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Monetary evaluation in LCA of WM: Everything engineers always wanted to know about it (but were afraid to ask)

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1. Introduction

Life-cycle assessment (LCA) has become a standard tool for waste management (WM) research; hundreds of scientific articles are published every year (Christensen et al., 2020; Mulya et al., 2022; Paes et al., 2020). It is also widely used to support policymaking, from the individuation of "best available technologies" to regulatory impact assessment (Sala et al., 2016).

Its merit is to encompass the direct and indirect consequences of alternatives, starting from raw material extraction and ending with the final disposal of waste. Its success is motivated by a standardised and easily replicable methodology, applicable to a vast range of cases, facilitated by the availability of detailed guidelines, specific software, and ready-for-use datasets.

In turn, LCA uniquely analyses physical aspects (environmental impacts, resource depletion, generation of waste) and neglects socio-economic ones (Ekvall et al., 2007). For this reason, it is necessary to accompany LCA with an equally systematic appraisal of economic and social aspects to provide a coherent support to decision-making (European Commission, 2003).

Life-cycle costing (LCC) has been developed to account for all the financial implications that arise during the whole life cycle of a project, therefore not limiting to initial investment but also considering operational costs, revenues and decommissioning (Settanni et al., 2014). More recently, attempts have expanded the range of economic analysis by encompassing cascading macroeconomic effects (Hendrickson et al., 1998; Hunkeler et al., 2008).

Similarly, other tools have been proposed to analyse the social dimension (Costa et al., 2022; Garrido, 2017). Social LCA (S-LCA) addresses issues such as the level and quality of employment, social conflicts, quality of life, and community engagement (Kühnen & Hahn, 2017).

LCC and S-LCA have been widely applied in WM research (Ghisellini et al., 2023; Luthin et al., 2023; Martinez-Sanchez et al., 2015; Mattos & Calmon, 2023).

Unfortunately, this is still insufficient: the final decision remains unpredictable until a way is found to reconcile and compare heterogeneous dimensions in a valuation framework that allows trade-offs, i.e., how much indicator x should increase to compensate for a lower value of any other indicator y. Economic valuation provides such a framework; its cornerstone is the conversion of heterogeneous environmental, financial and social indicators into a standard metric – monetary value.

Economists are often blamed for their imperialism toward other disciplines, yet if economics is needed somewhere, this is precisely for *valuation*. While often misunderstood as a *value judgment* related to concepts like ethics, justice, and beauty, valuation is ultimately concerned with choosing mutually exclusive alternatives: choosing something means giving up something else. Applying economic valuation at this stage is sometimes referred to as economic LCA (E-LCA) to distinguish it from LCC (Neugebauer et al., 2016).

There is an increasing interest in monetisation in the LCA community, facilitated by the publication of ISO 14008 norms. Diverse LCA methods incorporate monetary techniques (Amadei et al., 2021; Arendt et al., 2020; Pizzol et al., 2015). Until now, however, the majority of researchers and practitioners have preferred other approaches to integrated assessment, namely those based on multicriteria decision analysis (MCDA) (Carlsson Reich, 2005; Finkbeiner et al., 2010; França et al., 2021; Goulart Coelho et al., 2017; Torkayesh et al., 2022).

The present paper discusses the usefulness and the limits of using monetary indicators in LCA, focusing on WM. The article is structured around a simple question: How can we set socially desirable waste management targets? As a practical example, we consider the recycling rate here.

The European Waste Hierarchy (Dir. 2008/98) establishes a "priority ladder", posing waste prevention as the most desirable option, followed by reuse, recycling, recovery and disposal. To make this hierarchy operational, the EU sets many quantitative targets – minimum recycling and reuse rates, maximum allowed recourse to landfill, minimum content of recycled materials in new products, concentration limits for specific substances, etc. Derogations are sometimes admitted if proof of superior performance is given; LCA is considered the standard reference assessment methodology for setting targets and assessing derogations

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(Lazarevic et al., 2012).

We argue that the diffused distrust for economic valuation indeed owes something to an instinctive refusal of monetisation techniques, mainly due to conceptual misunderstandings about the meaning of monetisation.

Economic valuation cannot be enough for fundamental methodological reasons and more practical computational and empirical weaknesses. Incorporating monetary values in standardised software-based tools requires carefully understanding these limits.

Economists themselves disagree about the measure of value when environmental issues are concerned. Two competing paradigms (Environmental and Ecological Economics) affirm, with this respect, two equally contrasting approaches to sustainability ("weak" and "strong"), which also diverge regarding valuation criteria and, more specifically, the extent to which using the monetary metric is legitimate and appropriate and how far market prices – starting from the market interest rate – need to be corrected to represent a societal viewpoint.

This article is not addressed to readers who are already familiar with economic concepts but to practitioners and scholars with a non-economic background, and more specifically, to the community of researchers that has developed methodologically and thoroughly implements LCA models and tools.

2. Why valuate

2.1. Dreams of innocence

Bertolt Brecht famously said, "If I have to choose among two evils, I will choose none". However, this is a luxury we cannot afford: choices often imply unpleasant trade-offs, and we must accept giving up something to achieve something else. Refusing to decide helps to maintain moral virginity but not to solve problems.

Deciding is cumbersome, even when the decision only affects the private sphere. Doing so in the name of people and for the common good is even more cumbersome. The dream of many politicians – like President Truman in the opening quote – is to delegate responsibility to an expert – an equivalent to Plato's philosopher. However, this is equally naïve to Bertolt Brecht's claim.

Many decisions are technically complex and require the contribution of experts. However, one thing is to clarify the causal relations between actions and their consequences, possibly illuminating the less direct and obvious ones; another is asking experts to decide what is most desirable and transform expertise into "decision-making machines". In turn, experts can help politicians understand the linkages and implications, be more coherent, and possibly circumscribe the space of arbitrariness.

To reach a decision, we first need to understand the relevant spheres concerned. Each alternative affects different spheres. For example, in the case of WM, LCA considers local emissions, biosphere, resource depletion and climate change. Social consequences are also likely: jobs, land use, and urban development, among others. Damages to health and human lives are often a concern. Common goods such as landscapes, traditions, and cultural heritage may be affected. Someone could invoke ethical principles, e.g., justice and equity, or celebrate the virtues of parsimony. Finally, the financial dimension must be analysed since WM also implies using economic resources such as labour and capital.

Each sphere requires a measure of the impact, and to do so, specific indicators and metrics have to be identified – t of CO_2, concentration of pollutants, n. of endangered species, n. of jobs, level of poverty, decibels, and Euros. Others cannot be measured but only described qualitatively and eventually given a score – e.g., impacts on the landscape, beauty, reliability, and effectiveness.

The life-cycle approach enlarges the scope and allows us to understand the consequences of each alternative more in-depth, but it does not add anything in this respect. As Fig. 1 shows, LCA, LCC, and S-LCA provide a set of coherent indicators measuring the impact of the alternatives considered from many different viewpoints. However, they are still not comparable to each other.

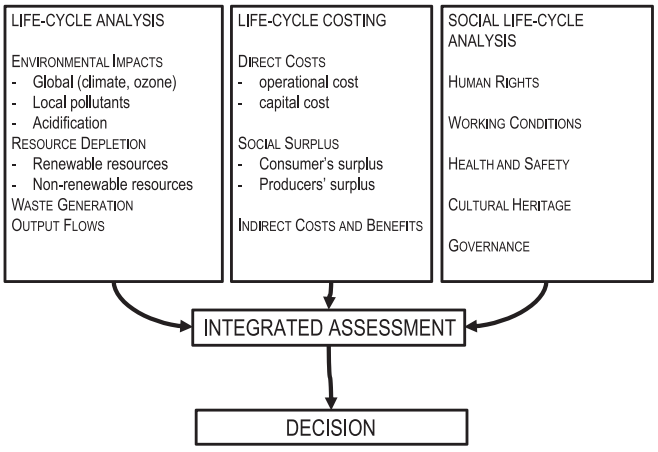

Fig. 1. From Life-Cycle indicators to decisions Source: our elaboration.

After identifying and measuring relevant impacts, a further step is required, possibly the most delicate: integrate them to reach a synthesis. This is tricky since each measure is incommensurable to the other. To compare incommensurable dimensions, we must necessarily reconduct them to a *standard metric* into which all must be translated. Which one?

A is more extended, B is heavier, C is taller, D is cheaper, and E is more intelligent: how to compare these dimensions depends on what we are looking for. A pivot for the college's basketball team? A fiancée? A reliable food dealer? A book to bring in the backpack this summer? Attributes have a different importance depending on our goal. However, we need a standard metric to make attributes comparable in all cases.

To choose "the best" alternative, we must establish a ***value hierarchy*** between attributes, which can only descend from attributes' relationship with goals. If A generates fewer PM-10 and more CO_2 than B, we must establish how much PM-10 equals 1 m^3 of CO_2.

In the end, any decision implies that some trade-off is made; however, very often, the way it is made remains hidden or implicit, and this is even more delicate when it is done by algorithms incorporated in decision-making tools, as in the case of LCA. Precisely, the characteristics that make LCA so successful (using automatised models and ready-for-use datasets and algorithms) require a careful understanding of these hidden assumptions.

2.2. Trade-offs and negotiable values

Generally speaking, a value hierarchy can be deducted in three ways (Kontoleon et al., 2001): investigation of collective preferences; participatory and deliberative approaches; and finally, by recurring to an exogenous source (e.g., an ethical principle).

In the LCA literature, the third approach is most often used, e.g., by techniques that rely on single items (e.g., cumulative energy demand, carbon or ecological footprint) or rank alternatives concerning the distance from some pre-determined targets (e.g., planetary boundaries). At the same time, the second involves panels of stakeholders or experts asked to assess the relative importance of impact categories through surveys and elicitation techniques (Sala et al., 2018).

In the MCDA, experts of different disciplines separately identify the relevant goals, how alternatives impact them, and how to measure them. Measures are later normalised, ranked and finally aggregated using complex algorithms. Rankings may be dictated directly by the involved experts. Still, they could also result from deliberative methods, e.g., interviewing policymakers and stakeholders and asking them to express their preferences via pairwise comparisons. Through the reiteration of these procedures, hierarchies of objectives can be derived, identifying "midpoints" (e.g., GHG) and "endpoints" (e.g., global warming).

Numerous alternative methodologies and techniques have been

proposed in the literature. Even more often, authors use their original variant, customised for the specific case and adapted to time and budget constraints. Environmental Footprint methods (European Commission-JRC, 2010) and endpoint impact assessment methods such as the LIME (C. Liu et al., 2021) are the most notable examples applicable to the waste sector.

MCDA is praised for its flexibility and capability to encompass many viewpoints (Rogers et al., n.d; Zanghelini et al., 2018). However, it is not immune from problems (Dean, 2020). Multiple dimensions are treated with complex ranking systems and algorithms, whose impact on the outcome is often difficult to interpret and can easily be distorted by arbitrary assumptions. The individuation of relevant categories, when left to the discretionary decision of the analyst, is highly at risk of neglecting some aspects and overemphasising or double-count others, especially when not accompanied by a comprehensive consultation of stakeholders in a genuinely deliberative process; this is often not possible due to time and resource limitation (Di Stefano & Krubiner, 2020; Gillespie, 2001).

Although flexibility is a great merit of MCDA, it also jeopardises methodological standardisation. Because they are incorporated in software tools or have been developed and adapted ad hoc for each specific study, the criteria adopted and the implicit assumptions behind them remain opaque and not easily replicable under alternative assumptions. Therefore, the method is prone to the analyst's arbitrary and subjective judgments (Beria et al., 2012; Gillespie, 2001). For example, the valuation result is sensitive to how ranks are given (e.g., the scale used to express value judgments) or the number of endpoints considered (Jamwal et al., 2021).

The ISO 14040 and 14,044 norms for LCA provide a general overarching framework, referring to normalisation and weighting, but do not dictate a specific method, thus encouraging the use of ad-hoc solutions (Finkbeiner et al., 2006). EU guidelines, in turn, provide no particular norms and simply recommend the good practice of highlighting eventual trade-offs (Dri et al., 2018; European Commission-JRC, 2010).

Furthermore, there is still the problem of ranking them against the financial cost. A solution may even be dominant concerning environmental or social criteria and still not necessarily optimal, considering respective financial needs. How much an environmental improvement is worth is a genuinely economic issue.

Economics adopts instead the first approach, i.e., the investigation of collective preferences (Mäler and Vincent, 2005). To do so, everything must be translated into a superior endpoint: human well-being. Reliance on methodological individualism is the foundational postulate of economics and must be kept very clearly in mind: economic valuation is intrinsically anthropocentric, i.e., it adopts the viewpoint of human beings and translates anything – meters, kilograms, picojoules, decibels – into something that is more or less desirable from an individualistic perspective.

It is impossible to know what precisely each individual wants since values are subjective and cannot be «measured» objectively. However, we can deduct values from observing what people do. Economics assumes that people behave as they do because they are guided by a rational appraisal of positive and negative implications on their well-being ("benefits" and "costs") and choose among feasible alternative actions the one that earns them the highest additional wellness. Assuming that individuals prefer to be better-off rather than worse-off, it is straightforward that when they choose A instead of B, this reveals that they expect their well-being will be higher than otherwise. With a backward inductive process, we can reconstruct each individual's value hierarchy.

The philosophy of economic valuation is to reduce whatever decision to the alternative of receiving (or having to pay) a given sum of money at a precise moment (usually when the evaluation is made): the implicit assumption is that there is always an equivalent sum of money (i.e., of alternative sources of well-being that could be obtained with it) that individuals would be willing to pay to obtain something – or symmetrically, that they would be willing to accept to prevent something – ending as well-off as before.

In a market economy, people decide whether to buy or sell something. They do so willingly: they expect to be better off by doing it. This is why market prices are such valuable information: they are good proxies of "true" values precisely because when operating on markets, people do not "lie" and reveal what is most desirable from their viewpoint. The implicit assumption is ***that goods are tradable***, i.e., that people are ready to accept giving up something in exchange for something else and be equally happy ((Bockstael & Myrick Freeman, 2005)). Whether trading in this way is always legitimate is the critical methodological issue of economic valuation ((Martinez-Alier et al., 1998)); we shall discuss this issue further in par. 5. But before that, we need to address what monetisation is about in more depth.

3. Lost in translation

3.1. Not for sale

Using money as a metric is one of the most often misunderstood features of economic valuation.

Non-economists often use scandalised tones to dismiss monetary valuation as biased, immoral, and fundamentally wrong. The typical argument is the one raised by John Adams, provokingly asking, "What is the price of your grandmother?" (Adams, 1974). In short, monetisation is blamed as an attempt to treat fundamental values as commodities.

Our ethics refuse that some things can be sold; attaching a monetary value means degrading them (Sandel, 2013). However, this kind of criticism neglects the fact that valuation (e.g., of human life) is not made for the purpose of selling human flesh to the market but for helping other decisions. Monetary valuation concerns the trade-offs we make when we decide and enables us to make them more explicit and understandable.

Life is non-negotiable, but we have to decide, for example, whether to invest in a safety measure that reduces the probability of being injured.

Think, for example, of speed limits. For every ten mph of increased speed, the risk of dying in a crash is double. In addition, speed increases the risk of severe injuries and damage to other people, vehicles and property. It could be easily demonstrated that reducing the maximum speed allowed would dramatically reduce these risks. Thence, why do we often drive faster? Why do many disagree with fixing the limit at 30 km/h?

Even if unpleasant to admit, our choices often reveal that a trade-off exists, at least implicitly. If I accept that the risk of having an accident is doubled in exchange for a shorter trip, I evaluate this risk as less worth the time savings. In some way, I am weighing the increasing risk with the advantage of arriving earlier. I am not selling anyone's life, not even my own; I am just trying to be coherent when allocating my (limited) resources.

If individuals make this kind of consideration – or behave consistently – why shouldn't we do the same when evaluating options that concern ourselves as a community?

3.2. Marginal and absolute values

A second misunderstood feature of monetisation is that it focuses on *marginal* and not *absolute* values ((Mankiw, 2017)). Absolute value represents the importance of a good but does not affect economic value. Marginal value reflects instead the value of an *additional quantity* of an item – the one concerned with the choice to be made. Misunderstanding this point confounds the many who follow Oscar Wilde, blaming economists for "knowing the price of everything and the value of nothing".

Therefore, an economist would never ask whether recycling is better or worse than energy recovery but rather whether, standing where we are, we should burn more (less) and recycle less (more).

The marginal value is a measure of *economic scarcity* rather than

importance. Air is fundamental for life (it has an immense absolute value) but holds no economic value until it is abundant and readily available. Similarly, the fact that something is available in a *limited quantity* does not make it economically valuable in automatic. My paintings are *limited* – there are only a few on planet Earth – but I am such an awful painter that not even my son is willing to have one.

What makes things economically valuable is neither *importance* nor *limitedness* but rather the degree of *rivalry*: how many competing uses of the same good there are and what must be sacrificed when choosing one. Allocating the good to use A prevents the possibility of using it for doing B; the value of the foregone opportunity, B, is what economists mean by "cost".

We have to stress that economics intends "cost" as "opportunity cost"; that is, the cost of X corresponds to what must be given away to have X. If an input has no alternative use, its opportunity cost is thus zero, regardless of its usefulness and necessity for producing X.

This is why the price of air is zero, while a Ferrari costs a lot of money. It does not mean that Ferraris are more important than air; simply, there is so much air available that the quantity everyone breathes is not rival, while a Ferrari requires a lot of inputs – labour, capital, etc. – that could be used in another way.

Market prices are good indicators of economic value since they reflect both the "willingness to pay" (WTP) – how much buyers are ready to give up to obtain an additional unit of the good – and the "willingness to accept" (WTA) – how much sellers would ask at minimum to supply that additional unit ((Farber et al., 2002)). The market price must be agreed upon both by sellers and buyers. If the seller accepts to sell at price p, it can supply the good at a cost lower than p. If the buyer accepts to buy at price p, it means that the additional value it attributes to the good is at least p or higher.

The fact that market transactions take place proves that both sellers and buyers are happy to make a deal at that price. It is noteworthy that p measures, at best, the *value of the last unit* – not that of all units. When a market price is established, all units, not only the last one, are traded at that price. Therefore, all those purchasing the other units with a higher WTP obtain a "surplus" – the difference between the maximum they are willing to pay and what they pay.

This is what the economic value is about – a concept that seemingly uses the term "value" with a sharply different meaning from that adopted by ethics.

3.3. Chicken and eggs: The value of time

A third cornerstone of economic valuation concerns the importance of time (Doganova, 2024). Despite so many religions sharing prohibitions and prescriptions about the interest rate, it is also one of the most natural and human attitudes to prefer "an egg today to a chicken tomorrow", implicitly accepting that a given quantity of goods has a higher value now than in the future (Broome, 1994).

There are both subjective and objective reasons for this: human psychology, risk aversion, uncertainty, and expectation to grow wealthier in the future. They deserve to be investigated in some detail (Prest, 2022).

First, people tend to be impatient, preferring their immediate well-being to future well-being. For example, the individual may be unable to take advantage of future availability (e.g., because he is not alive or in good health). Exogenous circumstances may impede obtaining the good, or the good may have lost some of its current attractiveness. The opportunity to enjoy something may depend on a combination of events that may not repeat.

In the second place, people may reasonably expect to grow wealthier because income and wealth have been increasing on average. Suppose individuals expect to be wealthier in the future. In that case, having an extra € today (when they are relatively poorer) is more valuable than having a € in the future (when they are relatively more prosperous and hence consuming more).

For the same reason, when considering possible damage, its occurrence today is evaluated higher than in the future because, in the future, we could be more able to handle the problem (e.g., thanks to superior technology).

Money at hand today can be saved or invested to earn a positive return, such as purchasing stocks or bonds or starting a new business. Therefore, the value of a € available today is greater than that of the same € received in the future because of the additional returns it could yield in the interim. These returns also depend on the investor's ability and differ from person to person, depending on what each could do with that €.

Finally, individuals are risk-averse, i.e., they prefer a given amount of money with certainty rather than making a bet with the same expected value. Since the future is more uncertain than the present, future values must be discounted to make them comparable.

The market interest rate provides a convenient proxy of the "value of time" since it results from many transactions where someone borrows and others lend financial resources. Since the transaction takes place voluntarily, both are satisfied by the deal.

In financial markets, interest rates are higher if the time is longer or the associated risk is higher. A convenient way to express this is to divide the interest rate into two sections: a "pure intertemporal time preference", which is subjective, and the risk premium, which depends on the nature of the investment. Therefore, from a private perspective, using the market rate to discount future values makes sense.

4. From private to social values

4.1. Society is not just a sum of individuals

Market prices have some undoubtful advantages: values can be expressed quantitatively, and therefore, a comparison is possible; market prices descend from the voluntary transactions among free-willing individuals and, therefore, effectively reveal individual preferences; last but not least, market prices are easily and readily observable.

However, the relevant perspective in our case is not the individual but that of society, which poses problems we must be aware of (Adler, 2019).

First, individuals often disagree about what is desirable. The same item adds something to an individual's utility and subtracts something else from another. We not only need to trade off values, but also among individuals. Even assuming that "the society" is nothing more than the individuals that are part of it, we still have the problem of comparing individuals' well-being to reach a consistent measure of collective preferences.

If group 1 is favourable and group 2 is not, it is not sufficient to count how many belong to each group; we should seek to know the "intensity" of each individual's preference. Whatever system we use to do such an aggregation is arbitrary and influenced by value judgments. MCDA is not immune from the same difficulties if it is any consolation. Why should "an expert" know better than individuals themselves what is good for them?

Second, we must consider that individuals fail to consider items unrelated to their well-being because they fall on third parties not concerned with the decision (externalities) or the collectivity as a whole (*common goods*). Moreover, people may be unaware of the consequences because of a lack of knowledge and poor information.

Third, monetary valuation ignores whether a low WTP highlights that something is undesirable or that people cannot afford it. If George's WTP for item A is 100, while Jane's WTP for avoiding it is 30, this could reveal that George is more interested in A than Jane, but also that George is more prosperous than Jane. In a market economy, it can be acceptable for the rich to access more goods than the poor, but should this also inform public decisions? Is the consequence on the poor's health less relevant than on the rich? On developing countries less than on developed ones?

Last but not least, some items are relevant from the individual's perspective, but not so for society. For example, a firm's labour cost is equal to the salary, including all taxes and contributions. In contrast, at the societal level, the same cost should be net of taxes and unemployment subsidies that are clearing entries.

Therefore, while market prices serve as valid proxies for private costs, as they reflect the concrete decisions made by individuals, they fail to represent social preferences and require at least some adaptation.

4.2. Markets are not perfect (but experts aren't, too)

A controversial postulate of economics, the "efficient market hypothesis" affirms that, on average, market prices are correct or at least tend to be so; no one else – central planners, professional investors, scientists, fortune-tellers – can systematically "beat" markets in the individuation of correct prices unless they can count on better sources of information. Despite much empirical proof, this assumption is problematic (Malkiel, 2003). The market outcome reflects, at best, what economic actors *perceive* are the costs and benefits based on the information they have at hand.

Of course, entrepreneurs may be wrong. If one is misguided by too optimistic expectations, it will invest to put an additional quantity on the market; this will cause an economic loss. If too many firms are at a loss, average expectations will reduce, and some will downsize or exit the market. Similarly, if they expect low prices, they will not invest and, therefore, miss the opportunity others will seize.

In the case of recycling, there are many reasons why expectations about relevant prices – recycled and virgin materials and disposal facilities – may be deceptive.

People may not adequately trust the quality of the material because they have little experience. Firms may not have adapted their production techniques to using recycled materials. Dealers may not sufficiently anticipate the future price increase of virgin materials and, therefore, be unwilling to pay now for recycled materials. People may have latent unmet needs and desires (e.g., recycled goods may become "fashionable"). Innovative entrepreneurs are those who understand in advance what others still don't know.

In general, however, secrets do not last for long: sooner or later, the market will "correct" operators' expectations and reveal the value of goods traded. In an ideal market, prices incorporate all available information and vary as soon as new information is available.

However, fundamental markets do not necessarily adjust smoothly. Speculative bubbles may over-inflate expectations of future price increases and attract investments to the wrong destinations; conversely, prices may not timely highlight the emerging scarcity, which will manifest only too late, when it will be difficult or impossible to provide. Alternative technologies may require time for adaptation and learning-by-doing. For example, building a WtE facility may require some years (project, authorisation, construction and start-up); people need time to get familiar with separate collection systems, change daily habits, etc.

The case of landfills in Italy provides an excellent example: gate fees have been kept low by public regulation; so, when scarcity of available land finally impeded the opening of new sites, there was not enough time to prepare for the transition. As a result, the gate-fee rocketed to 10 times higher in a few months (Massarutto, 2019).

Market imperfections must also be taken into account. Technological transitions require the coordinated effort of many actors, while the old technology still dominates the market until the existing infrastructure remains in place; incumbents may use their market power to prevent the entry of newcomers. Path dependence may slow down the transition, even when economically convenient. The introduction of extended producer responsibility and the creation of collective organisations to fulfil it represented an efficient innovation, enabling it to overcome many coordination problems (Massarutto, 2014).

However, even if there are some excellent reasons to believe that the actual market prices are wrong, we still need something that allows us to make better predictions. Is the "right" price higher or lower? How much? On which ground can we say so? What gives us the certainty that the state or some panel of experts has a better vision?

Despite their alleged "myopia", markets have been right most of the time. History does not report a single example in which a scarce resource has been used up, and no substitutes have appeared in due time. We have some memories of ancient civilisations swept away by ecological catastrophes. However, nothing similar has occurred historically, at least since capitalism has become the dominant economic model.

In 1970, a group of leading experts from the Club of Rome released a famous book, predicting that most essential raw materials for the Western economy would soon be used up (Meadows et al., 1972). According to these catastrophic predictions, we should have made a gigantic effort to decouple our economy from exhaustible raw materials. And would probably have wasted a lot of money, since 50 years later no sign of those predictions has appeared.

However, we can expect that markets function less well under certain circumstances.

Far-reaching technological transitions are an example since they require effective coordination. Economists refer to these as "transaction costs", which arise from coordination problems. An intense division of labour characterises a market, and very often, the success of one's initiative depends on the initiatives adopted by others.

Continuing with our example, developing recycling markets requires that consumers engage in separate collection, WM companies displace adequate equipment and services, recyclers invest in treatment facilities, potential users adapt their productive cycles, etc. Like an orchestra, all players must play the same music on time.

Uncertainty about what others will do acts as a mighty disincentive; as a result, many will not act, and this will undermine the efforts of others. Consequently, the cost that private firms perceive will be higher since it also incorporates uncertainty.

Last but not least, the fact that prices reflect marginal cost depends on the degree of competition that is taking place. The more competitors there are, the less likely firms will charge a higher price than the cost: if they try to do so, others can sell at a lower price and replace them.

Market concentration, in turn, allows firms to increase the price above the cost and obtain higher profits. This is why economists attribute so much importance to competition and affirm that monopolistic industries should be regulated. A relevant case for WM concerns the markets of "critical raw materials" monopolised by a few companies, expressed mainly by governments of a few countries. This feature allows suppliers to manoeuvre the market price to discourage searching for alternative supplies, such as "urban mining" and recycling (Favot & Massarutto, 2019).

4.3. The social rate of time preference

Nothing exemplifies these concerns better than the choice of social discount rate (SDR). Assuming that it is natural for humans to "prefer an egg today", as discussed in par. 3.3, should the society share the same preference?

Let's consider the social cost of carbon (SCC) while evaluating GHG emissions. Ideally, this cost can be calculated based on the expected damages associated with climatic events depending on temperature increase. Assuming that global warming is a function of atmospheric GHG concentration, we can associate the monetary cost of damages with GHG emissions. Yet, since these events are taking place in the future, we must convert them into present values. The SCC varies significantly depending on the SDR used, which may dramatically impact the conclusions.

The now-famous Stern vs. Nordhaus controversy exemplifies this issue perfectly (Nordhaus, 2007; Stern, 2006). To answer whether immediate aggressive action against climate change is justified, Stern applied a near-zero SDR (0,1%). In comparison, Nordhaus applied a 3 %, slowly declining towards 1 % in 300 years. The resulting SCC was, respectively, 7.40 USD/t, increasing 2–3 % every year, and 85 USD/t,

growing much faster, and this led both studies to reach fully diverging results.

With a market interest rate, the present value of events beyond a few decades is dramatically reduced; markets may be unfit to deal with potentially catastrophic events in the far future. There is an increasing consensus on the need to apply a discount rate significantly lower than the market rate when issues such as climate change are considered (Howard & Sylvan, 2015; van der Ploeg, 2020).

The first reason concerns uncertainty. Individuals are often myopic and not provident enough, but this does not mean society should be equally short-minded. Ultimately, we accept it as a normal thing that the state obliges everyone to save for the elderly age by investing in social security systems instead of leaving us free to decide whether and how much. Such a paternalistic attitude justifies, in the same way, that as a community, we adopt a more forward-looking approach.

Second, if risk-aversion is one of the reasons why individuals discount the future, this should not be true for society since risk-pooling allows one to handle risks more efficiently. This is especially true when we consider items such as human life. For a single individual, the possibility of dying or having serious health damage is a catastrophic occurrence, while for society as a whole, it is a statistical concept (expected lifetime, quality- or disability-adjusted, etc.).

A third reason descends from the fact that individuals necessarily have a finite horizon – everyone must die someday- while the same is hopefully not valid for humanity. We should, therefore, consider the perspective of a hypothetical immortal and always-healthy person representing all present and future generations, possibly taking into account also the expected increase in length and quality of the average lifetime.

Intergenerational solidarity implies that the well-being of future generations has the same weight in the decisions made today as that of the present generation. Whether future generations will be more or less wealthy than the present depends on the economic growth rate (proxied by GDP growth): following this line, it seems reasonable to set the social rate of time preference equal to the expected growth rate.

However, since this is highly uncertain data, the expected rate would be much closer to the lower end. To illustrate this point, let's assume that the future growth rate can be 0.1 % or 10 % with equal probability. A risk-neutral assumption would be the one that generates the average expected value, which depends on the time horizon. For example, if it is 100–500-1000 years, the expected growth rate to apply would be 0.8 % – 0.24 % – 0.17 %, respectively.

On the other hand, in favour of a positive discount rate, we should also account for the fact that each action undergone today has an "opportunity cost" represented by the alternative things that could be done with the same economic resources; this is particularly true when the effects analysed are intra-generational.

For this reason, the recommended values of the SDR exhibit a declining value over time.

In the US, the EPA suggest, for intra-generational effects, a rate of 2–3 % with a sensitivity test over the range of 2–3 %, while for intergenerational effects, a 0 % rate with a sensitivity test over the range of 0.5–3 %; while the UK government recommends a 3.5 % for impacts within 15 years, slowly declining to 1 % until 300 years (Florio & Sirtori, 2013).

As these examples show, while the market rate is easily observable in financial markets, the social discount rate rests on highly debatable assumptions and is ultimately an analyst's discretion. This may puzzle all those who, like President Truman, would like to have a clear-cut indication (yes or no) from experts and are tempted to dismiss economic valuation as a fundamentally arbitrary and useless methodology.

Yet, from another viewpoint, this seeming inconclusiveness could be regarded as merit: by varying the discount rate, we may find out where the turning point lies – the so-called "internal rate of return", that is, the value of the discount rate that makes the result change its sign. This exercise is helpful precisely because it illustrates which assumptions must be made to obtain a particular result.

4.4. Pricing the priceless

A further reason why market prices may misguide decisions descends from the fact that many valuable items have no market price because they are not traded on markets.

This happens fundamentally for three reasons. In the first place, because they belong to the category of public goods, namely goods that are enjoyed collectively and not individually; such goods are typically supplied by collective entities (primarily, although not uniquely, by the state) that recover the cost through different means, other than prices. This is because these goods are non-excludible (it is not possible to impede someone from accessing the good once it exists) and because it would be economically inefficient (an additional beneficiary does not imply an additional cost).

Second, the state decides that some goods must be provided for a free or subsidised price, essentially for political reasons. This is the case of goods that concern individual rights (e.g., those concerning health, education, and access to basic essential commodities) or pursue the national interest (e.g., security of energy supply, infrastructure).

Third, some items remain "external" to the market because the interested stakeholders are not involved in the transaction. This is typically the case of environmental impacts of production and consumption, which damage a "common good", causing negative implications for other people, future generations or non-humans.

All of these items are irrelevant from the individual viewpoint since the individual only computes costs and benefits that affect him directly; in turn, they must be considered from a social perspective.

It is important to stress that these items, although not having a market price, are nonetheless still *economic* goods, in the sense given above, i.e., rival goods that are commensurable with other goods based on the well-being they provide. Therefore, expressing their value in monetary terms allows us to consider them in the evaluation with the same rank as any other good. This is not an attempt to transform them into commodities. On the contrary, it is a way to "borrow" from markets the same approach that allows the market price to emerge on the assumption that it is conceptually similar.

The economic discipline has developed several ingenious techniques to quantify this value in monetary terms, which are now becoming standard (National Ecosystem Services Partnership, 2016; NCAVES and MAIA, 2022; OECD, 2018). These can be divided into two categories: indirect and direct methods.

Indirect methods rely on the market value of goods related to the priceless item. For example, we can refer to the market price of the best available substitutes providing similar functions. To estimate the economic value of recycled material, we can consider the market price of the equivalent virgin material, less the costs needed to collect and process waste streams and adapt production technologies to use the waste-derived input. To calculate the economic cost of damage to an ecosystem, we can consider the economic cost of restoring its pristine situation. Groundwater contamination can be proxied by the cost of removing pollutants from drinking water or replacing drinking water catchments. Damage to health can be proxied by the cost of health care and the GDP loss associated with sick leave. These methods have been extensively applied to the waste sector, for example, with concern to air emissions of incinerators in combination with impact-pathway models that translate emissions into the ambient concentration of pollutants, and these into pathologies based on epidemiologic studies (Eshet et al., 2006; Massarutto, 2015).

Other indirect methods use *revealed preferences*, i.e., deduce the value of non-market goods from the market value of goods that are influenced by the concerned one. For example, the "hedonic price" model assumes that the value of certain economic goods (e.g., real estate) is negatively influenced by the presence of environmental nuisances (e.g., smell, noise, traffic congestion) and positively by amenities (e.g., landscape,

access to infrastructure; recreational facilities). In the waste management literature, these techniques have been applied mainly to assess the external cost associated with disamenities caused by the proximity to treatment facilities (Eshet et al., 2005).

The economic value of some items can be at least partially deducted from the expenses that people sustain to access them, such as travel costs, purchase of equipment and similar. In other cases, a reference point could be how much people spend to protect themselves from adverse events associated with externalities or mitigate their impact (buying insurance, sound-absorbing panels, rainwater harvesting, drugs).

These techniques do not calculate intangibles' total value but aim at identifying lower or upper thresholds. They are relatively easy and cheap to apply, but their range of application is limited, and the outcome is somewhat imprecise. Nonetheless, they can provide helpful information about the range of magnitude of the results.

Direct techniques are based, instead, on surveys designed to investigate citizen preferences (Haab et al., 2020; Hanley & Czajkowski, 2019; Hoyos, 2010). This is done by staging a roleplay in which interviewees are asked about their willingness to give up some alternative goods or benefits (or ultimately money) in exchange for some combination of intangible attributes (e.g., the reduction of pollution and its negative consequences on health).

These methods have been extensively used in the waste sector. Among other research questions, for investigating households' preferences concerning waste collection and sorting (Chen, 2019; Jin et al., 2006; Massarutto et al., 2019; Sakata, 2007; Tarfasa, 2009; Zhang, 2023); attitudes concerning waste prevention, e.g., concerning food waste (Borrello et al., 2017; Dsouza et al., 2023; Walter et al., 2023)use of refillable containers to replace disposable packaging (Herbes et al., 2018; Magnier & Gil-Pérez, 2023; Patreau et al., 2023; Schuermann & Woo, 2022) or buying recycled products (Michaud et al., 2017; Polyportis et al., 2022; Ruokamo et al., 2022); preferences concerning waste handling techniques (Lim et al., 2014; Othman & Chuen Khee, 2014; Pek & Jamal, 2011);

Finally, it is possible to take advantage of structured methods of expert valuation. Engineering cost models estimate values based on the desktop project of hypothetical facilities and processes and simulate its cost through a metric computation of required inputs. Impact-pathway methods combine engineering, climatic and epidemiologic models to estimate the percentual increase of pathologies due to emissions with an economic valuation adapted to each impact depending on the impacted endpoint (Friedrich & Bickel, 2001). Benefit-transfer studies, possibly based on a *meta*-analysis of the previous literature, use the results of similar studies conducted in comparable settings (Johnston & Rosenberger, 2010). Delphi surveys and interdisciplinary focus groups allow us to reach consensual estimates of the range of environmental costs.

Monetary values obtained from applying economic valuation techniques can be used to account for benefits and costs not represented in market prices.

Table 1 provides a synthetic view of the most commonly used valuation techniques and exemplifies possible applications in the field of WM. As the table shows, monetary valuation techniques can address a broad spectrum of "intangibles". Among these, there are not only the

Table 1
Techniques of monetary evaluation and their applicability to WM.

	Rationale	Method	Advantages	Drawbacks	Applicability to Wm
1.1	Fundamental markets do not lie since prices reflect the value that individuals attribute to each item.	Market prices	Simple and easy to understand Market data easy to find	Readily available for marketed items only May be distorted by market power Fail to include externalities	Financial cost of waste processing phases Material price of materials and energy
1.2		Production function	Good proxy of market prices if not available	Requires ad-hoc assumptions about alternative solutions High data requirement	Compare recycled w/ virgin materials
1.3		Restoration cost	Appropriate to evaluate critical ES	May severely overestimate the value of non-critical ES It does not measure the value of the ES	Restoration of contaminated land External costs of mining
2.1	Even if a proper market does not exist, we can observe how people behave in other markets as a consequence of the concerned situation.	Hedonic Price Method	Based on actual market data (even indirectly linked with the relevant one) Relatively inexpensive if data is available	Data requirement Applicable only to limited cases Capture only a part of TEV	Disamenity cost of disposal facilities Availability of WM services
2.2		Averting behaviour	Relatively inexpensive if data are available	Value of ES influenced by proximity to settlements	Light damages to health Smell (e.g., proximity to disposal sites)
2.3		Travel Cost Method	Relatively simple and cheap	Only applicable to a few items	Value of amenities impacted by WM
3.1	Even if a proper market does not exist, we may directly ask people about their preferences.	Contingent valuation	Very flexible and cheap If correctly designed, enables to obtain coherent and comparable results	Hypothetical situation <=> biased answers "Protest zero" Easy to manipulate Respondents not qualified or informed Reflects volatile crowd's sentiments	Participation in separate collection Cost borne by households Willingness to buy recycled products WTP for improvements of WM service Demand for recycled products
3.2		Choice experiment			
4.1	If you do not know, ask someone who is supposed to know	Benefit transfer	Most inexpensive	Reliability of original studies Comparability of situations	Local emissions impacting air quality
4.2		Meta-analysis	With respect to 4.1 reduces arbitrariness	Results influenced by "cherry-picking"	Emissions impacting climate change
4.3		Engineering cost	Relatively inexpensive Also applicable to restoration cost	Requires ad-hoc assumptions Theoretical cost is not always coherent with market data	Financial cost of waste processing phases
4.4		Expert-based	Relatively inexpensive	Highly hypothetical and possibly biased	

typical ones on which LCA is focused (climate change, human toxicity, resource use, etc.) but also aspects that concern human well-being, such as the impact on the landscape or urban tidiness, the value associated with WM service quality (e.g., frequency, convenience, availability) or activities that service users must perform by themselves (e.g., washing, storing, using refillable containers for shopping). The latter dimensions are more frequently investigated via direct methods, such as choice experiments and contingent valuation studies (Birol et al., 2008; Massarutto et al., 2022; Sakata, 2007).

For example, the European guidelines for cost-benefit analysis in the case of WM projects recommend using market prices of materials and land to assess resource use and landfill; hedonic price methods for disamenities and shadow prices derived from established standards for GHG and human toxicity (European Commission, 2015).

In the case of LCA, these methods are particularly suitable for monetary assessments of polluting emissions. Several authors have published review studies that compare published studies, their results and methodologies (Amadei et al., 2021; Arendt et al., 2020; Pizzol et al., 2015). Other authors have published review articles of studies that more specifically addressed the emissions of waste management techniques (Eshet et al., 2005; Massarutto, 2015; Morris, 2017). These reviews show that there are still remarkable distances among the results obtained; reported differences depend on the geographical location of the study (remarkably, when concerning developed or developing countries), but more often, methodological features.

Nonetheless, some convergence can also be noticed, especially for the impact categories that are more frequently investigated, such as GHG or PM (Table 2). Fig. 2 illustrates the values of GHG emissions recommended by the EU and the World Bank for the appraisal of investment projects.

4.5. The "optimal recycling rate" from a private and a social perspective

To reconcile private and social costs and benefits, public authorities may introduce many policy measures, such as regulations, taxes, subsidies, liability principles (e.g., the extended producer responsibility), and soft measures (e.g., labelling, green procurement). Or they can introduce mandatory targets (e.g., recycling, reuse, content of recycled materials).

The European Union has widely used these instruments, particularly mandatory quantitative targets, that shape the recent updates of the Waste Framework Directive. At present, it foresees, for example, a 65 % target for municipal waste recycling (with higher targets for specific priority flows like packaging) and a maximum of 10 % for landfilling. How can we take advantage of economic valuation to assist the decision concerning these and other similar policy targets?

Fig. 3 illustrates how our discussion can be applied to determine the target regarding the recycling rate.

Let's consider it first from the perspective of a private company having to decide whether to invest in this industry in a market with no public intervention (suffix "unreg").

The benefit of recycling depends on the price of recycled materials, a function of the market price of virgin materials that can be replaced. The closer substitutes virgin and recycled materials are, the closer their price will be. We may add other benefits a private firm can monetise, such as saved waste disposal costs or reputation. Additional benefits arguably decline with the rate of recycling.

The cost includes economic inputs required to selectively collect materials, sort them, and prepare them for recycling, including transport costs. It is reasonable to assume that this cost is increasing with the recycling rate, given that the quality and purity of waste streams are declining (Massarutto et al., 2011).

Supposing that actual market prices do not adequately reflect the true economic value, the private marginal cost (PMC) and benefit (PMB) should shift from the initial position (suffix "unreg") to the new one (suffix "regmkt") as a result of taking into account market imperfections. As a result, the optimal rate shifts to point B. When considering all the external benefits of recycling and the external costs of non-recycling, the economic optimal level may shift to the right (point C), and the optimal level becomes R*.

Market operators will still be guided by the prices they observe and their expectations about future prices. Private initiatives will be coherent with the social optimum (R*) if market prices are adjusted coherently with the social marginal cost (SMC) and benefit (SMB).

However, assuming that all relevant economic costs have been adequately accounted for, it would be economically justified to reach R* but not to go further. To justify higher recycling targets (e.g., Re), we must invoke a superior non-economic principle. It could be because we

Table 2
Monetized values for indicators.

Impact category	Global impacts			Local impacts						
Indicator	Climate Change	Ozone Depletion	Acidification	Human Toxicity			PM-10	PM-2,5	Ionizing Radiation	Photochemical Ozone Formation
metric	€/kg CO2eq	€/kg CFC-11 eq	€/kgSO2 eq	€/kg 1–4 DB eq	€/kg C2H2Cl eq	€/CTUh	€/kgPM_{10}	€/kg$PM_{2,5}$	€/kBq U235 eq	€/kg NMVOC eq
n. of studies examined	16	11	13	5	2	2	6	2	6	14
Average	21,19	14,53	12,00	15,80	9,28	1.204,37	204,88	17,26	83,59	27,54
Min	2,83	8,50	1,87	2,83	8,73	1.044,83	4,40	9,79	1,01	1,18
Max	63,03	55,86	43,18	31,85	9,84	1.363,92	1.184,34	24,74	397,75	270,26
Std deviation	22,53	19,40	15,45	11,48	3,18	532,73	488,61	8,46	162,49	111,25

Impact category	Eutrophication			Water		Resource and land use				
Indicator	Terrestrial	Freshwater	Marine	Ecotoxicity	Use	Fossil		Mineral		Land use
metric	€/m^2 UES	€/kg P eq	€/kg N eq	€/kg 1–4 DB eq	€/m^2	€/kg oil eq	€/MJ	€/kg Fe eq	€/kg Sb eq	€/m^2 arable
n. of studies examined	1	14	6	4	3	7	4	8	4	3
Average	12,86	5,09	3,84	18,49	29,94	63,11	46,96	35,30	28,34	29,94
Min	12,86	1,88	1,94	3,40	4,38	10,12	10,12	1,65	1,65	4,38
Max	12,86	20,82	8,25	28,15	65,84	138,19	138,19	104,83	104,83	65,84
Std deviation	5,13	7,46	2,36	10,39	25,49	53,16	53,60	40,91	41,81	25,49

Source: our elaboration on (Amadei et al., 2021).

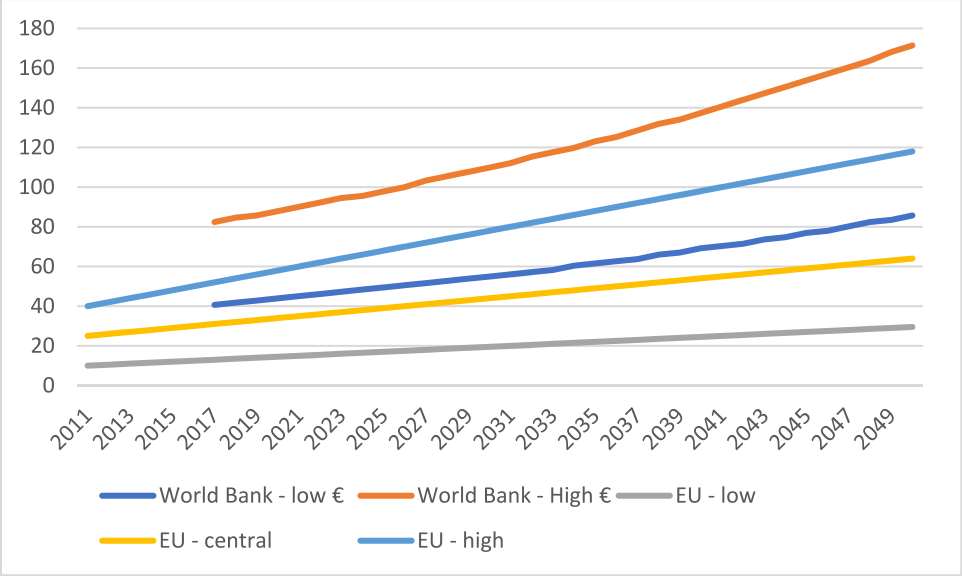

Fig. 2. Reference values for GHG emissions: European Investment Bank and World Bank (€/t CO_2-eq) Source: our elaboration on (European Commission, 2015; World Bank, 2017).

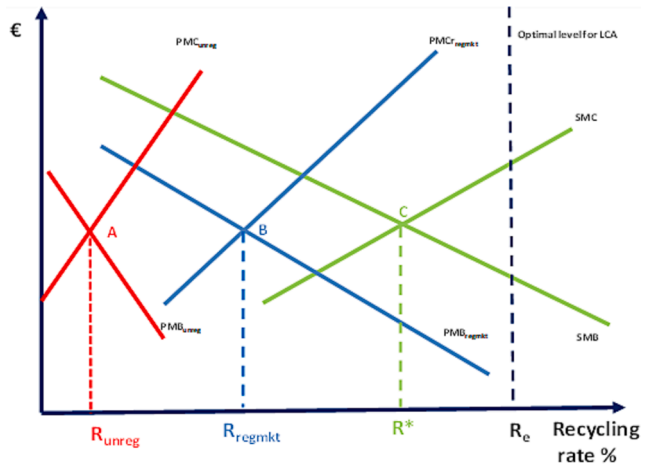

Fig. 3. The optimal rate of recycling from a private and a social perspective.

affirm that waste is a sin, or because we consider a specific material strategic for national security, or because we adopt a strictly ecocentric approach. Anyway, such a "superior reason" must be spelt out and cannot be affirmed as a self-evident argument.

Where are R_{unreg}, R_{regmkt} and R* located? Has their location changed over time?

There is a surprisingly small number of applied economic studies. In a comparative analysis of Japan and the US, Kinnaman estimates that the optimal rate not considering externalities would be around 10 % and 36 % when external costs are included (Kinnaman, 2014). In an Italian context, Massarutto et al. estimate an optimal rate of 50–65 % depending on the urban structure (Massarutto et al., 2011). A rigid interpretation of the EU waste hierarchy – i.e., saying that recycling is always preferable to landfilling – does not pass a cost-benefit test (Ackerman, 2005; Pearce, 2005).

It appears, however, that the optimal rate depends on several local circumstances that affect the cost of separate collection sorting and transport costs, among others, and therefore cannot be generalised (Porter, 2005). On the other hand, the optimal rate seems positively correlated with economic development, suggesting that it represents a necessary condition to augment social welfare in a growing economy (Bongers & Casas, 2022).

5. Economist you go, estimate you find

5.1. Technical limits of monetisation

The discussion in par. 4.5 assumes that monetisation has been able to capture all the relevant values. If so, targets higher than R* can only be justified by extra-economic motivations.

If this is not the case – because of conceptual or computational limits of monetary valuation – higher rates may be justified simply because some further values are not reflected in the monetary values that have been calculated.

Indeed, monetary valuation has both "technical" and "theoretical" shortcomings that must be considered.

Among the former, we must honestly acknowledge that there is still a massive gap between what monetisation can deliver in the abstract and what it has delivered so far.

Computational difficulties arising from the availability of data are still significant. As we have seen in par. 4.4, for many impact categories, there is still a considerable distance between the results of different studies focusing on the same topics depending on several factors. If something is clear, the results obtained from economic valuation are susceptible to the contingent contextual features where the study has been conducted, methodological choices, and assumptions made (think, in particular, of the social discount rate).

For this reason, economic valuation is often blamed for inconclusiveness. The same analysis by different researchers with slightly different assumptions may lead to opposite results.

One may observe, in response, that MCDA is not much more consistent. At least in principle, an advantage of monetisation, if conducted correctly, is that valuation methods are standardised, and assumptions are made explicit; the robustness of results can be checked more efficiently, and this reduces the risk of arbitrariness at least. Monetary valuation identifies a bottom line below which the optimal rate will not be found and allows for a more apparent highlight of which values have been investigated and are reflected in the monetary prices used and which are not.

Moreover, the fact that (some) results depend on contextual features is nothing bad: it sounds like a warning against arbitrary extrapolations based on very specific settings. Such generalisations are hazardous in the

case of LCA since they can be incorporated into software tools in a way that leaves the analyst unaware.

Therefore, only items for which a sufficiently agreed-upon range of values is consolidated should be incorporated into parametric functions. In other cases, LCA models should at least foresee a menu of alternative settings (e.g., high- and low-density areas) and coherently choose valuation parameters. Sensitivity analysis must be recommended in all cases.

Moreover, most of the time, monetary valuation does not measure *values* but, more likely, *lower-bound thresholds* below which the actual value will not fall. This happens because goods entail many different value dimensions at the same time.

People may attribute a value to the direct use depending on the direct usefulness of the good – i.e., considering a blue whale, this is the market value of the products that could be obtained from it. But they may also attribute value to indirect use – e.g., watching documentaries about blue whales on TV. Furthermore, people may feel happier regardless of using the good. Still, simply because it exists (*existence value*) or will be transmitted to the next generations (*bequest value*), or altruism makes them feel better (*warm-glow*). All of these components are still *economic* – i.e., concern the additional well-being of individuals. In principle, we can apply a monetary valuation technique to virtually all of them, but in practice, only some are addressed by any specific study. Depending on the methodology used and the research design, some components of the economic value may be left out; it is essential, before interpreting the results and eventually transferring them to other contexts, to understand precisely which value components have been investigated (and are reflected in the monetary estimate) and which have not.

This is an essential aspect to acknowledge, mainly because in real-world applications, it is very common, and to some extent unavoidable, that monetary values are not estimated ad-hoc but derive from previous studies and ready-for-use datasets, even provided by public authorities (as in the case of the reference values recommended by official guidelines for GHG emissions), or are incorporated in software tools, in such a way that final users cannot track adequately the methodologies used in the original studies and be aware of what is considered and what is not.

These weaknesses alone mean that monetary valuation provides a sufficient but not necessary justification: we can be sure that rates lower than R* are inefficient, but not of the contrary. If a higher rate does not pass the cost-benefit test, the conclusion should not be automatically dismissive; nonetheless, it obliges us to focus on the aspects the analysis has been unable to evaluate. This is useful since it allows us to circumscribe the arbitrariness of the decision, particularly in the case of LCA. During a well-conducted LCA, a systematic inventory of impact categories is made; it is pretty straightforward, at this stage, to verify for which of the concerned categories a reliable monetary valuation is available.

Recently developed LCA tools, such as Stepwise, allow flexible solutions, deciding which parameters to monetise and at what stage (midpoint or endpoint) to do so (Pizzol et al., 2015).

5.2. The reductionism of (mainstream) economics

Theoretical shortcomings are also worth considering.

Mainstream economics is firmly rooted in individualism: individuals are the sole judges of what improves their well-being, and there is no superior entity or norm from which we should derive universally valid value judgments. This is an advantage since valuation is more objective, but also a shortcoming, as far as more fundamental values (freedom, social justice, fairness, open-heartedness, environmental sustainability) are left out. Non-Western cultures may refuse individualism and adopt organicist, collectivist or communitarian normative models. Ecocentric approaches may elevate the rights of "nature" to the status of unchallengeable principles.

Of course, even if we refuse the utilitarian approach, we still have to make comparisons when making choices. Economic valuation rests on the assumption that "goodness" is a function of individual well-being. Physical properties – expressed in m^3, tons – are irrelevant to the decision unless they affect someone's well-being. Resource efficiency and GHG reduction are neutral and valueless until we find a way to correlate them with well-being.

It seems easy to dismiss this conceptual framework showing that such a character – a rational individual always making the best use of the available information – does not exist in reality. Flesh-and-blood humans are irrational, lazy, incoherent, greedy, influenceable, and dominated by passions. Their time horizon is short. Their principles are vague, fuzzy, and not necessarily "good" on ethical grounds. They are often wrong and make mistakes. Some humans are intelligent, but others are stupid, illiterate, and illogical. They change their mind spontaneously or because they are persuaded to do so. Preferences are not carved in the DNA but result from a social learning process and can be easily manipulated.

So, what do this beast's feelings and desires have to do with "goodness"? Can we fund moral judgments on this basis?

Even though this criticism may hit the mark, it leaves our problem unsolved: any alternative criterion implies the assumption of an exogenous source of superior values from which the correct decision should be deducted and poses the issue of how the authority of these values may be established. Ultimately, moral values or any other source of values should be founded on the agreement of individuals, at least if we believe in democracy – they aren't less "anthropocentric" than pure individualistic ones.

With a further reductionist step, economics affirms that well-being can be proxied by utility, which is a (positive) function of available goods. Again, one may complain that not all human aspirations can be satisfied by consuming goods.

This is why an influential guidelines document provided jointly by UNEP and the Society of Environmental Toxicology and Chemistry (SETAC) recommends considering monetary values only to represent "instrumental" values, while "intrinsic" values – that are given for the sake of existence itself – are outside their reach (Verones et al., 2017).

To overcome this criticism, we can observe that the economic concept of utility is, in fact, less narrow than its literal meaning and can encompass values such as emotional satisfaction, consideration of peers, reputation, love, altruism, and even the accomplishment of moral duties (Frey, 2018; Sen, 1970). It is not even so fundamental to remain faithful to orthodox individualism: we may accept that some values are exogenous and admit the existence of "merit goods", whose desirability descends from political will, constitutional values or superior ethical norms (Musgrave, 1987).

As a sort of *deus-ex-machina*, the merit good concept enables us to reconcile the utilitarian framework with values that appear alien to economic trade-offs. The "price" of merit goods is not emerging on the market but instead descends from the authority of those who legitimately interpret the people's wants. Following this line, we can conclude that many "inherent" values are, in fact, economic – at least conceptually, in the sense that they still have an anthropogenic origin and admit a trade-off. In the end, dinosaurs went extinct, and no one suffers from the disappearance of this "intrinsic value".

Critics of utilitarianism deem such extensions as a tautology: any behaviour can be ex-post justified in this way. They affirm, instead, that these and similar dimensions are untradable and must be affirmed as exogenous principles (McCauley, 2006).

For our discussion, these positions are not so distant: affirming that something is priceless (i.e., has an infinite value) or that it does have a price, but higher than the economic sacrifice because of a political will, ultimately yield the same results.

Therefore, economists and other scientists can peacefully agree that some values are impossible to capture – in practice at least – with a monetary approach. The relevant question becomes more practical: when is it legitimate to invoke similar arguments? To what extent are

superior values concerned when we discuss very practical issues, such as recycling a piece of paper or burning it to recover energy? How relevant are these values when we discuss municipal solid waste management? Which "inherent value" should we invoke to justify – let's say – a 40 % reuse target on beverage containers, where no evidence is provided of economic benefits, not even after accounting for GHG emissions and other social costs and benefits?

5.3. From mainstream to ecological economics: Weak vs strong sustainability

The relevant issue, therefore, is not whether values are "intrinsic" (related to existence) or "instrumental" (related to human utility) and, even less, whether their source is "anthropocentric" or derives from some other source. It concerns, instead, the admissibility of trade-offs, i.e., whether it is acceptable to give up something in exchange for something else.

Mainstream economics postulates that everything is replaceable. Any good can be produced with combinations of inputs (labour, capital, natural resources) that are mutually substitutable. Any good can be replaced by other goods and generate the same well-being. Therefore, nature is nothing special. The – relative – scarcity of natural resources can be compensated by man-made artefacts and leave humanity as well off as before. Following Colin Green's paradox, there will always be a large enough cup of coffee to repay us (and the world) for the extinction of the blue whale (Green, 1997).

A more recent branch of the economic discipline, ecological economics, however, admits the existence of ecological functions that cannot be replaced and, for this reason, are irreducible to the economic calculus (Common & Stagl, 2005). Although this declaratively implies the contribution of other disciplines, particularly environmental sciences, EE still tries to find a rational foundation for the distinction between tradable and non-tradable items (Shmelev, 2012).

First, the possibility of replacing naturally-based ecosystem services (natural capital, NC) with artificial capital (AC) ultimately depends on technology; we must believe in technological development's endless capability to find a solution. We have infinite proof of how many seemingly catastrophic unsolvable problems have been handled thanks to technological innovations – famine, COVID, acid rains and ozone depletion are just a few examples; nonetheless, we cannot be 100 % sure this will be the case forever.

Second, because we have limited knowledge of the multiple interrelations of ecological systems since economic values rely on human perceptions, unknown effects will be systematically neglected or undervalued and reveal their seriousness only when it is too late.

Third, an essential difference between NC and AC is that the latter is replicable as new productive capacity is established. NC is intrinsically finite, and its depletion is mostly irreversible. Unlike AC, NC is a "free gift" of nature that humans are obliged to use as such, having only limited possibility to interfere with how nature regenerates it (Ekins et al., 2003b).

For example, the natural water cycle depends on climatic and geological patterns, and humans cannot change them. Of course, this is only partially true: continuing with the example, man-made water systems have allowed humans to transform natural resources into usable ones: harvesting, transporting, treating, pumping, and ultimately desalinating sea water. Man-made capital can fill the gap between the erratic, fuzzy, and unpredictable natural supply and a reliable resource available when and where needed.

Despite this, it is still true that natural water resources are something that we cannot give up entirely. However, the boundary is mobile: new technologies can make substitution technically feasible or more affordable; social learning processes may change the perception of the ethical implications, and so on. Someday, it may be possible to interfere with climate and provoke rainfall upon request, and we will no longer be subject to nature's whims.

The key concept is that of "critical natural capital" (CNC), defined as the set of NC components that (i) cannot be replaced by man-made capital at the current state of knowledge in a given time horizon and (ii) whose loss would cause humanity an irremediable loss (Ekins et al., 2003b).

When a CNC is identified, a more prudential approach is legitimised. This entails setting "safe minimum standards", adopting a precautionary principle, and the inversion of proof burdens. For example, the depletion of a "critical" ecosystem should not be admitted. This has obvious implications on valuation: in similar cases, the choice of the SDR should be particularly prudent and future-oriented (which means close to zero), and the monetary value of CNC components should be infinite or very high since values are not fully comparable (Martinez-Alier et al., 1998).

The key question, therefore, becomes how can we identify CNC. This cannot be considered solely from the economic viewpoint but requires a dialogue with other disciplines; to make it possible, we must remove the most fundamentalist arguments from both sides and adopt a more flexible approach, seeing both "weak" and "strong" visions as a sort of continuum along which we can ideally position (Neumeyer, 2010). A definitive statement is, however, not possible but can be approximated with the use of multicriteria approaches (Chaplin-Kramer et al., 2022; Liu et al., 2020) or structured deliberative processes (Ekins et al., 2003a; Mavrommati et al., 2020; Pelenc & Ballet, 2015).

For example, De Groot et al. propose an operational methodology to identify CNC components based on the intersection of "importance" and "threats": the former depends on the human processes that rely on it, while the latter is measured as the distance from a boundary level regarded as safe (De Groot et al., 2003). Others affirm that ecosystems have a "carrying capacity" that should not be trespassed and must be identified by natural sciences (Richardson et al., 2023).

The impossibility of replacing CNC may descend from purely technological reasons but also from other dimensions, e.g., affordability, social and cultural acceptability, coherence with shared ethical values, and legal feasibility under the existing institutional rules (Chiesura & De Groot, 2003; Spash, 2011).

6. Conclusions

Can monetisation serve the purpose of integrating environmental, financial and social assessments (LCA, LCC and S-LCA)? In par. 2, we have observed that the LCA community is more favourable to using MCDA, whose weaknesses are, however, fundamental: arbitrariness, subjectivity, hidden trade-offs, complex algorithms often not replicable, and variability of results.

Does monetisation perform any better? One could contend that monetisation shares some of the same weaknesses, being equally inconclusive and complex. Economic studies often reach radically different and even opposite results just because a parameter has changed or a value dimension has been added.

Yet a closer look reveals that monetisation and MCDA have, if anything, complementary advantages and shortcomings (Beria et al., 2012).

Concerning its alleged inconclusiveness, President Truman was right in observing that economists never answer "yes" or "no" but rather "it depends". Frustrating as it may be, there is also good news: economic analysis can clarify what the outcome depends on and what are the crucial assumptions that make the answer pinned on one side or the other.

This turns into a merit since it reveals how deeply the answer depends on assumptions made, the specific settings where the investigation has been conducted, the micro-design of investigations, and the discount rate adopted. This is a welcome warning against the temptations of using predetermined valuation methods – a temptation analysts often fall into due to the lack of time and resources.

Even if its algorithms may seem as obscure as those applied by MCDA, they are at least based on a highly standardised methodology that ensures replicability. This allows us to test effectively how the

assumptions made are decisive for the result and whether different ones lead to different outcomes.

Monetary valuation is not a gimmick to privatise common goods or subject ethical values to the law of supply and demand. It allows us to reduce values to a standard metric and compare things of different natures. A standard metric is needed whenever we have to decide whether it is desirable to give up something in exchange for something else – even if "trading" takes place within our mind and not on the market. Apples and cars are different, and so are books, clothes and furniture, but all of them generate some well-being and can be traded off on this basis. The same principle can be applied, though with some caveats, to intangible items such as health, environmental quality, beauty and even to the most sacred values such as human life.

Economic valuation is often blamed for being stingy and low-minded, less sensitive to the "heart" and more to the "wallet". This criticism affirms that specific actions, like protecting the environment, are worth doing because they have an intrinsic value, regardless of the economic cost. Our answer is that trade-offs are unavoidable: like it or not, the "wallet" represents a powerful constraint that we must be aware of, and we must find a way to do the best we can with what we have in it.

On the other hand, other and not less fundamental reasons invoke caution and impede relying entirely on economic valuation as a decision-making tool are market imperfections, computational difficulties, misrepresentation of the ecological dimension, and failure to incorporate justice and equity. Moreover, monetisation requires a massive endowment of data that is not always readily available and is a very costly exercise. Both shortcomings can be reduced somewhat by using predisposed datasets and following recommended guidelines, which significantly impoverishes the valuation exercise.

This is particularly problematic when economic indicators are used as parameters and are incorporated into evaluation tools or officially recommended guidelines. A good rule is using a large dataset of studies and waiting until their result converges towards a reasonably acceptable range.

These difficulties should not be overemphasised, but they should suggest some caveats: the systematic use of sensitivity analysis techniques and prudence in generalising results should be recommended; assumptions made should be carefully displayed and made available to the public to facilitate the conduct of alternative studies.

This applies also to LCA indicators since monetary values must be incorporated into the valuation tool. A well-designed tool should, therefore, always foresee the possibility of customising them if the analyst disposes of better information for the specific case under examination and forces the default parameters for sensitivity analysis. Even better, tools should offer different sets of parameters, with recommended solutions depending on the specific background circumstances characterising each case.

Finally, even if economic valuation does not forget other more fundamental values, it remains based on an anthropocentric perspective, which is by definition refractory to any exogenous and possibly more fundamental source of values; however, invoking these more fundamental values is not always necessary or justified. The usefulness of economic valuation is precisely that of making trade-offs visible, clarifying the underlying assumptions behind each choice, and unmasking implicit value judgments. Economics obliges those who invoke non-tradeable values to make them explicit and reveal why they are persuaded this is needed.

Ecological economics represents a welcome additional insight since it provides a consistent framework for deciding when reliance on monetary values (weak sustainability) is acceptable and when it is more desirable and wiser to adopt a strong sustainability approach that also admits the existence of "non-economic" values. In this latter case, the money metric is still applicable; however, we need to acknowledge that values are not always comparable; even if this may be feasible in theory, we lack the information for doing this in practice. Precautionary principles and no-regret approaches should be applied to the ecosystem services we regard as "critical".

Economics can "help us make better choices" – as Colin Green has provocatively defined the aim of the economic discipline (Green, 2017). We argue that its most valuable contribution lies in making trade-offs more evident and forcing all those arguing about the need to refer to superior values to clarify what they mean. Sometimes, they are right: trade-offs are complex and cannot be reduced to a utilitarian calculus of benefits and costs. However, in many other cases, appealing to superior values is little more than rhetoric that masks debatable ideologies, arbitrary value judgments, or intellectual fashion. Economic thinking may effectively unveil hidden prejudices and apodictic conclusions that researchers may be unaware of.

CRediT authorship contribution statement

Antonio Massarutto: Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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