U.S. Department of Energy
Energy Efficiency and Renewable Energy

A Model for Optimization of PV Recycling Planning

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U.S. DEPARTMENT OF ENERGY

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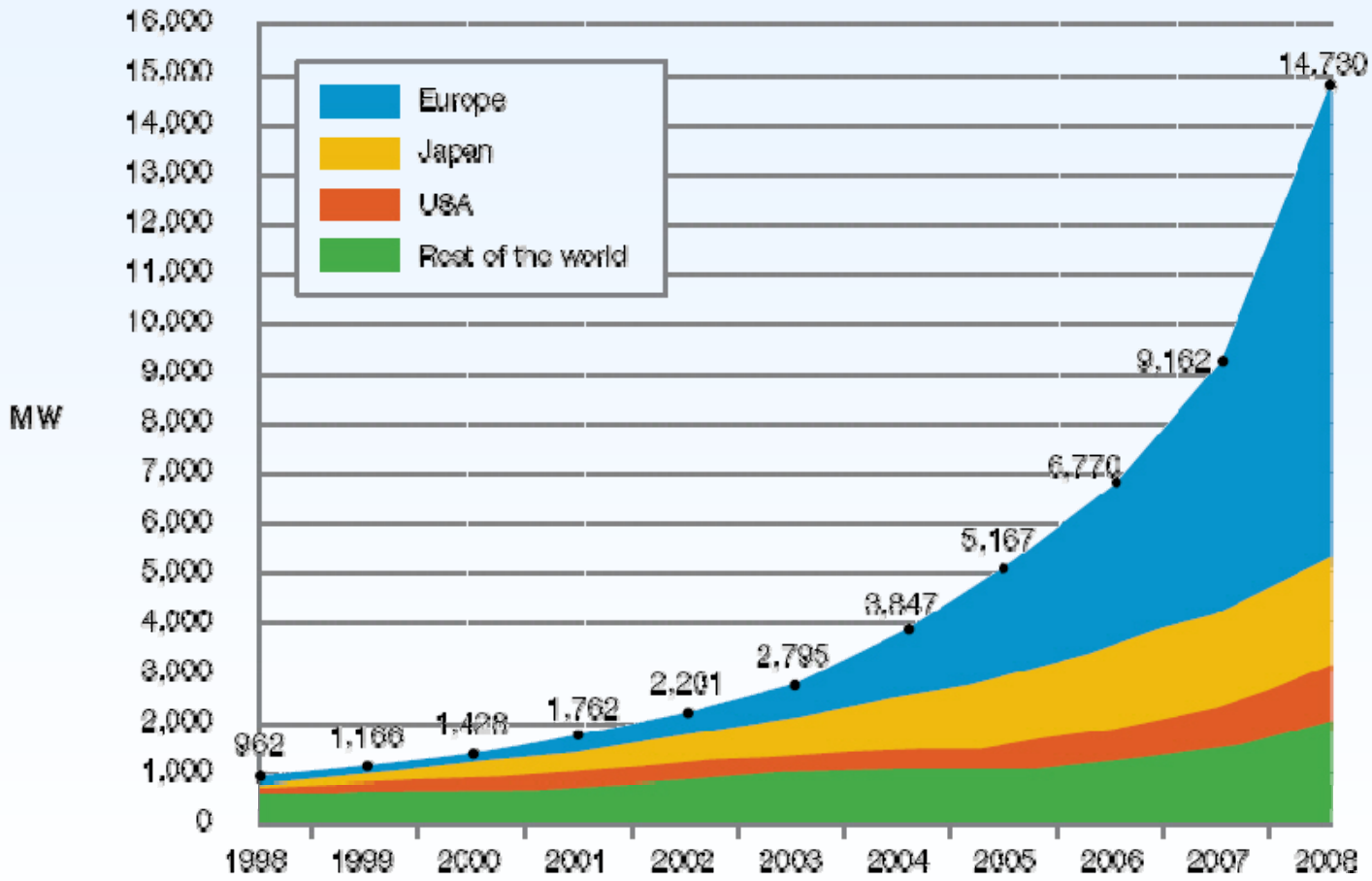
Cumulative installed PV Market



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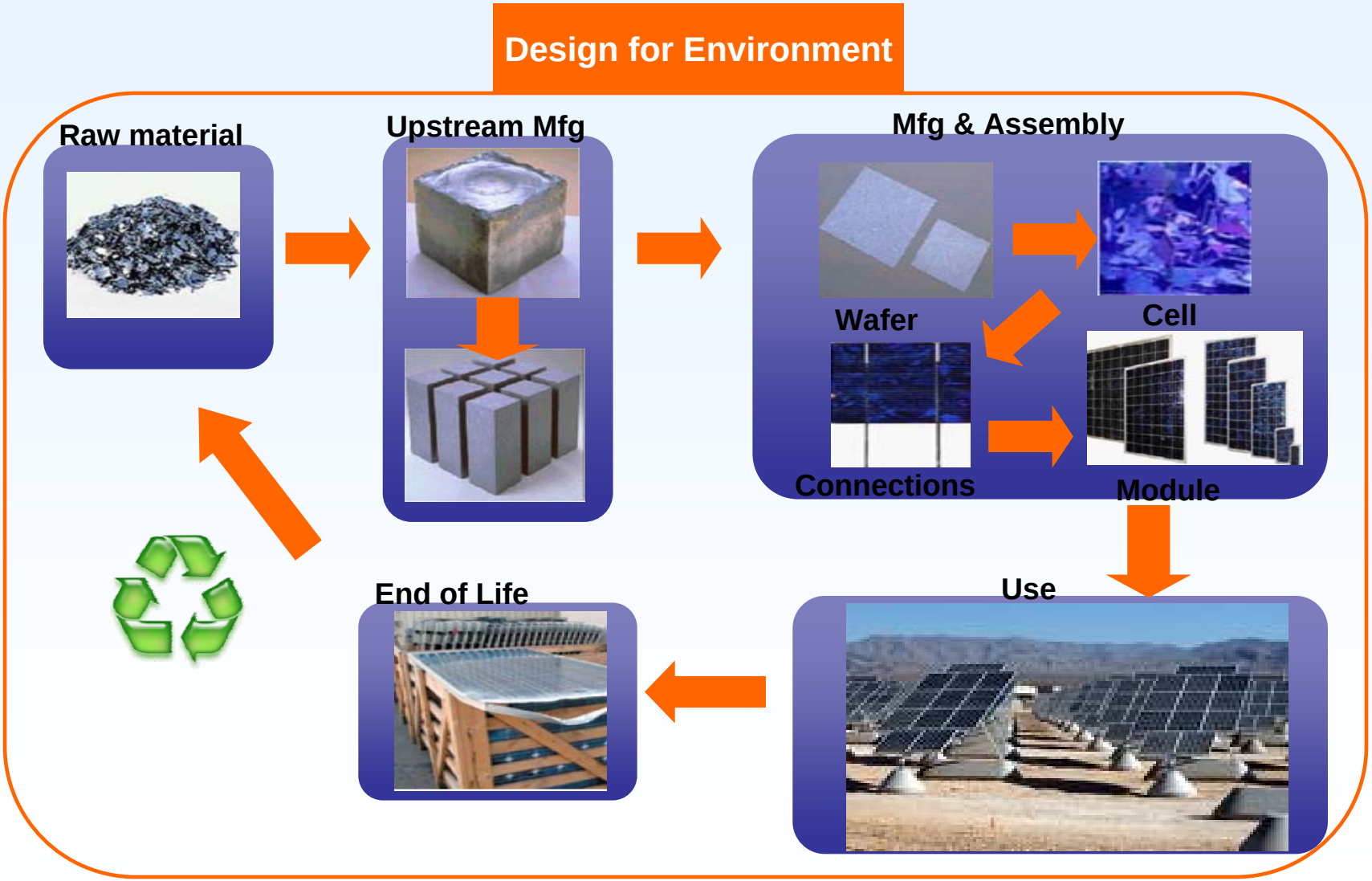
DfE & Lifecycle of PV



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Current Practices

Mission

How to plan for setting up efficient PV recycling infrastructure ?

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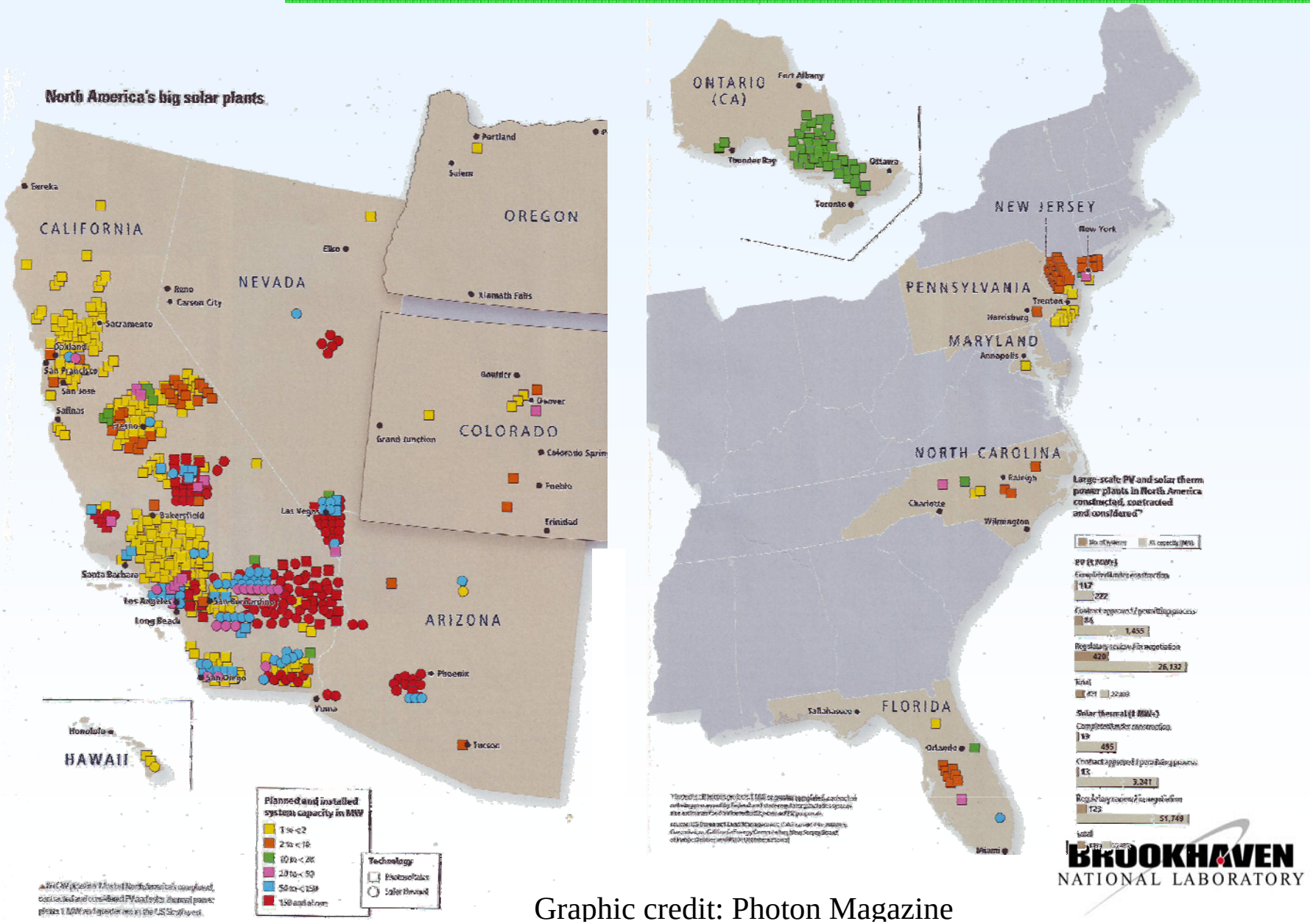
Large Solar Plants (current & planned)



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PV take-back center (PVTBC)

- Where to locate collection, dismantling and shredding centers to optimize the cost?
  - Density of population, insolation
  - Third party reverse logistics company?
  - PVTBC in manufacturing facilities ?
  - Stand alone near to installation site ?

- How to utilize current recycling infrastructure of other product parallel to PV recycling?

- How to maximize the revenue and/or minimize the cost of recycling plant?

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Economics of PV take-back center (PVTBC)

- Max. Revenue and Min. Cost => Max Profit
  - Type of PV to be recycled
  - Market value of the reclaimed raw materials
  - Volume of being recycled
  - Economics of the hazardous waste management
  - Variation of landfill tipping fees
  - Shipping methods
  - Processing costs
  - Inventory
  - Capital, labor, other

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New PV Technology

- There are various current PV manufacturing technologies
- New state-of-art technologies to market
  - DOE: Technology Pathway Partnership, Next Gen. PV, PV Tech Incubator, Energy Innovation Hubs
  - NREL incubator program
  - Stimulus money
- Development of new recycling technologies should be parallel to rapid trend of new PV manufacturing technology

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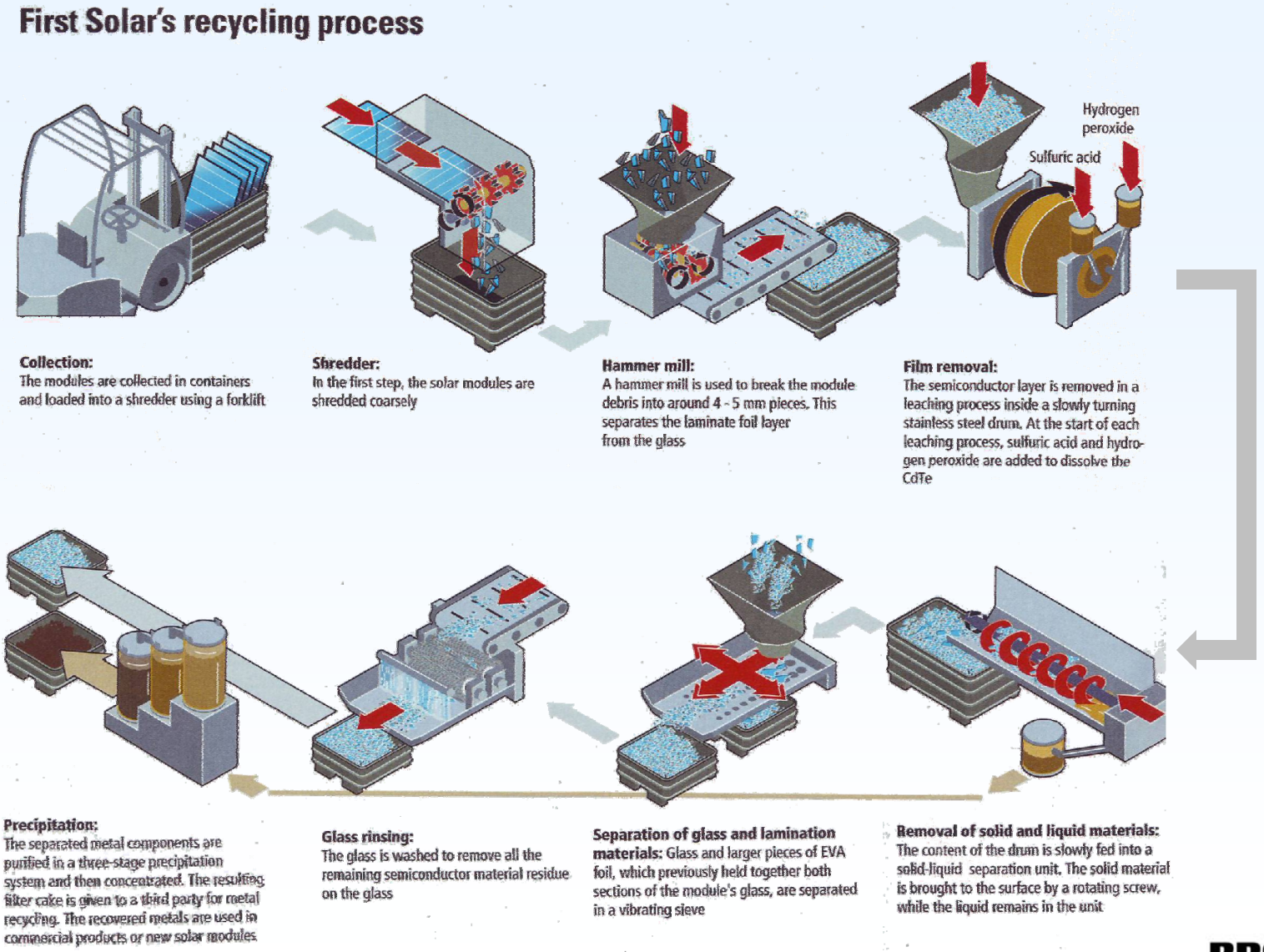
Need of a Generic Mathematical Model

- PVTBC will face challenging material separation decisions
- Must evaluate the trade-offs b/w different cost and revenue structures
- PVTBC will need quantitative tools to evaluate the optimal level of processing
- Computationally tractable generic model to provide sensitivity analysis on key parameters
- Encourage research opportunities for technology, recycling process design, and controls.

FS Recycling Process



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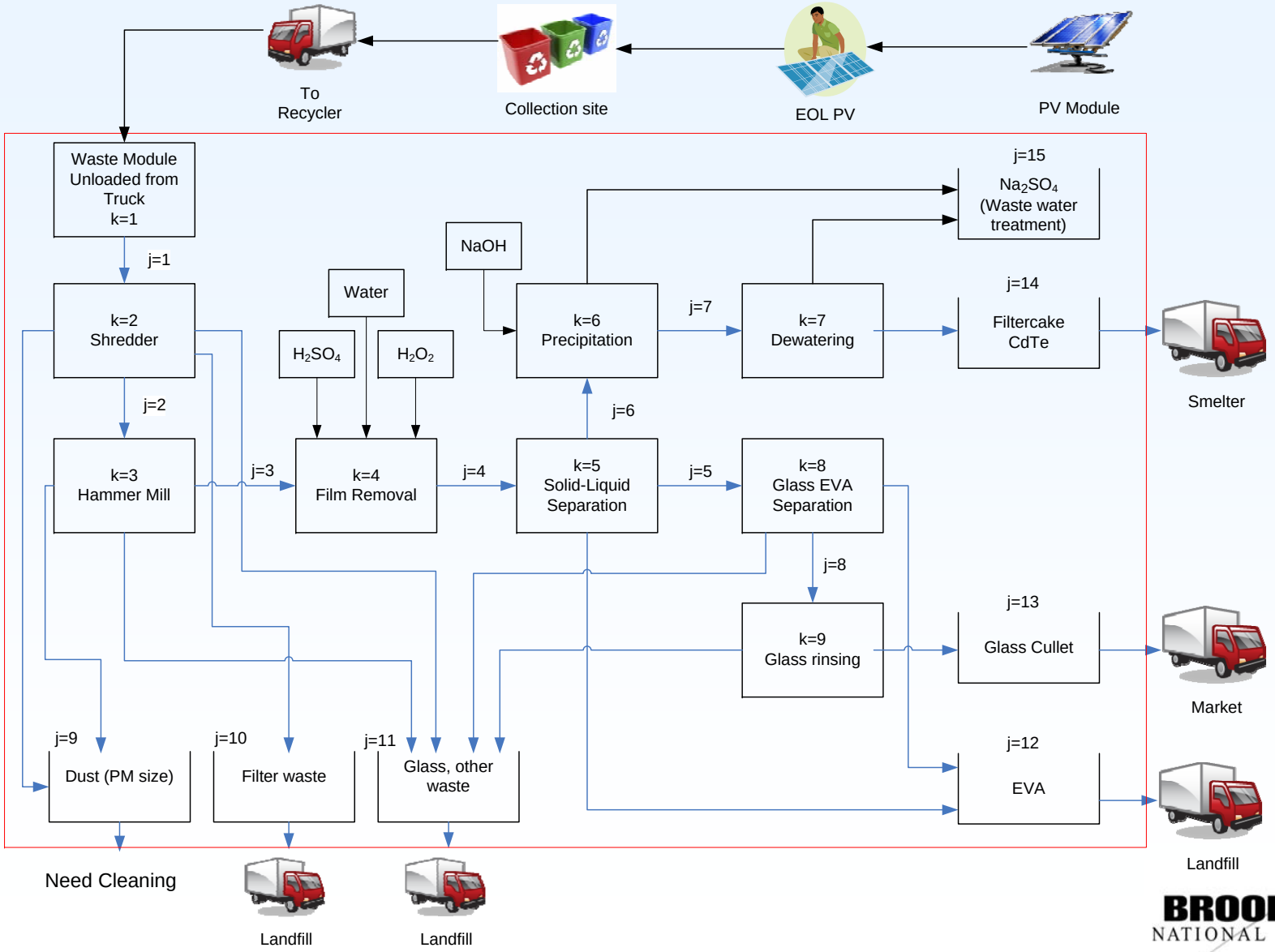
Process flow for modeling



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Base model for PVTBC

- Objective function

$$\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=9}^{14} r_{jk} N_{ijkt} - \sum_{t=1}^{T}\sum_{i=1}^{I} \lambda_{it} m_{it} - \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{K} c_k p_{ik} X_{it} - \sum_{t=1}^{T}\sum_{i=1}^{I} h_t \lambda_i I_{it}$$

revenue from output materials

cost of incoming modules

processing cost

Inventory cost of incoming modules

- Subject to
  - Material flow balance (incoming, transition, outgoing materials)
  - Capacity limit of equipment
  - Minimal inventory setup

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Experimental Design

- Scenarios are analyzed with variations of following
  - Cost of Incoming PV module
    - Freight, packaging, labor costs
  - Shipping costs
    - Transportation to landfill, labor costs
  - Market price of CdTe filter cake
  - Market price of glass cullet
  - Landfill tipping fees

- GAMS[1] (General Algebraic Modeling System) is used.

[1]http://www.gams.com/

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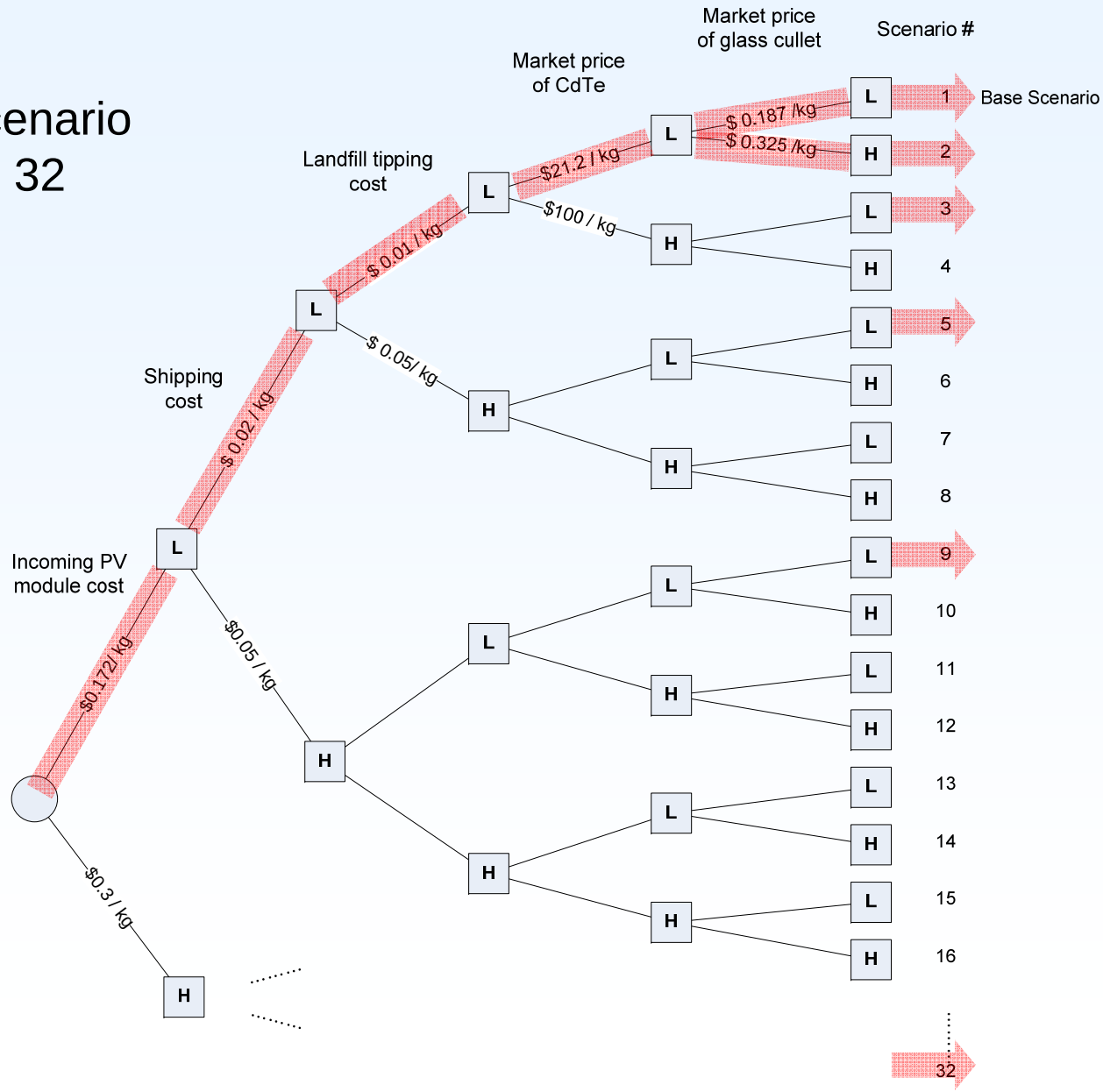
Variation of Landfill Tipping Fees

- U.S., Average Landfill tipping fee in the US is $34/ton

Decision Tree

of Scenario

$2^5 = 32$



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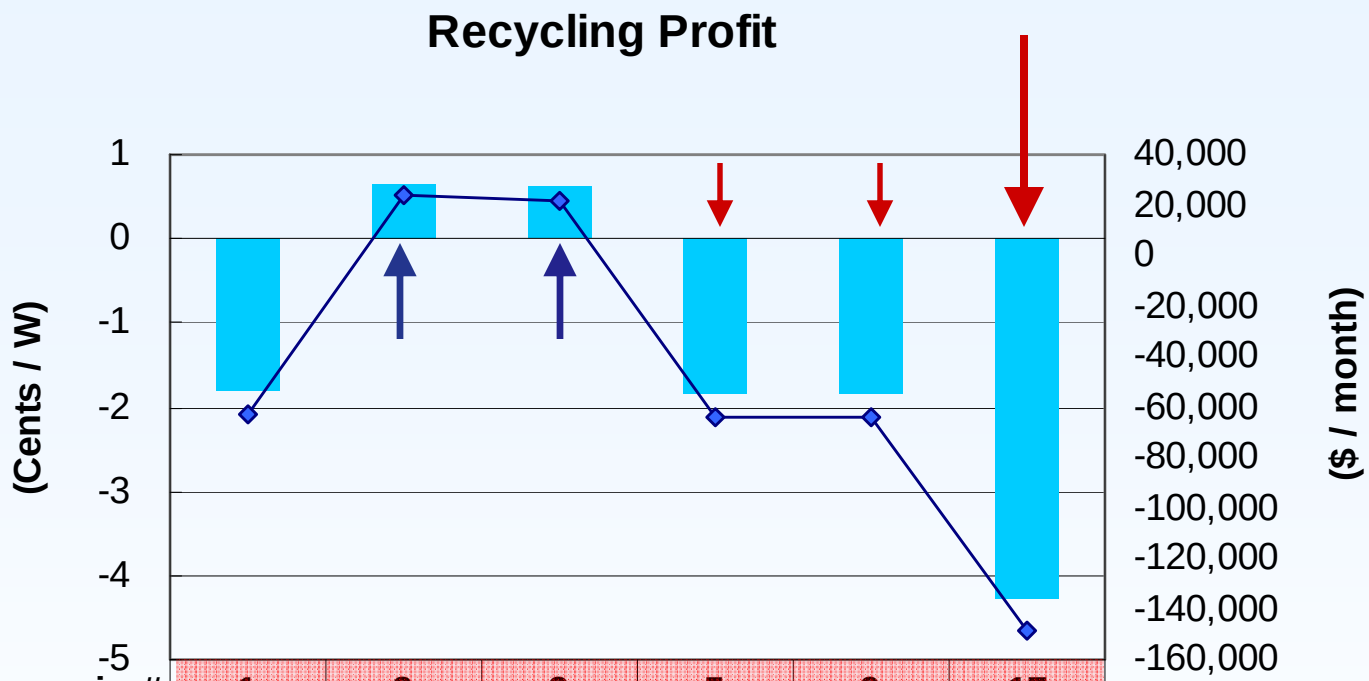
Sensitivity Analysis

Total: 672 tons
Module/month: 58195



Scenario #	1	2	3	5	9	17
Cents/W	-1.80	0.67	0.62	-1.84	-1.83	-4.27
$/month	-63,025	23,486	21,700	-64,361	-64,027	-149,044

- 1: Base scenario
- 2: Higher glass cullet price
- 3: Higher CdTe price
- 5: Higher Landfill tipping fees
- 9: Higher shipping cost
- 17: Higher cost for incoming PV

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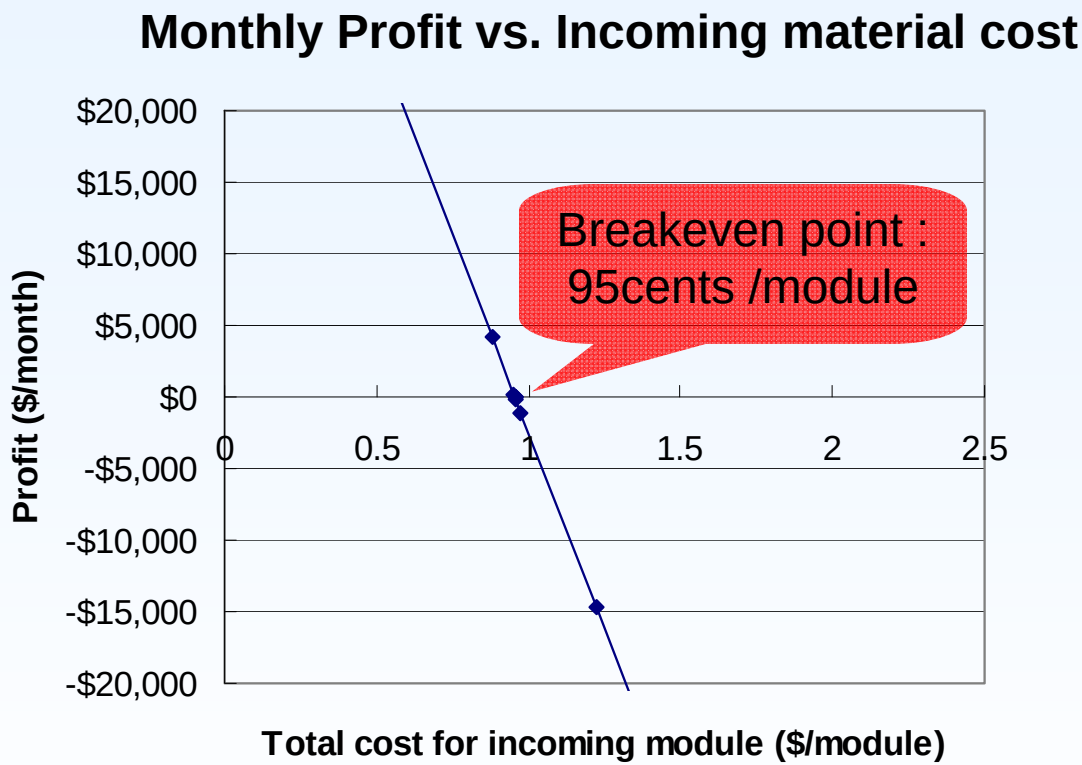
Analysis of Scenario 17



- Profit breakeven point for scenario 17 with variation of incoming module cost.
- PVTBC will remain profitable as long as the total incoming module cost does not exceed this value.

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Summary of Current Work

- Performed a preliminary study of recycling processes
- Created a mathematical model for analyzing the profitability of recycling technologies
- Intend to extend this model for building a general framework of various type of PV recycling planning.

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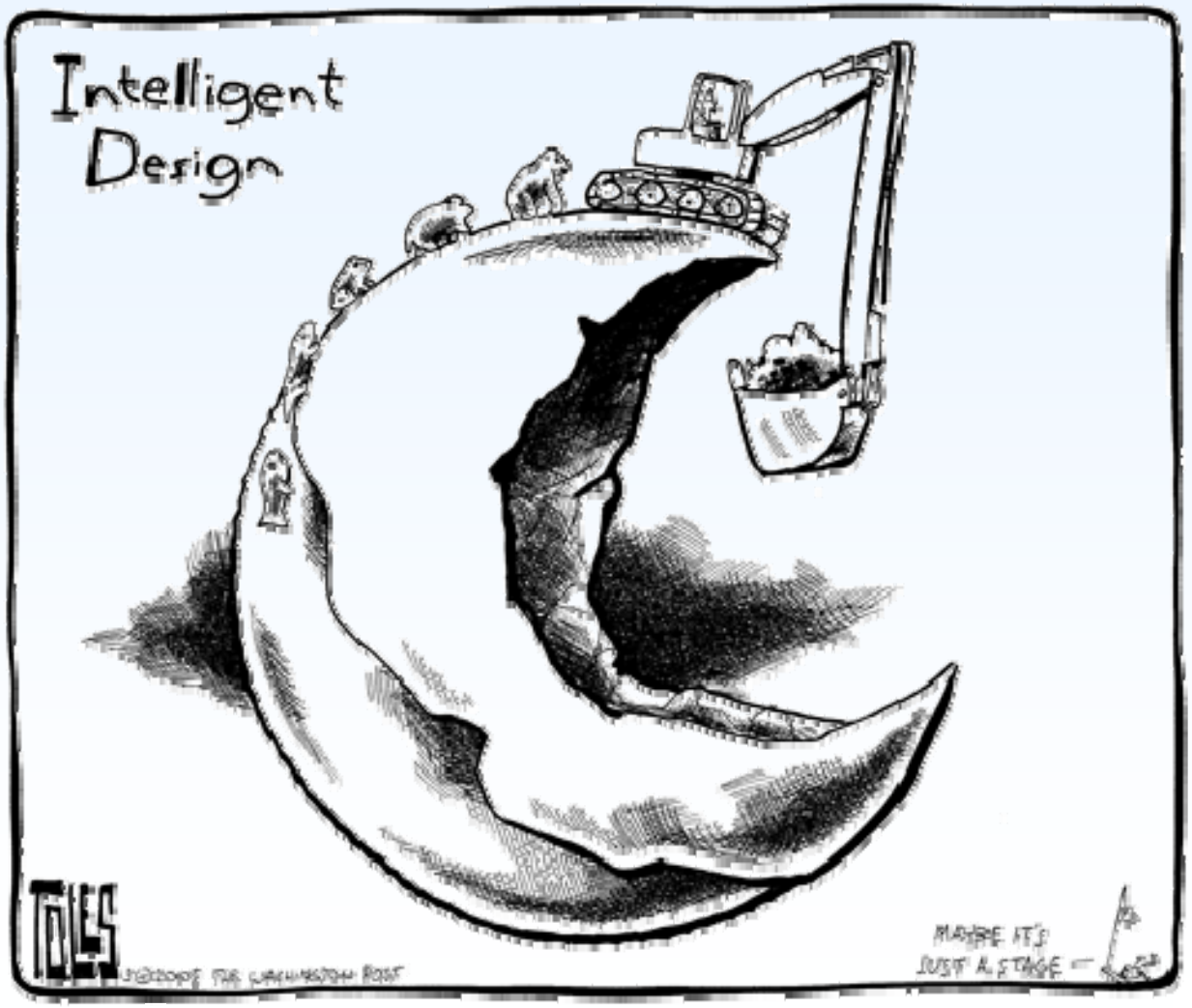

Washington Post, **March 30, 2005**

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Integrated Modeling

- What will be the relationship among
  - Environmental system
  - Economic system
  - Engineered system
  - Human (as final consumer or labor input)

- Need of integrated multiscale modeling
  - Enables to analyze the effect of change in one system to another
  - In various spatial and temporal scale

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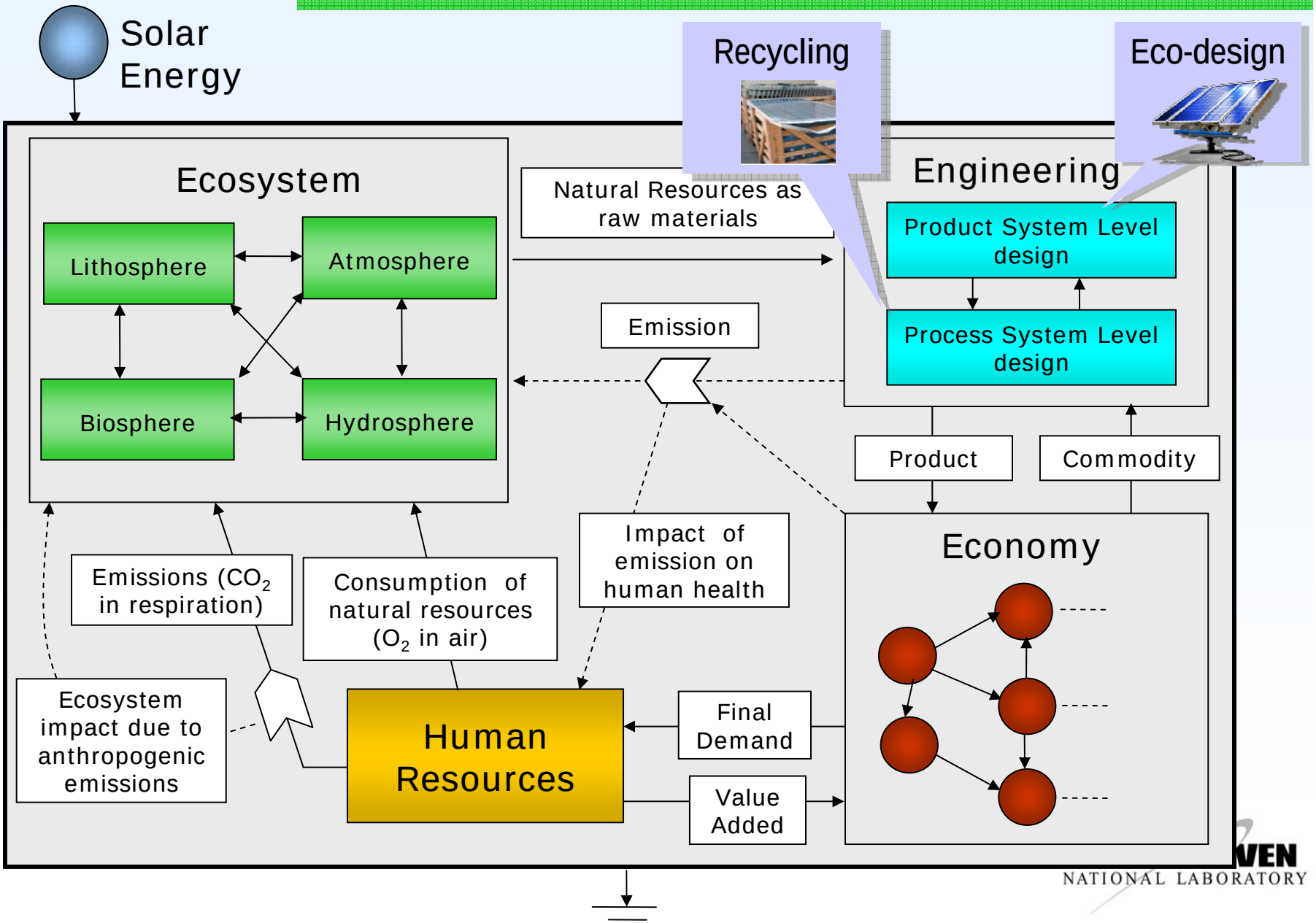
Network between Systems



Future Research

- Analyze the effect of *policy* in the macro economy level to the PV industry through *Multiscale Integrated Analysis*
- Analyze the *macro-level PV waste flow* through World Input-Output Model
- *Hybrid input-output LCA* for analyzing the effect of recycling to the reduction of resource uses and emissions

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Thank you