Mathematical Modeling for Cost Optimization of PV Recycling Infrastructure

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PV Recycling –Cost Optimization

1. **Where is the optimized location?**
   - Centralized/decentralized collection
   - How many PV take back centers (PVTBC)
   - Efficient routing/ logistics
   - Network with the secondary markets

2. **How to maximize the revenue of each recycling plant?**
   - Amount of returning PV modules
   - Fluctuation of market price of reclaimed materials

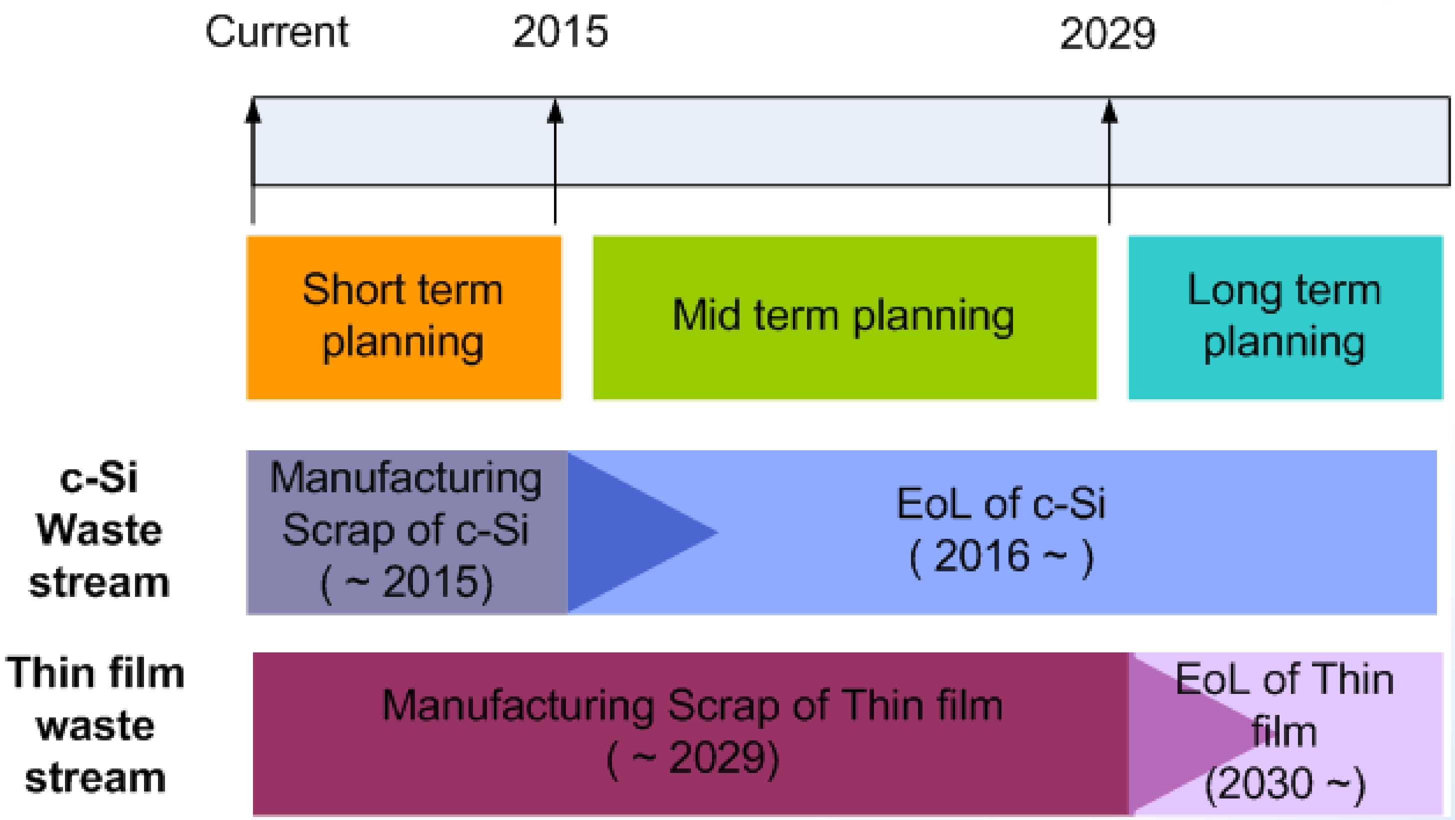
Macro-level Reverse Logistics Cost Model

- Determine the optimal locations of PVTBCs to minimize logistics costs by optimizing the economic trade-off of:
  - Max. capacity of a designated PVTBC
  - Capital cost of a PVTBC
  - Total cost for a given geographical area

Model Inputs

- The amount of manufacturing scraps or spent PV modules to be transported from each site
- Distance matrix between collection and recycling sites (actual distance between sites)
- Reverse logistics service costs (labor, contract fees)
- Transportation costs (fuel cost, mpg, truck size)
- Maximum capacity of plants
- Capital costs to open up a recycling center

Time Horizon for PV Recycling Infrastructure



This presentation focuses on short term planning: Only recycling of c-Si manufacturing scrap

The German Case (c-Si PV)

- Major c-Si PV manufacturing plants are selected as candidates for collection and recycling of manufacturing scrap
- Network in east Germany where 90% of the c-Si PV production capacity is located

German PV Manufacturing Cluster

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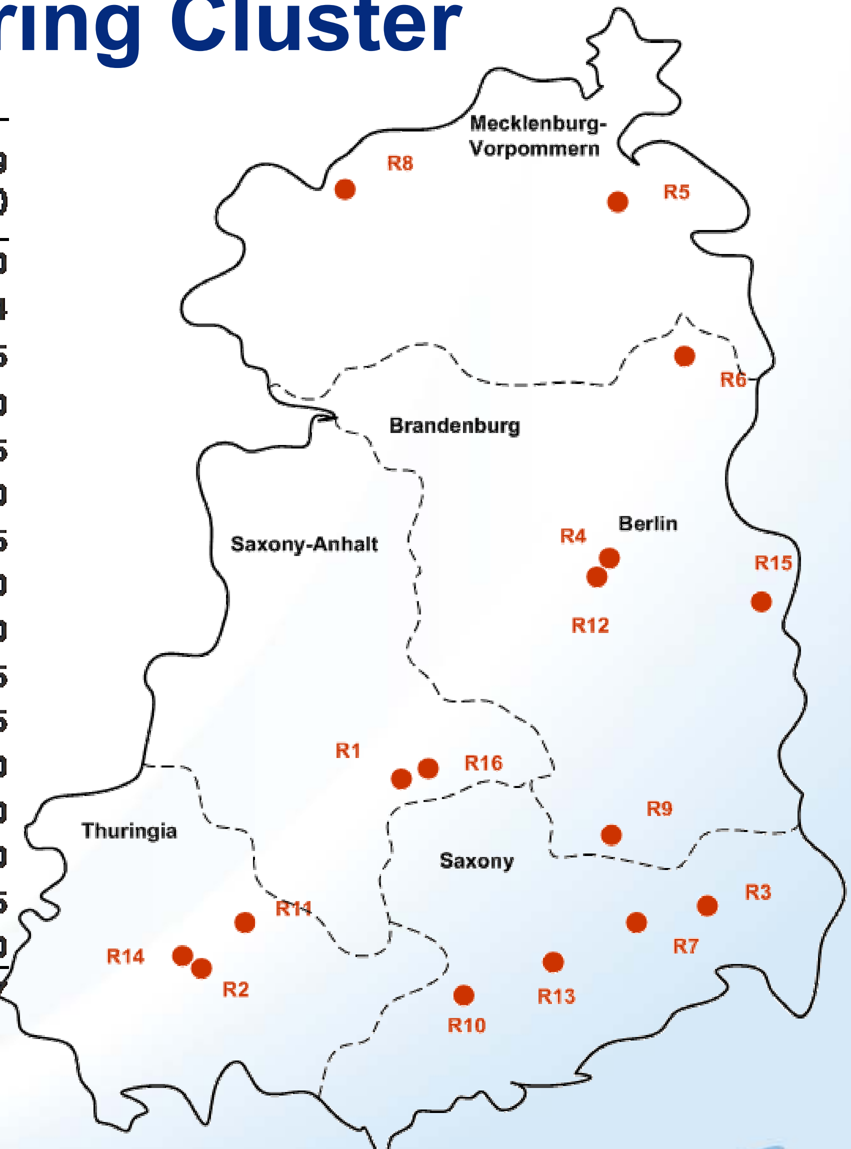
German PV Manufacturing Cluster

PV manufacturer	Location	Capacity 2009 [MWp]	Mfg scrap 2009 (MT)
R1	Thalheim	400	600
R2	Arnstadt	56	84
R3	Bischofswerda	57	85.5
R4	Berlin	100	150
R5	Greifswald	130	195
R6	Prenzlau	180	270
R7	Dresden	150	225
R8	Wismar	120	180
R9	Prösen	100	150
R10	Chemnitz	90	135
R11	Isseroda	25	37.5
R12	Berlin	20	30
R13	Freiberg	1100	1650
R14	Arnstadt	460	690
R15	Frankfurt (Oder)	750	1125
R16	Thalheim	540	810
	Sum	4278	6417



Source: German Trade and Invest (GTAI) website

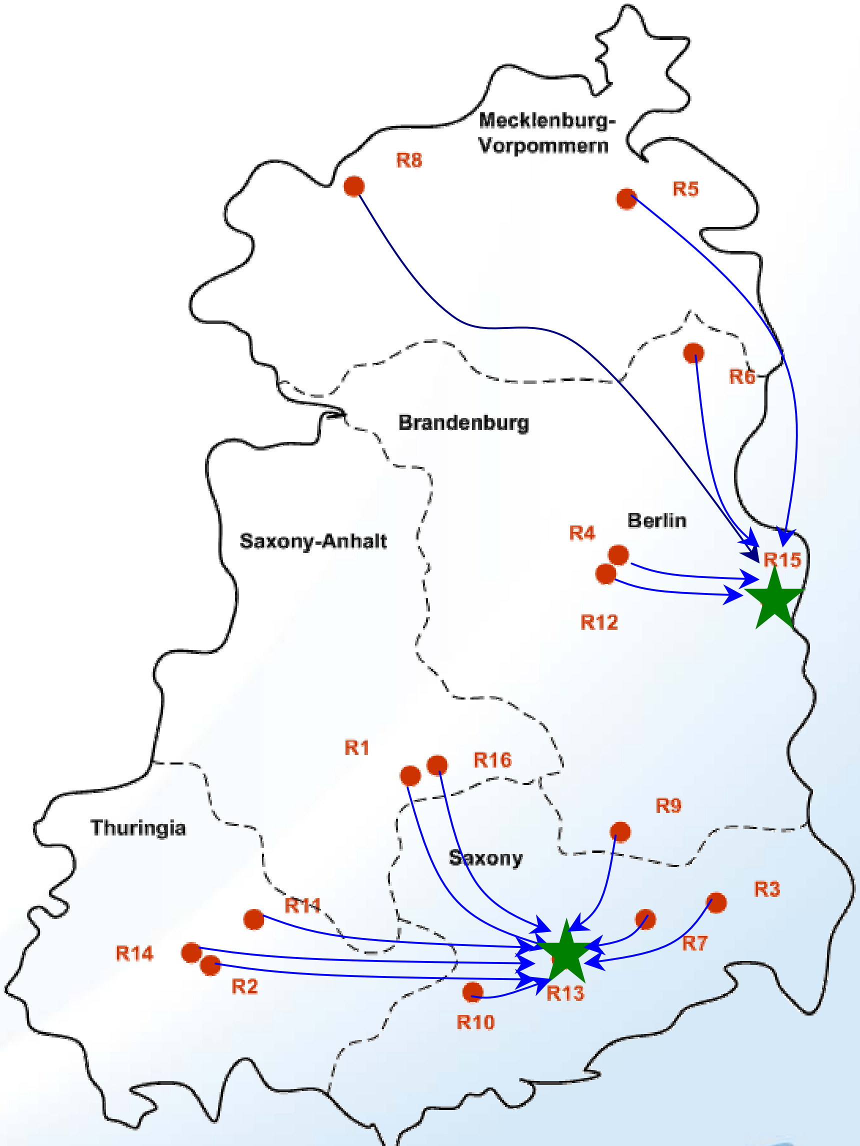
Example -Logistics Optimization-

		Fixed	5-yr total (2010-2015)	
Capital cost to open up a PVTBC ($K)	selected location	Capital cost ($K)	Reverse logistics cost ($K)	System optimal cost ($K)
>586	R16	586	1529	2115
563 - 586	R13+R15	1126	943	2069
360 - 563	R13+R15+R16	1079	583	1662
216 - 360	R13+R14+R15+R16	862	368	1230
178 - 216	R5+R13+R14+R15+R16	890	189	1079
56 -178	R6+R8+R13+R14+R15+R16	336	134	470

- For annual max. capacity of 20,000 MT
- Model allocates optimal location: Decision based on the quantity of manufacturing scraps from each collection points and the distances between the collection points to recycling points, subject to capital cost constraints

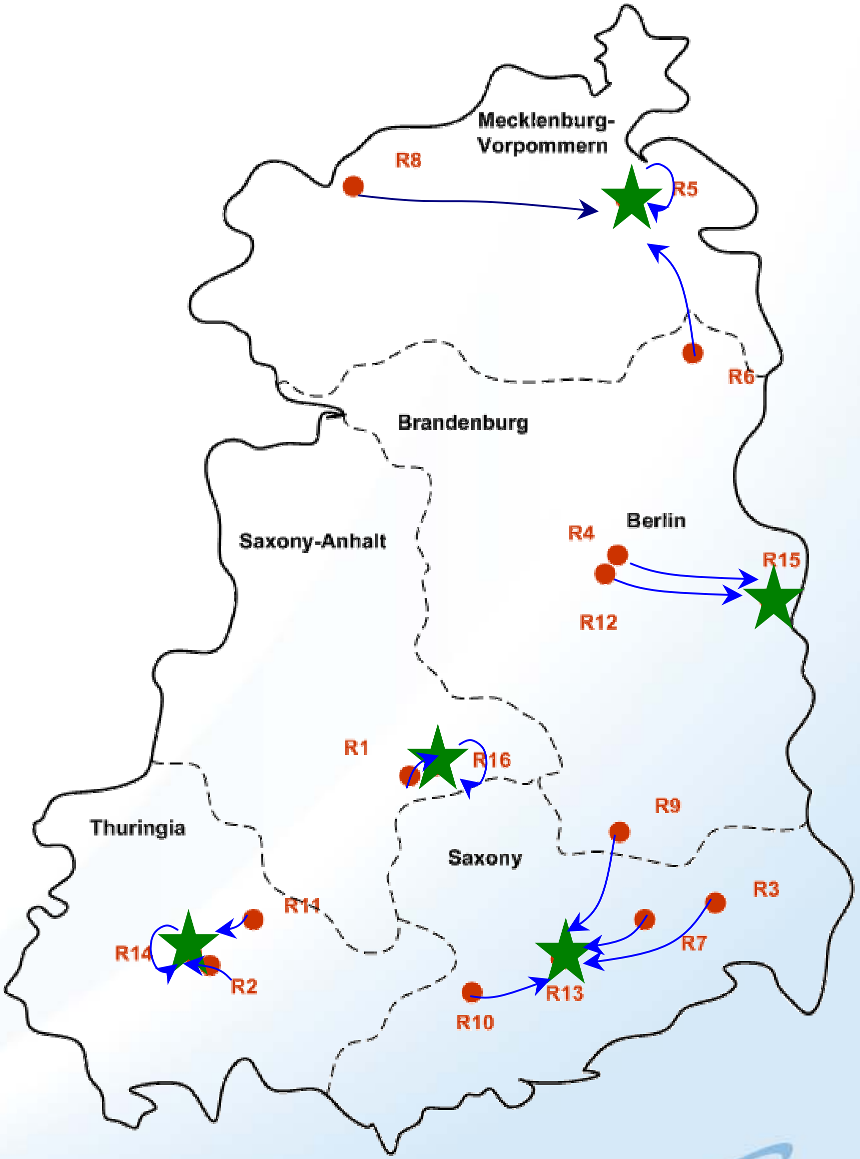
CASE I (two PVTBCs)

Capital cost to open up one PVTBC	$563K~$586K
Selected location	R13 + R15
Total capital cost	$1126K
Total reverse logistics cost	$943K
System optimal cost	$2069K



CASE II (five PVTBCs)

Capital cost to open up one PVTBC	$178K~$216K
Selected location	R5+R13+R14+ R15+R16
Total capital cost	$890K
Total reverse logistics cost	$189K
System optimal cost	$1079K



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   - PVTBC capacity

Process (example Solar World PVTBC)

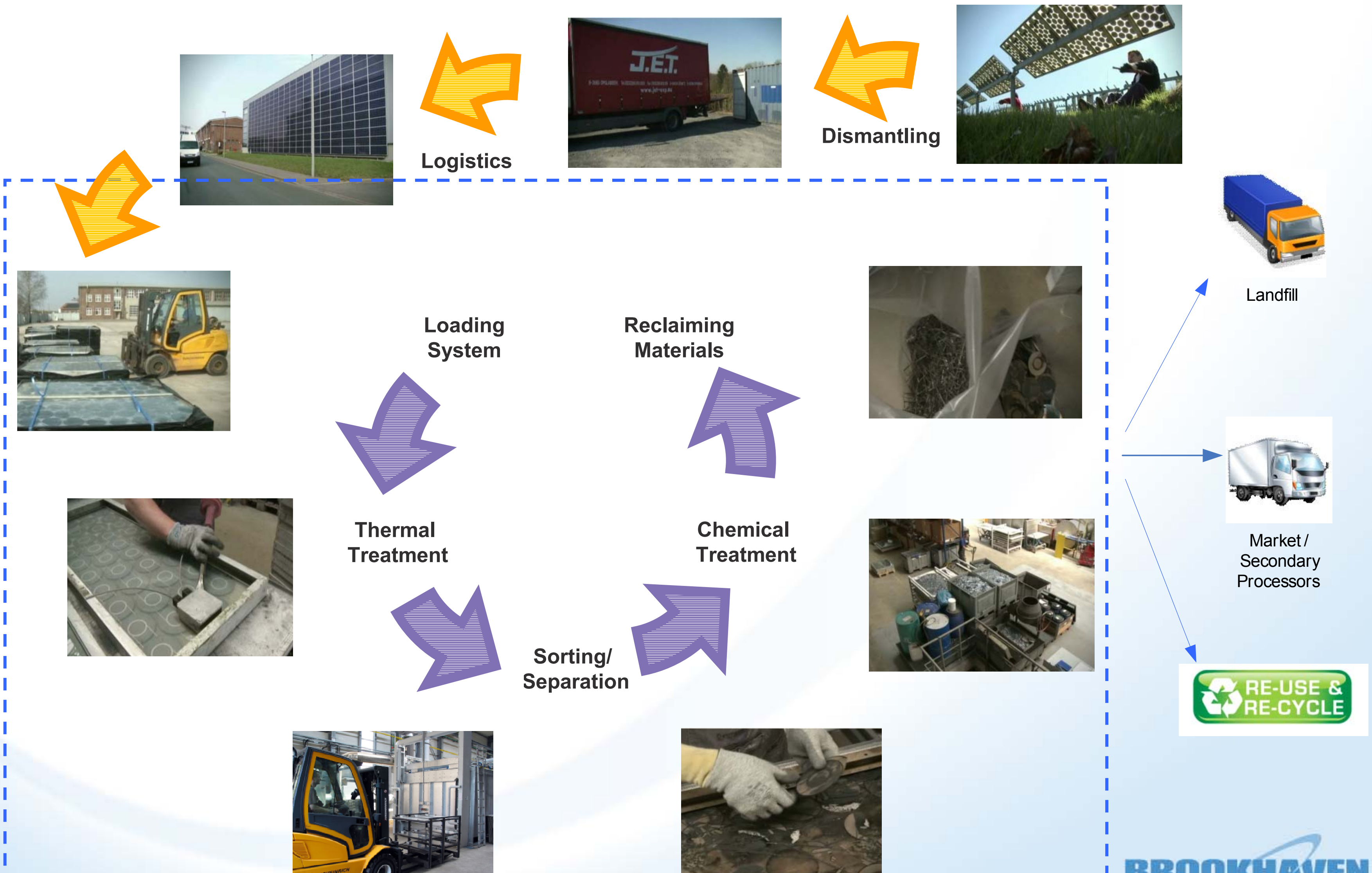

Photo credit: Solar World & PV CYCLE

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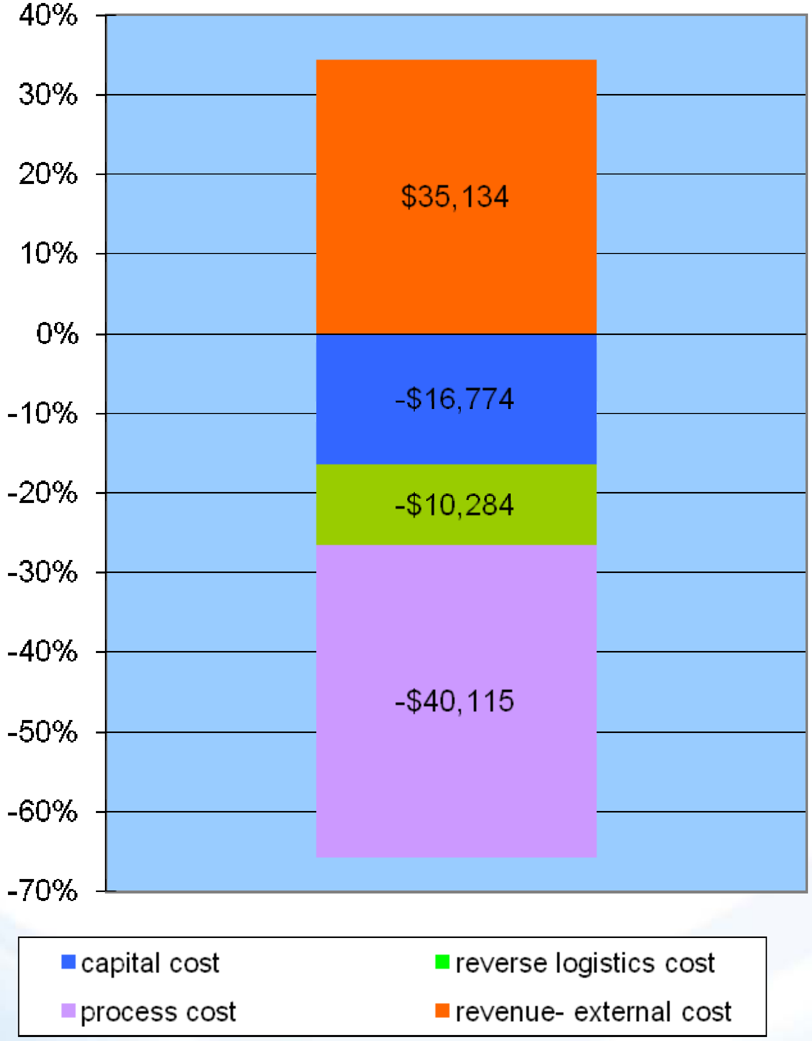
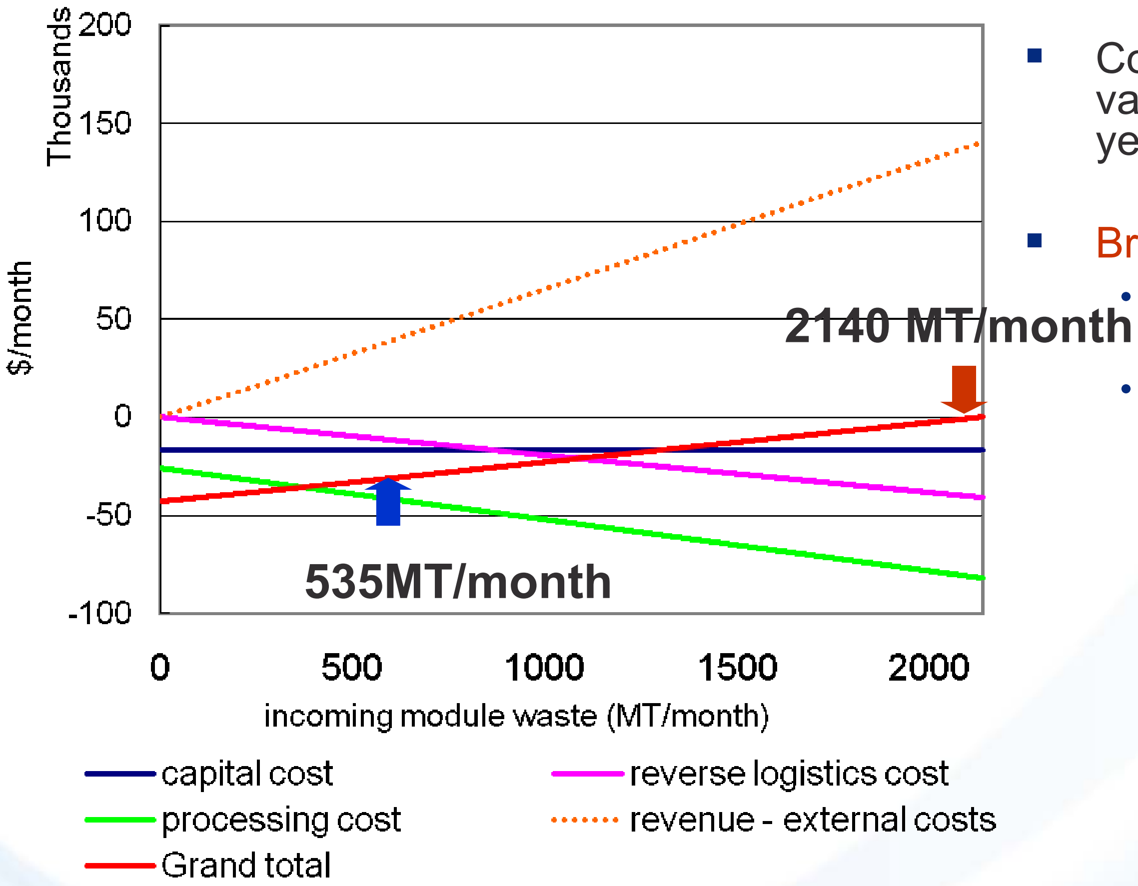
Example –Monthly Cost Breakdown (1 PVTBC)



- Processing for 2009 scraps: 535 MT/month
- Assumption: All scraps are transported to R13 Solar World facility
- Revenue for selling copper, glass, and silicon.
- External costs include landfill and incineration costs.
- Capital cost include depreciated value of land, buildings & equipment.

Example: Cost-benefit Analysis (1 PVTBC)



- Compares costs/benefits with the variation of incoming module per year for automated plant
- Breakeven point (red arrow):
  - Profitability starts from at 2140 MT/month.
  - Various breakeven points can be tested for changes in other external and process parameters

Conclusion and future work

- A model was developed to optimize system costs for opening and operating PV take-back and recycling centers (PVTBC).
- The model guides the selection of locations and capacities of PVTBC within a given geographical region.
- A near-term (2010-2015) forward analysis of recycling manufacturing waste from c-Si PV production facilities in Germany provided insights for optimizing a recycling network in the country.
- Work is in progress on an integrated framework that can guide policy planners.

Thank you

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Price assumption of outputs for modeling

Outputs	Assumption	Price
Waste	Landfill tipping fees	- $0.15/kg
Plastic	Incineration cost	- $0.1/kg
Junction box	Electronic scrap waste treatment company	- $0.1/kg
Glass	Glass recycler	+ $0.04/kg
Copper wire	Metal recycler	+ $5/kg
Aluminum frame	Internal recycling	N/A
Silicon	Recycler	+ $1.72/kg