Modeling Regional Renewable Energy Development

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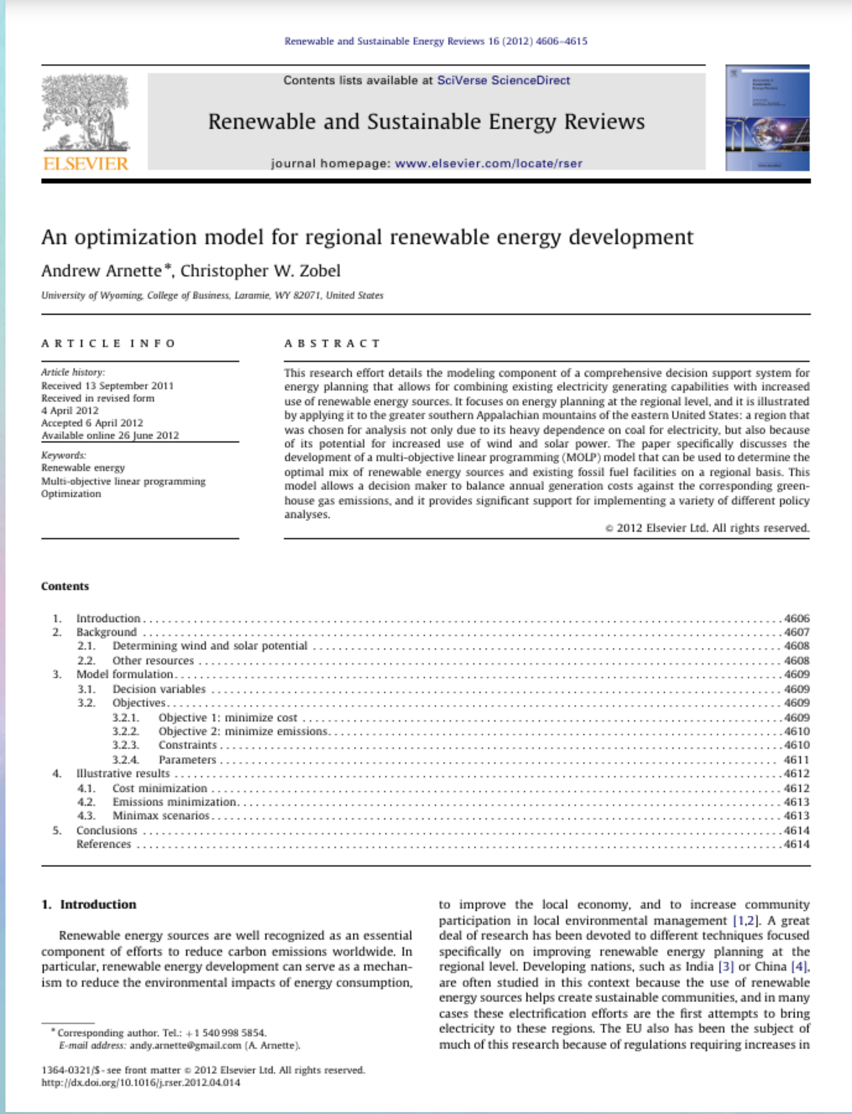
MSBA '25



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An optimization model for regional renewable energy development

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ABSTRACT

This research effort details the modeling component of a comprehensive decision support system for energy planning that allows for combining existing electricity generating capabilities with increased use of renewable energy sources. It focuses on energy planning at the regional level, and it is illustrated by applying it to the greater southern Appalachian mountains of the eastern United States: a region that was chosen for analysis not only due to its heavy dependence on coal for electricity, but also because of its potential for increased use of wind and solar power. The paper specifically discusses the development of a multi-objective linear programming (MOLP) model that can be used to determine the optimal mix of renewable energy sources and existing fossil fuel facilities on a regional basis. This model allows a decision maker to balance annual generation costs against the corresponding greenhouse gas emissions, and it provides significant support for implementing a variety of different policy analyses.

Contents

1. Introduction

Renewable energy sources are well recognized as an essential component of efforts to reduce carbon emissions worldwide. In particular, renewable energy development can serve as a mechanism to reduce the environmental impacts of energy consumption, to improve the local economy, and to increase community participation in local environmental management [1,2]. A great deal of research has been devoted to different techniques focused specifically on improving renewable energy planning at the regional level. Developing nations, such as India [3] or China [4], are often studied in this context because the use of renewable energy sources helps create sustainable communities, and in many cases these electrification efforts are the first attempts to bring electricity to these regions. The EU also has been the subject of much of this research because of regulations requiring increases in

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Introduction

- **Purpose of the Study:**
  - Develop a multi-objective optimization model for renewable energy integration.
  - Provide a decision-support tool to optimize the trade-offs between minimizing costs and reducing greenhouse gas emissions.
- **Focus Region:** Greater Southern Appalachian Mountains.
  - Selected for its heavy reliance on coal (84% of energy generation) and potential for increased renewable energy adoption.
- **Significance:**
  - Combines economic and environmental goals to aid policymakers in transitioning towards sustainable energy solutions.
  - Incorporates renewable energy sources like wind, solar, and biomass while addressing capital investment constraints and infrastructure challenges.

Background

- **Current Energy Landscape:**
  - The region relies predominantly on coal, generating significant greenhouse gas emissions (166.68 million tons annually).
  - Renewable energy contributes only 3.37% to the energy mix, far below national averages.
- **Renewable Potential:**
  - **Wind Power:** Excellent on-shore wind conditions, with 2.38% of the land meeting development criteria.
  - **Solar Energy:** Favorable solar insolation values, enabling opportunities for utility-scale solar farms.
  - **Biomass Co-Firing:** Utilization of solid wood waste can replace up to 8.7% of coal consumption with reduced emissions.
- **Challenges and Opportunities:**
  - Transitioning from coal dependence to renewables requires addressing cost barriers, regulatory constraints, and land-use challenges.
  - The optimization model evaluates site-specific renewable feasibility and enables analysis of policy scenarios like carbon taxes or renewable energy incentives.

Greater Southern Appalachian Mountain Region

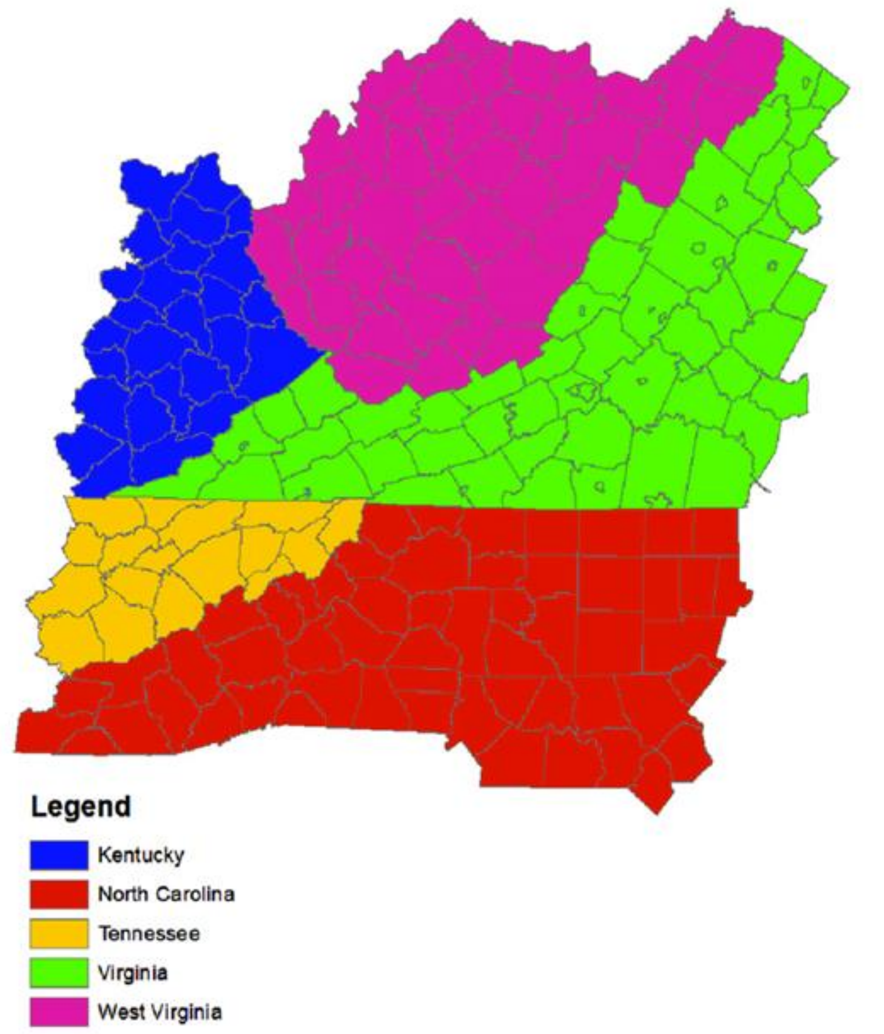


Fig. 1. Greater Southern Appalachian Mountain region.

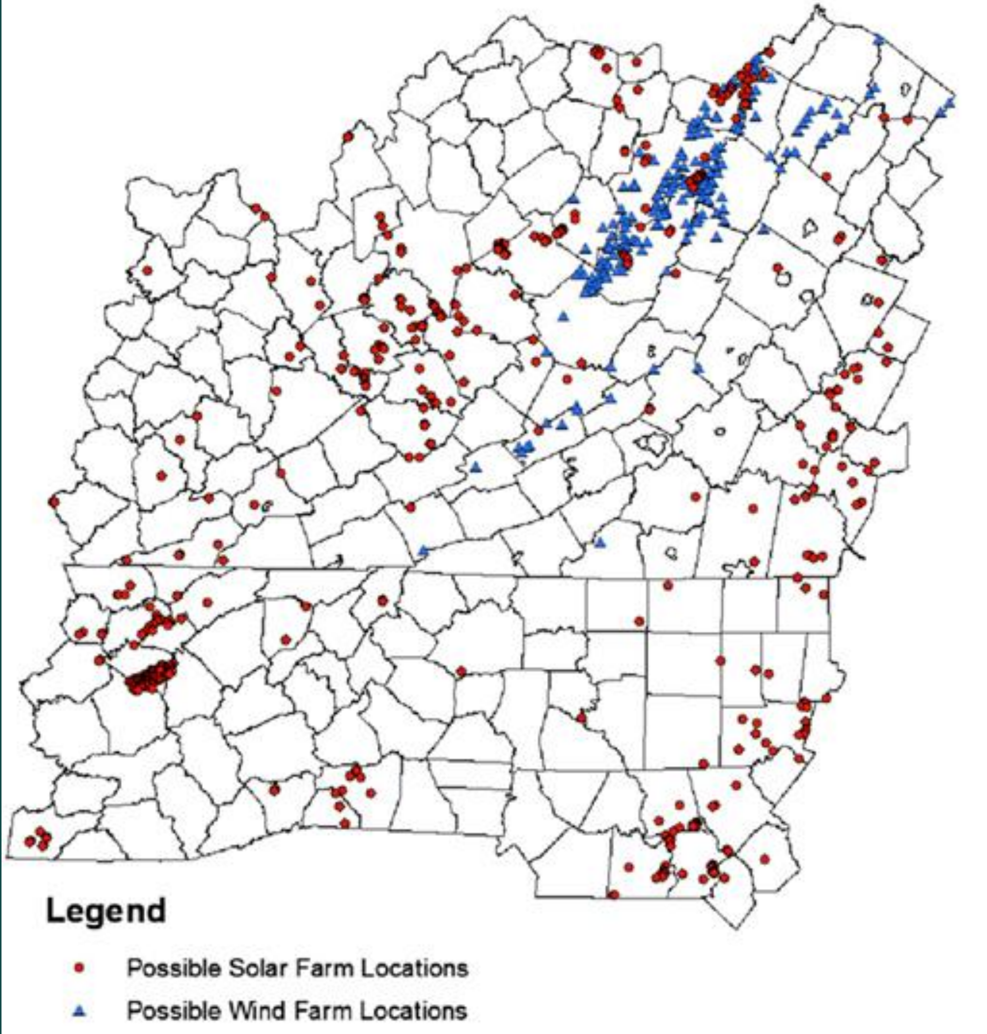


Fig. 2. Potential wind and solar farm sites within the region.

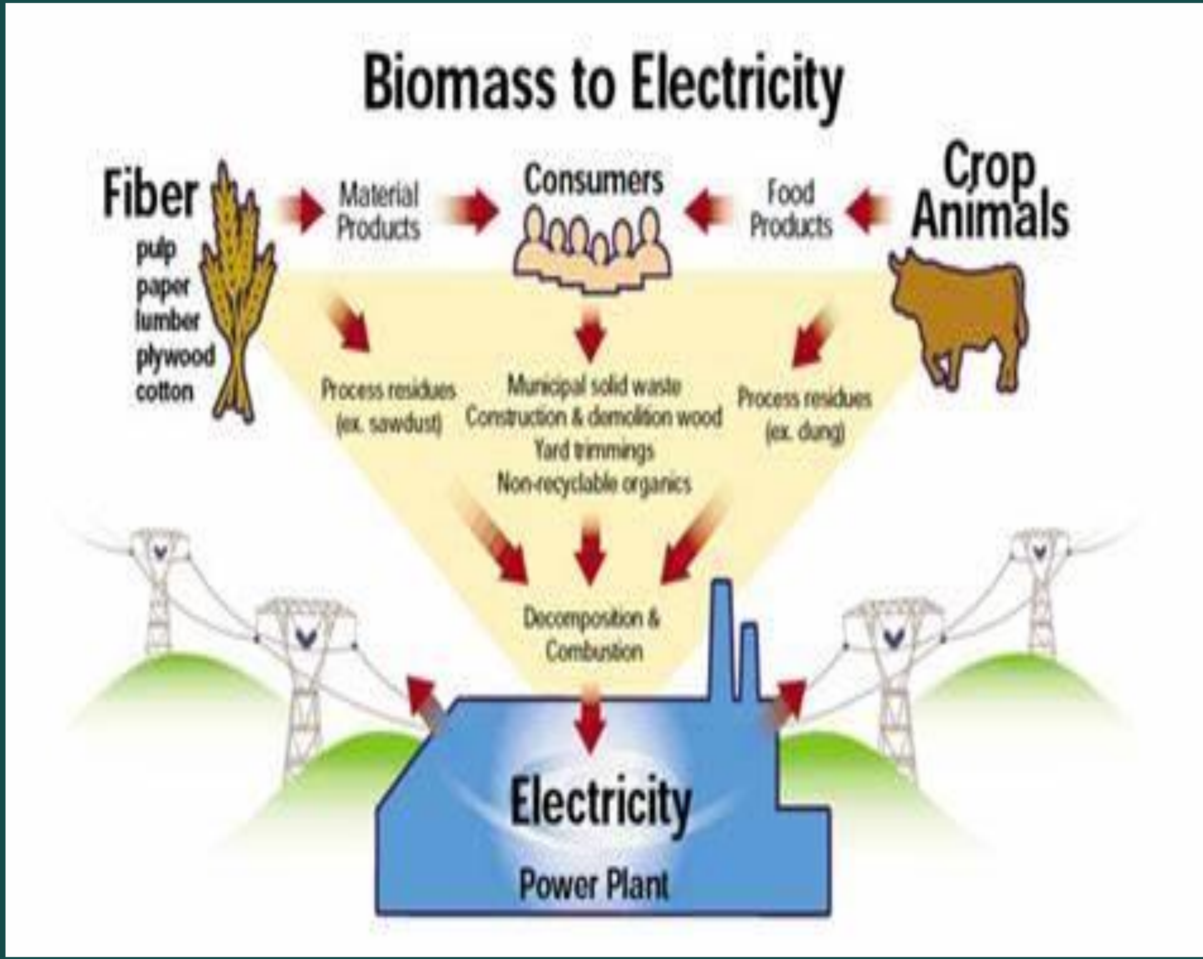
Model Formulation

- GIS (Geographic information System)
- Data:
  - **Nw** = Possible wind farm locations
  - **Ns** = Possible solar farm locations
  - **Nct** = Number of counties (indexed by *y*)
  - **Nc** = Existing coal-based electricity plants (indexed by *p*)
  - **Nnc** = Existing non-coal-coal based electricity plants (indexed by *q*)

- Decision Variables
  - **Wi** = 1 if wind farm is placed at location *i*, 0 otherwise
  - **Sj** = 1 if solar farm is placed at location *j*, 0 otherwise
  - **Byp** = tons of biomass to send from county *y* to coal plant *p*
  - **Uq** = how much of facility *q* to use
  - **Gp** = how much of facility *p* to use

Notes on Decision Variables

- **Biomass**
  - Biomass is being sent to coal plants to see how much coal can be replaced with biomass
    - Co-firing to reduce emissions
- **Coal and Non-Coal Plant Utilization**
  - **Gp** and **Uq** $\in [0, 1]$
    - Baseline MWh/year (megawatt per hour/year) for coal plant p is 100
    - **Gp** for coal plant p = 0.6 (optimal value)
    - Coal plant p is operating at 60% utilization
      - Balancing minimizing emissions and minimizing cost



Objective 1: Minimize Cost

- **Minimizing Cost**
  - **2 Components:**
    - **Wind and Solar costs:**
      - Capital investment costs
      - Fixed operating and maintenance costs
      - Variable operating and maintenance costs
    - **Costs associated with Coal-Fired Plants being considered for biomass co-fire:**
      - Capital investment to retrofit coal plants
      - Cost per ton of coal and biomass
      - Variable costs (labor + other costs)
      - Transportation of biomass
    - **Costs for Existing Non-Coal Facilities**
      - Operating costs, fuel costs, labor

$$
\begin{aligned}
f_{cost} = {} & \sum_{i=1}^{N_i} W_i(C_i^{vw} + C^{kwm}K_i^{w} + C^{mwm}M_i^{w}) + \sum_{j=1}^{N_j} S_j(C_j^{vs} + C^{ksm}K_j^{s} \\
& + C^{msm}M_j^{s}) + \sum_{p=1}^{N_p} \Bigg\{ (C_p^{vc} + C^{ac}G_pM_p^{c} + C^{tc}G_pT_p) + \sum_{y=1}^{N_y} (C^{tb}B_{yp} \\
& + C^{tbd}B_{yp}D_{yp} - C^{tc}B_{yp}F) \Bigg\} + \sum_{q=1}^{N_q} C_q^{mn}M_q^{n}U_q
\end{aligned}
$$

Objective 2: Minimize Emissions

- Using data from U.S. Department of Energy, and U.S. Environmental Protection Agency
    - Carbon Dioxide, Sulphur Dioxide, Nitrogen Oxides
        - Total Emissions
            - **Coal Plant Emissions**
                - Based on coal usage and utilization
            - **Adjustments for Biomass Replacement**
                - Reduction of emissions from biomass, while adding NOx
            - **Non-Coal Plant Emissions**
                - From gas or oil plants

$$
\begin{aligned}
f_{emissions} = \sum_{p=1}^{N_p} \Bigg\{ & ([E_p^{co-p} + E_p^{so-p} + E_p^{no-p}]G_p T_p)) \\
& - \sum_{y=1}^{N_y} ([E_p^{co-p} + E_p^{so-p} + E_p^{no-p}]B_{yp}F + [E_p^{co-b} + E_p^{so-b} \\
& + E_p^{no-b}]B_{yp} \Bigg\} + \sum_{q=1}^{N_q} [E_q^{co-q} + E_q^{so-q} + E_q^{no-q}]M_q^n U_q
\end{aligned}
$$

Total Emissions = Coal plant emissions – biomass replacement + non-coal plant emissions

Constraints 1 & 2

- **Constraint 1: County Biomass Constraint**
  - The amount of biomass sent from county (*y*) to coal plant (*p*) that use biomass cannot exceed the available amount in county (*y*)

$$\sum_{p=1}^{N_p} B_{yp} \leq B_y^{avail}$$

- **Constraint 2: Biomass Utility Constraint**
  - The biomass used at each coal plant does not exceed a specified percentage (x) of the total fuel input (coal + biomass) at that plant

$$\sum_{y=1}^{N_y} B_{yp} F \leq G_p T_p X$$

Constraint 3

- More formulations!
- **Constraint 3: Electricity Demand Constraint**
  - Electricity generated from wind farms
  - Electricity generated from solar farms
  - Electricity generated from non-coal plants
  - Electricity generated from coal plants
    - Needs to equal or be more than the demand

$$\sum_{i=1}^{N_i} M_i^w W_i + \sum_{j=1}^{N_j} M_j^s S_j + \sum_{p=1}^{N_p} M_p^c G_p + \sum_{q=1}^{N_q} M_q^n U_q \ge M^{base}(1+H)$$

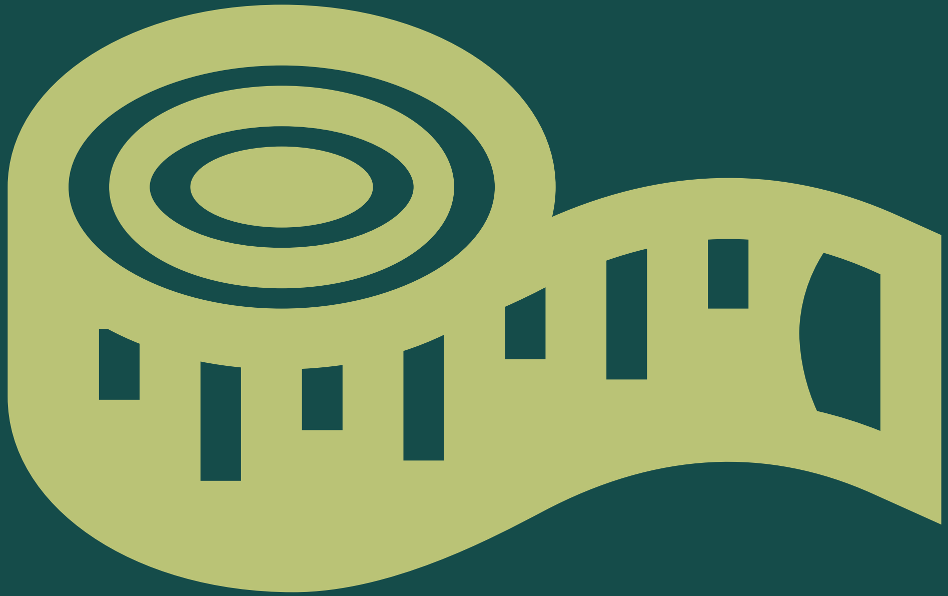
Constraint 4

- **Constraint 4: Capital Investment Constraint**
  - Total capital investments in wind and solar projects, coal plant retrofitting, and biomass transportation costs cannot exceed budget
  - Wind costs + solar costs + coal plant retrofitting and biomass transport <= budget (V)

$$\sum_{i=1}^{N_i} K_i^w \left(C^{kw} + C^{af} A_i^f + C^l L_i\right) + \sum_{j=1}^{N_j} C^{ks} K_j^s + \sum_{p=1}^{N_p} \left[C^{kb} \left(K_p^c / M_p^c\right) M_p^{tc} \sum_{y=1}^{N_y} B_{yp} F \right] \le V$$

Parameters

- The user defines their own costs and values in the model to find the optimal balance of minimizing cost and minimizing emissions for their specific project.
  - Parameters for biomass and coal co-fire, wind farm costs, solar farm costs, non-coal facility generation.
    - In each of these parameters, the user can input their own data.
  - For example, the user can input:
    - Cost of preparing forest land ($/acre) = $5000
    - Cost of electricity generation from Biomass ($/KWh) = $0.05200
    - Cost of biomass ($/ton) = $40.00



Overall Results

- **Total Estimated Capacity – Wind**
  - Cost: $13.72.B
  - 1.859 GW of wind power to be installed capable of generating 6.44 MWh each year
  - 3.24% of the baseline generation in this region
- **Total Estimated Capacity – Solar**
  - Cost: $32.6B
  - 5.08 GW of solar power that can create 6.44 MWh each year
  - 3.33% of baseline generation
- **Total Estimated Capacity – Biomass Co-Fire**
  - Cost: $164.96M
  - Could replace up to 8.7% of coal used in the region

Emission Minimization

Max Investment Value (V): $15B

Total Cost for All: $46.16B

- **Emissions Objective (without cost objective) :**
  - Total of 148.6M tons of emissions
    - Annual generation cost of $6.9B (16.01% over budget)
  - Coal remains the dominant source of power in the region
  - Power from renewable energy increases from 3.37% to 14.20%
    - Biomass generates 7.15% of total MWh at approx. $164.96M,
    - Reduces coal plants emissions by 10.92%
  - Wind generates 2.59% of total MWh, from 116 farms at $7.79B
  - Solar generates 1.17% of total MWh, from 73 farm locations at $7.05B
  - 99.99% of capital investment is used

* All biomass, co-fire, landfill, nuclear, water, and wind facilities operate at full capacity in this scenario

Cost Minimization

Max Investment Value (V): $15B

Total Cost for All: $46.16B

- **Cost Objective (without emissions consideration):**
  - Annual generation cost of $6.25B
  - Meets demand constraint but only $6.77B out of $15B the capital investment
    - Biomass is not used due to implementation costs, as it only increases cost per unit of power that come from coal plants
  - Wind farm development is 2.19% of power generation
  - Solar farm is 0.25% of power generation
  - Use of renewable energy sources is 5.73% up from a 3.37% baseline

Minimax Weighting Scenarios

Equally Weighted:

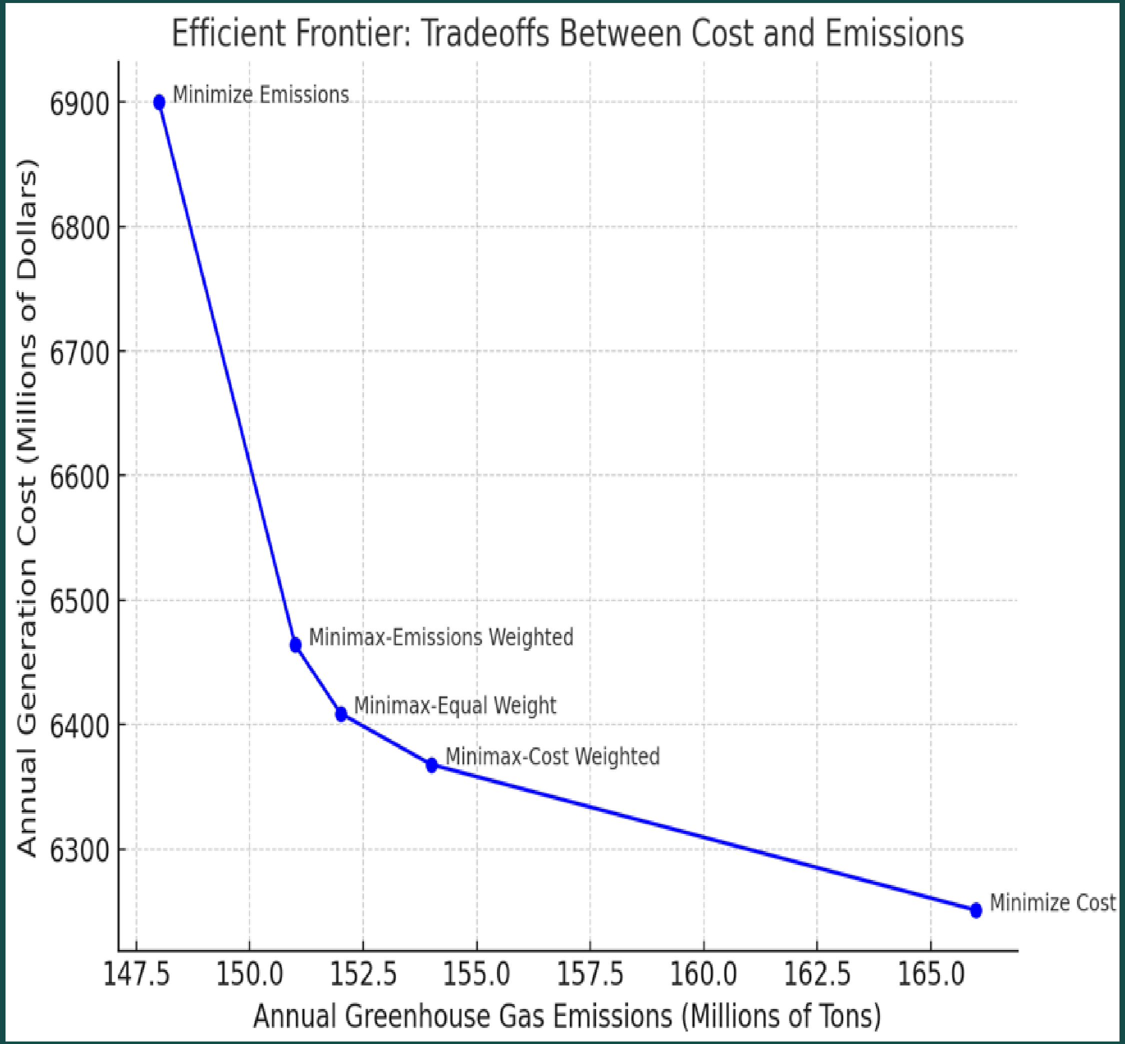
- Renewable share 12.70%; cost $6.41 billion Emissions-focused policies.

Cost Weighted:

- Renewable share 11.79%; cost $6.37 billion.

Emissions Weighted:

- Renewable share 11.79%; cost $6.37 billion.



Model Flexibility

Tradeoffs:

- Cost reductions.
- Emissions-focused policies.

Flexibility:

- Adaptable to different regions.
- Supports analysis of public policies.

Conclusion:

- What have we learned?

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