



CIRCULAR
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Overall optimization and economic analysis of the circular value network

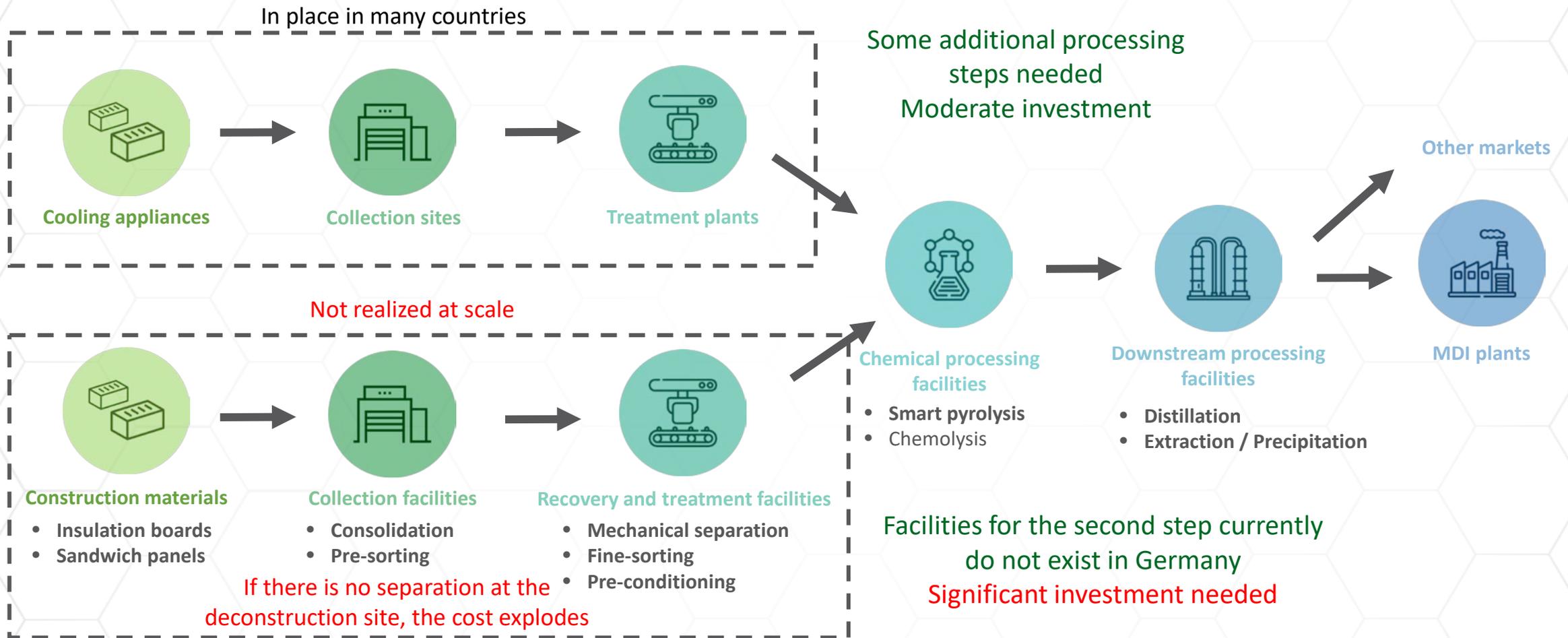
Merve Dalga Özkan, TU Dortmund, Sebastian Eggers, ZEDO e.V.,
Sebastian Engell, TU Dortmund and ZEDO e.V.

The challenge

- Hard PUR foam recycling requires to set up a large-scale complex multi-layer system
- Primary collection
 - Refrigerators
 - Construction waste
 - Distributed, very dependent on regulations
 - Wide coverage needed for good recycling quota
- Dismantling, sorting and separation, conditioning (Recovery and Treatment, RTF)
 - Well established for refrigerators
 - Not available up to now for construction waste
- Chemical processing – **smart pyrolysis** or chemolysis
- Purification (downstream processing)
- Logistics between the different facilities
- **Strong interdependencies of the design and operational parameters of all elements**
 - All decisions affect the economics and the CO₂-footprint



System view of recycling solutions for hard PUR foam



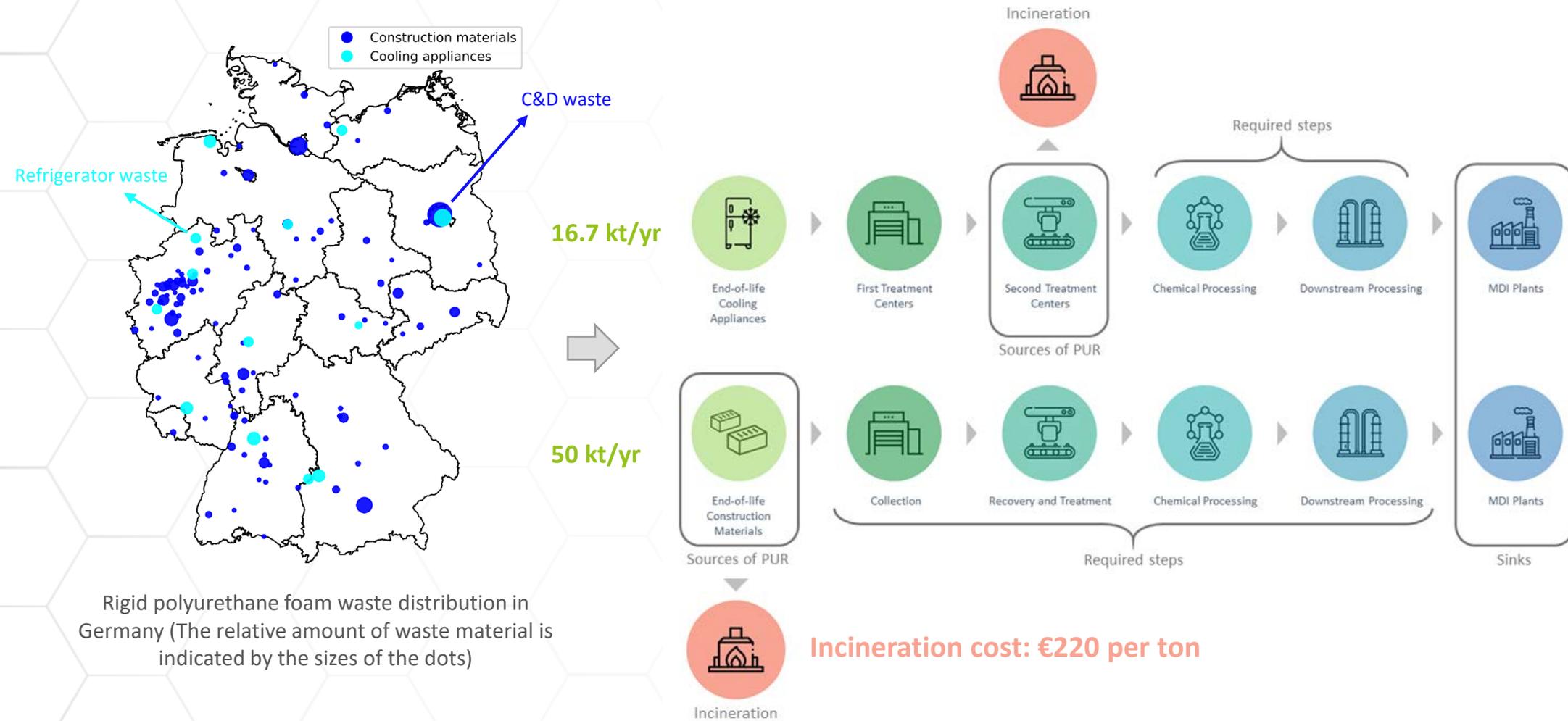
System-wide optimization model



- Design decisions
 - Number, location and size of the collection and processing facilities
 - Amounts of materials to be transported between the nodes of the network
- Goal: Minimization of cost for a given generation of waste
- Optimization for Germany
 - Includes material from cooling appliances and and construction / demolition
 - Incineration and chemical recycling are included as possible paths
- Design of a demonstration project for the upcycling of rigid PUR foam waste coming from insulation materials
 - A solution for North-Rhine Westphalia is possible with subsidies for CAPEX



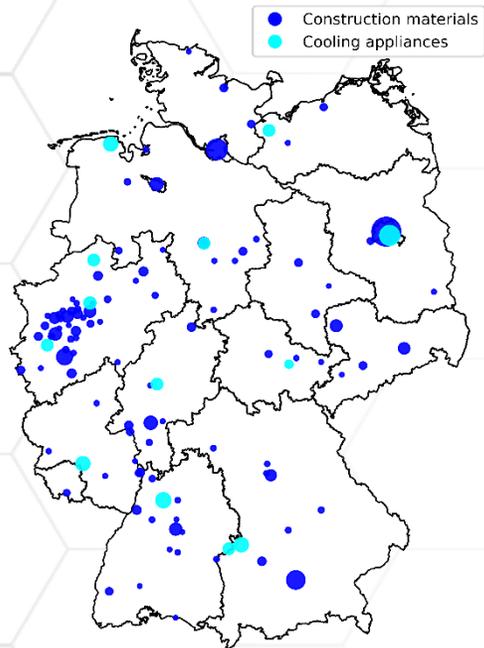
Recap – System design



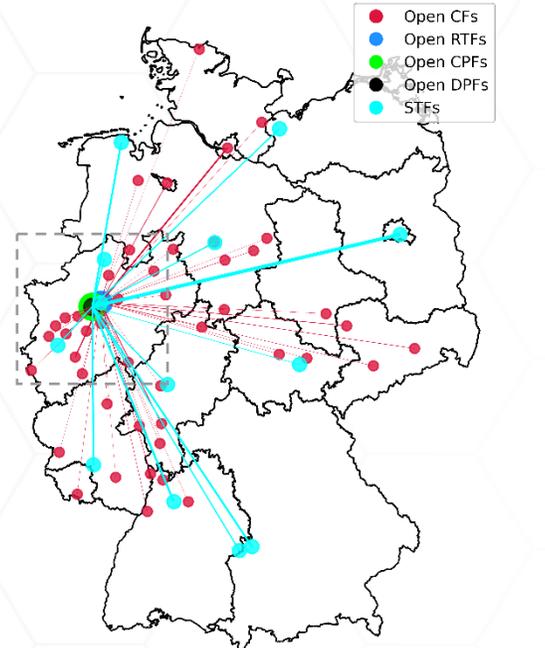
Rigid polyurethane foam waste distribution in Germany (The relative amount of waste material is indicated by the sizes of the dots)



Results

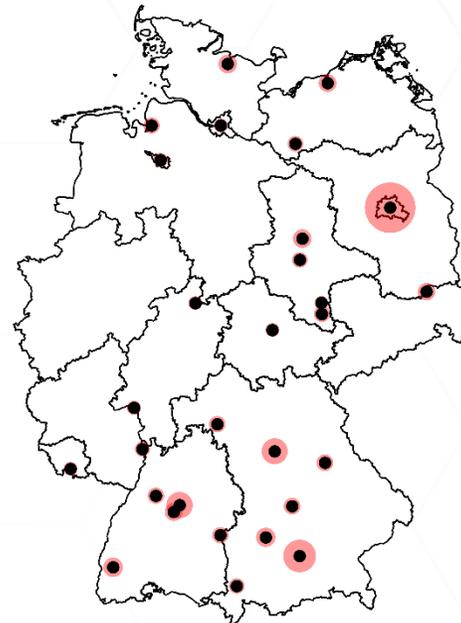


PUR foam waste distribution in Germany



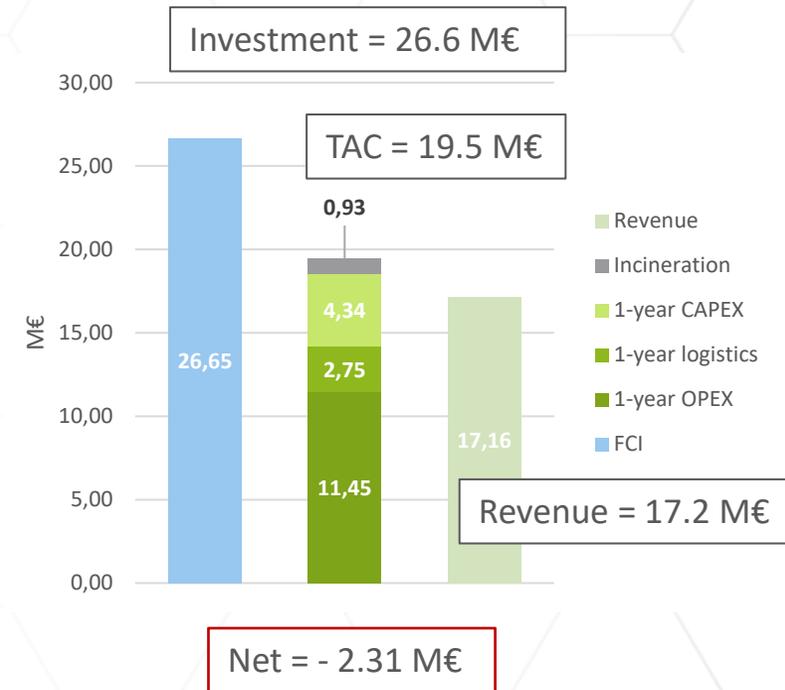
66% C&D waste (13.2 kt) 100% PUR briquettes (16.7 kt)

82% recycling rate in total



4.2 kt C&D waste (w/o metal) is incinerated

CF: Collection Facility
 RTF: Recovery and Treatment Facility
 CPF: Chemical Processing Facility
 DPF: Downstream Processing Facility

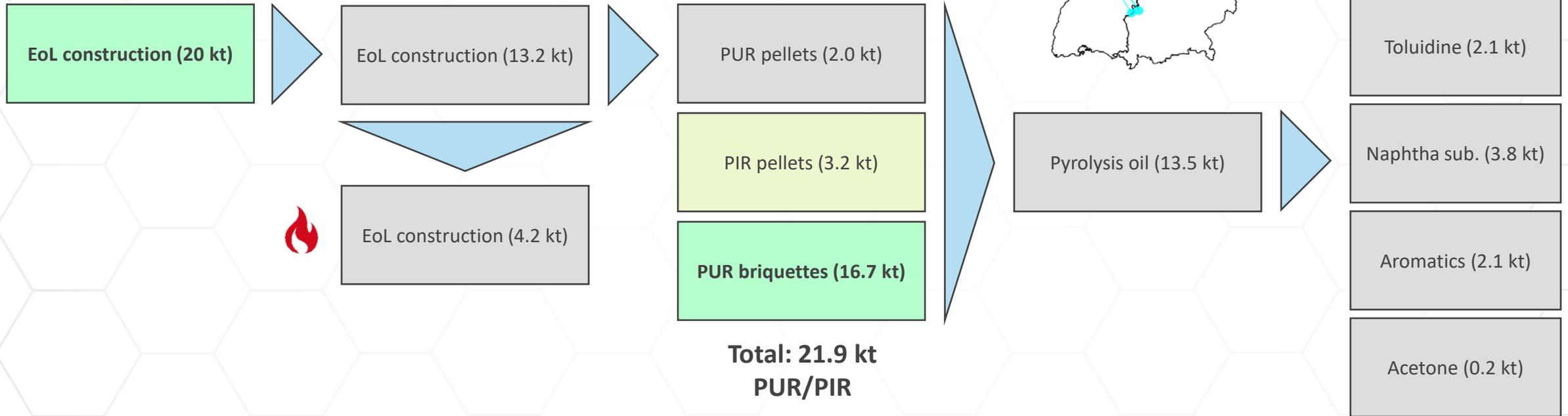


→ If all waste was incinerated, it would cost 6.4 M€



Results

Material flows per year:



Results

Revenue = 17.2 M€

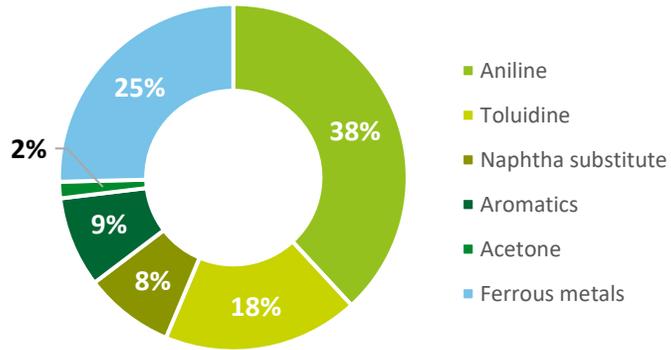


Fig. 1: Revenue breakdown

TAC = 19.5 M€

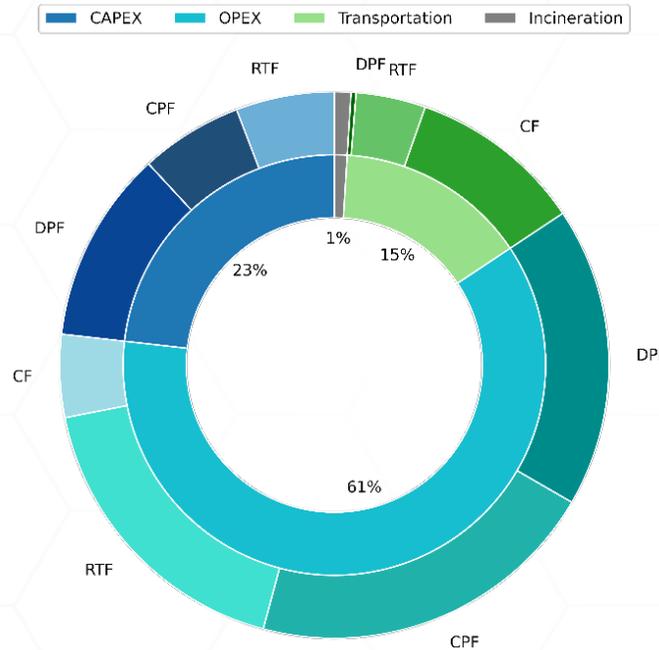


Fig. 2: TAC breakdown

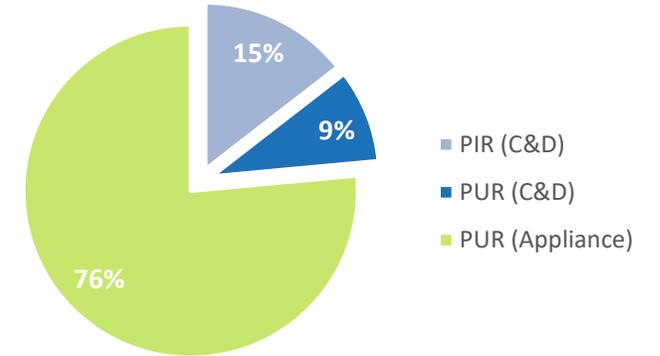


Fig. 3: Composition of the pyrolysis feedstock

CF: Collection Facility
 RTF: Recovery and Treatment Facility
 CPF: Chemical Processing Facility
 DPF: Downstream Processing Facility

Dalga Merve Özkan, Sergio Lucia, and Sebastian Engell:
 Strategic network design for the chemical recycling of polyurethane rigid foam waste in Germany.
 Computers & Chemical Engineering 2025, article 109273



Additional revenue stream

Construction waste

- Payment by the property owner for disposal of construction waste (approx. 170-190 €/t excluding logistics)

▶ Additional source of income

Cooling appliances

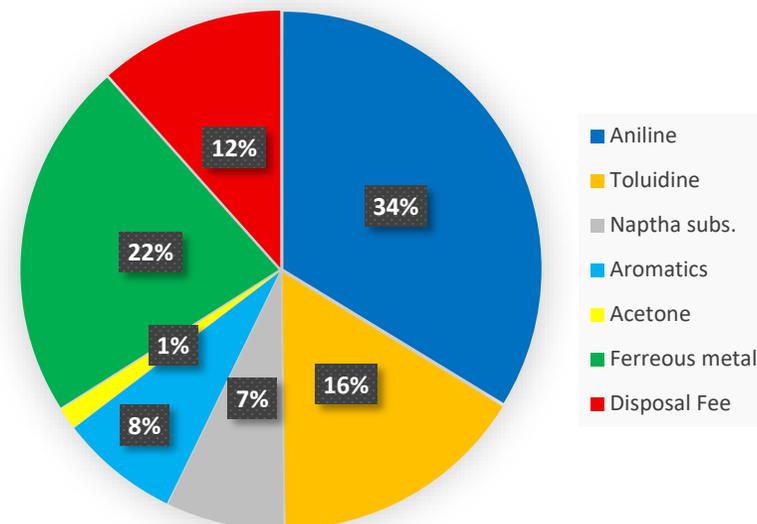
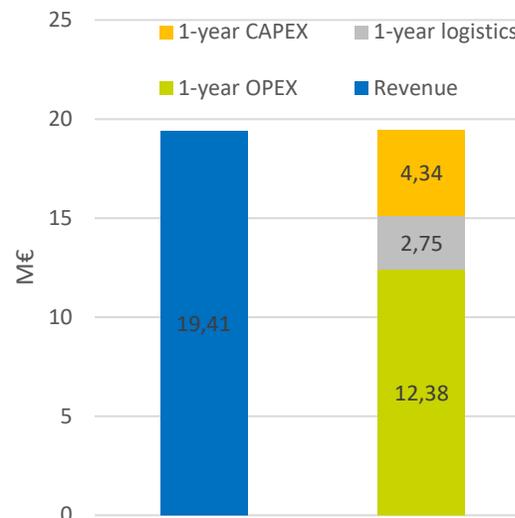
- Low additional processing costs expected (no exact data available)
- Significant savings from the elimination of incineration

▶ Possible additional source of income / could be charged as a fee

New economic figures

- Scenario as before
- Payment by the property owner included (170€/t)

Revenue [M€/yr]	19,4
Total Costs [M€/yr]	19,5

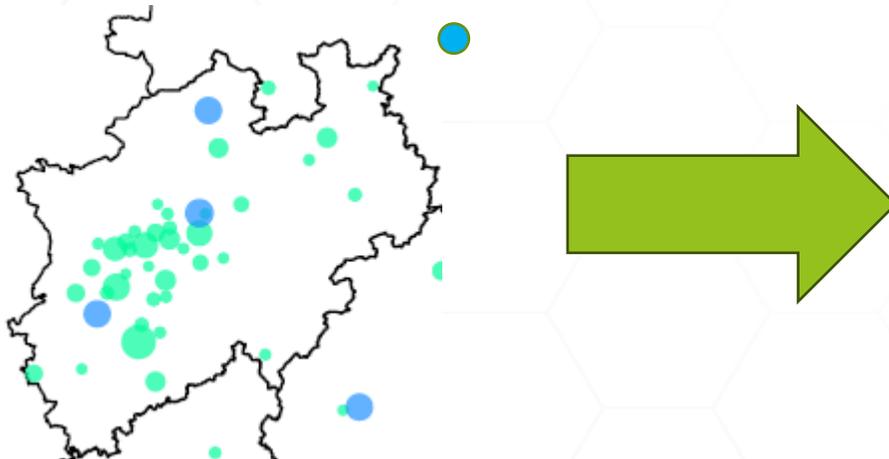


Design of a regional demonstration system for NRW

- The technical and logistic feasibility of the overall system must be demonstrated at a sufficient scale
- At small scale this is economically not attractive

Collection area:

North Rhine-Westphalia plus neighboring refrigerator treatment centers

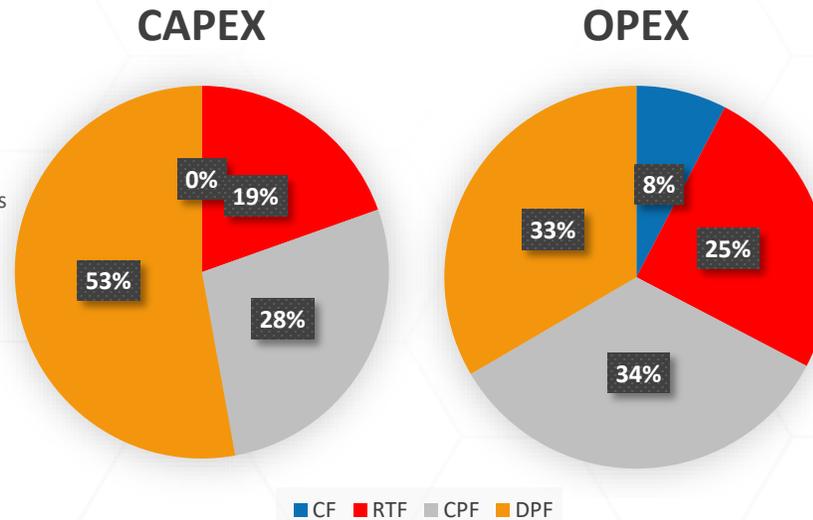
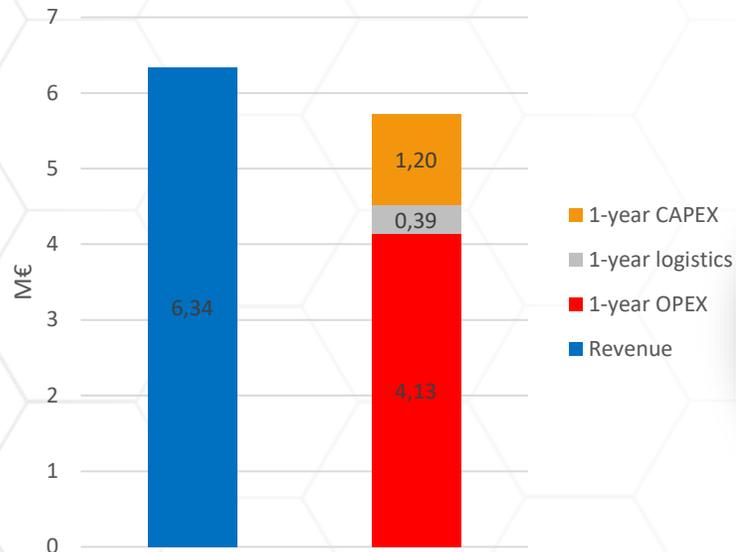


Total available waste per year:

- Refrigerator waste: 5 kt from 5 secondary treatment centers
- Construction & Demolition Waste (C&D): 40% of NRW waste, (2.4 kt/yr demolition & 2.0 kt/yr construction and production)

Regional demonstration system

- Income of 170 €/t from land owners for avoided incineration
- 85 €/t from production and construction waste and pellets from refrigerators
- Lower sorting cost for production and construction waste (only 20% of demolition waste)
- **40% subsidies on investments for the demonstration**



Total investment: 12,3 M€
Public support: 4,9 M€

Revenue [M€/y]	6,34
Total Costs [M€/y]	5,72
OPEX [M€/y]	4,13
CAPEX [M€/y]	1,20
Logistic costs [M€/y]	0,39
Profit [M€/y]	0,63
EBT-Margin [%]	9.9

Conclusions

- Recycling offers a more economically favorable option than incineration (considering the overall welfare of the system).
- Chemical processing is only economically viable at a sufficient scale
- PIR should be processed together with PUR to maximize efficiency.
 - High capital and operational costs of RTFs are only justifiable if PIR is also utilized
- Mechanical separation (RTFs) is an important cost driver in the system.
- If the elements are operated by different independent entities, the collection and sorting of demolition waste is not attractive.
- A regional demonstrator appears to be feasible with a realistic public support.
- Recycling of demolition waste must be enforced or subsidized.





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