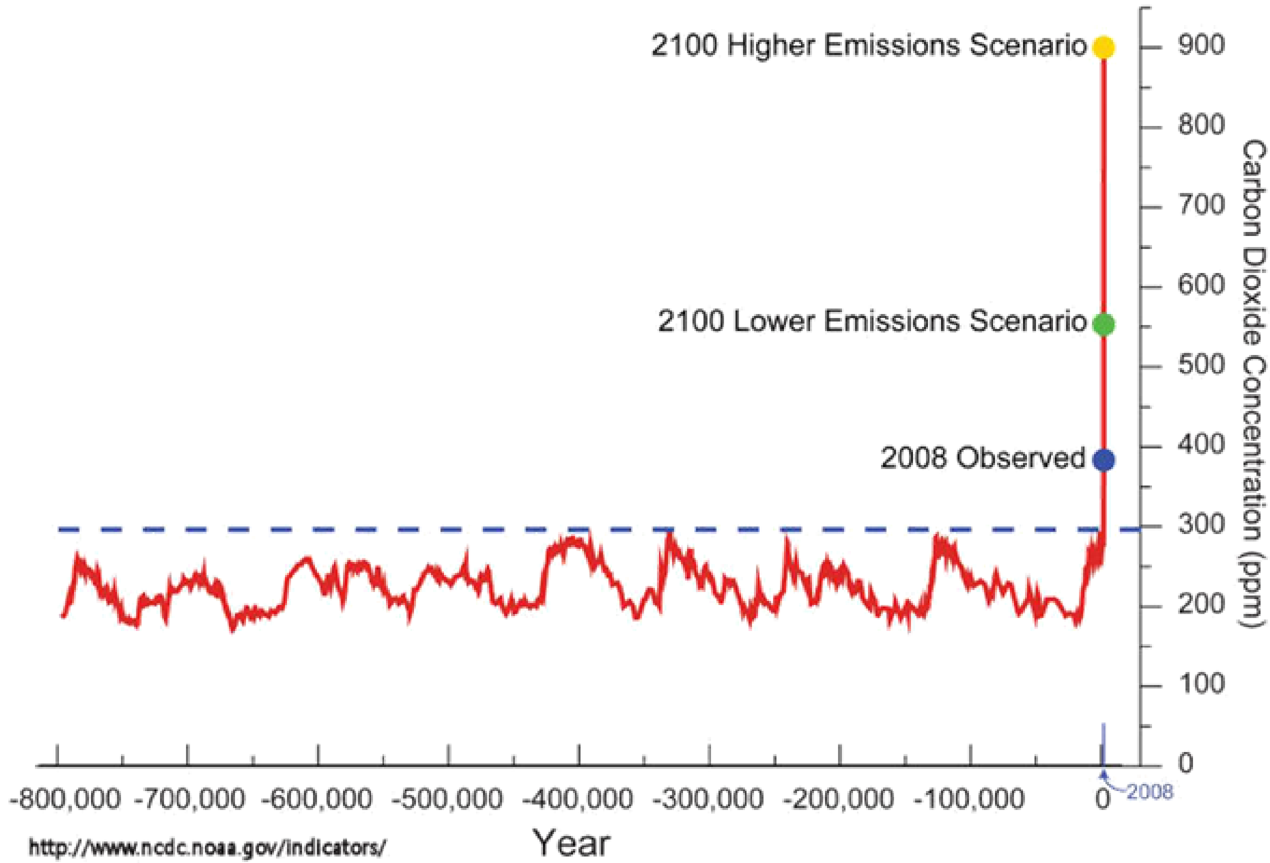
US energy supply from resources



- CO_2 EMISSIONS FROM FUEL COMBUSTION 2012, IEA

Introduction

800,000 Years of CO_2 Concentrations

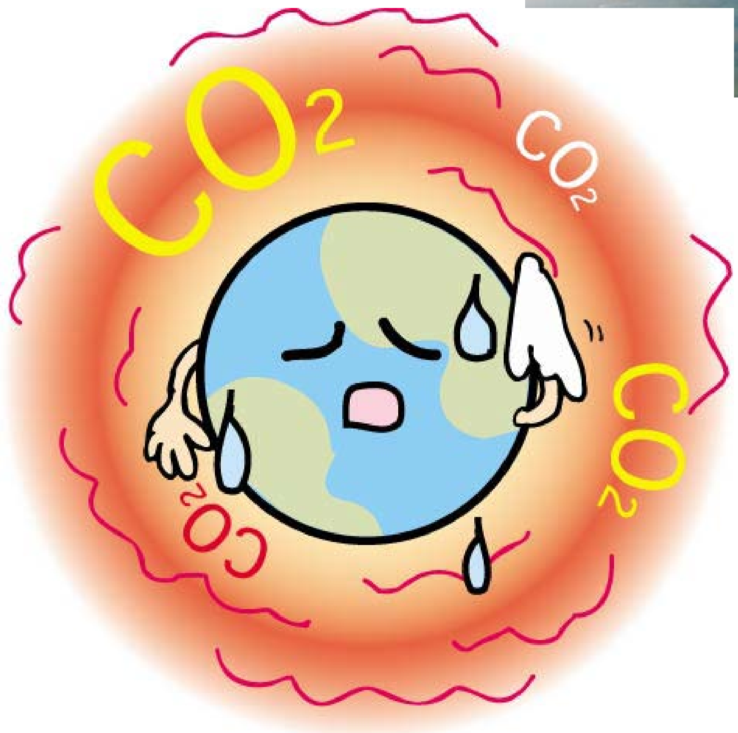


- NOAA Satellite and Information Service
- National Climatic Data Center
- http://www.ncdc.noaa.gov/indicators/

Introduction

Global Warming

Climate Change



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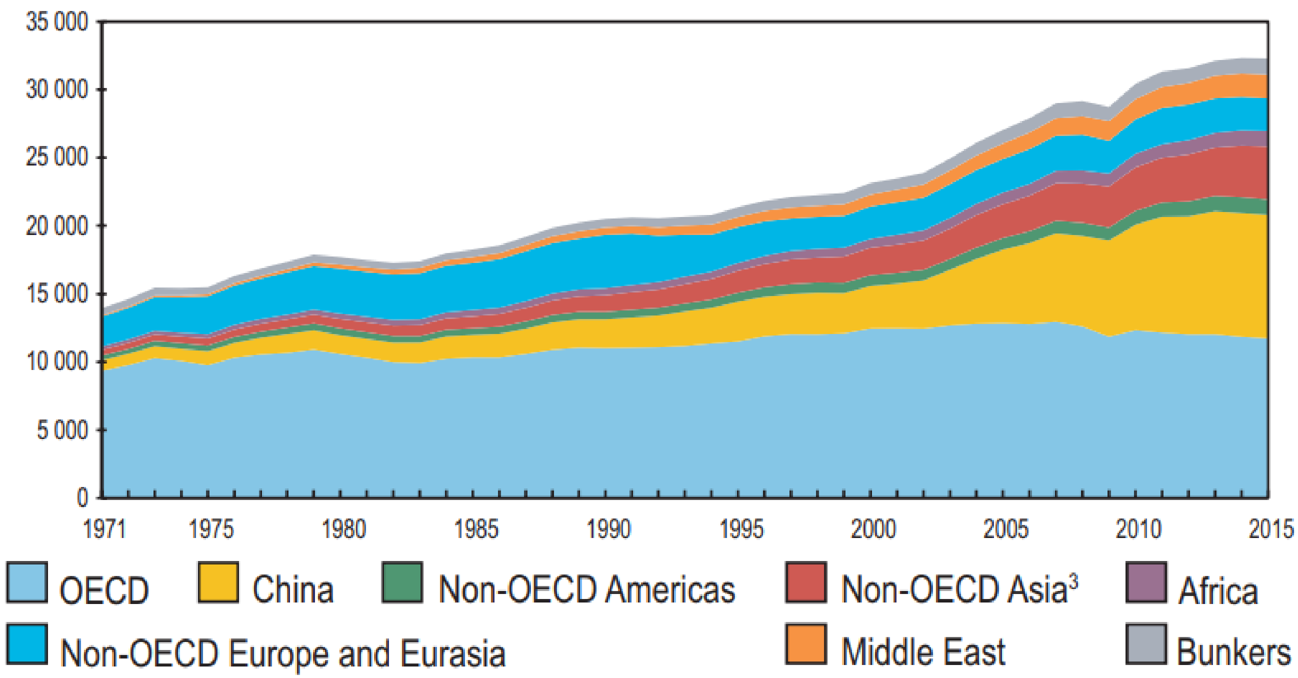
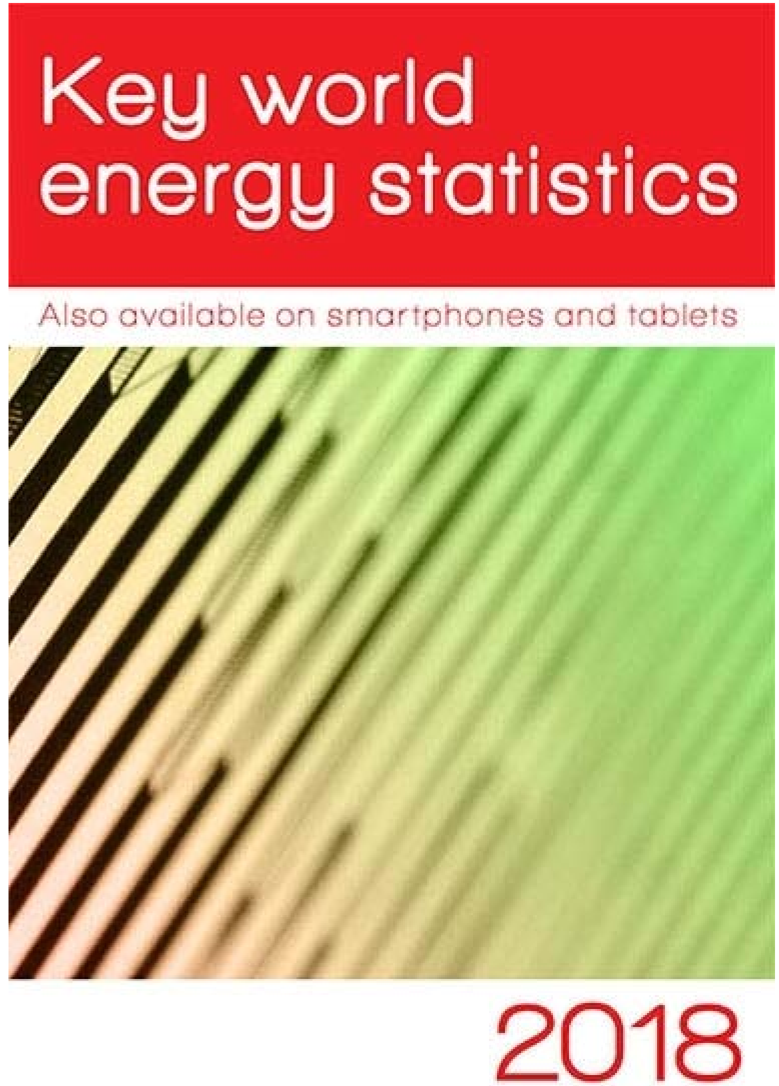
World[1] CO_2 emissions from fuel combustion[2] from 1971 to 2015 by region (Mt of CO_2)



https://www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf

For details see



https://webstore.iea.org/key-world-energy-statistics-2018

Introduction

The Solutions for CO_2 Emission Reduction in Power Systems

- CO_2 emissions control policies
  - Carbon tax
  - Cap-and-Trade system
  - Renewable portfolio standards
- Integration of CO_2 mitigation in power system operations
  - Generation expansion planning
  - Stochastic unit commitment
  - CO_2 capture in power generation optimization
- CO_2 capture and storage
  - CO_2 capture
  - CO_2 transportation
  - CO_2 sequestration

CO_2 Emissions Control Policies

- Carbon tax
- Cap-and-Trade system
- Renewable portfolio standards

CO_2 Emissions Control Policies

Carbon Emissions Taxes

- A market-based policy instrument to achieve emissions reductions.
- Taxes set a fixed price on emissions and forces the quantities of emissions to adjust accordingly.
- Limited to the Scandinavian countries, HongKong and Australia

- **Pros**
  - simplicity of taxes
  - creates revenues for recycling and redistribution
  - no price volatilities
  - stability in revenue
- **Cons**
  - political resistance to taxes
  - not easy to develop international trading programs
  - inflexible in terms of ways to achieve reductions

CO_2 Emissions Control Policies

Cap-and-Trade

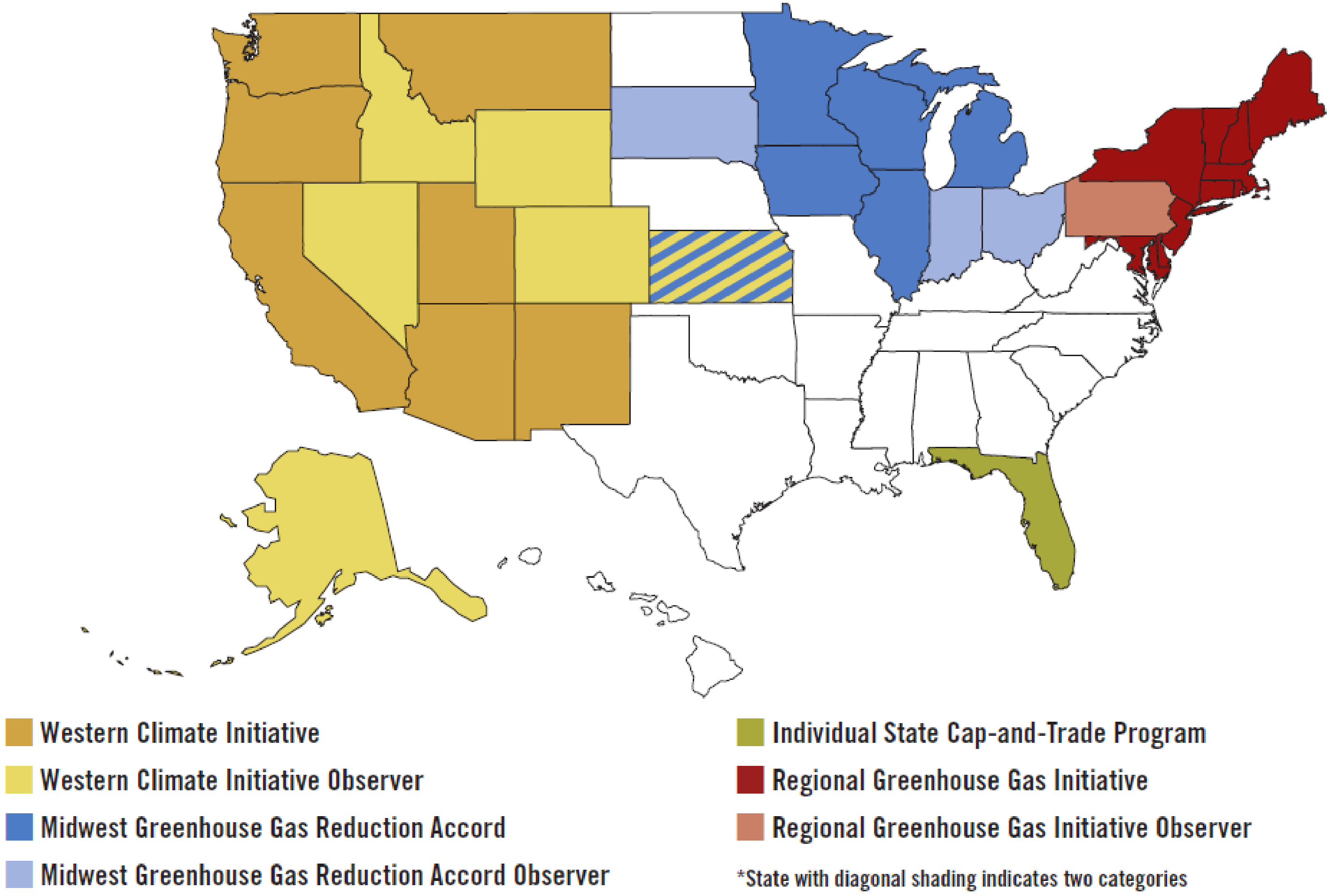
- Federal-Level Policies in the U.S.

Program Feature	Clean Energy & Security Act (CESA)	Clean Energy Jobs & American Power Act (APA)
Economy wide GHG reduction goals	2012 US GHG < 97% of 2005 GHGs 2020 US GHG < 80% of 2005 GHGs 2030 US GHG < 58% of 2005 GHGs 2050 US GHG < 17% of 2005 GHGs	2012 US GHG < 97% of 2005 GHGs 2020 US GHG < 80% of 2005 GHGs 2030 US GHG < 58% of 2005 GHGs 2050 US GHG < 17% of 2005 GHGs
Banking	Unlimited	Unlimited
Borrowing	no interest for immediate year, 15% interest for those allowances upto 5 years into the future	no interest for immediate year, 15% interest for those allowances upto 5 years into the future
Strategic Reserve	EPA sets aside pool each year and conducts quarterly auctions	EPA sets aside pool each year and conducts quarterly auctions (pool much larger)
Auction of Allowances	Quarterly with reserve price of $10/allowance	Quarterly with reserve price of $11/allowance
Non compliance penalty	excess emisisons multiplied by twice the auction clearing price of most recent auction.	Penalty equals twice the fair market price from registered exchanges
Offsets	By 2050, 66% can be met with offsets half from domestic and half from international sources	By 2050, 48% can be met with offsets, but 75% domestic and 25% international sources

CO_2 Emissions Control Policies

Cap-and-Trade

- Regional Cap-and-Trade Policies



CO_2 Emissions Control Policies

Cap-and-Trade

- **Pros**
- flexibility it offers to achieve emissions reductions
- has a history of success from the acid rain program for SO_X
- can be linked easily with other international climate policy efforts
- generates auction revenue that can be recycled

- **Cons**
- potential for price volatility of allowances
- administrative burden in creating the trading and tracking platforms
- potential for speculation by traders

CO_2 Emissions Control Policies

Cap-and-Trade Policy Model

GENCO f's profit maximization problem:

$$\text{Max } \textstyle\sum_j [P_j^0 - (P_j^0/Q_j^0)(\sum_g s_{gj}) - w_j] s_{fj}$$

$$- \textstyle\sum_{i,h} (C_{fih} - w_i) x_{fih} - \sum_{ih} I_{fih} \Delta x_{fih} + p^{CO_2} c_f$$

$$s.t. \quad \textstyle\sum_{ih} E_{fih}\, x_{fih} + c_f \le K_f \quad (\delta_f)$$

$$x_{fih} \le X_{fih} + \Delta x_{fih} \quad (\rho_{fih}) \quad \forall\, i, g, h$$

$$\textstyle\sum_j s_{fj} = \sum_{i,h} x_{fih} \quad (\theta_f)$$

$$s_{fj}, x_{fih}, \Delta x_{fih} \ge 0 \quad \forall\, f, i, j, h$$

- The emissions $\sum_{ih} E_{fih}\, x_{fih}$ and allowance sales c_f must not exceed the initial allowance K_f.
- Promoting new renewable generation capacity and reducing GHG emissions.

CO_2 Emissions Control Policies

Individual Market Participant Optimization Model

Consumers: $P_j^E = P_j^0 - \frac{P_j^0}{Q_j^0}(\sum_f s_{fj} + a_j),\ \forall j.$

Producers: Max $\sum_j (P_j^E - w_j] s_{fj} - \sum_{i,h}(C_{fih} - w_i) x_{fih}$

$$-p^{CO_2}(\sum_{i,h \in H^{CO_2}(i,f)} E_{fih}\, x_{fih} - N_f)$$

$$s.t.\ \ x_{fih} \le X_{fih},\ \ (\rho_{fih})$$

$$\sum_j s_{fj} = \sum_{i,h \in H\,(i,f)} x_{fih},\ \ (\theta_f)$$

$$s_{fj}, x_{fih} \ge 0 \ \ \forall f, i, j, h.$$

Power Arbitrager: $\mathrm{Max}_{a_i}\{\sum_i (P_i^E - w_i) a_i \mid \sum_i a_i = 0\}$.

Grid Operator/Independent System Operator: $Max_{y_i}\{\sum_i w_i y_i \mid \sum_i PTDF_{ki}\, y_i \le T_k,\ \ (\lambda_k)\}$.

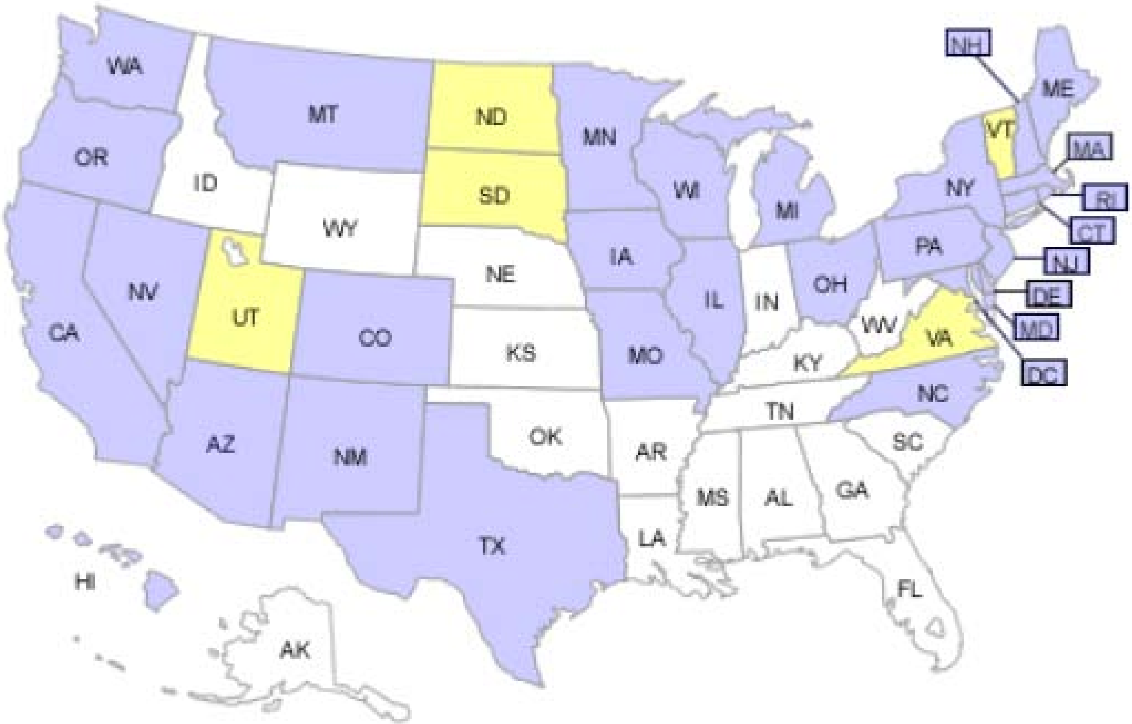
Market Clearing and Consistency Conditions: $\sum_f s_{fi} + a_i - \sum_{f,h \in H\,(i,f)} x_{fih} = -y_i,\ \forall i$

$$0 \le p^{CO_2} \perp \sum_{f,i,h \in H^{CO_2}(i,f)}(E_{fih}\, x_{fih} - N_f) \le 0.$$

CO_2 Emissions Control Policies

Renewable Portfolio Standards

- Regional Cap-and-Trade Policies



- States with RPS (blue) and RPS goals (yellow),
- Source: Environmental Protection Agency website on RPS

CO_2 Emissions Control Policies

Renewable Portfolio Standards

- Regional Cap-and-Trade Policies

➢ **Pros**

- direct impact on amount of renewable generation
- provide some flexibility with RECs

➢ **Cons**

- focus on technologies rather than emissions
- lack of strong enforcement mechanisms may limit its potential

Integration of CO_2 Mitigation in Power System

- Generation expansion planning
- Stochastic unit commitment
- CO_2 Capture in System Optimization

CO_2 Mitigation in Power System

Generation Expansion Planning (GEP)

- The long-term development of power resources from planning to operation.
- Necessary for the company to obtain a best scheme for well-balanced generation plannings.
- Environmental constraints and emission limits considered.
- State of the Art in GEP methodologies:
  - Traditional Deterministic Models
  - Portfolio Theory Models
  - Handing Uncertainties
  - Modeling Emission Limits
  - Multiobjective Models
  - Methods based on artificial intelligence
  - Models based on fuzzy logic

CO_2 Mitigation in Power System

Generation Expansion Planning

- Risk Management in Long Term Generation Planning
  - A Net Present Value maximization model for GEP
  - Considering the risks from energy market and fuel supplying
  - Formulated by MILP and solved by the Lagrangian Relaxation method
  - Constraints including the energy balance, the minimum generation from renewable resources and CO_2 emission limits.

CO_2 Mitigation in Power System

- **Generation Expansion Planning**

The Formulations of Single GENCO Model

- $Max \ \sum_{i=1}^{N_y}\sum_{k=1}^{N_s}\frac{1}{(1+r)^{i-1}}[\rho_{ik}^{e}E_{ik}^{sold}+\rho_{ik}^{gc}(G_{ik}^{sold}-G_{ik}^{bou})+ \rho_{ik}{}^{CO_2}(Q_{ik}^{sold}-Q_{ik}^{bou})-\sum_{j\in N_{tot}^{new}} w_{jik}(C_j(E_{ik}^{new})+I_{jik})-\sum_{j\in N_{tot}^{ex}} C_j E_{ik}]$
- s.t. $\sum_{j\in N_{tot}^{ex}} E_{ijk}+\sum_{j\in N_{tot}^{new}} w_{jik}E_{ijk}^{new}=E_{ik}^{sold}, \quad \forall i\in N_y, k\in N_s$
- $\sum_{k=1}^{N_s}[\sum_{j\in N_{ren}}(E_{jik}+w_{jik}E_{jik}^{new})+G_{ik}^{bou}]= \sum_{k=1}^{N_s}[\sum_{j\in N_{therm}}\eta_i(E_{jik}+w_{jik}E_{jik}^{new})+G_{ik}^{sold}], \ \forall i\in N_y$
- $\sum_{k=1}^{N_s}[\sum_{j\in N_{rem}}\varepsilon_j^{CO_2}(E_{jik}+w_{jik}E_{jik}^{new})+(Q_{ik}^{sold}-Q_{ik}^{bou})]=A_i^{CO_2}, \forall i\in N_y$
- $Q_{ik}^{bou}\ge 0, Q_{ik}^{sold}\ge 0, \ \forall i\in N_y, k\in N_s.$
- $0\le E_{jik}\le E_{jik}^{max}, \quad \forall i\in N_y, k\in N_s, j\in N_{tot}^{ex}$
- $0\le w_{jik}E_{jik}^{new}\le E_{jik}^{max}, \quad \forall i\in N_y, k\in N_s, j\in N_{tot}^{ex}$
- $0\le E_{jik}\le \psi_j V_{jik}^3, \quad \forall i\in N_y, k\in N_s, j\in N_{eol}^{ex}$
- $0\le w_{jik}E_{jik}\le w_{jik}(\psi_j V_{jik}^3), \quad \forall i\in N_y, k\in N_s, j\in N_{tot}^{ex}$

CO_2 Mitigation in Power System

Stochastic Unit Commitment and Self-scheduling

- Short-Term Unit Commitment and Self-Scheduling Problems
  - Deciding when a unit is ON/OFF and the generation level when it’s ON.
  - Planning horizon: 1 day to 1 week, with hourly time stages.

- Solution Methodologies
  - Priority list
  - Dynamic Programming
  - Lagrangian relaxation
  - MILP
  - Branch-and-bound
  - Heuristic and evolutionary methodologies

CO_2 Mitigation in Power System

Stochastic Unit Commitment and Self-scheduling

- Short-Term Unit Commitment Model:

  Min Total operation cost of system

  s.t. Operational constraints

  Emission constraints

- The generation cost function is

$$C_{tot} = \sum_{i=1}^{N} \sum_{t=1}^{T} (C_{it} + C_{up,i} + C_{d,i}) .$$

- The emission function (valid both for SO_2 and CO_2) is

$$E_{jit} = e_{fij} (k_{0i} + k_{1i} P_{it} + k_{2i} P_{it}^2).$$

- The compromise objective function consists of a convex combination of unit costs and emissions.

$$f(x,u,p) = w \sum_{k \in K} \sum_{i \in I} C_{ik} + (1-w)\lambda \sum_{k \in K} \sum_{i \in I} E_{ik}$$

where $C_{ik}(x_{ik}, u_{ik}, p_{ik}) = C_{ik}^{sc}(x_{ik}, u_{ik}) + C_{ik}^{fc}(u_{ik}, p_{ik})$, and

$$E_{ik}(u_{ik}, p_{ik}) = u_{ik}\left(a_i + b_i p_{ik} + c_i p_{ik}^2\right).$$

CO_2 Mitigation in Power System

Stochastic Unit Commitment and Self-scheduling

- ***Emission constraints*** for the whole system emission over the total scheduling period.

$$\sum_{i=1}^{N}\sum_{t=1}^{T} E_{jit} + \sum_{i=1}^{N}[E_{up,j,i} + E_{d,j,i}] \leq E_{j,tot}, \forall\, j \in J.$$

where

$$E_{jit} = e_{fij}\left(k_{0i} + k_{1i}P_{it} + k_{2i}P_{it}^2\right),$$

$$E_{up,j,i} = e_{0ji} + e_{1ji}\left(1 - e^{\frac{T_{di}}{\tau_i}}\right),$$

$E_{j,tot}$ is the cap, total emission of pollutant j from electric power production (kg).

- ***System constraints*** includes system load, spinning reserve requirements, generation limits, minimum up- and down- times, ramp rate limits, and prespecified commitment.

CO_2 Mitigation in Power System

Stochastic Unit Commitment Modeling

- A general **deterministic** formulation:
- $Min_{u,z} \; \sum_{i=1}^{N} \sum_{t=1}^{T} (g_i(z_t^i) + c_i u_t^i + h_i(u_{t-1}^i, u_t^i))$

  s.t. $\sum_{i=1}^{N} z_t^i \geq d_t, \forall\, t \in T$

  $\sum_{i=1}^{N} Q_i\, u_t^i \geq d_t + r_t, \forall\, t \in T$

  $q_i u_t^i \leq z_t^i \leq Q_i u_t^i, \forall\, i \in N,\; t \in T$

  $u_t^i - u_{t-1}^i \leq u_\tau^i,\; \tau = t+1, \ldots, \min\{t + L_i - 1, T\}, t \in T/\{1\}$

  $u_{t-1}^i - u_t^i \leq 1 - u_\tau^i,\; \tau = t+1, \ldots, \min\{t + l_i - 1, T\}, t \in T/\{1\}$

- A general **stochastic** programming formulation:
- $Min_{u,z} \; \sum_{s=1}^{S} Prob^s (\sum_{i=1}^{N} \sum_{t=1}^{T} (g_t^{s,i}(z_t^{s,i}) + c_t^{s,i} u_t^{s,i} + h_t^{s,i}(u_{t-1}^{s,i}, u_t^{s,i})))$

  s.t. $\sum_{t=1}^{N} Z_t{}^{s,i} \geq d_t^s$

  $u \in U, z \in Z(u)$

  where non-anticipativity constraints are included in sets U_i and $Z_i(u^i)$.

CO_2 Mitigation in Power System

CO_2 Capture in System Optimization

- CO_2 capture is one of essential components of CCS.
- System Optimization for the integration of CO_2 capture
- Economic objectives: capital investment minimization, return of investment minimization, or CO_2 capture cost minimization.
- Energetic objectives: energy efficiency maximization or efficiency penalty minimization.

- $Min \ \frac{(COE)_{capture} - (COE)_{ref}}{(CO_2 kWh^{-1})_{ref} - (CO_2 kWh^{-1})_{capture}}$

where

$(COE)_{capture}$ is the cost of electricity in the capture system.

$(COE)_{ref}$ is the cost of electricity in the reference system (without capture).

$(CO_2 kWh^{-1})_{ref}$ are the CO_2 emissions per kWh produced in the reference system.

$(CO_2 kWh^{-1})_{capture}$ are the CO_2 emissions per kWh produced in the capture system.

CO_2 Mitigation in Power System

CO_2 Capture in System Optimization

- CO_2 capture constraints: Second Law of Thermodynamics

- Cost of electricity
  - ❑ $COE = ((\mathrm{F} \times \sum CAPEX_i) + \mathrm{OPEX})/\mathrm{EP}$
- Capital Costs
  - ❑ $CAPEX_i = f(layout, equipment, size)$
- O&M Costs
  - ❑ $OPEX = Fixed\ cost + \sum(ER_i \times EC_i)$
- Energy Requirements
  - ❑ $ER_i = f(capture\ system, CO_2\ Captured)$
- Electricity Production
  - ❑ $EP = f(power\ plant,, CO_2\ Captured, ER_i)$
- Specific CO_2 emissions
  - ❑ $CO_2 kWh^{-1} = f(power\ plant,, CO_2\ Captured, EP)$
- CO_2 capture system process
  - ❑ $CO_2\ Captured = f(capture\ system, operational\ variables)$

CO_2 Capture and Storage

- CO_2 capture
- CO_2 transportation
- CO_2 sequestration

Carbon Capture and Storage (CCS)

Our Goals

- To promote the employment of CCS in power expansion planning
- To fill the gap between technical and economic analysis of CCS
- To build a connection from technique research to project planning

Methodology

- Apply the optimization approach in the areas of energy expansion planning, CO_2 network transportation or storage problems to achieve the comprehensive economic evaluations,
- Provide the insights of CCS resource integration and viable project management.

- Y. Huang, S. Rebennack, and Q. P. Zheng
  Techno-economic analysis and optimization models for carbon capture and storage: A survey. Energy System, 2013, pp. 315-353.

Carbon Capture and Storage

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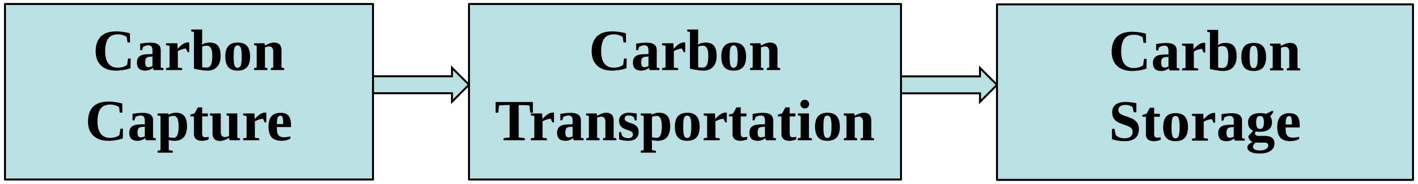


Carbon Capture and Storage

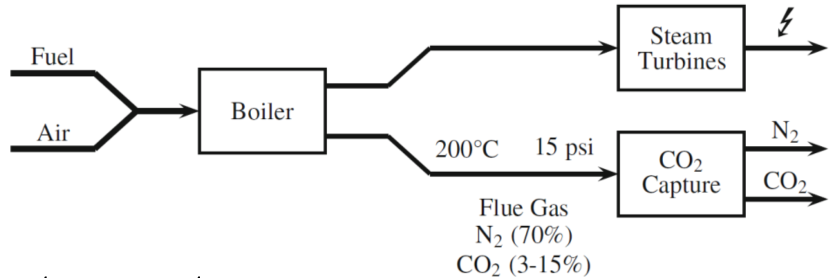
Carbon Capture

- A process that separates the CO_2 from flue gas (e.g., resulting from fossil fuel combustion) and then captures it to abate CO_2 emissions
- Three main technologies:
  - I. post-combustion capture,
  - II. pre-combustion capture, and
  - III. oxy-combustion capture.
- Three properties of a carbon capture system:
  - I. CO_2 concentration in the flue gas,
  - II. pressure and temperature of the flue gas, and
  - III. flue type (gas or solid).

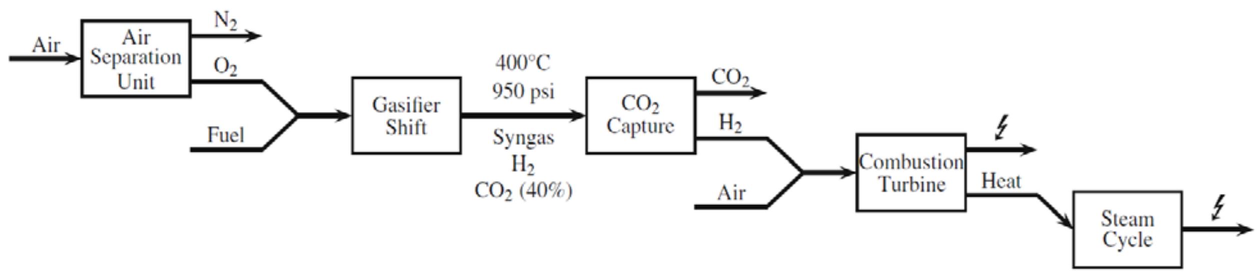
Carbon Capture and Storage

Carbon Capture Processes

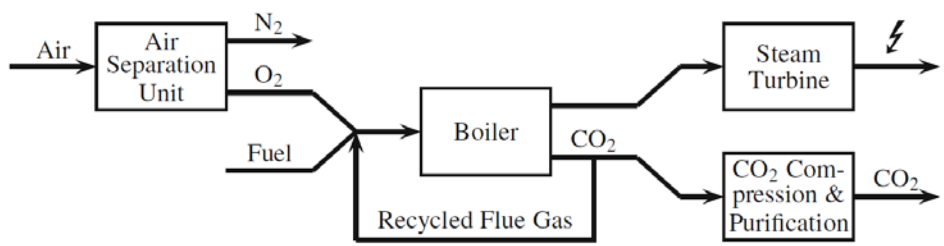
- post-combustion capture



- pre-combustion capture



- oxy-combustion capture



Carbon Capture and Storage

Carbon Capture

- optimal planning of electricity generation with CO_2 emission considerations
  - adjusting the structure of energy supply (new generation mix)
  - fuel balancing, fuel switching, CO_2 capture, and renewable resources

- Objective functions of energy planning with CO_2 reductions: to minimize energy (expansion) planning costs, including

Component	Single-objective			Multiple-objective			
Paper	[36]	[37]	[38]	[39]	[40]	[41]	[42]
Fossil fuel generation	P, J	P, J	J, T	P	P, T	P, T	P, T
Non-fossil fuel generation	P	P	P, T				
Retrofit	P, J	P, J	P, T				
Capital investment		P	P		P	P, T	P, T
O&M		P	P, T		P, T		
CO_2 credits			T				
CCS technology			P				
CO_2 emissions	P, J			P	P, T	P, T	P, T
Other						T	

P plant/generator, *J* fuel type, e.g. coal, oil and gas, *T* time/period

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Carbon Capture and Storage

Carbon Capture

The typical objective function is formulated involving fuel cost functions (1a), O&M cost (1b) and pre-operational costs (1c).

$$Min \quad F_1^1(e) + F_2^1(x,y) + F_3^1(h,n,C^{Cre})$$

where

$$F_1^1(e) = \sum_{t\in T}\sum_{i\in F\cup W^F}\sum_{j\in J} Cost_{ijt}^F\left(e_{ijt}^F\right) + \sum_{t\in T}\sum_{i\in N\cup W^N} Cost_{it}^N\left(e_{it}^N\right) + \sum_{t\in T}\sum_{i\in F^C\cup W^C}\sum_{j\in J}\sum_{k\in K} Cost_{ijkt}^C\left(e_{ijkt}^F, e_{ikt}^W\right) \qquad (1a)$$

$$F_2^1(x,y) = \sum_{t\in T}\sum_{i\in F}\sum_{j\in J} M_{ijt}^F x_{ij} + \sum_{t\in T}\sum_{i\in W^F}\sum_{j\in J} M_{ijt}^F y_{ij} \qquad (1b)$$

$$F_3^1(h,n,C^{Cre}) = \sum_{t\in T}\sum_{i\in F} R_{it} h_{it} + \sum_{t\in T}\sum_{i\in W} S_{it} n_{it} + \sum_{t\in T} P_t C_t^{Cre} \qquad (1c)$$

where $Cost\ (\boldsymbol{e})$ is the fuel cost function with respect to fossil fuel plant, non-fossil fuel plant and the plant with CCS, respectively. M_{ijt} , R_{it} , S_{it} , P_t are defined as O&M cost, retrofit cost, capital cost and cost for purchasing CO_2 credits, respectively.

Carbon Capture and Storage

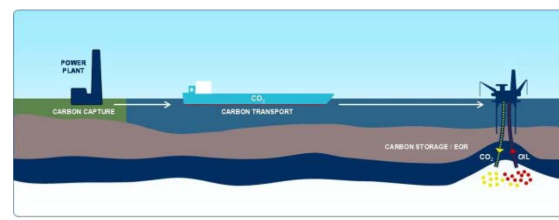
Carbon Capture

- *Constraints of energy planning with CO_2 reductions*
  - ✓ **Electricity demand satisfaction**
  - ✓ **Plant capacity**
  - ✓ **Fuel selection and plant shut-down**
  - ✓ **Operational changes**
  - ✓ **Selection of CO_2 capture process**
    - $\sum_{k \in K} z_{ik}^F \leq \sum_{j \in J} x_{ij}, \quad \forall\, i \in F^c$
    - $\sum_{k \in K} z_{ik}^W \leq \sum_{j \in J} x_{ij}, \quad \forall\, i \in W^c$
  - ✓ **CO_2 emission limits**
    - $\sum_{k \in K} \sum_{i \in F^c} \left(\sum_{j \in J} G_{ij}^{CO_2,F} e_{ijt}^F \right) \varepsilon_{ij}^F z_{ik}^F + \sum_{k \in K} \sum_{i \in W^c} \left(\sum_{j \in J} G_{ij}^{CO_2,W} e_{ijt}^W \right) \varepsilon_{ij}^W z_{ik}^W - C_t^{Cre} \leq C_t^{limit}, \quad \forall\, t \in T$
  - ✓ **Capacity constraints on the capture process**
    - $e_{ikt}^F \leq z_{ik}^F E_k^{max}, \ \forall\, i \in F^C, k \in K, t \in T$
    - $e_{ikt}^W \leq z_{ik}^W E_k^{max}, \ \forall\, i \in W^C, k \in K, t \in T$
  - ✓ **…**

Carbon Capture and Storage

Carbon Transportation

- Common transportation types:
  - pipelines, trucks and ships.
- Pipeline Network
  - Hydraulic design and techno-economic evaluations
  - Vary significantly depending on the scale of facilities and networks.
  - On the system-level infrastructure: an optimal CCS system with trunk and feeder pipelines
  - Similar to natural gas pipelines



- Trucks and Ships
  - Flexible means of CO_2 transportation
  - Less capital intensive, less construction time
  - complement the needs of short-term storage and unreachable storage sites through pipelines

Carbon Capture and Storage

Carbon Transportation

The objective function for CO_2 transportation problems is to minimize the construction cost and operating cost regarding CO_2 sources (3a), transport processes (3b) and CO_2 sinks (3c).

$$Min \quad F_1(\boldsymbol{x},\boldsymbol{f}) + F_2(\boldsymbol{y},\boldsymbol{f}) + F_3(\boldsymbol{z},\boldsymbol{f})$$

where

$$F_1(\boldsymbol{x},\boldsymbol{f}) = \sum_{i\in R} C_i^R x_i + \sum_{t\in T} \sum_{i\in R} \sum_{j\in N\setminus \mathrm{R}} V_i^t f_{ij}^t \qquad (3a)$$

$$F_2(\boldsymbol{y},\boldsymbol{f}) = \sum_{(i,j\in A)} Cost_{ij}^P(f,l)\, y_{ij} + \sum_{t\in T} \sum_{(i,j)\in A} V_{ij}^t f_{ij}^t \qquad (3b)$$

$$F_3(\boldsymbol{z},\boldsymbol{f}) = \sum_{j\in S} C_j^S z_j + \sum_{t\in T} \sum_{i\in N\setminus \mathrm{S}} \sum_{j\in S} V_j^t f_{ij}^t \qquad (3c)$$

where $Cost\ P(\boldsymbol{f},\boldsymbol{l})$ is the cost function for CO_2 pipeline network construction that depends on the flow over the pipe and its distance. C_j^R and C_j^S are defined as the costs to open CO_2 sources and sinks, respectively. V_t represents the operating cost at time t.

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Carbon Capture and Storage

Carbon Transportation

- *Constraints of* CO_2 *transportation problems*
  - ✓ **Flow balance**
    - $\sum_{j:(i,j)\in A} f_{ij}^t - \sum_{j:(i,j)\in A} f_{ji}^t = 0, \quad \forall\, i \in N\backslash R\backslash S.$
  - ✓ **Flow rate limit**
    - $f_{ij}^t \le Q_{ij}^P y_{ij}, \quad \forall\,(i,j) \in A, t \in T.$
  - ✓ **CO_2 supply limit**
    - $\sum_{j\in N\backslash R} f_{ij}^t \le Q_i^{max} x_i, \ \forall\, i \in R, t \in T.$
  - ✓ **CO_2 injection limit**
    - $\sum_{j\in N\backslash S} f_{ij}^t \le Q_j^{max} z_j, \quad \forall\, i \in S, t \in T.$
  - ✓ **CO_2 capture target**
    - $\sum_{t\in T} \sum_{j\in N\backslash R} f_{ij}^t \ge D_i, \quad \forall\, i \in R.$
  - ✓ **CO_2 storage capacity**
    - $\sum_{t\in T} \sum_{j\in N\backslash S} f_{ij}^t \ge M_j, \quad \forall\, j \in S.$
  - ✓ …

Carbon Capture and Storage

Carbon Storage

- Three common reservoir types:
  - I. oil and gas reservoirs,
  - II. unmineable coal seams, and
  - III. saline formations.

- The storage *without* energy benefits:
  - sequestration in depleted gas or oil reservoirs, in saline aquifers and ocean storage.

- The storage *with* energy benefits:
  - oil or gas recovery and coal bed methane production,
  - offset CO_2 sequestration operational cost.

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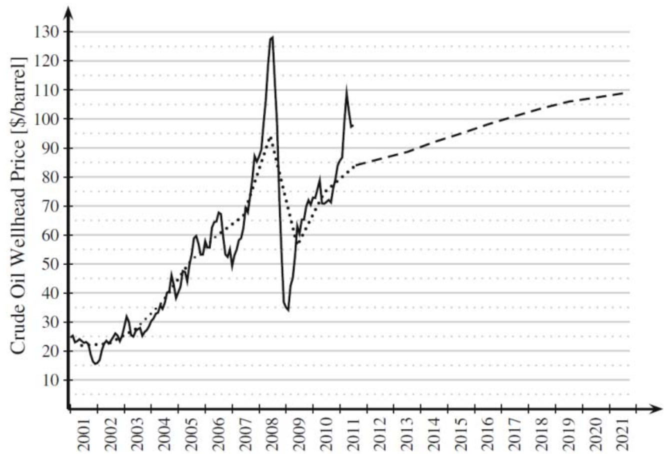
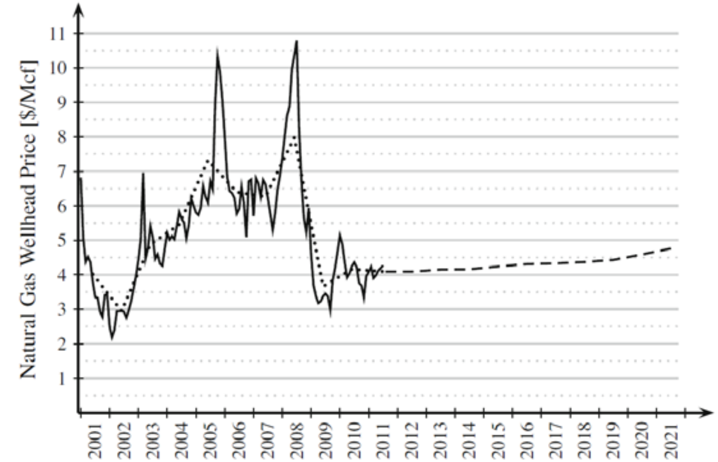
Carbon Capture and Storage

Carbon Storage





- Storage *without* energy benefits:

$$CFBT^{credit} = Revenue^{CH_4} - \mathrm{Cost}^{\mathrm{CO_2}} - \mathrm{Cost}^{\mathrm{O\&M}}$$

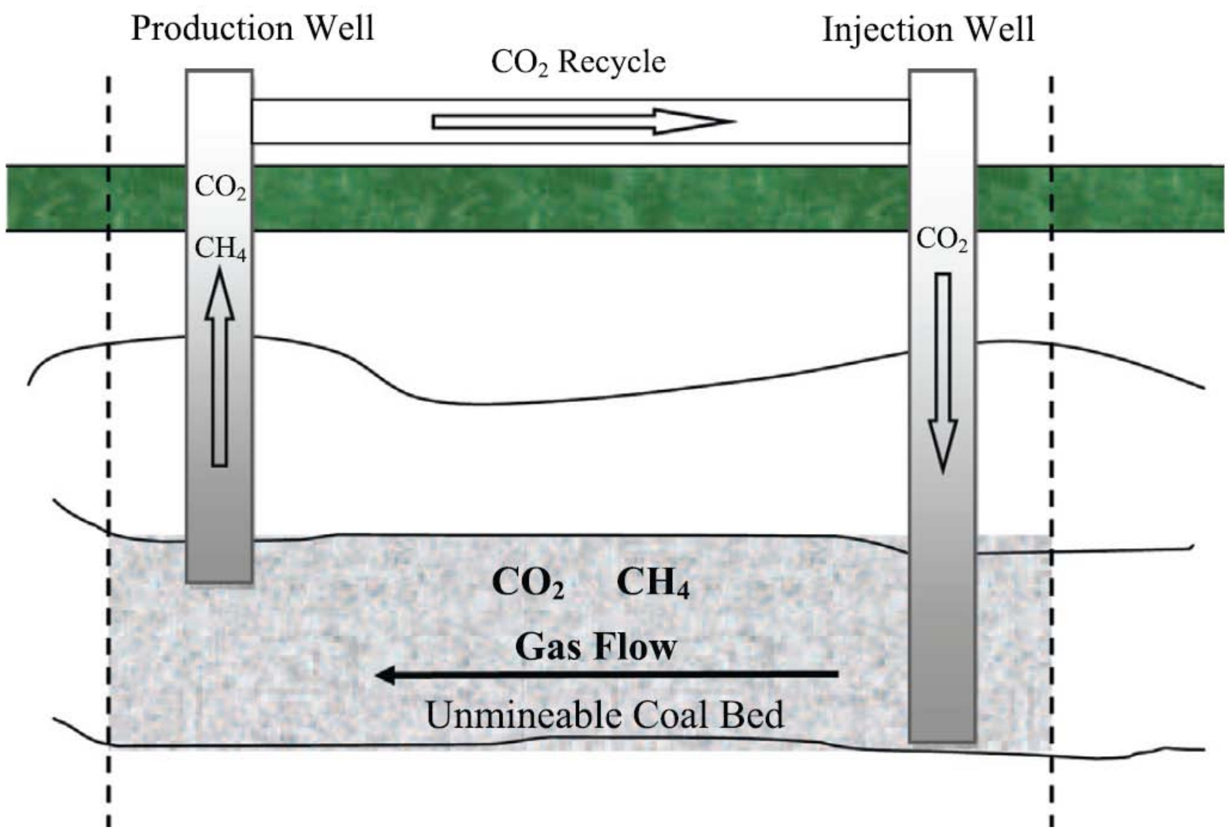
- Storage *with* energy benefits :

$$CFBT^{credit} = Revenue^{CH_4} + \mathrm{Credit}^{\mathrm{CO_2}} - \mathrm{Cost}^{\mathrm{CO_2}} - \mathrm{Cost}^{\mathrm{O\&M}}$$

$CFBT$: cash flow before tax

Carbon Capture and Storage

Enhanced Coal Bed Methane Production with CO_2 Injection

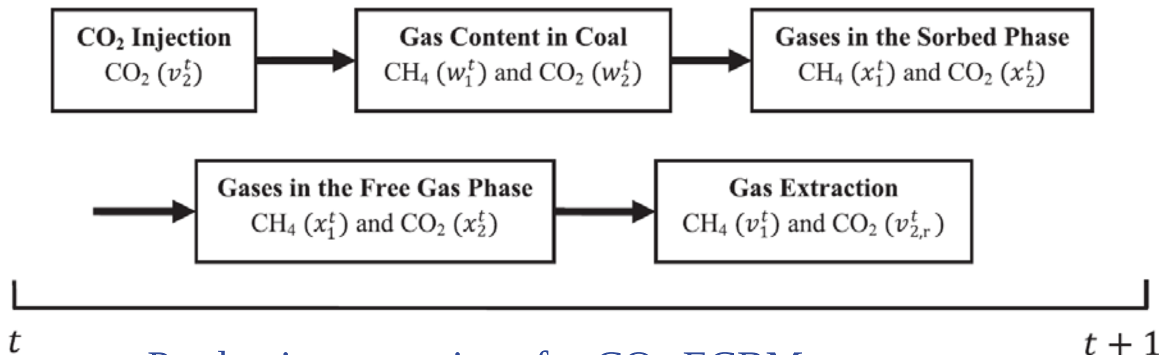


CO_2-ECBM Recovery Process: single well CO_2 injection

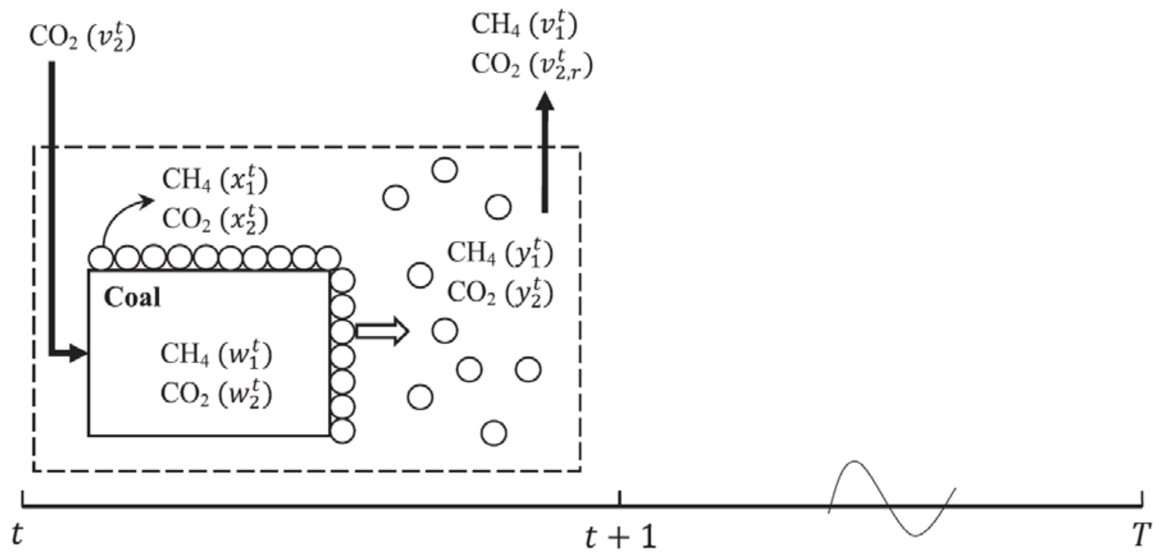
❖ Y. Huang, Q. P. Zheng, N. Fan, and K. Aminian
Optimal scheduling for enhanced coal bed methane production through CO_2 injection, Applied Energy, 113, 2014, pp. 1475-1483.

Carbon Capture and Storage

CO_2-ECBM



Production operations for CO_2-ECBM recovery



Gas adsorption and desorption processes

Carbon Capture and Storage

CO_2-ECBM

Optimization for CO_2-ECBM recovery process

- Considering the project economy, environmental policies, technical operation requirements, physical reaction and geological features.

- The objective is to maximize the profit of CO_2-ECBM production over a planning horizon.
  - Coal bed methane production revenue, $\sum_{t=0}^{T} P_1^t v_1^t$
  - CO_2 credits trading revenue, $\sum_{t=0}^{T} P_2^t v_2^t$
  - Mixed gas production cost, $\sum_{t=0}^{T} C_1^t (v_1^t + v_{2,r}^t)$
  - CO_2 operation cost, $\sum_{t=0}^{T} C_2^t v_2^t$
  - CO_2 removal cost, $\sum_{t=0}^{T} C_{2,r}^t v_{2,r}^t$

  - $$f(\boldsymbol{v}_1, \boldsymbol{v}_2, \boldsymbol{v}_{2,r}) = \sum_{t=0}^{T} P_1^t v_1^t + \sum_{t=0}^{T} P_2^t v_2^t - \sum_{t=0}^{T} C_1^t \left(v_1^t + v_{2,r}^t\right) - \sum_{t=0}^{T} C_2^t v_2^t - \sum_{t=0}^{T} C_{2,r}^t v_{2,r}^t$$

Carbon Capture and Storage

CO_2-ECBM

Constraints for CO_2-ECBM Production

- CO_2 Supply:
  - $v_2^t \le N_2^t + S_2^t + \tau v_{2,r}^{t-1}, \quad \forall\, t \in T$
- CH_4 Supply:
  - $\sum_{t=0}^{T} Q^t \delta y_1^t \le GIP$
- Composition of sorbed phase:
  - $x_2^t = 1 - x_1^t, \ \forall\, t \in T$
  - $x_1^t = \frac{w_1^{t-1}}{w_1^{t-1} + w_2^{t-1}}, \ \forall\, t \in T$
- Composition of gas phase:
  - $y_1^t = \frac{x_1^t}{\theta + (1-\theta) x_1^t}, \quad \forall\, t \in T$
  - $y_2^t = 1 - y_1^t, \quad \forall\, t \in T$
- Variations of gas contents:
  - $M_c w_1^t = M_c w_1^{t-1} - Q^t \delta y_1^t, \quad \forall\, t \in T$
  - $M_c w_2^t = M_c w_2^{t-1} + v_2^t - Q^t \delta y_2^t, \quad \forall\, t \in T$
- CH_4 extraction:
  - $v_1^t \le \sum_{i=0}^{t} Q^i \delta y_1^i - \sum_{i=0}^{t-1} v_1^t, \quad \forall\, t \in T$
  - $y_1^t \ge \gamma, \quad \forall\, t \in T$
- CO_2 extraction:
  - $v_{2,r}^t = \frac{v_1^t y_2^t}{y_1^t}, \quad \forall\, t \in T$

Carbon Capture and Storage

CO_2-ECBM

- The uncertainties of CH_4 prices and CO_2 trading prices
- Multistage stochastic programming model

- $$Max \ \sum_{k=1}^{K} prob^k f(\boldsymbol{v}_1^k, \boldsymbol{v}_2^k, \boldsymbol{v}_{2,r}^k)$$
  $$\text{s.t.} \ \{\boldsymbol{v}_1^k, \boldsymbol{v}_2^k, \boldsymbol{v}_{2,r}^k, \boldsymbol{x}_1^k, \boldsymbol{x}_2^k, \boldsymbol{y}_1^k, \boldsymbol{y}_2^k, \boldsymbol{w}_1^k, \boldsymbol{w}_2^k\} \in \Psi_k$$
  $$\boldsymbol{v}^{t,k} = \boldsymbol{v}^{t,l}, (k,l) \in S_t^n, n \in N$$

- Challenges and Future Work
  - Multistage stochastic nonlinear program
  - Large-sized multistage stochastic program
  - Optimization for the integration with carbon capture facilities and carbon transportation

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Activities

❖ Publications
Journal Articles & Book Chapters

- Y. Huang, Q. P. Zheng, N. Fan, and K. Aminian. ***Optimal scheduling for enhanced coal bed methane production through CO_2 injection.*** Applied Energy, Volume 113, January 2014, pp. 1475-1483.

- Y. Huang, S. Rebennack, and Q. P. Zheng. ***Techno-economic analysis and optimization models for carbon capture and storage: A survey.*** Energy System 2013, pp. 315-353.

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- S Rebennack, P.M. Pardalos, and M.V. Pereira. ***Stochastic Hydro-Thermal Scheduling under CO2 Emissions Constraints***. IEEE Transactions on Power Systems, VOL. 27, NO. 1 (2012), pp. 58-68.

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- M. Rahmani, G. Vinasco, M.J. Rider, R. Romero, and P.M. Pardalos. ***Multistage Transmission Expansion Planning Considering Fixed Series Compensation Allocation.*** IEEE Transactions on Power Systems, Vol. 28, No. 4 (Nov 2013), pp. 3795-3805.

- L. Wang, R. Yang, P.M. Pardalos, L. Qian, M. Fei. ***An Adaptive Fuzzy Controller based on Harmony Search and Its Application to Power Plant Control.*** International Journal of Electrical Power & Energy Systems, Volume 53 (2013), pp. 272-278.

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- G. Vlontzos, S. Niavis, and P.M. Pardalos. ***Testing for Environmental Kuznets Curve in EU Agricultural Sector through an Eco-(in)efficiency index.*** Energies, 10, 1992 (2017).

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- G. Vlontzos and P.M. Pardalos. ***Assess and prognosticate green house gas emissions from agricultural production of EU countries, by implementing DEA Window analysis and artificial neural networks.*** Renewable & Sustainable Energy Reviews, Vol. 76, pp. 155-162,

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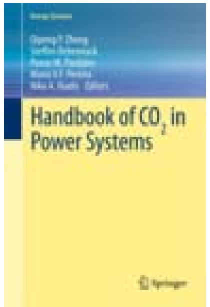

Handbook of CO_2 in Power System

Q. P. Zheng, S. Rebennack, P. M. Pardalos, N. Iliadis, M. V. F. Pereira (eds.)

Springer 2012

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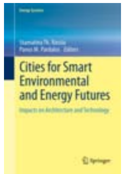

Cities for Smart Environmental and Energy Futures
Rassia, Stamatina Th., Pardalos, Panos M.
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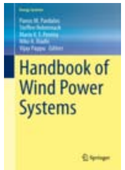

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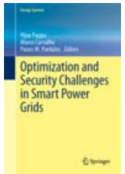

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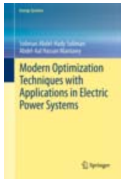

Modern Optimization Techniques with Application in Electric Power Systems
Soliman, Soliman Abdel-Hady, Mantawy, Abdel-Aal Hassan
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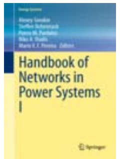

Handbook of Networks in Power System I
Sorokin, A., Rebennack, S., Pardalos, P., Iliadis, N.A., Pereira, M.V.F.
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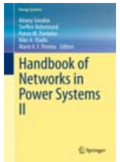

Handbook of Networks in Power System II
Sorokin, A., Rebennack, S., Pardalos, P., Iliadis, N.A., Pereira, M.V.F.
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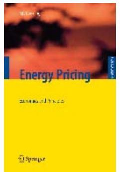

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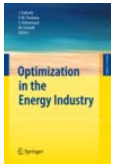

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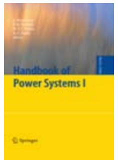

Handbook of Power System I
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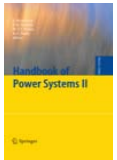

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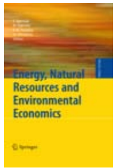
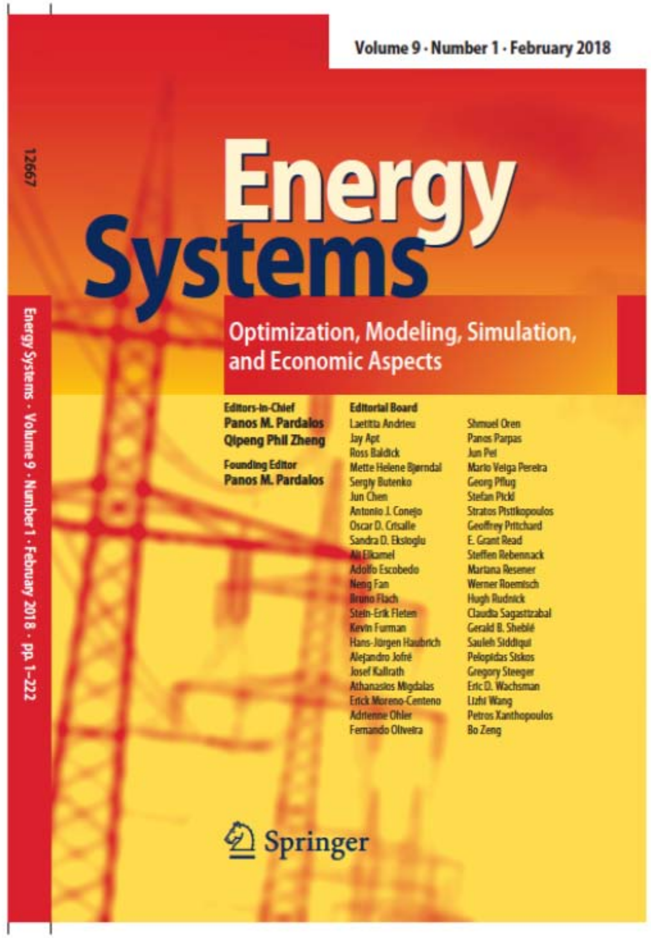


Energy, Natural Resources and Environmental Economics
Bjørndal, E., Bjørndal, M., Pardalos, P., Rönnqvist, M.
Springer 2010

Activities

- **Energy Systems Journal**



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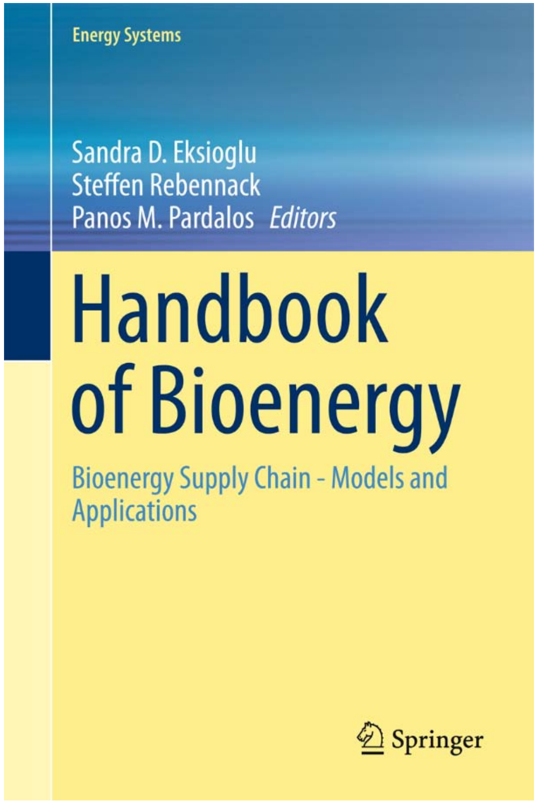

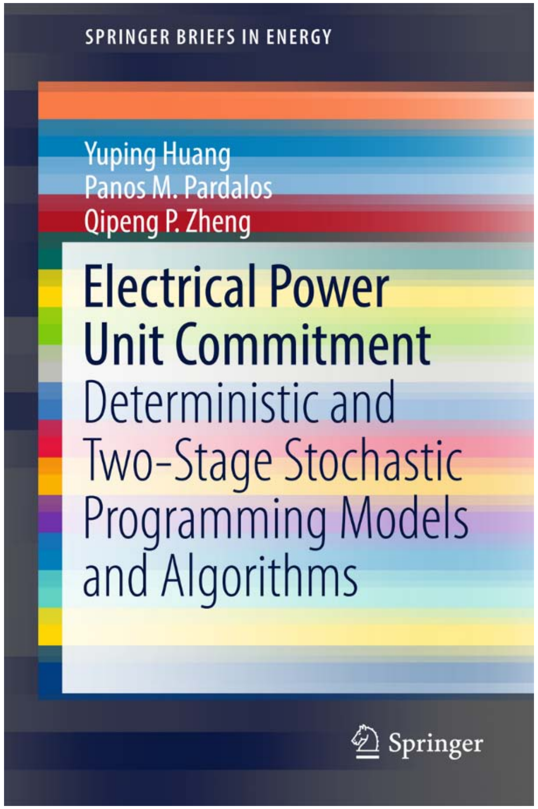

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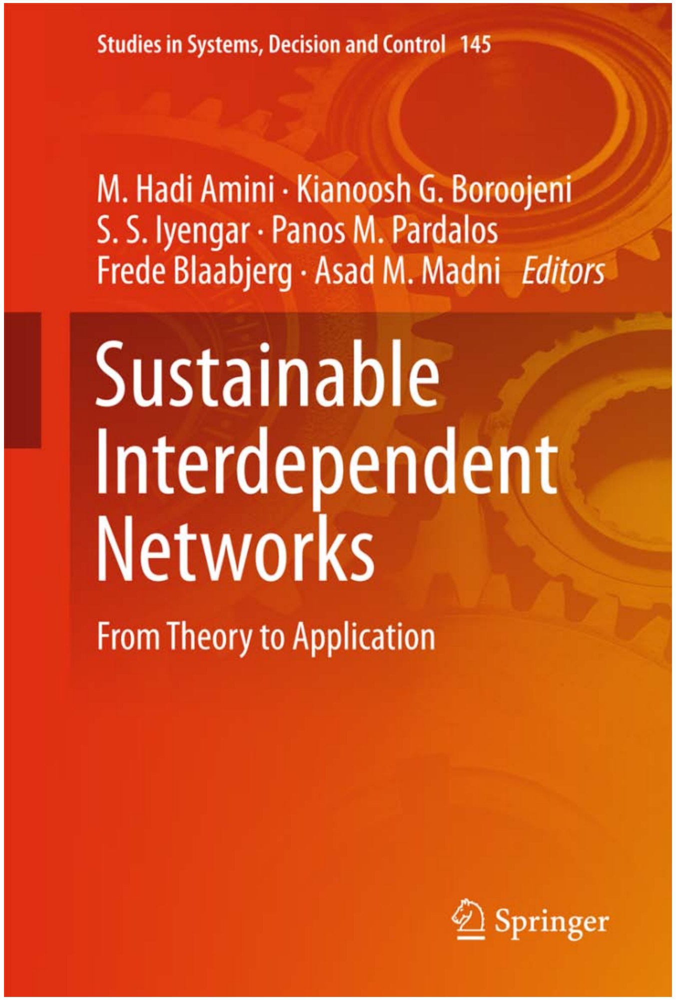

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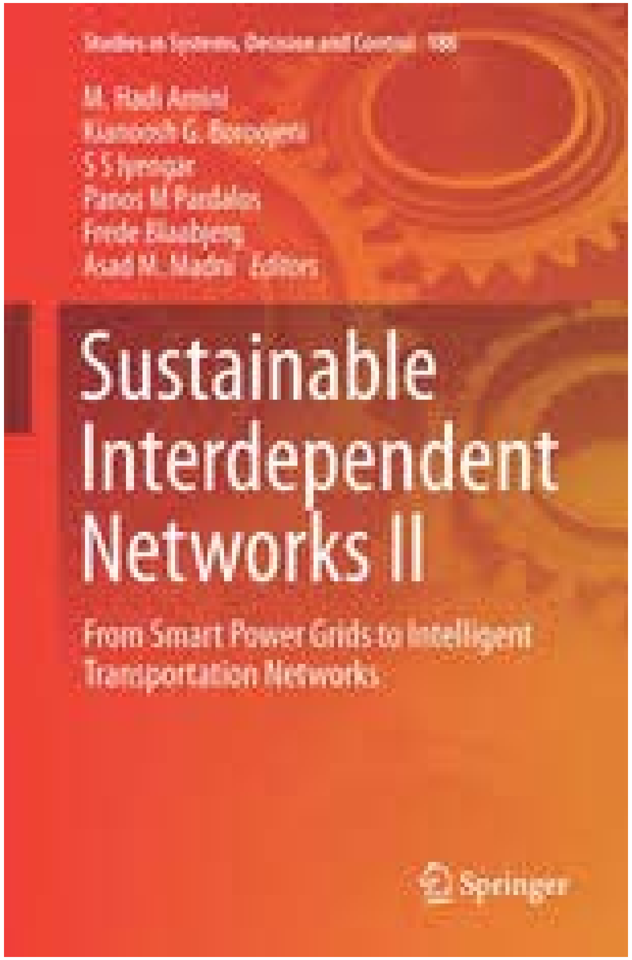

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Challenges and Opportunities for Building a Sustainable Energy Future

- Energy efficiency, conservation, decarbonization of our energy sources
- Clean electricity (and affordable) generation
- Solar, wind, nuclear (technological or political challenges?)
- Energy storage
- Water and Cooling
- Security issues and the smart grid
- New tools (in optimization, sensors, IoT, data sciences, blockchain, etc.)
- Energy education

"If we don't change direction soon, we'll end up where we're heading"
IEA's World Energy Outlook
https://www.nature.com/articles/nature11475

Blockchain & Energy Systems Conference (BEST2019)

- January 18-20, 2019, Orlando, FL, USA
- Organizing Committee: Panos M. Pardalos, Qipeng (Phil) Zheng
- **http://caopt.com/BEST2019/**

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The Foundation for The Gator Nation