Matter matters: Efficient recycling policies under tight markets for scrap

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Let's Recycle!

- Multiple policy initiatives to reduce the environmental footprint by limiting the production of primary resources and ultimate waste while promoting recycling:
  - 2012 Waste Electrical and Electronic Equipment Directive
  - 2015 Circular Economy Action Plan
  - 2023 Critical Raw Materials Act
- Main waste policies include:
  - ✓ Tax on waste disposal (unit pricing)
  - ✓ Deposit - refund system (product tax + recycling subsidy)
  - ✓ Recycled content regulation (minimum secondary materials)
  - ✓ Extended producer responsibility (eco-design)

The Literature

- The current dominant stance on waste disposal policies
  - rests on **perfect competition** (pub econ: instruments): Dinan (1993), Fullerton & Kinnaman (1995), Palmer & Walls (1997), etc;
  - !!! but ignores supply-side linkages between virgin and recycled materials!
- Yet, supply-side linkages are underscored by
  - a large literature in IO relying on **imperfect competition**: Gaskins (1974), Swan (1980), Ba & Mahenc (2019), Ba & Soubeyran (2023), Belleflamme & Ha (2024)
  - a literature in macro-dynamics: Weinstein & Zeckhauser (1973), Schulze (1974) or Dasgupta & Heal (1979), De Beir et al. (2010), Fodha & Magris (2015), Boucekkine & El Ouardighi(2016), Fabre, Fodha, Ricci (2020)
  - !!! but without policy considerations!

Our Stance

- We reconsider classic questions of **policy design** relying on perfect competition, but highlight **supply-side linkages** that determine the availability of recyclable materials!
- Constrained supply of recyclable materials is highly relevant in several sectors now and soon:
    - Agricultural waste for biogas production in Germany;
    - Recycled rPET for packaging materials in the US;
    - Very important from the energy transition perspective!

Growing Demand for Critical Minerals

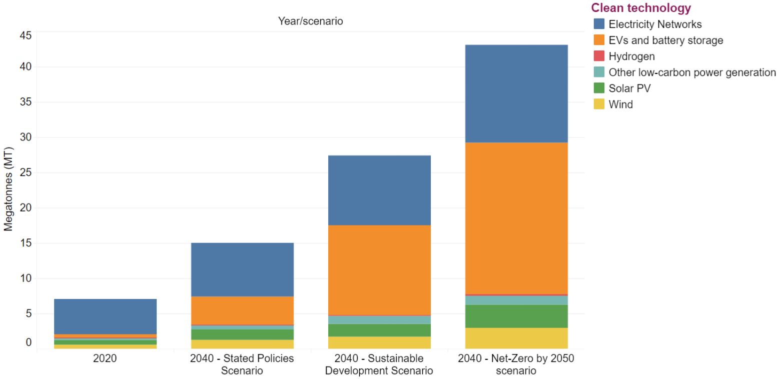

Figure 1: Global minerals demand for clean energy technologies (IEA)

- Primary production can't meet sharp increase in demand for mineral resources, increasing need for recoverable materials;
- There may not be enough scrap that is readily available now or soon to meet these demands.

What We Do

Research Questions: How does the potentially constrained supply of recyclable materials affect the policy prescriptions for waste disposal?

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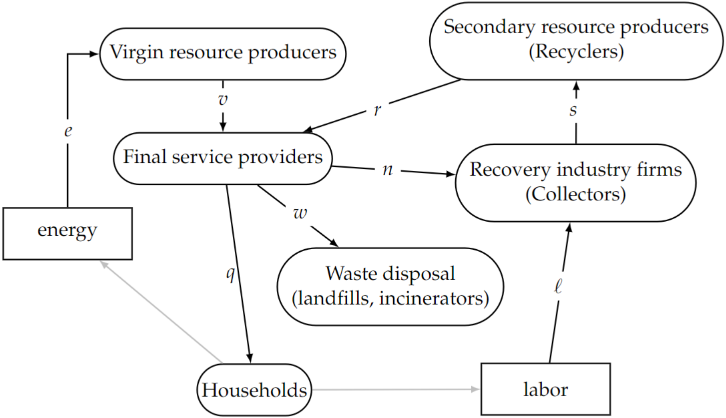
$\Downarrow$

1. Build a model of the recycling value chain:
   - Focus on recovery and recycling of materials embedded in end-of-life energy equipment, closer to industrial waste
   - Distinguish two scenarios: recyclable materials are scarce and fully recovered, or some disposed of as definite waste!
2. Introduce negative externality due to waste disposal and discuss policies:
   - ✓ Pigouvian tax on waste disposal;
   - ✓ Deposit–refund (output/virgin tax + recycling subsidy)
   - ✓ Recycled content standard

A Model of the Value Chain



- Perfectly competitive complete markets;
- Partial equilibrium with l specific to recycling and e to primary;
- EOL products are owned or managed by the original producer of the products $\Longrightarrow$ final good = final service

Resource Producers and Consumers

- Virgin producers employ energy inputs e_t to produce the raw virgin resource according to:

$$v_t = ae_t^{\alpha}, \quad \alpha \in (0,1)$$

!!! Here we abstract from resource scarcity.

- Secondary resource producers convert scrap into recycled materials according to:

$$r_t = bs_t^{\beta}, \; \beta \in (0,1)$$

- Households:
  - Supply (perfectly) elastic inputs: labor ℓ, energy e
  - Consume final services q_t to get utility, but suffer from pollution damage caused by waste disposal:

$$\max_{q_t > 0} \; \theta q_t - \xi w_t - p_{q,t} q_t$$

Final Service Providers

- Convert virgin v_t and recycled r_t material inputs into service according to a linear technology: $q_t = \gamma(v_t + r_t)$;
- At date t, they are responsible for their EOL products from the previous period (m_t) : $m_t = v_{t-1} + r_{t-1}$;
    - "Sell" an amount n_t of virgin materials embedded in EOL products to collectors (**recycling at most once**) : $n_t \leq v_{t-1}$;
    - Dispose of quantity w_t to landfills at constant unit cost p_w

$$w_t = m_t - n_t = v_{t-1} + r_{t-1} - n_t$$

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- Final service sector firms' problem:

$$\max_{\{v_t, r_t, n_t\}} \sum_{t=1}^{\infty} \left(\frac{1}{1+\rho}\right)^{t-1} \Big[p_{q,t}\gamma(v_t + r_t) - p_{v,t}v_t - p_{r,t}r_t + p_{n,t}n_t - p_w(v_{t-1} - n_t + r_{t-1})\Big],$$

$$s.t. \qquad n_t \leq v_{t-1}.$$

Denote by λ_t the multiplier of the intertemporal (life-cycle) constraint.

Collectors

- Employ c units of labor to convert one unit of EOL into ϕ units of scrap s:

$$s_t = \min\left\{\frac{1}{c}\ell_t\ ,\ \phi n_t\right\}, \quad \phi \in (0,1)$$

- Recovery industry firms' problem:

$$\max_{n_t > 0} \pi_{s,t} = \left(p_{s,t} - c p_\ell - \frac{1}{\phi} p_{n,t}\right) \phi n_t$$

Some Remarks

- v and r are not linked through demand:
  - Perfectly elastic demand for final services AND perfect substitutability between virgin and recycled resource materials in production!
- One-round recycling is qualitatively robust to multiple rounds if imperfect recycling.
- Our approach is "almost static":
  - The final service firms trades-off across time only because current production is linked to the management of EOL equipment next period;
  - There is no underlying dynamic process (resource scarcity increasing with exhaustion, technological change, etc).

The Market Equilibria

- Distinguish two cases:
  1. Some avoidable waste (waste disposal):

$$n_t < v_{t-1},\ \lambda_t = 0$$

     - Equilibrium under waste disposal

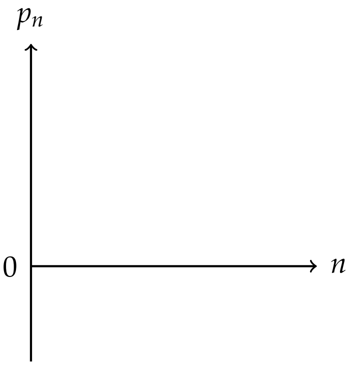
  2. Scarce recyclable materials (full recycling):

$$n_t = v_{t-1},\ \lambda_t > 0$$

     - Equilibrium under full recycling

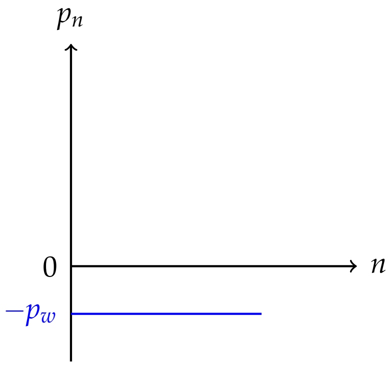
λ_t: the multiplier of the EOL products availability constraint

The Recovery and Scarp Markets: Waste Disposal



EOL recovery market

The Recovery and Scarp Markets: Waste Disposal



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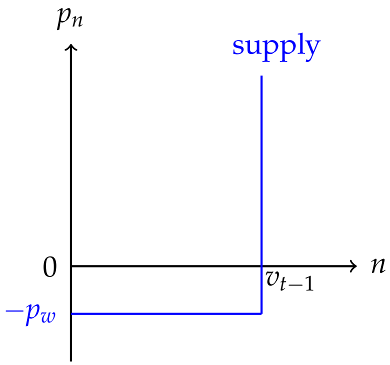

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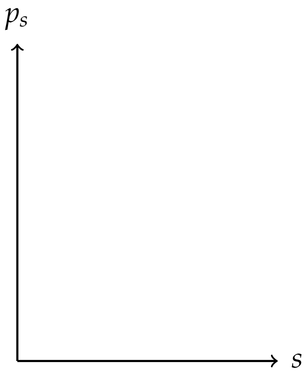
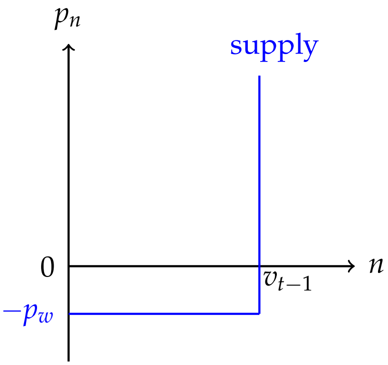


Scrap market



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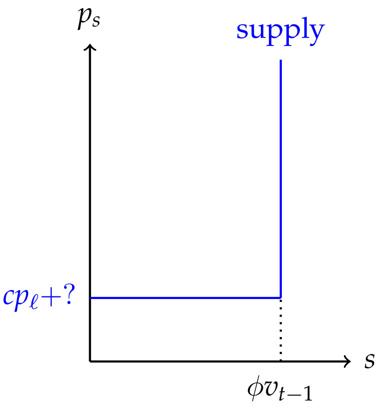

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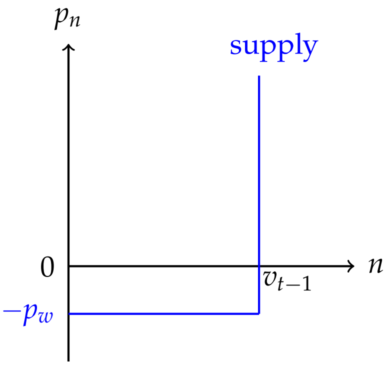

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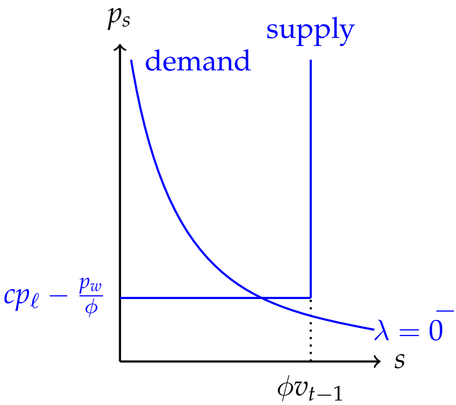

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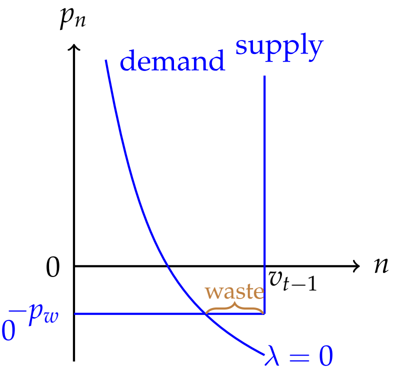
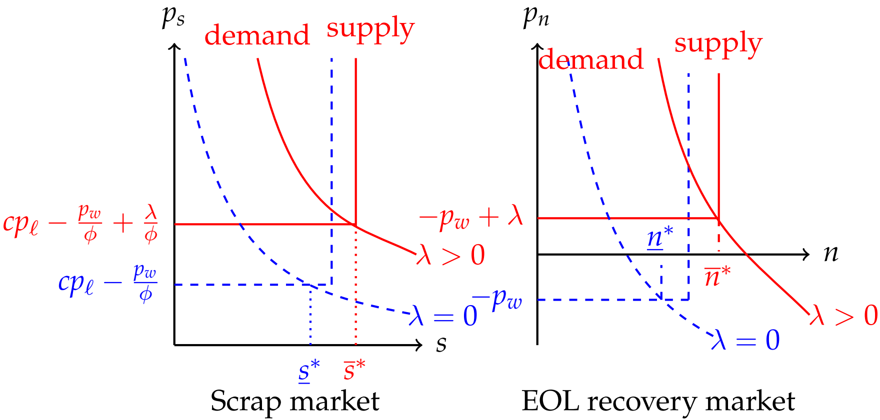


EOL recovery market

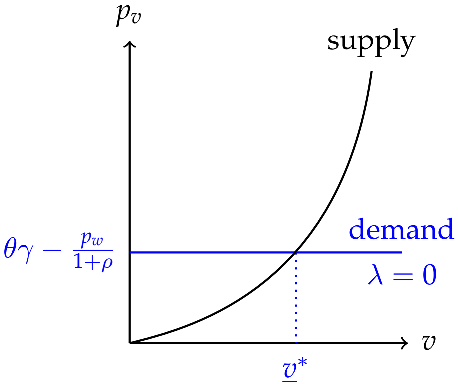
The Recovery and Scarp Markets: Scarce Scrap

λ: the multiplier of the EOL products availability constraint



Primary Resource Market

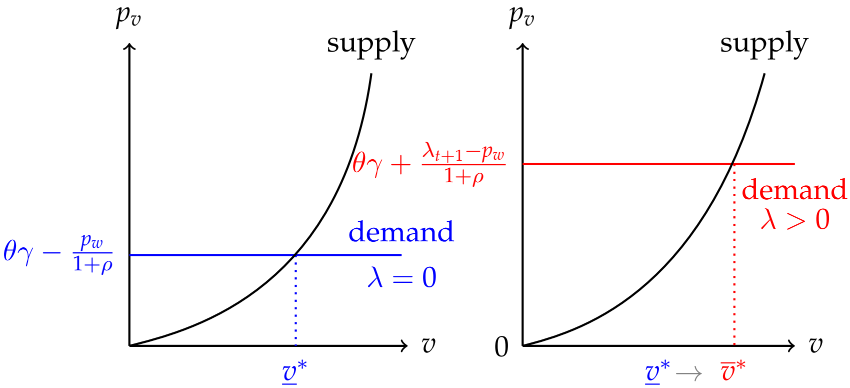
λ: the multiplier of the EOL products availability constraint



Case with waste disposal

Primary Resource Market

λ: the multiplier of the EOL products availability constraint



Case with waste disposal   Case of scarce scrap

The Efficient Equilibrium

1. Under waste disposal:
   - The primary and secondary markets are disconnected;
   - Factors stimulating recycling improve recovery and reduce waste, but do not affect primary production.
2. Under the case of scarce recyclable materials:
   - The scarcity value of scrap is internalized by market operators and transmitted upstream through the value chain, taking the form of a higher primary resource price;
   - The quantity of primary resource is *ceteris paribus* larger, since the demand schedule shifts up in response to the rent upon sale of EOL products on the scrap market.

Pollution Externality from Waste Disposal

- The utility function of consumers becomes:

$$U_t = \theta q_t - \xi(v_{t-1} - n_t + r_{t-1}).$$

- Under laisser-faire, the market is
  1. Waste disposal:
     - ✓ producing too much in the primary sector;
     - ✓ doing too little recovery and recycling if $\theta\gamma > \frac{1}{1+\rho}\phi c p_\ell$;
     - ✓ doing too much recovery and recycling if $\theta\gamma < \frac{1}{1+\rho}\phi c p_\ell$;
  2. Full recycling: producing too much virgin and doing too much recovery and recycling.

- **Regulation 1**: Pigouvian tax at the source of pollution, irrespective of the market state for scrap:

$$\tau_d^* = \xi$$

The Deposit-Refund System

Regulation 2: Tax production of final services (τ_q) and subsidize recycling (σ)

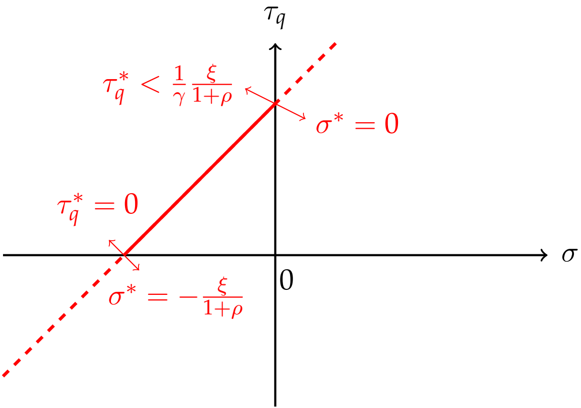
- **Waste disposal:** a unique combination of tools

$$\tau_q^* = \frac{1}{\gamma}\frac{\xi}{1+\rho} > 0 \quad , \quad \sigma^* = \frac{\xi}{\phi}\left(\frac{\theta\gamma - \frac{p_w+\xi}{1+\rho}}{cp_\ell - \frac{p_w+\xi}{\phi}}\right) > 0$$

- **Full recycling:** multiple (linear) combinations of (τ_q^*, σ^*) due to supply-side linkages, including a single tool

$$\tau_q^* = \frac{1}{\gamma}\frac{\frac{\xi}{1+\rho} + \sigma^*}{1 + \frac{1+\rho}{\beta b}\phi^{-\beta}\overline{v}_t^{1-\beta}}$$

Deposit-Refund Approach under Full Recycling



1. Just tax recycling!
2. Or tax only final services, but less than under waste disposal
3. Allow for more flexible choice by decision-makers!

Another Deposit-Refund Scheme

- **Regulation 3**: Tax the production of virgin materials (τ_v) and subsidize recycling (σ)
- **Waste disposal**:

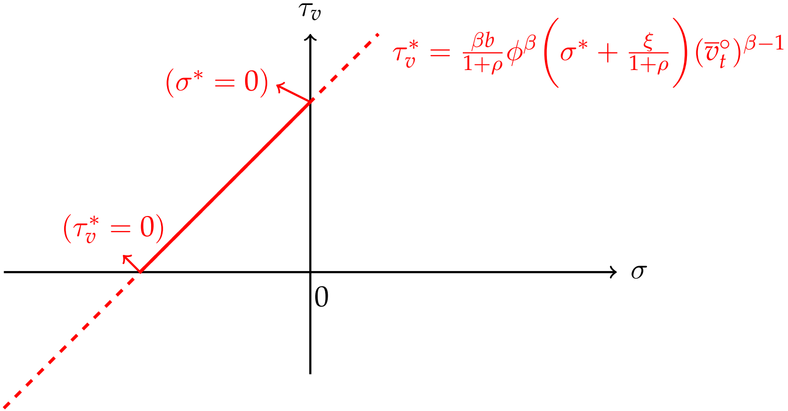
$$\tau_v^* = \frac{\xi}{1+\rho} > 0, \;\; \sigma^* = \frac{\xi}{\phi} \frac{\theta\gamma - \frac{1}{1+\rho}\phi c p_\ell}{c p_\ell - \frac{1}{\phi}(p_w + \xi)} \begin{cases} > 0 & \text{if } \theta\gamma > \frac{1}{1+\rho}\phi c p_\ell \\ < 0 & \text{if } \theta\gamma < \frac{1}{1+\rho}\phi c p_\ell \end{cases},$$

$\Rightarrow$ tailor subsidies to the circumstances!

- **Full recycling**: multiple combinations of (τ_v^*, σ^*) due to supply-side linkages
  - $\tau_v^* = 0, \quad \sigma^* < 0;$
  - $\tau_v^* > 0, \quad \sigma^* = 0;$

$$\vdots$$

Optimal Policy Mix under Full Recycling



- Sharply contrast with Dinan (1993), Fullerton & Kinnaman (1995): tax alone can't restore efficiency.

Regulation 4: Recycled Content Standard

Set a technical standard as a minimum requirement:

$$\frac{r_t}{v_t + r_t} \geq \widehat{\delta} \quad \Leftrightarrow r_t \geq \frac{\widehat{\delta}}{1-\widehat{\delta}} v_t \equiv \delta v_t \quad \mu_t > 0$$

- Introduce a wedge between demand schedules:

$$p^d_{v,t} = p^d_{r,t} - (1+\delta)\mu_t$$

- **Waste disposal**: Affects the ratio of primary to secondary materials, but cannot control their overall quantity and thus waste. A second instrument is required.
- **Full recycling**: Cannot be freely set, but RCS controls the overall quantity of resources and thus of waste. RCS alone can restore the first-best outcome, but implies a hidden cost.

Take Home

1. Disconnected primary and secondary markets under the scenario of abundant recyclable materials;
2. Connected markets when recyclable materials are scarce, conferring a scarcity value internalized by market operators and transmitted upstream through the value chain.
3. Policy design should be context-specific.
    - Common policy prescriptions do not apply.
    - Under scarce recyclable materials, the first best can be restored with a single instrument.
    - Taxing recycling can be efficient!

Limitations and Future Extensions

1. Other relevant market or regulatory failures?
   - negative externalities from the treatment of EOL products;
   - positive externalities from recycling;

— Imperfect competition along the value chain
   - network externalities: natural monopoly;
   - extended producer responsibility: regulatory design.

2. Calibration on data?
3. Incorporate dynamics?
   - Nonrenewable resources for virgin materials;
   - Stock pollution externalities;
   - Limited capacity for waste disposal.

THANK YOU!

Equilibrium under Waste Disposal

- The amount of virgin materials and their price:

$$v_t^* = a^{\frac{1}{1-\alpha}} \left[\frac{\alpha}{p_e} \left(\theta\gamma - \frac{1}{1+\rho} p_w \right) \right]^{\frac{\alpha}{1-\alpha}}, \quad p_{v,t}^* = \theta\gamma - \frac{1}{1+\rho} p_w;$$

- The amount of recycled materials and their price:

$$r_t^* = b^{\frac{1}{1-\beta}} \left[\frac{\beta \left(\theta\gamma - \frac{1}{1+\rho} p_w \right)}{c p_\ell - \frac{1}{\phi} p_w} \right]^{\frac{\beta}{1-\beta}}, \quad p_{r,t}^* = \theta\gamma - \frac{1}{1+\rho} p_w;$$

- The amount of scrap and its price:

$$s_t^* = \left[\frac{\beta b \left(\theta\gamma - \frac{1}{1+\rho} p_w \right)}{c p_\ell - \frac{1}{\phi} p_w} \right]^{\frac{1}{1-\beta}}, \quad p_{s,t}^* = c p_\ell - \frac{1}{\phi} p_w;$$

- The amount of EOL products and their price:

$$n_t^* = \frac{1}{\phi} \left[\frac{\beta b \left(\theta\gamma - \frac{1}{1+\rho} p_w \right)}{c p_\ell - \frac{1}{\phi} p_w} \right]^{\frac{1}{1-\beta}}, \quad p_{n,t}^* = -p_w;$$

- The amount of waste: $w_t^* = v_{t-1}^* - n_t^* + r_{t-1}^*$.

◂ Market Equilibria

Equilibrium under Full Recycling

- The amount of virgin materials v_t^{**} is the solution to

$$G(v_t) = \frac{p_e}{\alpha} a^{-\frac{1}{\alpha}} v_t^{\frac{1-\alpha}{\alpha}} - \theta\gamma - \frac{1}{1+\rho}\left[\beta b \phi^{\beta}\left(\theta\gamma - \frac{1}{1+\rho}p_w\right) v_t^{\beta-1} - \phi c p_\ell\right] = 0,$$

with $\quad p_{v,t}^{**} = \theta\gamma + \frac{1}{1+\rho}\left[\beta b \phi^{\beta}\left(\theta\gamma - \frac{1}{1+\rho}p_w\right)(v_t^{**})^{\beta-1} - \phi c p_\ell\right];$

- The amount of EOL products and their price:

$$n_t^{**} = v_{t-1}^{**}, \quad p_{n,t}^{**} = \beta b \phi^{\beta}\left(\theta\gamma - \frac{1}{1+\rho}p_w\right)(v_{t-1}^{**})^{\beta-1} - \phi c p_\ell;$$

- The amount of scrap and its price:

$$s_t^{**} = \phi v_{t-1}^{**}, \quad p_{s,t}^{**} = \beta b\left(\theta\gamma - \frac{1}{1+\rho}p_w\right)\left(\phi v_{t-1}^{**}\right)^{\beta-1},$$

- The amount of recycled materials and their price:

$$r_t^{**} = b\left(\phi v_{t-1}^{**}\right)^{\beta}, \quad p_{x,t}^{**} = \theta\gamma - \frac{1}{1+\rho}p_w;$$

- The amount of waste:

$$w_t^{**} = r_{t-1}^{**} = b\left(\phi v_{t-2}^{**}\right)^{\beta}.$$

◂ Market Equilibria