Agent-based modeling for the circular economy: lessons learned from three case studies

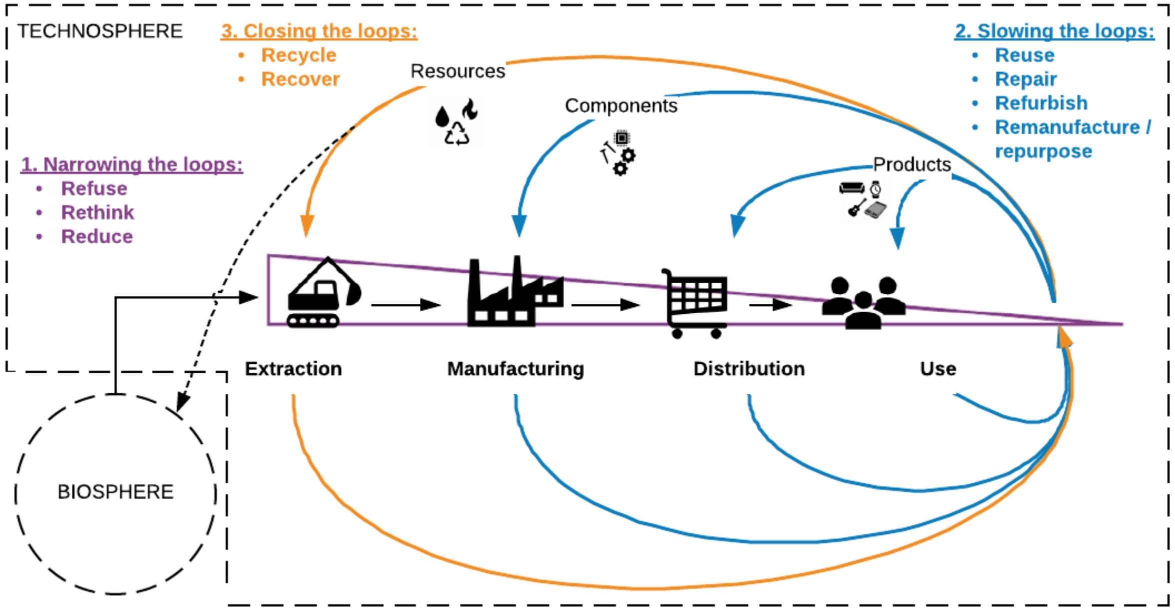
Julien Walzberg, Annika Eberle, Alberta Carpenter, Garvin Heath

September 23rd, 2021

Background – Problem statement

- **Problem:** In the next decades demand for raw materials is expected to increase (e.g., 3000% for photovoltaics (PV) between 2015 and 2060 (Sovacool, 2020))
  - 100 billion metric tonnes of materials consumed each year, 177 billion by 2050 (Circle Economy, 2021)
  - Increases the risk posed by sudden supply restrictions (Schrijvers et al., 2020)
  - Contributes to global GHG emissions due to their embodied energy and freight transport (Circle Economy, 2021)

- **A solution?** The circular economy (CE) spurs material efficiency e.g., through reusing/recycling products and transforms waste to wealth by:
  - Narrowing flows (use less)
  - Slowing flows (use longer)
  - Regenerating flows (make cleaner)
  - Cycling flows (use again)



Background –
Agent-based modeling

- Techno-economic solutions are necessary but not sufficient to improve circularity (Friant et al., 2020)

- Transitioning to a CE implies changes in patterns of production and consumption
  - Businesses and individuals need to change their behaviors
  - A good method to model human behaviors is agent-based modeling

- Agent-based modeling (ABM):
  - Bottom-up modeling where each agent follows its own behavioral rules
  - Agent: individual entity which has its own characteristics, behaviors and can interact with each other and with the environment
  - **Goal:** Understand how a system's macro level behavior emerges from the individual behaviors of the agents

- This study uses ABM to include behavioral factors when assessing the circularity transition

Agent-Based Modeling for the Circular Economy (CE ABM)

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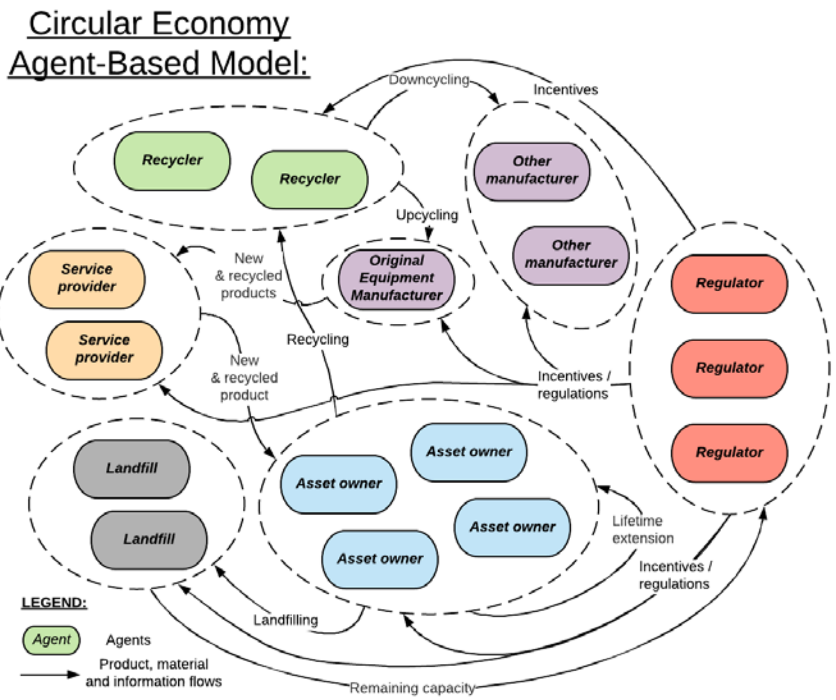
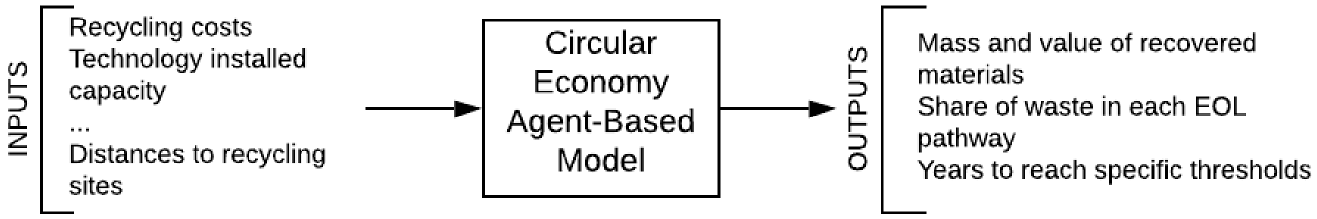
Core Team Members: Julien Walzberg, Robin Burton, and Aubryn Cooperman

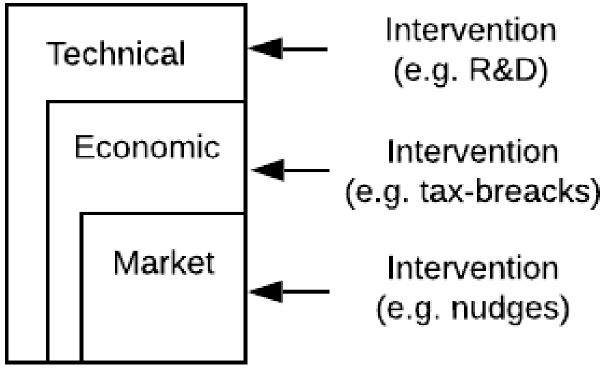
Timeline: November 2019 to November 2021



Primary research questions:

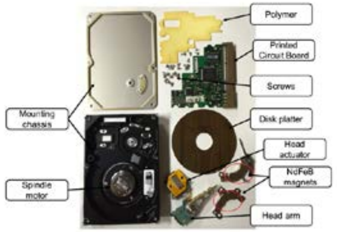
What are the technical, economic, and market conditions that maximize the value retention and minimize raw material inputs when applying CE strategies to energy-generating and energy-consuming technologies?





Material efficiency potentials

3 case studies:



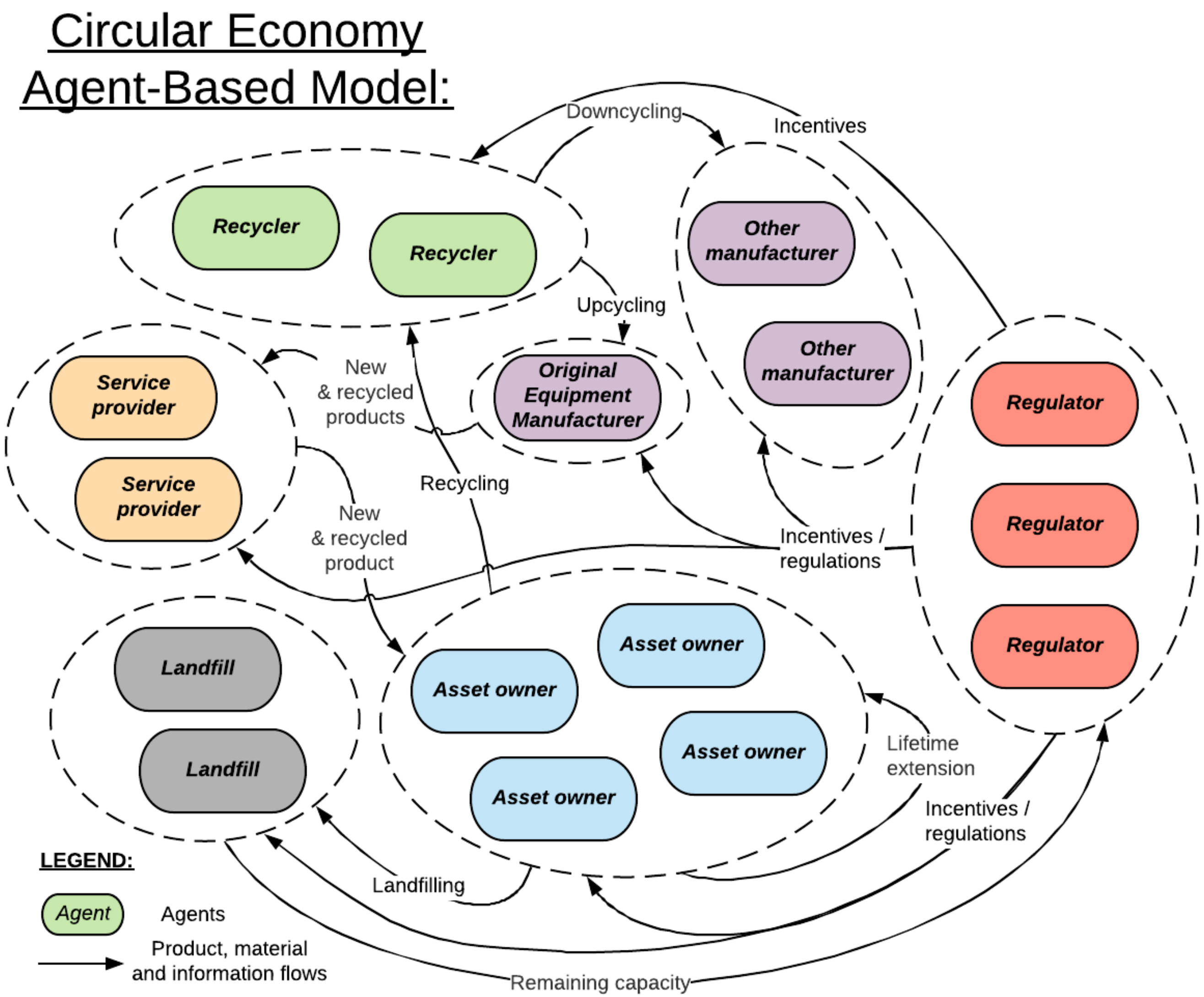
Hard-disk drives

PV

Wind

Image sources: NREL Image Gallery, München and Veit (2017)

CE ABM – Model overview, design concepts & details



Design concepts:

- Model implementation:
  - Python with Mesa and NetworkX libraries (Git here)
  - Agent types are python classes (1 agent=1 class instance with instance methods (agents' behavioral rules) and variables (agents' characteristics))
  - The model python module activate agents and collect outputs
- Modular design:
  - Mesa enables easily adding new agent types to the model as new python modules
  - Networkx facilitate the construction of networks to define agents' relationships and include geographical elements
- Simulations:
  - Time step = 1 year
  - Studied period = 2020-2050
  - Scope: the United States

CE ABM – Model overview, design concepts & details

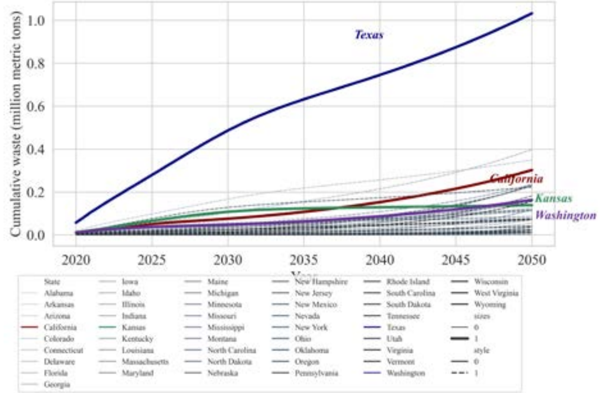
Details – asset owners:

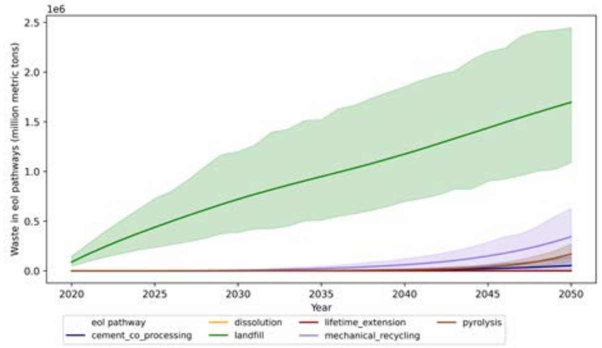
- The TPB is used to model the purchase decision (i.e., new versus used/refurbished assets)
- A Weibull function is used to generate the quantity of EOL assets at each time step
- The TPB is used to model the EOL management decision (i.e., repair, reuse, recycle, landfill, storage)

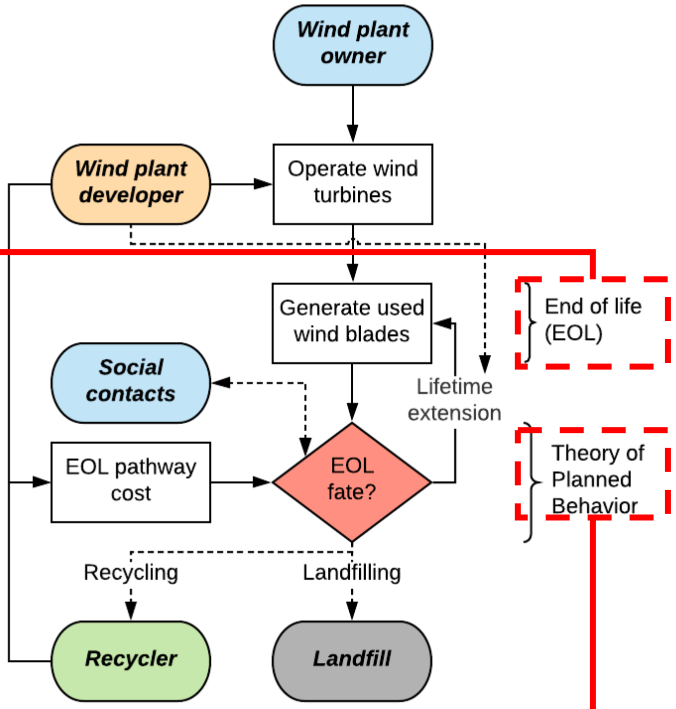
CE wind ABM example:

- 1320 wind plant owners (one for each wind plant project in the US) defined from the USWTDB
- Texas wind plant projects generate most of the EOL wind blades

$$ELW_i^t = RPC_i^t \times (1 - e^{-(t/T)^{\alpha}})*$$







$$B_{ij}^t = w_{BI}(w_A A_{ij} + w_{SN} SN_{ij}^t + w_{dPBC} PBC_{ij}^t) + w_{iPBC} PBC_{ij}^t + w_P P_{ij}^t + w_{BA} BA_{ij}**$$

*ELW_i^t: end of life waste of agent i at t; RPC_i^t: remaining wind power capacity of agent i at t; T: average lifetime; α Weibull shape factor

**Where at t, for each agent i and option j: BI = behavioral intention of performing the behavior; A = attitude toward the behavior; SN = subjective norms; PBC = perceive behavioral control over the behavior; P = pressures; BA = barriers; w_{BI}, w_A, w_{SN}, w_{dPBC}, w_{iPBC}, w_P, w_{BA} = regression coefficients

Summary of the case studies

CE ABM attributes	PV ABM	HDD ABM	Wind ABM
Number of asset owners	1000 (proxy)	1000 (proxy)	1320
Number of landfills	48 (proxy)	48 (proxy)	1294
BOL options	New/used module	New/used HDD	Thermoset/thermoplastic blade
Asset growth rate	2020-2030: 17%, then 4.5%	16%	Depends on the state
Weibull function parameters	$T = 30, \alpha = [2.5 - 5.4]$	$T = 6, \alpha = [1.3 - 2.2]$	$T = 20, \alpha = 2.2$
EOL options	Repair, reuse, recycling, landfill, storage	Reuse, magnet reuse, recycling, landfill, storage	Repair, recycling, landfill
Initial recycling rate	10%	70%	1%
Initial reuse rate	1%	6%	-
Transportation model	Shortest path on $G = (V, E)$ with $n(V) = 48$ & $n(E) = 107$	Shortest path on $G = (V, E)$ with $n(V) = 48$ & $n(E) = 107$	Openrouteservice API
Decision model	Basic TPB	Basic TPB	Extended TPB
Initial recycling costs	[25-30] $/module	[1-5] $/HDD	[300-2000] $/blade
Material mass fractions	{Aluminum: 8%, Glass: 76%, Copper: 3%, Silicon: 4%, Silver <1%}	{Aluminum: 45%, Steel: 31%, Plastics: 7%, Printed circuit board: 1%, Magnets: 4%, Ceramics: 8%, Copper: 1%}	{Steel: 5%, Plastic: 9%, Resin: 30%, Glass fiber: 56%}

Lessons learned from the CE perspective – Korhonen et al. (2018) limits to circularity

<u>6 limits to circularity:</u>

- Thermodynamic limits
- System boundary limits
- Limits posed by physical economic growth
- Path dependencies and lock-in
- Intra-organizational versus inter-organizational strategies and management
- Definition of physical flows

By modeling stakeholders' decisions, the CE ABM can help in exploring some of these limits

Ecological Economics 143 (2018) 37–46

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Circular Economy: The Concept and its Limitations

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ARTICLE INFO

Article history:
Received 10 January 2016
Received in revised form 26 June 2017
Accepted 29 June 2017
Available online 12 July 2017

Keywords:
Circular economy
Business strategy
Scientific research
Global net sustainability
Thermodynamics
System boundaries
Six limitations

ABSTRACT

Circular economy (CE) is currently a popular concept promoted by the EU, by several national governments and by many businesses around the world. However, the scientific and research content of the CE concept is superficial and unorganized. CE seems to be a collection of vague and separate ideas from several fields and semi-scientific concepts. The objective of this article is to contribute to the scientific research on CE. First, we will define the concept of CE from the perspective of WCED sustainable development and sustainability science. Second, we will conduct a critical analysis of the concept from the perspective of environmental sustainability. The analysis identifies six challenges, for example those of thermodynamics and system boundaries, that need to be resolved for CE to be able to contribute to global net sustainability. These six challenges also serve as research themes and objectives for scholars interested in making progress in sustainable development through the usage of circular economy. CE is important for its power to attract both the business community and policy-making community to sustainability work, but it needs scientific research to secure that the actual environmental impacts of CE work toward sustainability.

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1. Introduction

Circular economy (CE) is a concept currently promoted by the EU, by several national governments including China, Japan, UK, France, Canada, The Netherlands, Sweden and Finland as well as by several businesses around the world. The European Commission recently estimated that circular economy-type economic transitions can create 600 billion euros annual economic gains for the EU manufacturing sector alone (COM, 2014; EMAF, 2013; see also CIRAIG, 2015 and COM, 2015). Finland's Independence Celebration Fund (FICF, SITRA) and Mckinsey (2014) jointly estimate 2.5 billion euros annual gains for the national economy of Finland through circular economy. The global economy would benefit 1000 billion US dollars annually (FICF and Mckinsey, 2014; see e.g. EMAF, 2013). China, as the first country in the world, adopted a law for the circular economy in 2008 (CIRAIG, 2015). Circular economy is recommended as an approach to economic growth that is in line with sustainable environmental and economic development (see EMAF et al., 2015; EMAF, 2013; EMAF, 2012; CIRAIG, 2015; COM, 2015; COM, 2014).

The current and traditional linear extract-produce-use-dump material and energy flow model of the modern economic system is unsustainable (Frosch and Gallopoulos, 1989). Circular economy provides the economic system with an alternative flow model, one that is cyclical (see EMAF et al., 2015; EMAF, 2013; EMAF, 2012; CIRAIG, 2015). The idea of materials cycles has been around since the dawn of industrialization. The idea has also been practiced accompanied by the argument that it reduces negative environmental impacts and stimulates new business opportunities already during the birth of the industrialization (Desrochers, 2004; Desrochers, 2002). But the linear throughput flow model has dominated the overall development causing serious environmental harm. Unlike traditional recycling the practical policy and business orientated circular economy (hereafter CE) approach emphasizes product, component and material reuse, remanufacturing, refurbishment, repair, cascading and upgrading as well as solar, wind, biomass and waste-derived energy utilization throughout the product value chain and cradle-to-cradle life cycle (EMAF, 2013; Rashid et al., 2013; Mihelcic et al., 2003; Braungart et al., 2007).

However, the concept of CE and its practice have almost exclusively been developed and led by practitioners, i.e., policy-makers, businesses, business consultants, business associations, business foundations etc. (see e.g. EMAF, 2013; COM, 2014; CIRAIG, 2015). The scientific research content of CE remains largely unexplored. Ecological economics may be the most fruitful source from which the new practical, policy and business orientated concept of CE could find scientific and theoretical support and guidance. Ecological economics has a long tradition in recycling and other CE-type concepts on the macroeconomic level although not presented under the CE term. Also on the microeconomic level, CE-type papers have been published in ecological economics, e.g.

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http://dx.doi.org/10.1016/j.ecolecon.2017.06.041
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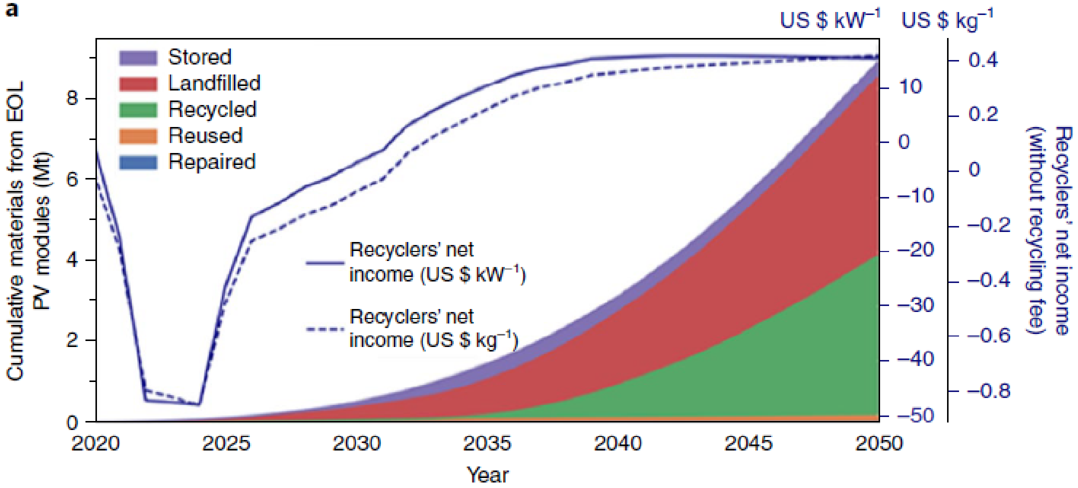
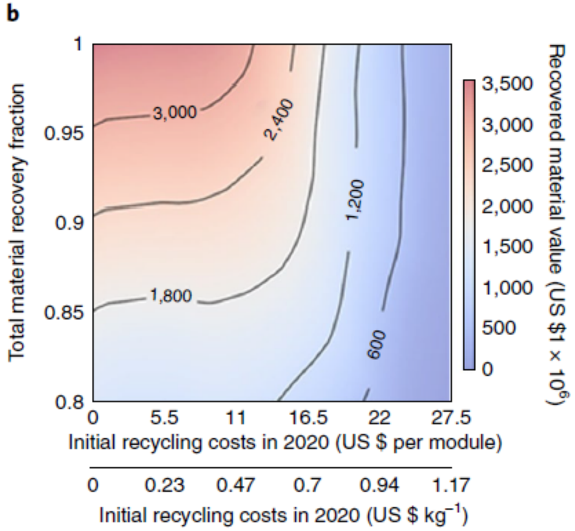
Lessons learned from the CE perspective – Thermodynamic limits

Materials	Recovery fractions & purity (%)			
	Baseline (mechanical separation)	FRELP	ASU	Purity
Insulated cable	100	100	100	NA
Silver metal	0	94	74	99
Copper metal	72	97	83	99.9
Aluminum scrap	92	99.4	94	Scrap
Silicon metal	0	97	90	Metallurgical grade
Glass cullet	85	98	99	98

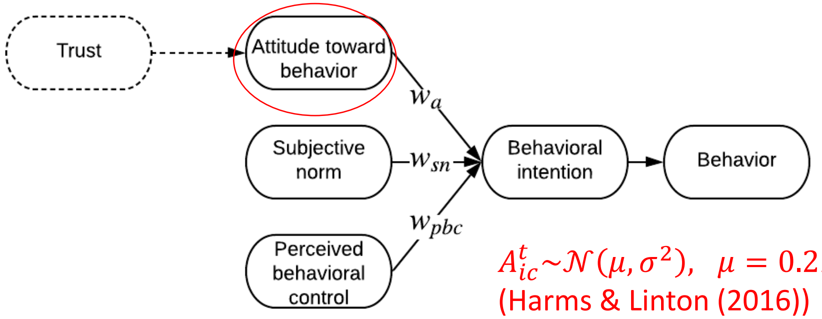


Key takeaways:

- Improving material recovery and profitability of the PV recycling process:
  - Increases the recycling rate from 7.7% to 52% (**a**)
  - Recyclers cumulative net income in 2050 = $1.6 billion as compared to -$160 million in the baseline (**a**)
  - High materials recovery and low initial recycling costs have a synergistic effect on value generation (**b**)
- However, there are several limits to PV recycling:
  - Silver represents < 1% of PV module mass but ~50% of PV module value → recyclers must recover as much silver as possible, but manufacturers produce modules with less and less silver content
  - Recycling destroys most of the embedded energy and value of products on the contrary to more circular options such as reuse
    - In 2050, recycling could recover a maximum of $35 million/percentage point while reuse could recover about $152 million/percentage point



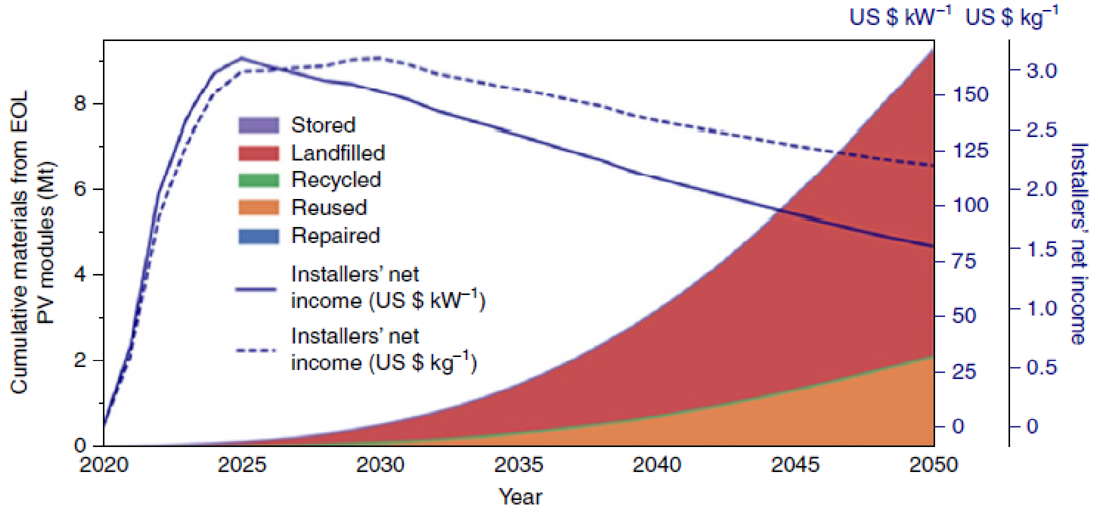
Lessons learned from the CE perspective – Modeling lock-in

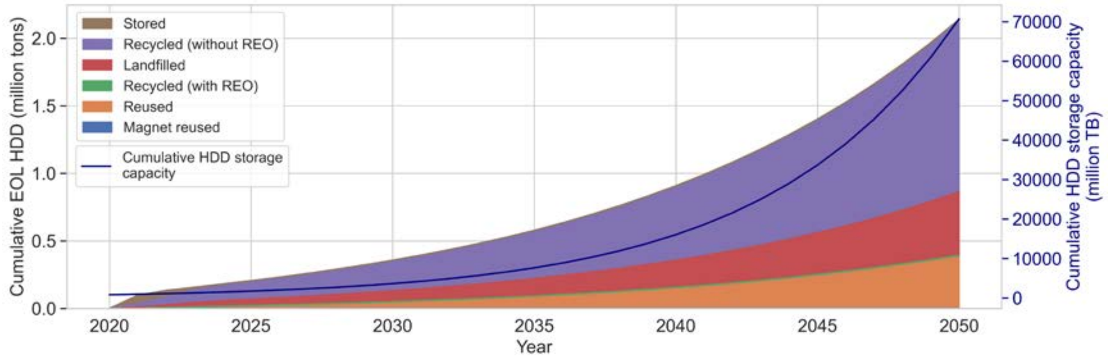


$A_{ic}^{t} \sim \mathcal{N}(\mu, \sigma^2)$, $\mu = 0.22 \rightarrow \mu = 0.5$
(Harms & Linton (2016))

Key takeaways:

- In the PV case, reuse is limited by PV owners' willingness to purchase used PV modules (demand side)
  - Improving attitude toward used product (e.g., with warranties) increases the reuse rate from 1.2% to 23%
  - CE strategies compete → recycling is greatly reduced (7.7% to < 1%)
- In the HDD case, reuse is limited by end-users' lack of trust toward data-wiping due to privacy concerns → most HDD are shredded (supply side)
  - If end-users' decisions were based only on economics, HDD reuse rate would be higher as data-wiping is less costly than shredding
  - Improving trust toward data-wiping increases the reuse rate from 6% to 18% and saves an additional 2 million tons of CO_2 eq

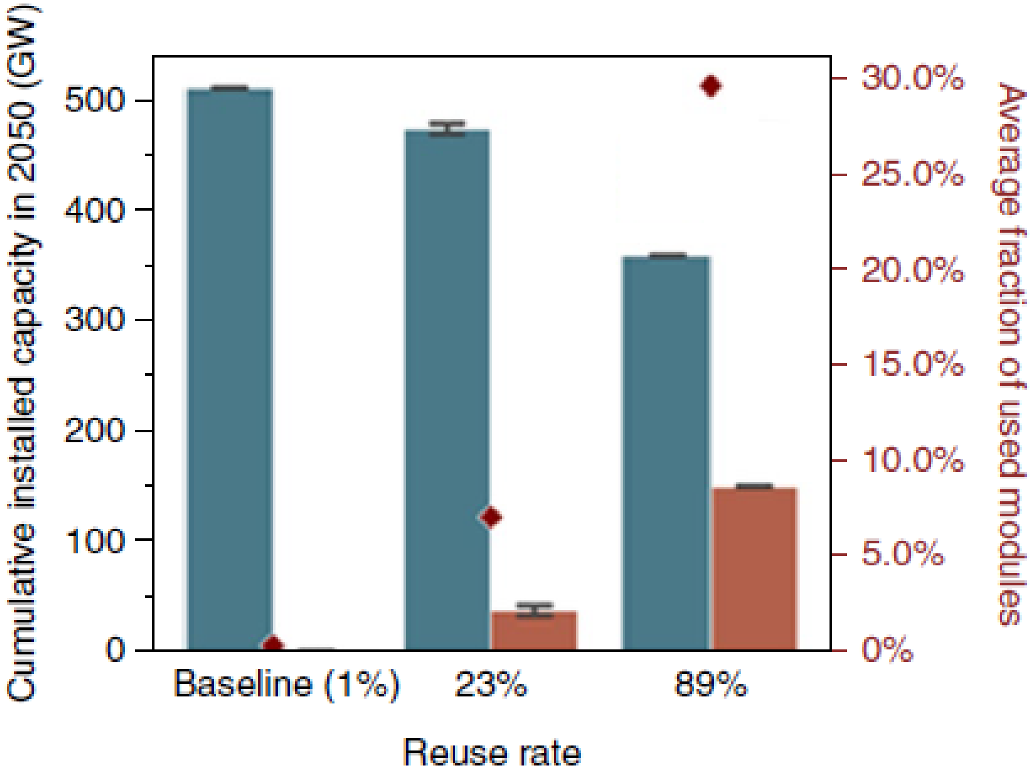




Lessons learned from the CE perspective – Limits posed by physical economic growth

Key takeaways:

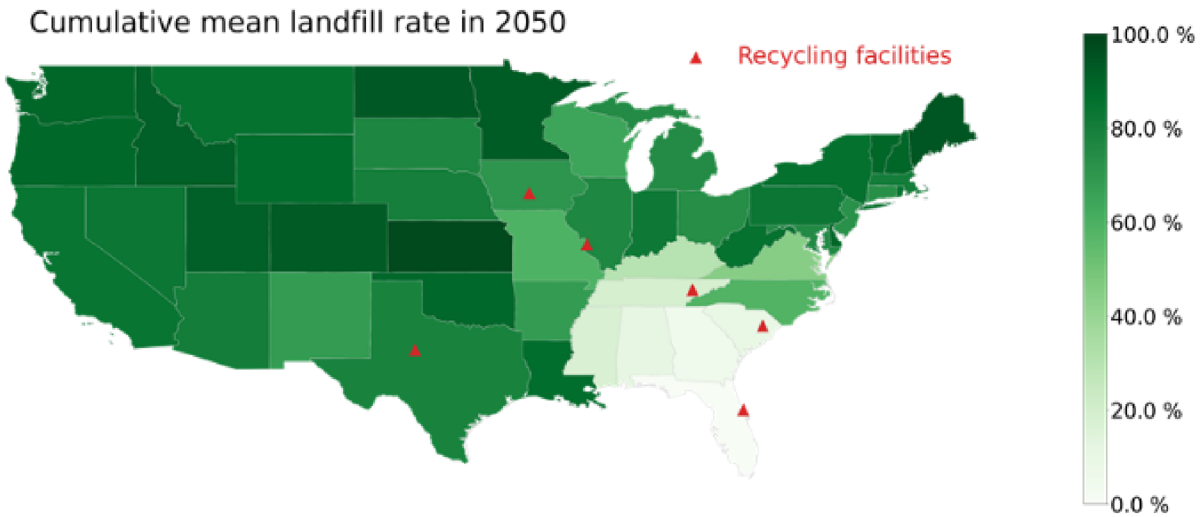
- PV ideal reuse case (reuse rate = 89%):
  - Set by removing all constraints to reuse (except that modules can only be reused once)
  - Only a third of the demand for PV modules is met, highlighting physical limits to that CE strategy
  - Waste from modules reaching their second life represent about 10% of the cumulative EOL PV modules in 2050 → recycling is still crucial
- Most assets present technical constraints to reuse
  - About half of PV modules, HDDs, and wind blades are in a good enough shape to be reused
  - Used modules need to pass safety certifications to be used on-grid
  - Used HDDs with capacities < 320 GB don't find customers

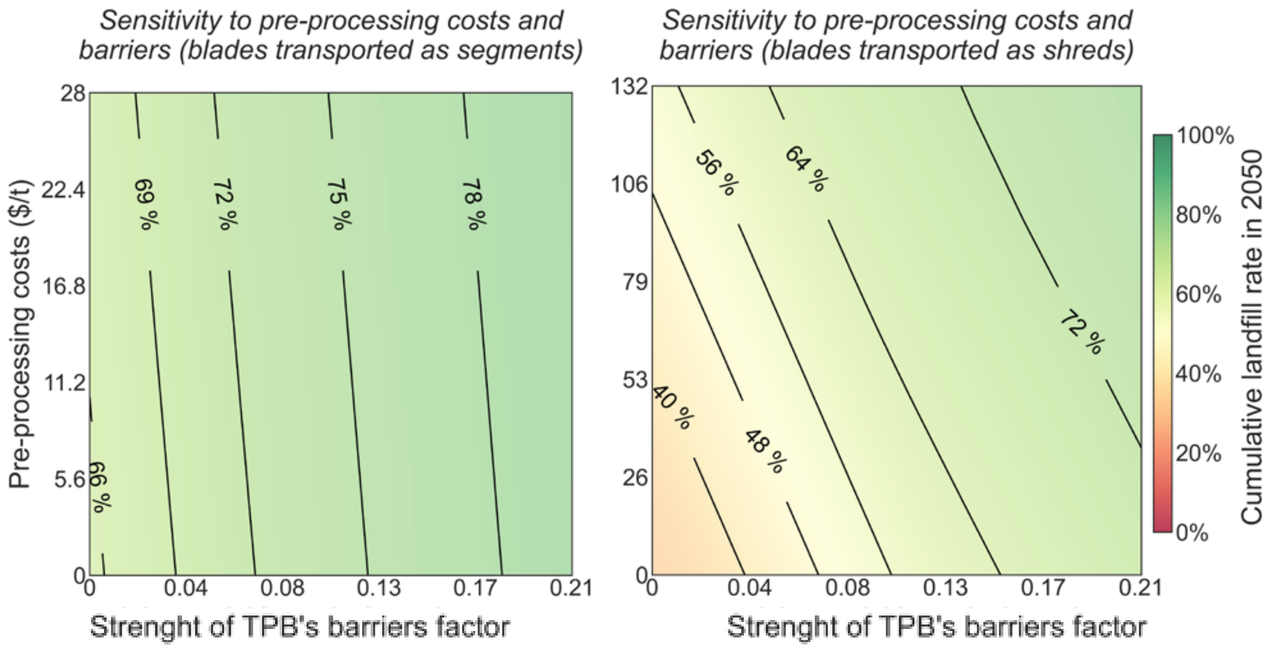


Lessons learned from the CE perspective – Defining physical flows

Key takeaways:

- States have different regulations regarding oversize/overweight road transportation
- Wind blades are considered construction & demolition waste or industrial waste depending on the state
- Transportation is costly, but shredding blades on-site may decrease transportation costs:
    - Cutting costs of $28/metric ton and $3.7–$4.4/metric ton-mile for 40–45-meter blade segments
    - Shredding costs of $116/metric ton and $0.05–$0.12/metric ton-mile for shredded blades
- Similar regulations to rubber tires could be applied (i.e., landfill ban on whole blades only or on whole and shredded blades depending on the state)

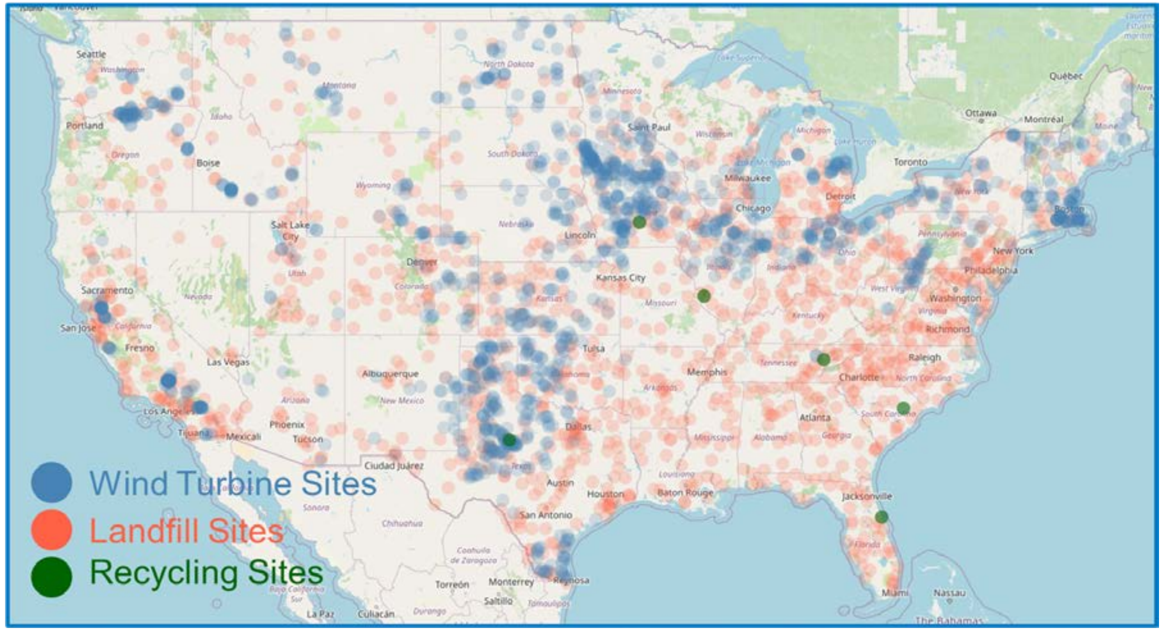


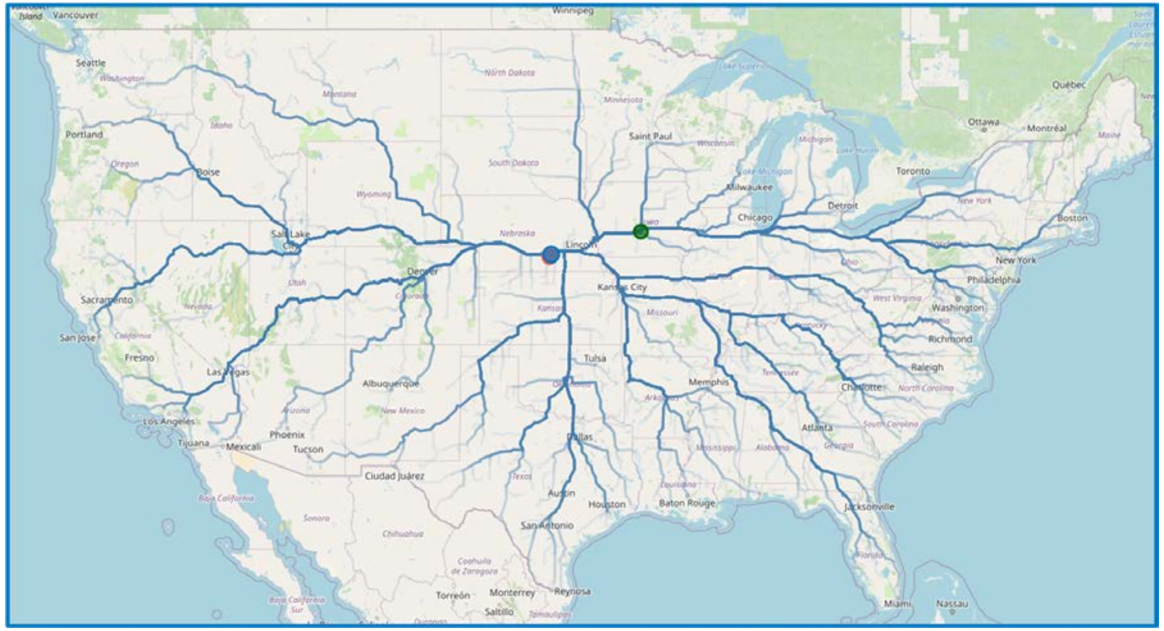


Lessons learned from the ABM perspective – Benefits

Benefits of the ABM method:

- Model stakeholders' decisions leading to adoption of different CE strategies and their effects on circularity
  - For instance, in the wind ABM, the adoption of lifetime extension (between 5 and 15 years) avoids about 10% of the 2050 cumulative EOL blade amount generated in the baseline
- Keep track of variables at agents and system level and assign individual characteristics to the agents
  - For instance, geographic coordinates are given to wind plant owners, landfills, and the recycling facility → avoids a 16-percentage point underestimation of the landfill rate when compared to a simplified approach





Lessons learned – Key takeaways

CE ABM results	PV ABM	HDD ABM	Wind ABM
Baseline recycling rate	10%	68%	22%
Baseline reuse/repair rate	1%	6%	55%
Barriers to increased circularity	High recycling costs, underdeveloped secondary markets, low landfill costs	Lack of trust toward data-wiping, REO recovery	Transportation costs and logistics, downcycling, low landfill costs
Enablers to increased circularity	Lower recycling costs (e.g., by increasing profits), better warranties for used modules, regulations, high landfill fees	Improve end-users' attitude toward data-wiping by increasing trust, develop magnet reuse, regulations	Facilitate on-site shredding of blades, develop easy-to-recycle composites, regulations, high landfill fees
Machine learning metamodel	Yes	No	Yes
Monte Carlo analysis	No	Yes	No

Avenues for future research

- Drawbacks of the ABM method:
  - Needs to be combined with other methods (e.g., LCA) to provide information on environmental impacts
  - Computationally expensive

- Combining ML and ABM is a recent trend that has several advantages (Rand, 2019), either to:
  - Explore ABM’s parameter space (Vadhati et al. 2019 and the PV and wind ABM study)
  - Design ABM’s behavioral rules (Zhang et al. 2016)

- An exciting avenue for future research could be to combine reinforcement learning with agent-based modeling
  - Rather than defining the behavioral rules from theories such as the TPB, rules are “discovered” by the agents during the simulations

- Possible further research:
  - Combining the CE ABM with life cycle assessment to compute environmental impacts of EOL options
  - Using a reinforcement learning algorithm to set up the behavioral rules in the CE ABM

Thank you!

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NREL/PR-6A20-80037

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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