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Xie, Fei and Huang, Yongxi, "Sustainable Biofuel Supply Chain Planning and Management under Uncertainty" (2013). *Graduate Research and Discovery Symposium (GRADS)*. 50.
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Sustainable Biofuel Supply Chain Planning and Management under Uncertainty

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Introduction

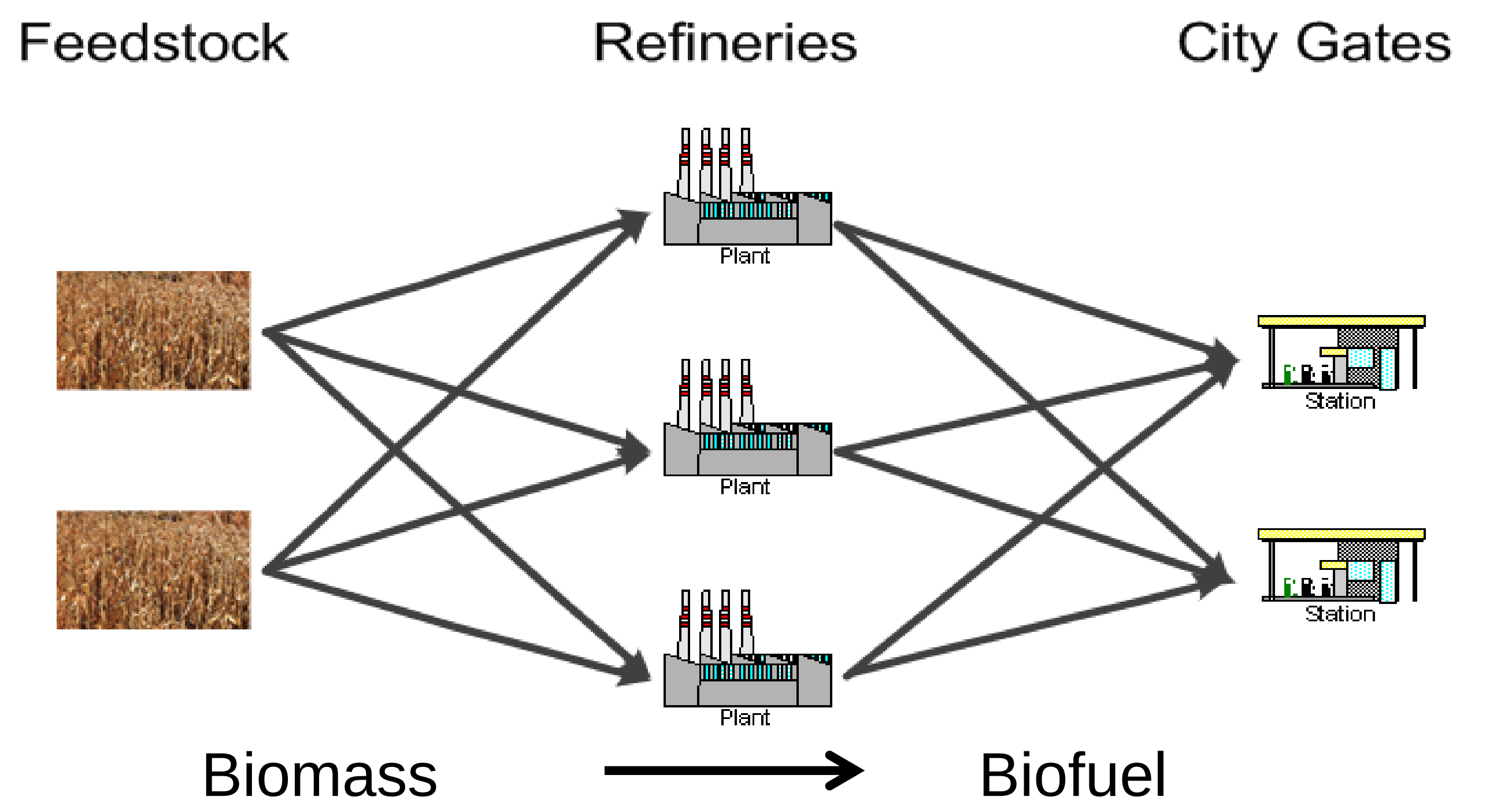
Objective

This study aims to:

- Integrate "environmental thinking" in sustainable cellulosic biofuel supply chain planning and management;
- Develop a multi-objective modeling framework in achieving economic and environmental sustainability in biofuel supply chain system against uncertainty in conversion uncertainty;
- Use the proposed model to evaluate the economic potentials and environmental impacts for California cellulosic biofuel system development.

Background — Sustainable Cellulosic biofuel

- The majority of biofuels in US is corn grain-based biofuel obtained from food crops;
- Corn grain-based biofuel is not sustainable (pressure on food supply);
- Cellulosic biofuel is alternative to corn grain-based biofuel;
- Cellulosic biofuel is bio-wasted based biofuel and has better life cycle performance;
- Sustainable biofuel system: **cost competitiveness** v.s. **environmental quality**
- Uncertainty in conversion technology

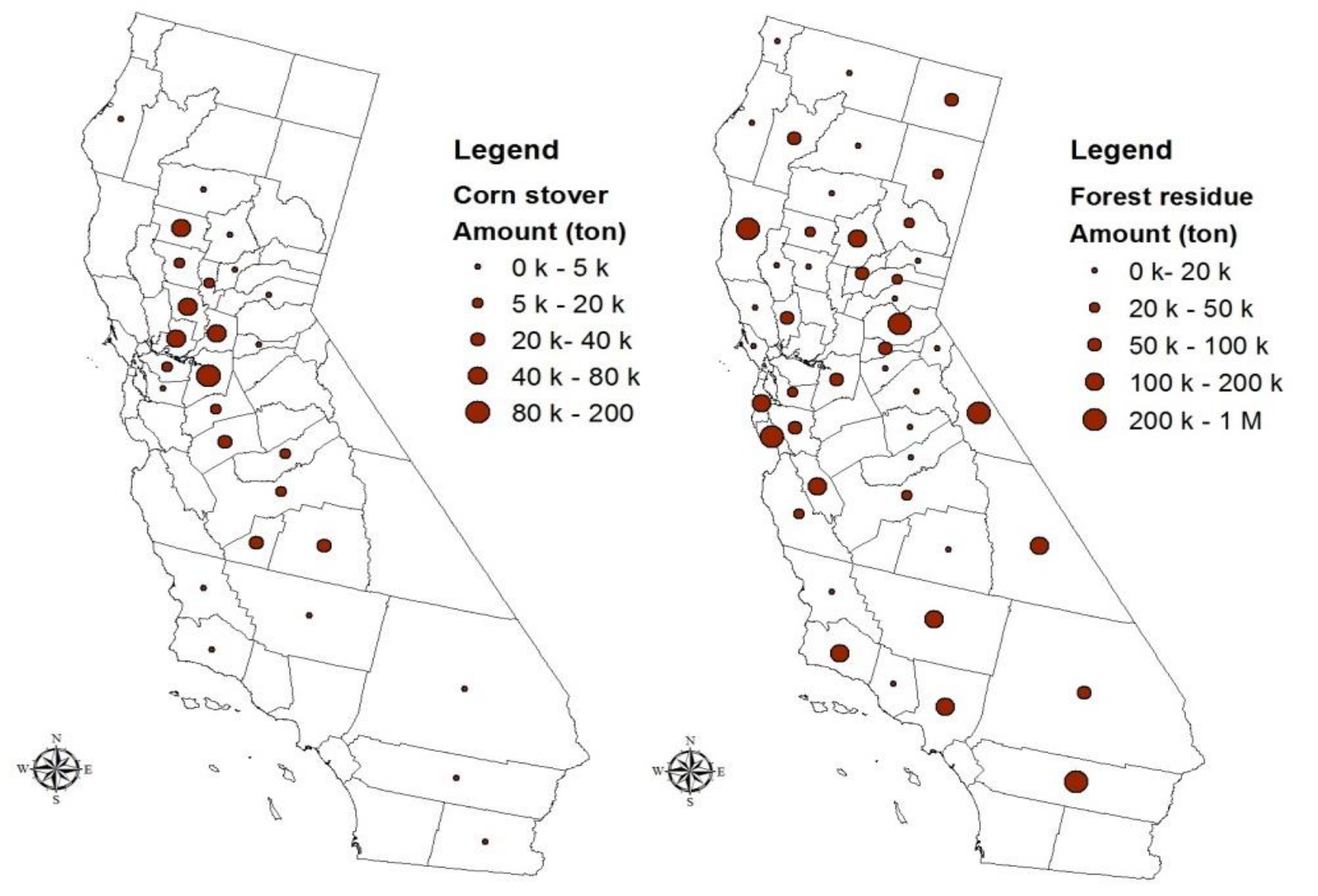


This study simplifies the biofuel supply chain system with three infrastructure layers: feedstock sites, refineries and city gates.

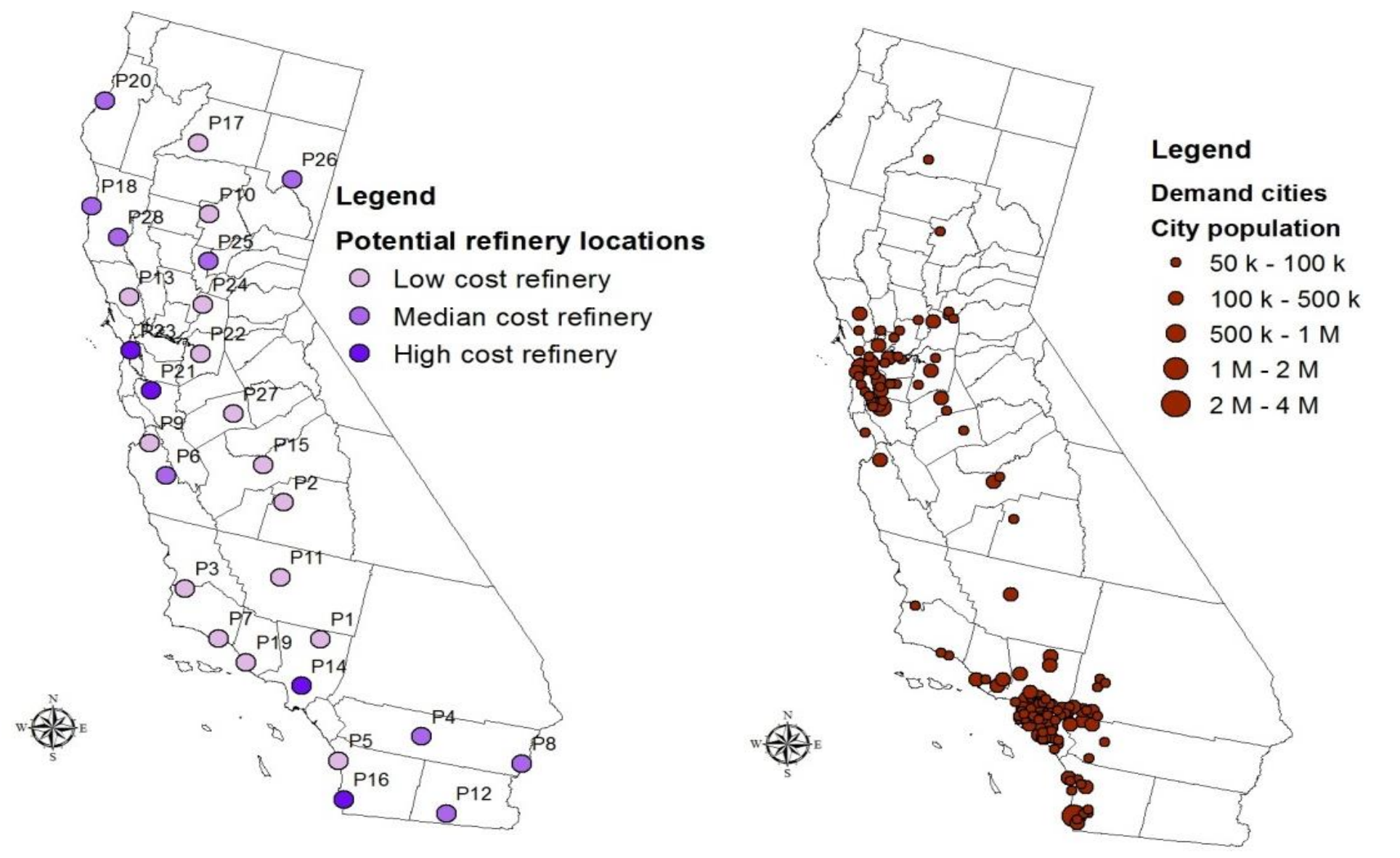
Potential California Cellulosic Biofuel System

Technical Data Inputs

- **Ethanol Demand:** 272 MGY in 2020
- **Conversion Technology:** LignoCellulosics Ethanol (LCE) via hydrolysis and fermentation conversion technology with Dilute Acid pretreatment process
- **Feedstock Types:** Corn stover, forest residues
- **Refinery Capacity:** 60~100MGY
- **Demand Centers:** 143 cities
- **Transportation mode:** Truck
- **GHG data:** GREET model

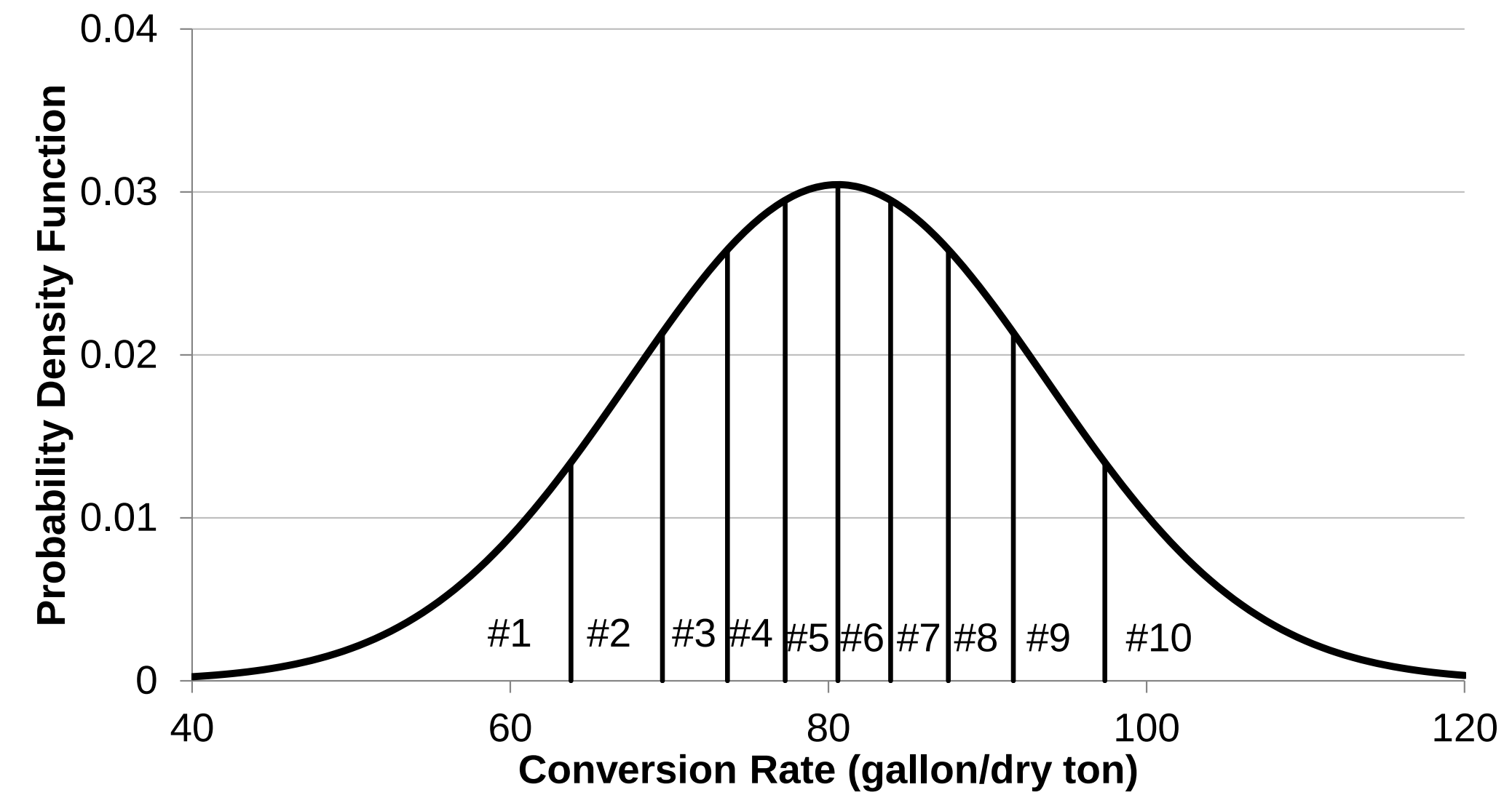


Feedstock sites



Locations of refineries and city gates

Uncertainty in Conversion Technology



Ten scenarios with equal probabilities are generated

- **Uncertainty:** conversion technology
- **Distribution:** normal distribution with σ=13.1 gallon/dry ton
- **Scenario-dependent parameters:** conversion rate and production emission

Methods

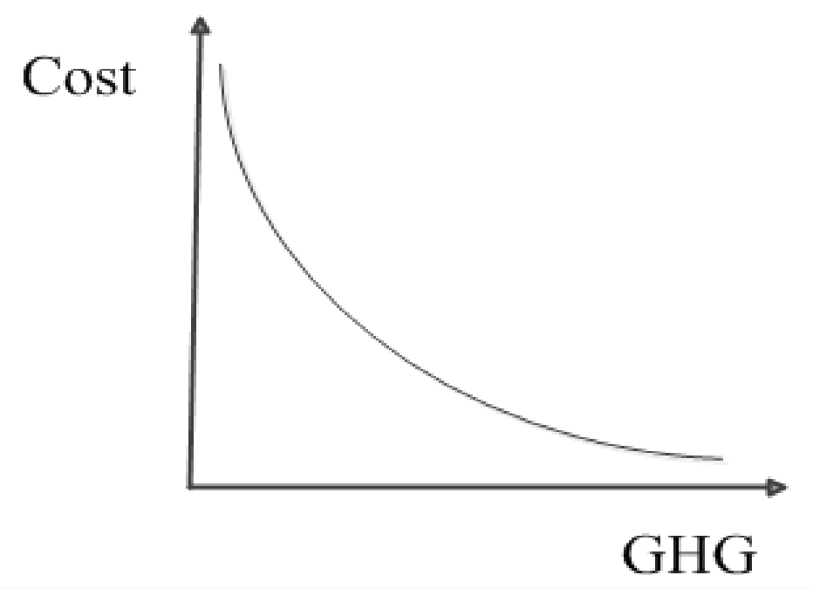
Modeling Description

Modeling Objectives:

- Minimization of system cost (f_1)
- Minimization of system greenhouse gas (GHG) emission (f_2)

Modeling Techniques:

- Two-stage stochastic programming method
- Multi-objective optimization — Compromise method

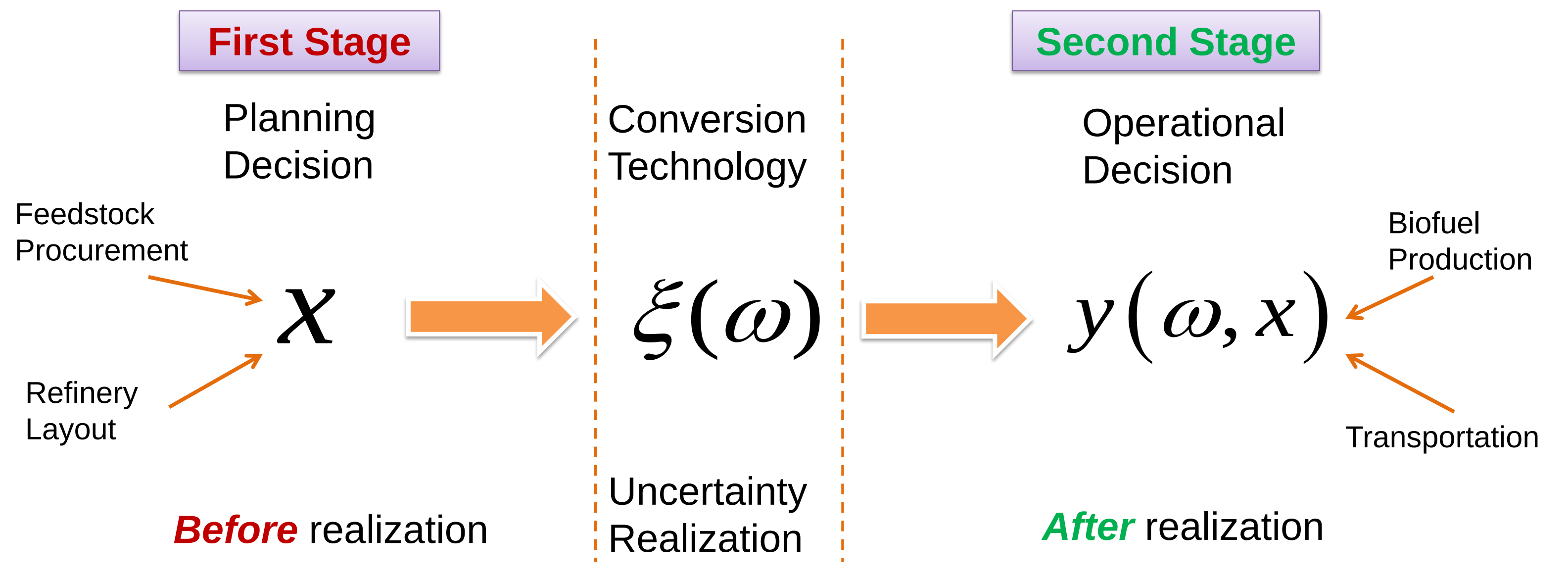


Decision Variables:

- Feedstock procurement strategies
- Refinery locations and sizes
- Biofuel production
- Biomass and biofuel transportation

Modeling Uncertainty

Two-stage stochastic programming method is adopted to model uncertainty:



First Stage

Planning Decision

Feedstock Procurement

Refinery Layout

x

Before realization

Conversion Technology

$\xi(\omega)$

Uncertainty Realization

Second Stage

Operational Decision

$y(\omega, x)$

Biofuel Production

Transportation

After realization

Planning decisions are made before the uncertainty is realized. After the uncertainty realization, the operational decisions are determined.

Multi-objective Optimization: Compromise Method

$$\text{Minimize } f = \sum_{i=1}^{2} W_i \frac{f_i - f_i^{o}}{f_i^{ao} - f_i^{o}}$$

Preferential weight

i th objective function

Anti-optimal result

Optimal result

1 ≡ "Cost"
2 ≡ "GHG"

Pay-off Matrix

Min	Cost	GHG
$f_1 - \text{cost}$	f_1^{o}	f_2^{ao}
$f_2 - \text{GHG}$	f_1^{ao}	f_2^{o}

Example:

$$\begin{array}{l} \min f_1 \Rightarrow x_1^* \\ \min f_2 \Rightarrow x_2^* \end{array} \Rightarrow \begin{cases} f_1(x_1^*) = f_1^{o} \equiv \text{optimal system cost} \\ f_1(x_2^*) = f_1^{ao} \equiv \text{anti-optimal system cost} \end{cases}$$

Construct the pay-off matrix following the example above and use attained four optimal and anti-optimal result to formulate the compromise model

Results

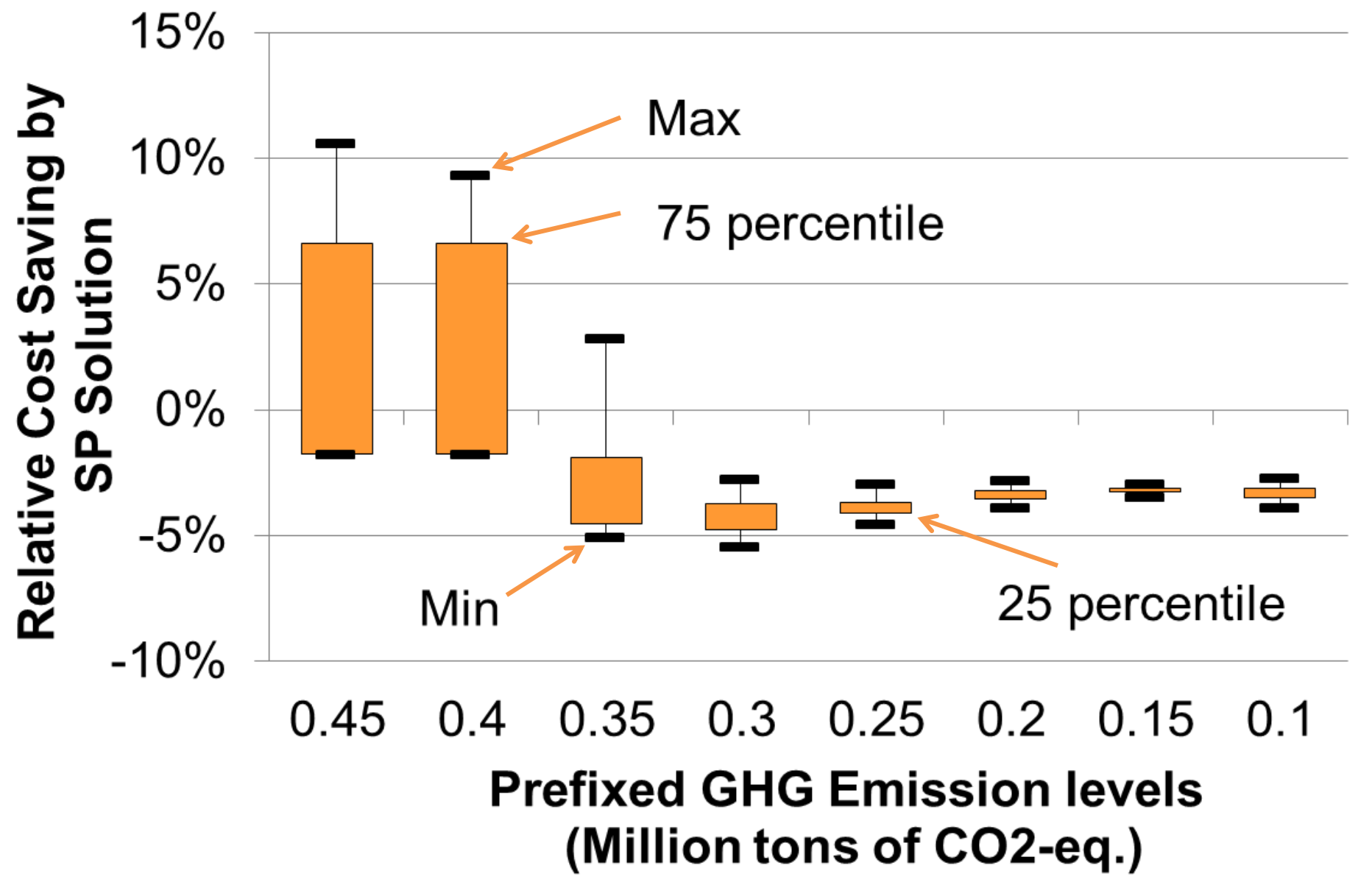
System Planning Strategies and Outcomes

Three types of solutions are evaluated: 1) **SP solutions** are obtained from the stochastic model; 2) **Wait-and-See solutions** are based on the assumption that uncertainty is revealed before planning decisions are made; and 3) **EV solutions** are determined by taking all possible scenarios by expectation.

		SP soln	Wait-and-See Solutions by Scenarios										EV soln
			#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	
Refinery Size (MGY)	#17	60	60	65	60	60	60	60	60	60	60	60	60
	#20	87	66	75	80	83	87	90	93	94	92	88	88
	#22	65	60	72	72	69	65	62	60	60	60	60	63
	#25	NA	60	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	#28	60	60	60	60	60	60	60	60	60	60	64	61
Feed-stock proc. (million dry tons)	Corn stover	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Forest	2.9	3.6	3.1	2.9	2.7	2.6	2.5	2.4	2.3	2.2	2	2.6
Total system cost (billion $)		0.63	0.69	0.64	0.62	0.61	0.60	0.59	0.58	0.58	0.57	0.55	0.59
Total GHG emission (million tons of CO_2-eq)		0.37	0.47	0.43	0.41	0.39	0.38	0.36	0.35	0.34	0.33	0.31	0.37

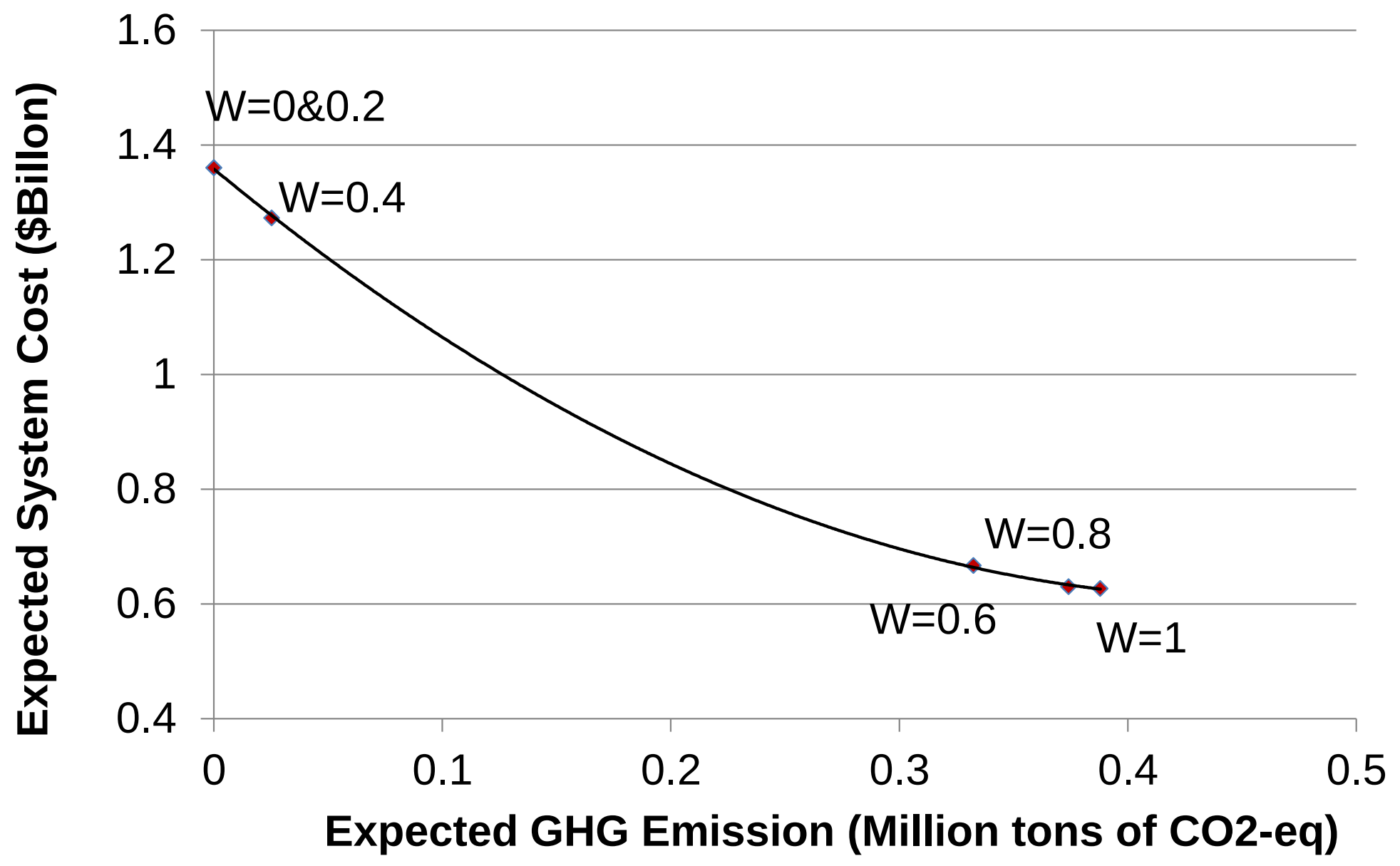
Results Evaluation

The authors compared the SP solution and EV solutions under 10 scenario sets. In the following figure, each box plot shows distribution of relative cost saving by SP solution compared to EV solutions under each emission level.



SP solution outperforms the EV solution with high emission caps. However, SP solution has lower performance with low emission caps.

To understand the relationship between cost and GHG, the authors compared a wide range of best-compromised solutions with different preferential weights (W).



By raising the goal for one objective, we leave more space for the other objective to be improved.

Conclusion

- Develop an integrated biofuel supply chain system: sustainability concepts and production uncertainty
- Address the uncertainty in conversion technology: impact on system planning strategy
- Demonstrate benefits of stochastic method compared to deterministic methods
- Immediate extension: uncertainties in natural fluctuations or human-made disasters