Modeling all alternative solutions for highly renewable energy systems

Tim T. Pedersen, Marta Victoria, Morten G. Rasmussen, Gorm B. Andresen

Presentation by:
Tim Pedersen
PhD Fellow
Aarhus University – Denmark
ttp@mpe.au.dk
INTRODUCTION

Motivation:
INTRODUCTION

Motivation:
• Energy system optimization models
INTRODUCTION

Motivation:

• Energy system optimization models
• Complex political agendas
INTRODUCTION

Motivation:

• Energy system optimization models
• Complex political agendas
• Solutions with desirable qualities other than cost
INTRODUCTION

Motivation:

• Energy system optimization models
• Complex political agendas
• Solutions with desirable qualities other than cost
• Land use, transmission expansion, equality in energy generation, transition speed
INTRODUCTION

Motivation:

• Energy system optimization models
• Complex political agendas
• Solutions with desirable qualities other than cost
• Land use, transmission expansion, equality in energy generation, transition speed
• Improve on Modelling to Generate Alternatives (MGA) [1]

INTRODUCTION

Motivation:

• Energy system optimization models
• Complex political agendas
• Solutions with desirable qualities other than cost
• Land use, transmission expansion, equality in energy generation, transition speed
• Improve on Modelling to Generate Alternatives (MGA) [1]

Research question:

INTRODUCTION

Motivation:
• Energy system optimization models
• Complex political agendas
• Solutions with desirable qualities other than cost
• Land use, transmission expansion, equality in energy generation, transition speed
• Improve on Modelling to Generate Alternatives (MGA) [1]

Research question:
• How do we explore all near-optimal model solutions?

INTRODUCTION

Motivation:
• Energy system optimization models
• Complex political agendas
• Solutions with desirable qualities other than cost
• Land use, transmission expansion, equality in energy generation, transition speed
• Improve on Modelling to Generate Alternatives (MGA) [1]

Research question:
• How do we explore all near-optimal model solutions?
• What information do the near-optimal solutions provide?

ENERGY SYSTEM MODEL
ENERGY SYSTEM MODEL

- Model of European power sector [2]

ENERGY SYSTEM MODEL

- Model of European power sector [2]
- Generators: Solar PV, wind and OCGT
- Storage: Battery and hydrogen storage

ENERGY SYSTEM MODEL

- Model of European power sector [2]
- Generators: Solar PV, wind and OCGT
- Storage: Battery and hydrogen storage
- 95% CO2 reduction relative to 1990

ENERGY SYSTEM MODEL

- Model of European power sector [2]
- Generators: Solar PV, wind and OCGT
- Storage: Battery and hydrogen storage
- 95% CO2 reduction relative to 1990

---

ENERGY SYSTEM MODEL

- Model of European power sector [2]
- Generators: Solar PV, wind and OCGT
- Storage: Battery and hydrogen storage
- 95% CO2 reduction relative to 1990

Input

- Weather data
- Energy demand
- Network topology
- Technology costs
- Technical constraints

Output

- Technology dispatch
- Line capacities
- Total system cost

\[
\min f(x) \\
\text{s.t.} \\
g_i(x) \leq 0 \quad i = 1..m \\
h_j(x) \leq 0 \quad j = 1..p
\]

ENERGY SYSTEM MODEL

- Model of European power sector [2]
- Generators: Solar PV, wind and OCGT
- Storage: Battery and hydrogen storage
- 95% CO2 reduction relative to 1990

SOLUTION SPACE

\[ x_2 \]

Insalled solar PV capacity [GW]

Insalled wind capacity [GW]

\[ x_1 \]
SOLUTION SPACE

\[ f(x) \]

Total system cost

\[ x_1 \]

Insalled wind capacity [GW]

\[ x_2 \]

Insalled solar PV capacity [GW]
SOLUTION SPACE

\[ f(x) \]

Total system cost

\[ g_i(x) \]

Technical constraints

Insalled wind capacity [GW]

Insalled solar PV capacity [GW]

\[ x_1 \]

\[ x_2 \]
SOLUTION SPACE

\[ f(x) \]  
Total system cost

\[ g_i(x) \]  
Technical constraints

\[ x_1 \quad \text{Insalled wind capacity [GW]} \]

\[ x_2 \quad \text{Insalled solar PV capacity [GW]} \]

\[ x^* \quad \text{Cost optimal solution} \]
SOLUTION SPACE

$\mathbf{x}_2$

Insalled solar PV capacity [GW]

Insalled wind capacity [GW]

$f(\mathbf{x})$

Total system cost

$g_i(\mathbf{x})$

Technical constraints

$\mathbf{x}^*$

Cost optimal solution

Near-optimal solution space

Slide 22 of 8
NEAR-OPTIMAL SOLUTIONS

\[ f(x) \]

Total system cost

\[ g_i(x) \]

Technical constraints

Carriers
- Wind
- Solar
- OCGT
- Battery
- H2

Wind capacity [GW]

Solar PV capacity [GW]

\[ x_1 \]

\[ x_2 \]
NEAR-OPTIMAL SOLUTIONS

![Map of Europe with different carriers and capacities highlighted.]

- **Carriers:** Wind, Solar, OCGT, Battery, H2

- **Optimal solution:**
  - Wind capacity: 300 GW
  - Solar PV capacity: 100 GW
  - Line capacity: 50 GW

- **Technical constraints:**
  - Near-optimal solutions
  - Low CO2 emission

- **Equations:**
  - Total system cost: $g(x)$
  - Technical constraints: $g_i(x)$
  - Objective function: $f(x)$

- **Graph:**
  - Wind capacity vs. Solar PV capacity
  - Near-optimal solution highlighted
NEAR-OPTIMAL SOLUTIONS

Optimal solution

Carriers
- Wind
- Solar
- OCGT
- Battery
- H2

Wind capacity [GW]
Solar PV capacity [GW]

Technical constraints

Near-optimal

Total system cost

High wind penetration

(a) Optimum
(b) High equality
(c) Large wind capacity
(d) Low CO2 emission

Tech capacity

Optimal solution near-optimal

Total system cost

Technical constraints

Near-optimal

High wind penetration
NEAR-OPTIMAL SOLUTIONS

Optimal solution

(f(x)) Total system cost

(g_i(x)) Technical constraints

Carriers
- Wind
- Solar
- OCGT
- Battery
- H2

High solar PV penetration

High wind penetration

Near-optimal

Optimum

High equality

Large wind capacity

Low CO2 emission

Wind capacity [GW]

Solar PV capacity [GW]

Tech capacity

Total system cost

Technical constraints

Near-optimal solution

300 GW

100 GW

50 GW

25 GW

Wind

Solar

OCGT

Battery

H2

TTP@MPE.AU.DK
22 SEPTEMBER 2021
PHD FELLOW

Slide 5 of 8
NEAR-OPTIMAL SOLUTIONS

Optimal solution

High solar PV penetration

High equality

High wind penetration

Carriers
- Wind
- Solar
- OCGT
- Battery
- H2

f(x) Total system cost

gi(x) Technical constraints

Wind capacity [GW]

Solar PV capacity [GW]

Near-optimal

Total system cost

Technical constraints

300 GW

100 GW

50 GW

25 GW

Near-optimal solution

(a) Optimum

(b) High equality

(c) Large wind capacity

(d) Low CO2 emission
MAPPING ALL ALTERNATIVES

- Optimal solution
- Sample point
- Optimization direction
- Intermediate solution boundary
- Full solution boundary
1) Find optimum

- Optimal solution
- Sample point
- Optimization direction
- Intermediate solution boundary
- Full solution boundary
1) Find optimum
2) Add constraint on maximum total system cost
\[ f(x) \leq f(x^*)(1 + \epsilon) \]
1) Find optimum
2) Add constraint on maximum total system cost
   \[ f(x) \leq f(x^*)(1 + \epsilon) \]
3) Maximize and minimize all variables
MAPPING ALL ALTERNATIVES

1) Find optimum
2) Add constraint on maximum total system cost
   \[ f(x) \leq f(x^*)(1 + \epsilon) \]
3) Maximize and minimize all variables
4) Define convex hull containing known solutions

Diagram:

- Optimal solution
- Sample point
- Optimization direction
- Intermediate solution boundary
- Full solution boundary

Steps:
1. Exploring solution boundary
2. Populating the solution space

Sample point
Volume
Optimal solution
Full solution volume
MAPPING ALL ALTERNATIVES

1) Find optimum
2) Add constraint on maximum total system cost
   \[ f(x) \leq f(x^*)(1 + \epsilon) \]
3) Maximize and minimize all variables
4) Define convex hull containing known solutions
5) Search in face normal directions

\[
\text{minimize } f_{\text{MAA}}(x) = n \cdot x \\
\text{subject to } x \in W
\]
1) Find optimum
2) Add constraint on maximum total system cost
   \[ f(x) \leq f(x^*)(1 + \epsilon) \]
3) Maximize and minimize all variables
4) Define convex hull containing known solutions
5) Search in face normal directions
   \[ \text{minimize} \ f_{\text{MAA}}(x) = n \cdot x \]
   subject to \( x \in W \)
1) Find optimum
2) Add constraint on maximum total system cost
   \[ f(x) \leq f(x^*)(1 + \varepsilon) \]
3) Maximize and minimize all variables
4) Define convex hull containing known solutions
5) Search in face normal directions
   \[ \text{minimize } f_{\text{MAA}}(x) = n \cdot x \]
   subject to \( x \in W \)

\[ x_1 \]
\[ x_2 \]

Optimal solution
Sample point
Optimization direction
Intermediate solution boundary
Full solution boundary
1) Find optimum
2) Add constraint on maximum total system cost
   \[ f(x) \leq f(x^*)(1 + \epsilon) \]
3) Maximize and minimize all variables
4) Define convex hull containing known solutions
5) Search in face normal directions
   \[ \text{minimize } f_{\text{MAA}}(x) = n \cdot x \]
   \[ \text{subject to } x \in W \]
MAPPING ALL ALTERNATIVES

1) Find optimum
2) Add constraint on maximum total system cost $f(x) \leq f(x^*)(1 + \epsilon)$
3) Maximize and minimize all variables
4) Define convex hull containing known solutions
5) Search in face normal directions
   
   minimize $f_{\text{MAA}}(x) = n \cdot x$
   subject to $x \in W$
6) Evenly sample convex hull

$p_{\text{new}} = \sum_{i=1}^{m} p^i s_i$
1) Find optimum
2) Add constraint on maximum total system cost
   \[ f(x) \leq f(x^*)(1 + \varepsilon) \]
3) Maximize and minimize all variables
4) Define convex hull containing known solutions
5) Search in face normal directions
   \[ \text{minimize } f_{\text{MAA}}(x) = n \cdot x \]
   \[ \text{subject to } x \in W \]
6) Evenly sample convex hull
   \[ p_{\text{now}} = \sum_{i=1}^{m} p^i s_i \]

---

**Full solution volume**

- **Optimal solution**
- **Sample point**
- **Optimization direction**
- **Intermediate solution boundary**
- **Full solution boundary**

**Graphical Representation**

- **Axes:** \( x_1, x_2 \)
- **Points:** Sample points, optimal solution
- **Line:** Full solution boundary
- **Curve:** Full solution volume

**Legend:**

- Red dot: Optimal solution
- Black dot: Sample point
- Green arrow: Optimization direction
- Dotted line: Intermediate solution boundary
- Solid line: Full solution boundary

---

**MAPPING ALL ALTERNATIVES**
RESULTS
RESULTS

• Solutions different in technology mix
RESULTS

• Solutions different in technology mix
• Maximum 10% increase in system cost from optimum
RESULTS

• Solutions different in technology mix
• Maximum 10% increase in system cost from optimum
• 500,000 near-optimal solutions
RESULTS

- Solutions different in technology mix
- Maximum 10% increase in system cost from optimum
- 500,000 near-optimal solutions

![Diagram showing technology mix with markers for optimum, high equality, low CO₂ emission, and large wind capacity.]
RESULTS

- Solutions different in technology mix
- Maximum 10% increase in system cost from optimum
- 500,000 near-optimal solutions

(a) Optimum
(b) High equality
(c) Large wind capacity
(d) Low CO2 emission

Optimum
High equality
Low CO2 emission
Large wind capacity

Solar PV [GW]
Wind turbines [GW]

Line capacity
- 50 GW
- 25 GW

Tech capacity
- 300 GW
- 100 GW

Carriers
- Wind
- Solar
- OCGT
- Battery
- H2
RESULTS
RESULTS

Findings

• Large variation in solutions at small changes in total system cost
RESULTS

Findings

• Large variation in solutions at small changes in total system cost

• Negative correlation between hydrogen storage and OCGT
RESULTS

Findings

• Large variation in solutions at small changes in total system cost

• Negative correlation between hydrogen storage and OCGT

• Strong correlation between solar PV and equality in energy production
RESULTS

Findings

• Large variation in solutions at small changes in total system cost

• Negative correlation between hydrogen storage and OCGT

• Strong correlation between solar PV and equality in energy production

• Strong correlation between solar PV and battery