Bioeconomy Real Options and Sustainability – Measuring the Contribution of EU Bioeconomies to Sustainable Development

Maximilian Kardung, Wageningen University, Hollandseweg 1, 6706KN, Wageningen, the Netherlands, maximilian.kardung@wur.nl

Kutay Cingiz, Wageningen University, Hollandseweg 1, 6706KN, Wageningen, the Netherlands, kutay.cingiz@wur.nl

Justus Wesseler, Wageningen University, Hollandseweg 1, 6706KN, Wageningen, the Netherlands, +31317482621, justus.wesseler@wur.nl

Abstract

Measuring the sustainability of the bioeconomy is crucial to evaluating its continuous contribution to wellbeing. Previous studies that have addressed sustainability measurement vary in their emphasis on sustainability dimensions and countries' scores. Studies that have addressed the sustainability of the bioeconomy have focused on indicators that measure specific contributions to sustainability. We devise a framework directly linked to the 1987 Brundtland Report's definition of sustainable development. Our framework uses the concepts of intergenerational wellbeing and genuine investment, whereby sustainability is defined as non-declining intergenerational wellbeing over time. Sustainability-related investment projects include uncertainty and irreversibility, which we model explicitly in contrast to previous works. We calculate two related indicators—hurdle rate and maximum incremental social tolerable irreversible costs (MISTICs)—which have a forward-looking approach, investigating whether future investment projects in the bioeconomy are sustainable. We use these two indicators to empirically analyze the sustainability of European Union (EU) Member States' (MSs) bioeconomies and sectors. We found that the hurdle rate in the bioeconomy is lower for the bio-based part than for the non-bio-based part for most countries, indicating a high potential for further sustainable investments in the transition toward an EU bioeconomy. The majority of countries have overall negative MISTICs for their bioeconomy, implying that bioeconomy projects need to provide irreversible benefits. However, all the countries have bioeconomy sectors with positive MISTICs. Our findings are consistent with Ecological Footprint's report indicating ecological deficits for most EU MSs, as they have a greater footprint than biocapacity.

Keywords: EU, bioeconomy, irreversibility, uncertainty, sustainability

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1. Introduction

Assessing a country's societal wellbeing goes beyond standard economic indicators, such as gross domestic product (Stiglitz *et al.* 2010). The bioeconomy, which entails all economic sectors and systems linked to biological resources and their functions and principles, can contribute meaningfully to societal wellbeing (European Commission 2018). Measuring the sustainability of the bioeconomy is crucial to evaluating its continuous contribution to wellbeing.

The updated European Union (EU) Bioeconomy Strategy stresses that "[…] the need to achieve sustainability constitutes a strong incentive to modernize our industries and to reinforce Europe's position in a highly competitive global economy, thus ensuring the prosperity of its citizens" (European Commission 2018 p. 4). The overall objective is to ensure the "prosperity" of EU citizens, and measuring this objective is directly linked with sustainable development (European Commission 2018; OECD 2009; von Braun 2018). Sustainable development was defined in the 1987 Brundtland Report as "Development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs." A good understanding of measuring sustainable development is vital for deriving indicators for monitoring the bioeconomy to ensure that such indicators can be directly linked to sustainable development.

Many researchers have addressed sustainability measurement, which is a controversial topic because the ambiguity of the sustainability concept makes it difficult to have agreed-upon measures (Parris and Kates 2003; Salas-Zapata and Ortiz-Muñoz 2019). The literature includes several suggestions for measuring sustainability, such as the Ecological Footprint (EF) (Wackernagel and Rees 1996), the United Nation's (UN) Human Development Index (HDI) (Sagar and Najam 1998), Bhutan's Gross National Happiness Index (GNH) (Mukherji and Sengupta 2004). These sustainability indices emphasize different sustainability dimensions: the EF focuses on the environmental dimension, the HDI focuses on the economic and social dimension, and the GNH focuses on the environmental and social dimension (Strezov *et al.* 2017). The Organization for Economic Co-operation and Development

(OECD) has a wide range of work on measuring wellbeing with indicators beyond the gross domestic product (GDP). They assess progress toward the Sustainable Development Goals' targets (OECD 2019) and measure inclusive growth using a set of economic indicators (OECD 2018). Lastly, the OECD estimates wellbeing for 362 regions using indicators for nine dimensions, such as income, health status, and environmental quality (OECD 2014).

Previous sustainability measurement studies vary in their emphasis on sustainability dimensions and in the countries' scores. One striking aspect is that Western countries with high GDPs, which are conventionally considered model countries, do not always rank high. For example, regarding the Happy Planet Index, founded by the New Economics Foundation (2006), countries in Latin America and the Asia Pacific region lead the way with their high life expectancy, wellbeing, and ecological footprints. Another major study is the OECD's Measuring Wellbeing and Progress: Well-being Research, which also supports the idea that macro-statistical indices such as GDP fall short of measuring diverse experiences and living conditions. The study, measuring material conditions, quality of life, sustainability, and their relevant dimensions, and resources for future wellbeing, also aims to bridge the gap between existing metrics and policy interventions[1].

Much discussed is the World Bank's measure of genuine savings and Arrow, Dasgupta, and Mäler's (2003) approach to genuine wealth and investment. Both concepts serve as measures of sustainable economic development over time. The genuine savings rate is computed by subtracting resource depletion and environmental degradation from traditional net savings while adding investment in human capital (Hamilton and Clemens 1999; Hamilton and Naikal 2014). The concepts of inclusive wealth and genuine investment are similar: a society's inclusive wealth is determined by measuring the shadow value of the economy's stock of capital assets (including manufactured capital assets, natural capital assets, human capital, etc.). The object of interest is intergenerational wellbeing, the

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[1] https://www.oecd.org/statistics/better-life-initiative.htm

discounted flow of current and future generations' utilities. The main point is that wellbeing is not only the wellbeing of the current generation but also the potential welfare of the generations to follow. Genuine investment is then defined as a measure of changes in the economy's set of capital assets weighted at shadow prices. Accordingly, positive genuine investment is used as an indicator of sustainable development.

Arrow et al. (2012) presented a theoretical framework for analyzing the sustainability of economic development over time using the concepts of intergenerational wellbeing and genuine investment, among others. They define intergenerational wellbeing as the discounted flow of current and future generations' utilities, where utility is derived through consumption of the economy's stock of capital assets, including manufactured goods, services provided by nature, health services, and many more. Barbier (2013) extended Arrow et al. (2012)'s approach with ecosystem services as a special type of natural capital. The author regarded this extension as possible but challenging because many ecosystem goods and services are not traded on the market and have no or only unreliable valuation estimates. Furthermore, the depreciation of natural capital is frequently irreversible (Barbier 2013), which stresses the need to consider irreversibility in sustainability measurement.

Previous studies on the sustainability of the bioeconomy have focused on indicators that measure its contributions to sustainability. These indicators usually measure a specific aspect of sustainability and do not constitute a comprehensive measure. The EU Bioeconomy Monitoring System has several indicators mapped to the Sustainable Development Goals, but the level at which they are sustainable is unclear[2]. D'Adamo et al. (2020) presented a framework based on multi-criteria decision analysis that could provide a country's overall sustainability score for the bioeconomy once sufficient data were gathered. A great deal of previous research into sustainability has focused on the land dimension, especially land use change, and its impact on biodiversity greenhouse gas (Bringezu *et al.* 2021;

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[2] https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en

Liobikiene *et al.* 2020; O'Brien *et al.* 2017). The existing literature quantitatively assesses the sustainability of the bioeconomy in the past or develops a framework for its future assessment (Egenolf and Bringezu 2019; Jander *et al.* 2020).

Contrary to other studies measuring the bioeconomy's sustainability, we devise a framework that is directly linked to the 1987 Brundtland Report's definition of sustainable development. Our framework is based on Arrow et al. (2012)'s framework, which uses the concepts of intergenerational wellbeing and genuine investment. By including future generations' wellbeing, we directly assess the ability of future generations to meet their own needs. We advance their framework by explicitly including uncertainty and irreversibility. Irreversible is relevant because if we could reverse a decision at zero cost, and the changes implemented today do not turn out to be as desired in the future, we could reverse back, and no harm would have been done. However, this is rarely the case, and the costs of reversing an investment decision are often substantial. Additionally, uncertainty is even more critical if decisions include irreversible costs. We can calculate whether the benefits are larger than the costs if we know exactly what would happen. Uncertainty can be understood as a decision with more than one possible outcome, where no probabilities can be assigned to each outcome. The implications of the future growth of the bioeconomy for sustainability largely depend on irreversibility effects, which are driven by uncertainty about future benefits and costs, including technical change and their degree of irreversibility (Arrow *et al.* 2012; Dasgupta 2008; Wesseler 2009). Irreversibility is important for sustainable development because it ensures that the resources we use today will be available for future generations. When we make decisions that have irreversible consequences, we are essentially depleting resources that cannot be replenished.

This principle, including uncertainty and irreversibility, can be measured with an indicator called the maximum incremental social tolerable irreversible costs (MISTICs) (Wesseler *et al.* 2007; Wree *et al.* 2016). These irreversible costs can be tolerated by introducing new technology or other changes to the bioeconomy. The larger the value, the more sustainable an economy will be. We derive the indicator for several sectors and subsectors of the EU bioeconomy. Our indicators have a forward-looking approach, investigating whether future investment projects are sustainable. We not only assess past development and current state, but we also directly investigate where bioeconomy investment should take place. We apply our framework empirically to the bioeconomy sectors of the EU-28 countries, measuring the sustainability of the transition to a bioeconomy. We estimate reversible and irreversible costs and benefits using bioeconomy value added and greenhouse gas emissions. This estimation allows us to calculate the MISTICs that a sustainable transition to a bioeconomy would entail.

The paper is structured as follows: Section 2 provides a detailed description of our conceptual framework, and Section 3 outlines the computation of the discount rate. Section 4 presents the empirical application of the EU bioeconomy. Section 5 discusses the implications of our results and concludes the paper.

2. Conceptual Framework

Arrow et al. (2012) presented a theoretical framework for analyzing the sustainability of economic development over time, using the concepts of intergenerational wellbeing V(t) and genuine investment $\Delta V_t = dV/dt$ – among others. The authors defined intergenerational wellbeing as the discounted flow of current and future generations' utilities, where utility is derived through consumption of the economy's stock of capital assets, including manufactured goods, services provided by nature, health services, and many more. Arrow et al. (2012) then defined sustainability as non-declining intergenerational wellbeing over time $\Delta V_t \geqslant 0$, and genuine investment is defined as a measure of changes in wellbeing ΔVt, that is, as a measure of changes in the economy's set of capital assets weighted at shadow prices. The authors' definition of genuine investment implies that intergenerational wellbeing V(t) is augmented (or deteriorated) via investments solely if the genuine investment's shadow value is positive (or negative). Thus, positive genuine investment is an indicator of sustainable economic development.

Nonetheless, it is important to acknowledge that sustainability-related investment projects (as well as investment projects in general) are additionally, but not to the same degree, characterized by the following features: (1) the investment's expected future rewards are uncertain, as are its expected future losses; (2) the investment's immediate costs are partially or completely irreversible (i.e. sunk costs), as is the investment itself; and (3) the investment's timing is flexible, in that waiting for better future insight is generally possible (e.g. Arrow and Fisher 2013; Dixit and Pindyck 1994). As an illustration of uncertainty, sustainability-related investment projects mostly aim at long-term goals, such as the reduction of greenhouse gas emissions, enhanced production and resource use efficiency, and preservation of non-renewable capital assets. These types of projects are inherently uncertain. As an illustration of the irreversibility, the conversion of virgin forests for other uses inevitably entails the loss of biological diversity. Further, the expansion into arable land areas or coastal areas protecting mangrove forests to provide for a growing population causes irreversible and uncertain changes. Lastly, as an illustration of flexibility, the flexible timing of investment projects is generally possible, but a delay entails a cost of foregone benefits. For example, the introduction of a new biorefinery may be postponed due to low current production efficiency and uncertainty about future markets for bio-based products. Technical changes may increase production efficiency, and the markets for bio-based products may develop over time. All three features of investments—uncertainty, irreversibility, and flexibility—need to be considered for the assessment of genuine investment.

Investment might generally be defined as "[…] the act of incurring an immediate cost in the expectation of future rewards" (Dixit and Pindyck 1994 p. 3). The notion of genuine investment is based on Arrows' et al.'s (2012) contribution to *sustainability and the measurement of wealth.* For explanatory purposes, the author's formal concepts of wellbeing and genuine investment are illustrated in Appendix A.

Arrow et al.'s (2012) model requires a forecast of the economy's future after time t to well-define the intergenerational wellbeing. The forecast depends on the stock of assets at time t, advancements in technology, consumer preferences, and institutions beyond t. Given that Arrow et al. (2012)

captured these time-varying factors as exogenous, we suppose $\hat{V}(t)$ following a geometric Brownian motion (GBM), which enables us to endogenous future prices and costs without explicitly modeling them.

Moreover, we also analyze the flexibility of investment McDonald and Siegel (1986) and compare the value of an immediate genuine investment decision to the option value of a postponed genuine investment decision. Hence, we implement the real options methodology (Scatasta et al., (2006). For the option value to invest calculations, we follow Dixit and Pindyck (1994). The model is illustrated in Appendix A.

From the methodologies illustrated in Appendix A, we calculate the coefficient:

$$\frac{\beta_1}{\beta_1 - 1}, \tag{1}$$

which is called the hurdle rate (Demont et al., 2004). The incremental benefit of the new investment costs needs to be at least $\frac{\beta_1}{\beta_1-1}$ times the net irreversible costs of the genuine investment project to be considered more beneficial than the best alternative investment available. As the hurdle rate $\frac{\beta_1}{\beta_1 - 1} > 1$, this result has important implications for the measurement of sustainable investments. First, private sector companies taking the irreversibility effects of the investments into account will invest only if the value is larger than $\hat{V}^*$. The values of these investments will be observable, and the related value added will be captured by national accounting statistics. Second, investments with a value below $\hat{V}^*$ will not be observable, but their value is greater than or equal to zero (see equation 14). Not considering these values underestimates the economic value of the bioeconomy. Third, the size of the threshold value $\hat{V}^*$ is larger than one. A lower threshold level, ceteris paribus, increases the incentives for immediate investment, while a higher threshold level decreases them. The size of the threshold level depends not only on market data, such as prices and investment costs but also on policies. Costs for research and development and market approval are outcomes of regulatory policies, and many of these can be considered fixed costs. Policies that reduce these fixed costs can have a positive effect on private sector incentives to invest in and develop the market for bio-based products. Hence, monitoring the regulatory policy environment becomes even more important.

Equation 2 can be rearranged by providing:

$$I < I^{*} = \hat{V}\frac{\beta_1 - 1}{\beta_1}. \qquad (2)$$

Equation (2) is a formula for the threshold level of irreversible costs I^{*} to be accepted while staying on a sustainable development path defined as previously defined, $d\hat{Y}/dt \geq 0$. Wesseler (2003), Scatasta et al. (2006), and Wesseler et al. (2007) called this threshold value the MISTICS, that is, the maximum amount of irreversible costs society should be willing to tolerate as compensation for an investment's benefits. Since $\beta_1 > 1$, the MISTICs or I^{*} have to be lower than $\hat{V}_t$ by the factor $(\beta_1 - 1)/\beta_1$ (the reverse hurdle rate). The hurdle rate $\beta/(\beta - 1)$ reflects the degree of uncertainty and flexibility associated with investment projects. A hurdle rate of 1.5, for example, indicates that the benefits of a genuine investment project have to be at least 1.5 times greater than its irreversible costs to be considered sustainable (Wesseler *et al.* 2007). Further, since $\hat{V}_t$ is expected to increase over time, the MISTICs will increase as well.

MISTICs can be used as an indicator of the sustainability of a specific investment against irreversible environmental impacts. Possible uncertainties are explicitly considered, and the threshold value is reduced by the size of the hurdle rate, as the benefits $\hat{V}_t$ are divided by the hurdle rate. This adds an additional level of precaution to the assessment. The larger the threshold value, the larger the potential negative irreversible environmental impacts can be, and the more sustainable the specific investment will be, while a lower value indicates the opposite. The MISTICs for investments in the bioeconomy can be estimated for different investments, and changes over time provide an indication of improved or decreased sustainability.

3. Empirical Application

1.1. Sustainable development of the bioeconomy

We used the framework presented in Section 2 to empirically analyze the sustainability of EU Member States' (MSs) bioeconomies and sectors. We followed the delimitation of the bioeconomy in terms of bioeconomy sectors from Kardung et al. (2021), which is based on the Statistical Classification of Economic Activities in the European Community (NACE). Table 1 shows the sectors according to the International Standard Industrial Classification of All Economic Activities (ISIC) Rev. 4 codes, as used by the OECD, as well as the corresponding NACE codes.

Table 1: **Comparison of the BioMonitor bioeconomy sectors according to the NACE codes with the equivalent ISIC sectors used in the analysis.**

BioMonitor sectors (NACE codes)	ISIC sectors
A01: Crop and animal production, hunting and related service activities A02: Forestry and logging A03: Fishing and aquaculture	01T03: Agriculture, forestry and fishing
C10: Manufacture of food C11: Manufacture of beverages C12: Manufacture of tobacco	10T12: Food products, beverages, and tobacco
C13: Manufacture of textiles C14: Manufacture of wearing apparel C15: Manufacture of leather and related products	13T15: Textiles, wearing apparel, leather, and related products
C16: Manufacture of wood and products of wood and cork, except furniture;	16: Wood and of products of wood and cork (except furniture)
C17: Manufacture of articles of straw and plaiting materials C18: Manufacture of paper and paper products	17T18: Paper products and printing
C19: Manufacture of coke and refined petroleum products	19: Coke and refined petroleum products
C20: Manufacture of chemicals and chemical products C21: Manufacture of basic pharmaceutical products and pharmaceutical preparations	20T21: Chemicals and pharmaceutical products

C22: Manufacture of rubber and plastic products	22: Rubber and plastic products
C31: Manufacture of furniture	31T33: Other manufacturing; repair and installation of machinery and equipment
D35: Electricity, gas, steam, and air conditioning supply D3511: Production of electricity E36: Water collection, treatment, and supply E37: Sewerage E38: Waste collection, treatment, and disposal activities; materials recovery E39: Remediation activities and other waste management services	35T39: Electricity, gas, water supply, sewerage, waste, and remediation services
F41: Construction of buildings F42: Civil engineering	41T43: Construction
G46: Wholesale trade, except for motor vehicles and motorcycles G47: Retail trade, except for motor vehicles and motorcycles	45T47: Wholesale and retail trade: repair of motor vehicles
H: Transportation and storage	49T53: Transportation and storage
I55: Accommodation I56: Food and beverage service activities	55T56: Accommodation and food services
M7211: Research and experimental development on biotechnology	TTL_69T82: Other business sector services
R9104: Botanical and zoological gardens and nature reserves activities	90T96: Arts, entertainment, recreation, and other service activities

The value of investments in bioeconomy projects is taken from Cingiz et al. (2021), who calculated the bioeconomy share of value added for 28 EU MS and 36 sectors from 2005 to 2015 using input–output tables. We used a risk-adjusted discount rate of 10.5 percent, as is common in this type of analysis (Demont *et al.* 2004; Wesseler *et al.* 2007). Table 2 presents the riskless rate of return for the EU-28, calculated by the 10-year average long-term interest rate from the OECD (2021). Following McDonald and Siegel's (1986) approach, we calculated the β_1 coefficient, see Appendix B:

$$\beta_1 = \frac{1}{2} - \frac{r - \gamma_v}{\sigma^2} + \sqrt{\left[\frac{r - \gamma_v}{\sigma^2} - \frac{1}{2}\right]^2 \frac{2r}{\sigma^2}} \tag{3}$$

where r is the riskless rate of return, γ_v is the difference between the discount rate and the temporal trend of value added, σ^2 is the temporal variance of value added.

The hurdle rate (15) is then calculated for each country and sector:

$$hurdlerate = \frac{\beta_1}{\beta_1 - 1}. \tag{4}$$

Table 2: Riskless rate of return for EU Member States

Country	Riskless rate	Country	Riskless rate
AUT	0.030	ITA	0.041
BEL	0.032	LTU	0.050
DEU	0.026	LVA	0.054
DNK	0.027	NLD	0.029
ESP	0.040	POL	0.050
FIN	0.029	PRT	0.054
FRA	0.030	SVK	0.037
GBR	0.034	SVN	0.042
GRC	0.087	SWE	0.027
HUN	0.068		
IRL	0.045	Average	0.041

Source: Adapted from OECD (2021)

We can now calculate the MISTICs, which indicate how much a society should be willing to tolerate to stay on a sustainable path. MISTICs can also have a negative value, implying that the investment would need irreversible benefits to be sustainable. For example, the impact of the investment could be an increase in biodiversity. MISTICs are calculated as follows:

$$MISTIC = \frac{W}{\frac{\beta_1}{\beta_1 - 1}} + R, \tag{5}$$

where *W is* social incremental reversible benefits, which are weighted by the hurdle rate, and *R* is social incremental irreversible benefits.

1.2. Estimating the social incremental reversible benefits

The social incremental reversible and irreversible benefits of investing in the bioeconomy are challenging to quantify because they are manifold and partly intangible. Social benefits are hard to estimate because they cover the full spectrum of costs and benefits, including social and environmental effects. This concept, combined with the bioeconomy, which contributes to sustainable development in multiple ways, makes it challenging to estimate holistic social benefits. First, we must define the social incremental reversible benefits (SIRBs) of investing in the bioeconomy. We calculated the average yearly change in bioeconomy value added over the 2006–2015 period. This average indicates the economic benefit that the bioeconomy provided for a sector over this period.

1.3. *Estimating the social incremental irreversible benefits*

Moving on to the social incremental irreversible benefits (SIIBs), we follow a straightforward and consistent approach to investigating how investing in the bioeconomy affects climate change mitigation, a major policy objective of transitioning to a bioeconomy. We estimated the SIIBs based on greenhouse gases emitted in a sector in relation to the change in bioeconomy value added. The greenhouse gas emissions data are from OECD's Air Emission Accounts and are provided by ISIC Rev. 4 activities[3]. The greenhouse gas emissions given in tons of CO_2 (carbon dioxide) equivalent include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride. We assumed that the level of greenhouse gas emissions ($GHGe_{ij}$) in year *i* and sector *j* is a linear function of the bioeconomy value added ($BBVA_{ij}$), non-bioeconomy value added ($NBVA_{ij}$), and other factors. We estimated the effect of bioeconomy value added, non-bioeconomy value added if present, and several control variables on greenhouse gas emissions using multiple linear regression, as follows:

$$GHGe_{ij} = \beta_0 + \beta_1 * Year_i + \beta_2 * Country + \beta_3 * BBVA_{ij} + \beta_4 * NBVA_{ij} + \beta_5 * BBVA_{ij} * NBVA_{ij} + \varepsilon_{ij}, \quad (6)$$

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[3] We downloaded the data from the official website of the OECD, which is freely available at https://stats.oecd.org/Index.aspx?DataSetCode=AEA.

where $GHGe_{ij}$ is the level of total greenhouse gases in year *i and sector j*, $Year_i$ is the number of years from 2004, $Country$ is the country of origin, $BBVA_{ij}$ is the bioeconomy value added, $NBVA_{ij}$ is the non-bioeconomy value added, $BBVA_{ij} * NBVA_{ij}$ is the interaction between the two types of value added components, and ε_{ij} is the error term.

The regression coefficients β_3 and β_4 represent the marginal effect of an additional unit of bioeconomy value added on greenhouse gas emissions. For fully bio-based sectors, we did not have β_4 and thus treated as zero. Then, the difference between β_3 and β_4 provides the complete marginal effect of an additional unit of bioeconomy value added, as we assumed a substitution between bioeconomy and non-bioeconomy.

Table 3a: Regression results of bioeconomy value added on greenhouse gas emissions per sector.

	Dependent variable					
	GHGe					
	01T03	10T12	13T15	16	17T18	19
Year	-569,453.5**	-97,642.0***	-34,395.4***	-21,533.6***	-45,749.5*	45,993.5
Country	-127,986.6	11,337.1	-80.0	-473.3	-11,794.8	7,013.5
BE_VA	2,321.0***	279.3***	-1,814.9***	197.1***	498.3***	-24,403.0**
Non_BE_VA			352.0***			8,514.5***
BE_Non_BE_VA			-0.1***			-17.4***
Constant	9,402,511.0***	746,144.9***	212,028.6***	194,912.3**	632,735.6***	172,394.2
Observations	245	245	245	245	245	245
R^2	0.74	0.91	0.85	0.42	0.79	0.74
Adjusted R^2	0.74	0.91	0.85	0.41	0.78	0.73
Residual Std. Error	11,403,827.0 (df = 241)	967,372.9 (df = 241)	255,610.1 (df = 239)	341,896.9 (df = 241)	1,069,230.0 (df = 241)	3,625,068.0 (df = 239)
F Statistic	233.6*** (df = 3; 241)	817.3*** (df = 3; 241)	277.9*** (df = 5; 239)	57.1*** (df = 3; 241)	293.6*** (df = 3; 241)	136.1*** (df = 5; 239)

	Dependent variable					
	GHGe					
	20T21	22	35T39	45T47	49T53	55T56

Year	-384,471.6***	-43,857.3***	-3,094,534.0***	-122,313.1***	-1,046,048.0***	-22,059.9**
Country	36,594.0	8,934.2**	285,747.5	51,004.0***	-156,898.7**	1,272.1
BE_VA	9,347.1***	2,919.9***	-13,678.2*	294.5***	-5,208.1***	182.5***
Non_BE_VA	240.3*	-153.0***	3,531.8***	86.1***	1,440.6***	131.6***
BE_Non_BE_VA	-0.1***	0.04**	0.5***	-0.001***	-0.1***	-0.01***
Constant	2,919,148.0***	206,634.2*	30,151,178.0***	-110,693.2	10,944,786.0***	-26,540.7
Observations	245	245	245	245	245	245
R^2	0.71	0.72	0.78	0.91	0.88	0.87
Adjusted R^2	0.70	0.71	0.78	0.91	0.87	0.87
Residual Std. Error (df = 239)	4,845,240.0	493,903.9	37,675,915.0	1,726,956.0	8,773,358.0	418,105.9
F Statistic (df = 5; 239)	115.3***	121.0***	173.6***	487.9***	341.7***	329.2***

Note: *p <0.1; **p <0.05; ***p <0.01

Table 3b: Regression results for a change in bioeconomy value added on greenhouse gas emissions per sector.

	Dependent variable:	
	GHGe	
	69T82	90T96
Year	-83,257.8***	-30,604.8***
Country	27,719.8***	9,074.8**
BE_VA	19.6	871.1***
Non_BE_VA	35.7***	-9.8*
BE_Non_BE_VA	-0.000	0.001*
Constant	461,120.7	136,663.5
Observations	245	245
R^2	0.75	0.87
Adjusted R^2	0.74	0.87
Residual Std. Error (df = 239)	1,252,136.0	488,280.0
F Statistic (df = 5; 239)	140.7***	332.9***

Note: *p <0.1; **p <0.05; ***p <0.01

Tables 2a and 2b present the multiple linear regression results for each sector within the bioeconomy scope. The first model for agriculture, forestry and fishing (01T03) shows a positive coefficient, significant at 0.01 percent, suggesting that an increase in bioeconomy value added correlates with an increase in greenhouse gas emissions. We can illustrate how we calculate the SIIBs for bioeconomy sectors using textiles, wearing apparel, leather, and related products (13T15) as an example. This partly bio-based sector has statistically significant coefficients for *BE_VA* (-1,814.9) and non_BE_VA (352.0). Thus, we calculate -1,814.9 minus 352.0, which equals 2,166.9. Then, we multiply this value by the carbon price and the average change in the bioeconomy value added in a sector, resulting in the SIIB for a sector for a country. We use Rennert et al.'s (2022) preferred mean social cost of carbon dioxide estimate of €191[4] per ton of CO_2.

Having estimated the social incremental reversible benefits and reversible benefits, we have all the elements for calculating the $MISTICs_{jk}$ for sector *j* and country *k* as follows:

$$MISTICs_{jk} = \frac{\beta_1 - 1}{\beta_1}_{jk} * \Delta VA_{jk} - \Delta VA_{jk} * (\beta_{3j} - \beta_{4j}) * CO_2 price, \quad (7)$$

where $\frac{\beta_1 - 1}{\beta_1}$ is the reverse hurdle rate for sector *j* and country *k*, ΔVA is the average yearly change in added bioeconomy value added, β_{3j} (β_{4j}) is the marginal effect of an additional unit of (non-) bioeconomy value added on greenhouse gas emissions, and $CO_2 price$ is the social cost of carbon dioxide.

1.4. *Hurdle rates for bioeconomy sectors*

To analyze the potential for sustainable investment in the EU bioeconomy, we examined the hurdle rates for all bioeconomy sectors across all countries. Table 3 presents the hurdle rates for all bioeconomies in the EU-28, differentiating between the bio-based and non-bio-based parts of these sectors. The countries with the lowest hurdle rate for their bioeconomy are Italy, the Netherlands, and Portugal, with 1.01, followed closely by Austria, Belgium, Cyprus, Germany, and France, with 1.02. The

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[4] Converted from $185, 2020 US dollars via https://www.oanda.com/.

hurdle rate is lower for the bio-based part for 23 out of 28 countries, with Germany, Finland, France, Ireland, and Romania as exceptions. However, the hurdle rate for the bio and non-bio parts is relatively low for Germany, Finland, and France. Lithuania has the highest hurdle rate (3.91), followed by Latvia (3.16), Ireland (2.95), and Estonia (2.79).

The graphs in Figures 3a and 3b show high variability in the sectorial hurdle rates within and between the countries[5]. The whiskers of the boxplots in Figure 3b extend further than in Figure 3a, with Slovakia, Lithuania, Estonia, Bulgaria, Latvia, and Romania as extreme cases, with hurdle rates ranging from -6 to 20. It may be that these extreme values stem from volatile bioeconomy value-added values; these countries are all relatively small, with lower levels of value added, where smaller absolute changes lead to greater relative changes. Figures 3a and 3b confirm Italy, the Netherlands, Portugal, and France as the countries with the lowest hurdle rates, as their medians (the band inside the box) are the lowest. The highest hurdle rate medians are exhibited by Romania, Latvia, and Bulgaria. These countries also have a high interquartile range (the width of the box), which is generally higher for countries with higher hurdle rate medians.

We ranked all bioeconomy sectors from highest to lowest according to their hurdle rates. Table 3 presents the five highest sectors for all countries, which shows where sustainable investment is the most difficult. By contrast, Table 4 presents the five sectors with the lowest hurdle rates. Considering all countries, coke and refined petroleum products (19) is the sector that occurs most often among the five highest sectors (16 occurrences) and the sector with the highest hurdle rate (12 occurrences). Other sectors with a frequently high hurdle rate, twelve times, are agriculture, forestry, and fishing (01T03), other manufacturing; repair and installation of machinery and equipment (31T33), and electricity, gas, water supply, sewerage, waste, and remediation services (35T39). Rubber and plastic

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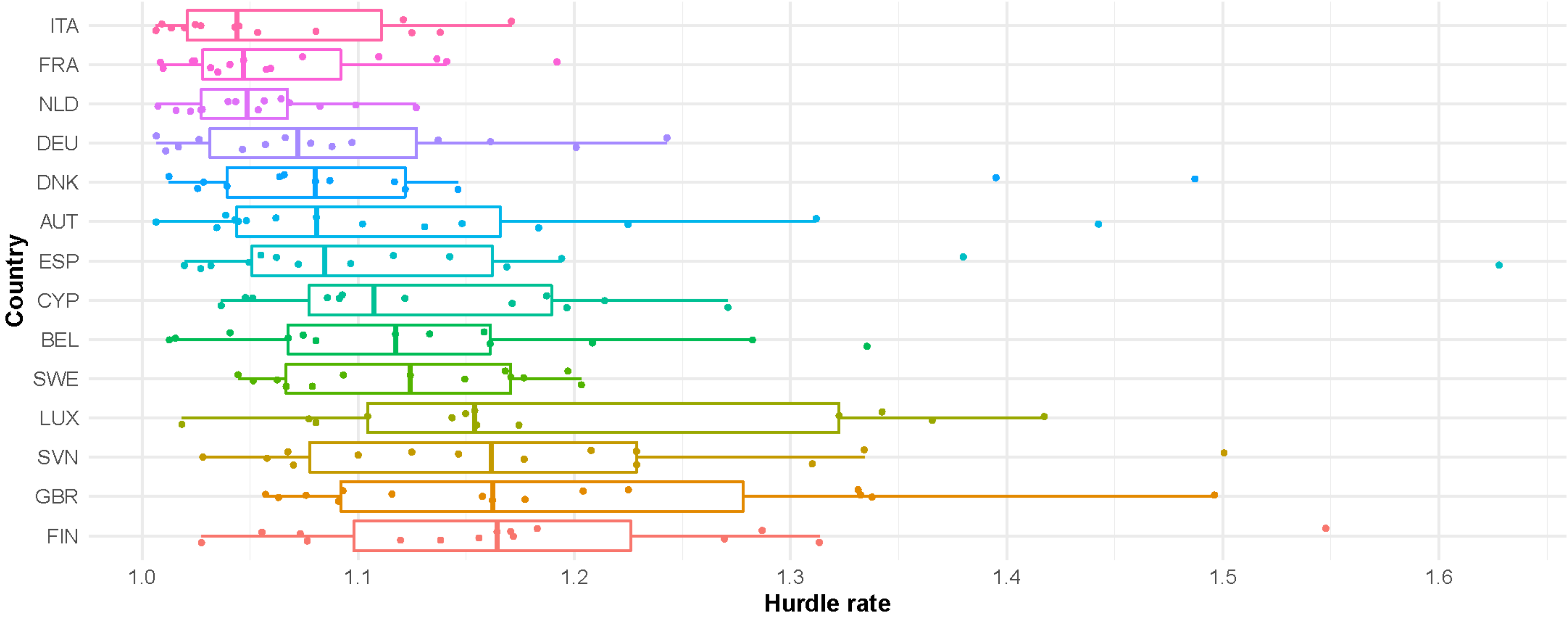
[5] The outliers, values greater (less) than the third (first) quartile plus (minus) 1.5 * the IQR, have been removed for these graphs.

products (22) stand out as having the highest hurdle rate in the Czech Republic, Greece, Croatia, Hungary, and Romania.

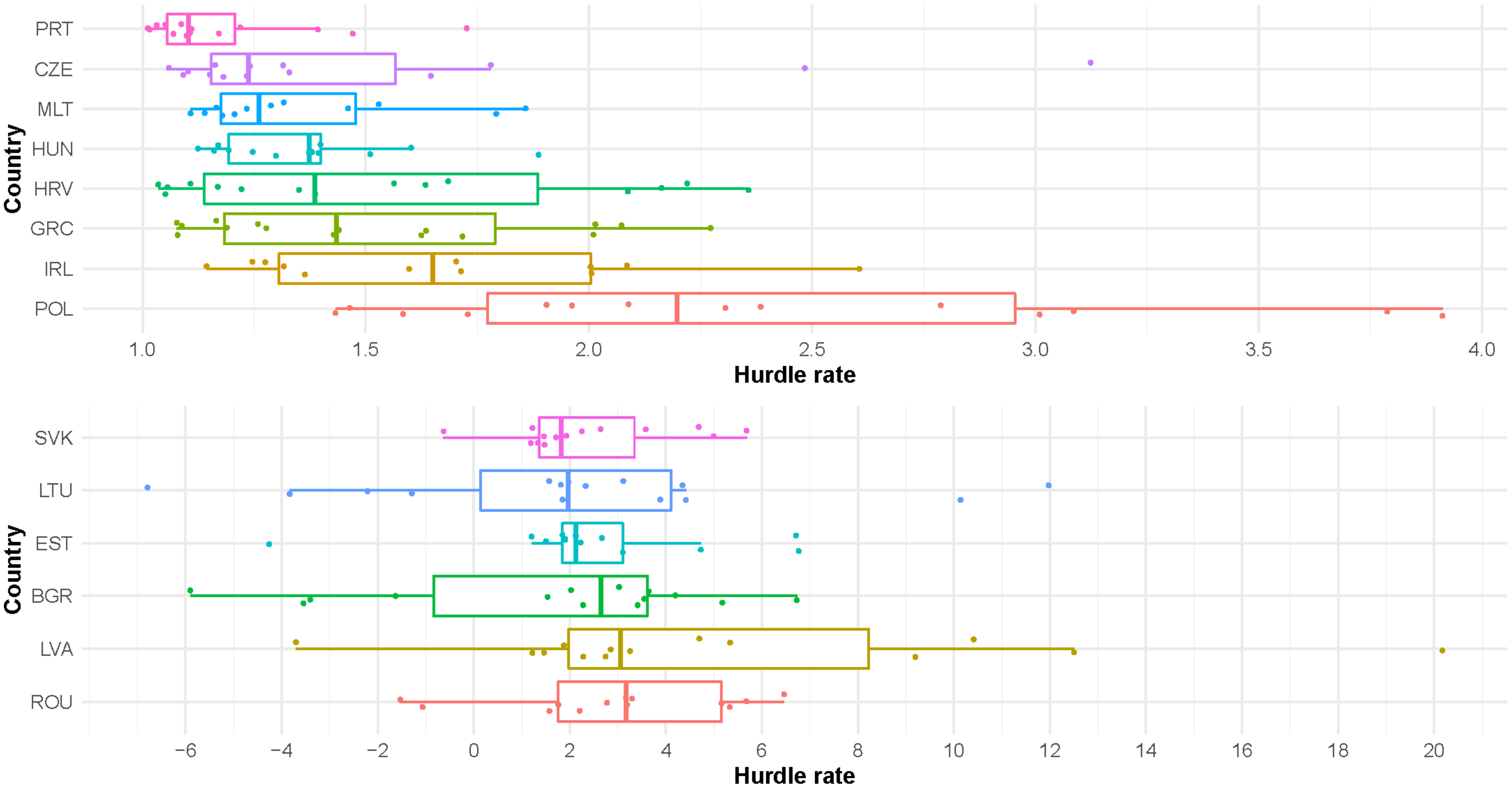
Turning now to the sectors with the lowest hurdle rate, food products, beverages, and tobacco (10T12) lead other sectors, with 21 occurrences. This sector is followed by paper products and printing (17T18), with 17 occurrences. Therefore, these conventional bioeconomy sectors frequently provide the least obstacles to bioeconomy investment. In particular, food products, beverages, and tobacco stand out as the sector with the lowest hurdle rate in eight countries. The third most frequent sector is wholesale and retail trade; repair of motor vehicles (45T47) with 14 occurrences. Transportation and storage (49T53), accommodation, and food services (55T56), other business sector services (69T82), and arts, entertainment, recreation, and other service activities (90T96) also have a frequently low hurdle rate, with nine occurrences among the five lowest sectors each.

Figure 1a: Hurdle rates for the bioeconomy per sector for each country as box plots with jittered data points



*Note: A box plot illustrates the hurdle rates for each country. The band inside the box corresponds to the median and the width of the box to the interquartile range (IQR). The upper (lower) whisker extends from the hinge to the largest (lowest) value no further than 1.5 * IQR from the hinge. The points correspond to the values of each sector. The points correspond to the values of each sector. The outliers, values greater (less) than the third (first) quartile plus (minus) 1.5 * the IQR, have been removed.*

Figure 1b: Hurdle rates for the bioeconomy per sector for each country as box plots with jittered data points



*Note: A box plot illustrates the hurdle rates for each country. The band inside the box corresponds to the median and the width of the box to the interquartile range (IQR). The upper (lower) whisker extends from the hinge to the largest (lowest) value no further than 1.5 * IQR from the hinge. The points correspond to the values of each sector. The points correspond to the values of each sector. The outliers, values greater (less) than the third (first) quartile plus (minus) 1.5 * the IQR, have been removed.*

Table 4: Hurdle rates for bioeconomies and the highest bioeconomy sectors for each EU Member State

Country	Hurdle rate Bioeconomy		Five highest sectors									
	Bio	Non-bio	#1	Hurdle rate	#2	Hurdle rate	#3	Hurdle rate	#4	Hurdle rate	#5	Hurdle rate
AUT	1.02	1.02	**19**	9.42	**31T33**	1.44	**20T21**	1.31	**22**	1.22	**35T39**	1.18
BEL	1.02	1.02	**19**	3.39	**31T33**	2.27	**41T43**	1.99	**22**	1.34	**13T15**	1.28
BGR	1.68	12.81	**55T56**	136.18	**10T12**	6.73	**20T21**	5.18	**13T15**	4.2	**49T53**	3.64
CYP	1.02	1.07	**35T39**	4.96	**55T56**	1.64	**69T82**	1.51	**13T15**	1.27	**90T96**	1.21
CZE	1.14	1.27	**22**	5.68	**19**	5.53	**69T82**	3.12	**35T39**	2.48	**01T03**	1.78
DEU	1.02	1.01	**19**	1.53	**13T15**	1.44	**01T03**	1.24	**49T53**	1.2	**31T33**	1.16
DNK	1.03	1.03	**31T33**	2.15	**20T21**	1.88	**01T03**	1.49	**55T56**	1.4	**35T39**	1.15
ESP	1.03	1.03	**19**	2.93	**41T43**	1.68	**69T82**	1.63	**35T39**	1.38	**49T53**	1.19
EST	2.79	2.89	**16**	48.35	**90T96**	34.82	**22**	6.77	**69T82**	6.71	**01T03**	4.73
FIN	1.05	1.03	**19**	1.56	**13T15**	1.55	**35T39**	1.31	**16**	1.29	**20T21**	1.27
FRA	1.02	1.01	**19**	1.29	**31T33**	1.19	**01T03**	1.14	**90T96**	1.14	**13T15**	1.11
GBR	1.09	1.18	**19**	2.74	**35T39**	1.5	**01T03**	1.34	**55T56**	1.33	**13T15**	1.33
GRC	1.04	1.09	**22**	2.27	**19**	2.07	**41T43**	2.01	**16**	2.01	**35T39**	1.72
HRV	1.08	1.09	**22**	5.57	**90T96**	2.36	**41T43**	2.22	**19**	2.16	**69T82**	2.09
HUN	1.33	1.56	**22**	3.04	**20T21**	2.89	**31T33**	2.87	**01T03**	1.89	**45T47**	1.6
IRL	2.95	1.72	**20T21**	5.79	**31T33**	3.46	**13T15**	2.61	**69T82**	2.09	**01T03**	2.01
ITA	1.01	1.01	**19**	1.48	**41T43**	1.45	**69T82**	1.17	**13T15**	1.14	**20T21**	1.12
LTU	3.91	4.60	**10T12**	11.97	**41T43**	10.14	**49T53**	4.42	**90T96**	4.35	**22**	3.88
LUX	1.04	2.12	**90T96**	6.34	**13T15**	1.85	**01T03**	1.42	**35T39**	1.37	**45T47**	1.34
LVA	3.16	4.90	**19**	80.97	**41T43**	20.17	**20T21**	12.5	**31T33**	10.41	**16**	9.19
MLT	1.07	3.37	**49T53**	5.99	**55T56**	3.12	**16**	1.86	**45T47**	1.79	**22**	1.53
NLD	1.01	1.01	**19**	1.54	**35T39**	1.21	**20T21**	1.13	**55T56**	1.1	**01T03**	1.08
POL	1.76	2.52	**69T82**	3.91	**31T33**	3.79	**17T18**	3.09	**20T21**	3.01	**49T53**	2.79
PRT	1.01	1.02	**19**	7.18	**35T39**	6.79	**13T15**	1.73	**49T53**	1.47	**41T43**	1.39
ROU	1.68	-3.20	**22**	14.72	**55T56**	6.46	**31T33**	5.68	**41T43**	5.33	**90T96**	5.16
SVK	1.93	3.70	**01T03**	5.68	**69T82**	5	**90T96**	4.69	**49T53**	3.58	**31T33**	2.64
SVN	1.05	1.13	**41T43**	2.78	**19**	2.25	**22**	1.5	**49T53**	1.33	**20T21**	1.31
SWE	1.08	1.11	**19**	1.81	**01T03**	1.62	**31T33**	1.56	**35T39**	1.2	**16**	1.2

Table 5: Hurdle rates for lowest bioeconomy sectors for each EU Member State

	Five lowest sectors									
Country	#1	Hurdle rate	#2	Hurdle rate	#3	Hurdle rate	#4	Hurdle rate	#5	Hurdle rate
AUT	17T18	1.01	45T47	1.03	55T56	1.04	49T53	1.04	10T12	1.04
BEL	10T12	1.01	17T18	1.02	16	1.04	90T96	1.07	49T53	1.07
BGR	90T96	-254.3	69T82	-5.9	35T39	-3.55	17T18	-3.41	22	-1.63
CYP	19	-0.38	10T12	1.04	17T18	1.05	45T47	1.05	41T43	1.09
CZE	10T12	1.06	49T53	1.09	45T47	1.1	55T56	1.15	16	1.16
DEU	10T12	1.01	17T18	1.01	45T47	1.02	35T39	1.03	69T82	1.05
DNK	19	-2.36	90T96	1.01	10T12	1.03	17T18	1.03	69T82	1.04
ESP	55T56	1.02	17T18	1.03	31T33	1.03	10T12	1.05	01T03	1.05
EST	55T56	-11.47	19	-4.26	13T15	1.2	31T33	1.5	49T53	1.85
FIN	10T12	1.03	55T56	1.06	45T47	1.07	31T33	1.08	90T96	1.12
FRA	17T18	1.01	10T12	1.01	20T21	1.02	45T47	1.02	49T53	1.03
GBR	45T47	1.06	90T96	1.06	10T12	1.08	17T18	1.09	20T21	1.09
GRC	01T03	1.08	13T15	1.08	17T18	1.09	45T47	1.17	90T96	1.19
HRV	49T53	1.04	13T15	1.05	10T12	1.06	01T03	1.11	45T47	1.17
HUN	10T12	1.12	41T43	1.16	19	1.17	55T56	1.19	13T15	1.25
IRL	10T12	-2.63	19	-1.5	45T47	1.14	35T39	1.25	49T53	1.28
ITA	10T12	1.01	45T47	1.01	17T18	1.01	16	1.02	55T56	1.02
LTU	31T33	-13.42	45T47	-6.8	69T82	-3.83	17T18	-2.21	20T21	-1.29
LUX	31T33	-2.95	17T18	1.02	69T82	1.08	10T12	1.08	16	1.1
LVA	35T39	-287.74	69T82	-3.7	13T15	1.22	49T53	1.46	10T12	1.88
MLT	90T96	-17.04	69T82	-6.85	41T43	1.11	17T18	1.14	01T03	1.17
NLD	17T18	1.01	31T33	1.02	69T82	1.02	10T12	1.03	49T53	1.03
POL	41T43	-16.15	22	-3.35	13T15	1.43	01T03	1.46	35T39	1.58
PRT	55T56	1.01	10T12	1.02	01T03	1.03	90T96	1.05	45T47	1.07
ROU	20T21	-40.99	19	-8.61	69T82	-1.53	35T39	-1.07	01T03	1.57
SVK	22	-75.25	16	-33.29	41T43	-0.63	10T12	1.19	13T15	1.22
SVN	10T12	1.03	45T47	1.06	17T18	1.07	31T33	1.07	55T56	1.1
SWE	17T18	1.04	10T12	1.05	90T96	1.06	20T21	1.07	22	1.08

1.5. *Maximum incremental social tolerable irreversible costs for the bioeconomy*

We estimate the MISTICs to analyze the level of irreversible impact that can be considered sustainable for the bioeconomy. MISTICs can be positive or negative, affecting the value's interpretation. A positive value means that society can bear the irreversible costs of investing in the bioeconomy while staying on a sustainable path. For example, an investment project to produce biomass might induce irreversible land use changes that decrease biodiversity and are still sustainable. A negative value means the opposite: a project must increase biodiversity to be sustainable.

The first (second) column in Table 6 provides the total (per capita) MISTICs for the EU-28 bioeconomies. The major shares of countries have negative MISTICs for their bioeconomies. We used the per capita values to compare the countries. Portugal has the highest value (€7.71), followed by Cyprus (€4.42), Greece (€2.17), and Romania (€2.04). On the contrary, the MISTIC is the lowest for Ireland (€-70.87), followed by Sweden (€-29.71), Denmark (€-20.18), and Finland (€18.44). However, each of these countries has bioeconomy sectors with positive MISTICs.

As before, we ranked all bioeconomy sectors from highest to lowest according to their MISTICs. Table 6 presents the five highest sectors for all countries, which indicates the sectors in which bioeconomy investment has the highest benefits. By contrast, Table 7 provides the five sectors with the lowest benefits. Considering the EU-28 bioeconomies, electricity, gas, water supply, sewerage, waste, and remediation services (35T39) occur most frequently among the five highest sectors (26 occurrences). In 20 countries, 35T39 has the highest MISTICs. It is followed by other business sector services (69T82; 24 occurrences), transportation, and storage (49T53; 22 occurrences), and textiles, wearing apparel, leather and related products (13T15; 32 occurrences). Transportation and storage (49T53) stands out, with being the first and second highest MISTICs, with 5 and 15 occurrences, respectively. Considering the EU-28 altogether, the five sectors with the highest MISTICs (4 occurrences) are electricity, gas, water supply, sewerage, waste, and remediation services (35T39) in Spain, Great Britain, Italy, and Poland, and transportation and storage (49T53) in Germany.

Agriculture, forestry, and fishing (01T03) have 27 occurrences among the sectors with the lowest MISTICS, making them last place. In 22 countries, this sector has the lowest MISTICs. Second to last is 10T12, with 25 occurrences, and third from last, chemicals, and pharmaceutical products (20T21), with 24 occurrences. Chemicals and pharmaceutical products sector (20T21) has 4 and 19 occurrences as the lowest and second to lowest sectors, respectively. If we consider all countries, the five sectors with the lowest MISTICS are agriculture, forestry, and fishing (01T03) in France and Italy; chemicals and pharmaceutical products (20T21) in Germany; and agriculture, forestry, and fishing (01T03) in Great Britain and Spain, all with two occurrences. This bottom five is closely followed by Ireland’s chemicals and pharmaceutical products (20T21).

Table 6: MISTICS for bioeconomies and the highest bioeconomy sectors for each EU Member State

Country	MISTICS		MISTICS five highest sectors									
	Mio (€)	€ per capita	#1	Mio (€)	#2	Mio (€)	#3	Mio (€)	#4	Mio (€)	#5	Mio (€)
AUT	-23.8	-2.84	**35T39**	70.89	**49T53**	28.24	**69T82**	0.57	**13T15**	0.06	**55T56**	-1.79
BEL	-61.2	-5.63	**35T39**	47.37	**49T53**	24.46	**19**	12.08	**69T82**	0.58	**13T15**	0.01
BGR	-7	-0.95	**35T39**	30.62	**49T53**	7.82	**13T15**	0.85	**69T82**	0.09	**55T56**	-0.24
CYP	3.6	4.42	**35T39**	3.62	**10T12**	0.43	**90T96**	0.27	**17T18**	0.12	**45T47**	0.11
CZE	-51.1	-4.89	**35T39**	66.52	**19**	2.46	**69T82**	0.34	**55T56**	-0.07	**13T15**	-0.13
DEU	-263.1	-3.23	**49T53**	225.9	**35T39**	179.6	**19**	6.1	**13T15**	5.5	**69T82**	1.59
DNK	-111.8	-20.18	**19**	9.98	**10T12**	5.94	**49T53**	5.25	**22**	2.11	**17T18**	1.1
ESP	-28.2	-0.61	**35T39**	338.04	**49T53**	139.2	**17T18**	3.6	**13T15**	2.08	**16**	2.04
EST	-4.2	-3.16	**35T39**	9.45	**49T53**	4.23	**19**	2.76	**69T82**	0.06	**13T15**	0.05
FIN	-98.9	-18.44	**35T39**	33.11	**69T82**	0.28	**17T18**	0.27	**13T15**	0.1	**55T56**	-0.2
FRA	-388.9	-6.00	**35T39**	116.62	**49T53**	102.66	**22**	6.92	**17T18**	4.59	**69T82**	0.8
GBR	-60.7	-0.97	**35T39**	300.31	**49T53**	112.68	**19**	31.15	**13T15**	6.52	**69T82**	2.24
GRC	23.9	2.17	**01T03**	26.43	**35T39**	21.82	**17T18**	8.09	**90T96**	3.11	**45T47**	1.23
HRV	4.7	1.10	**35T39**	23.97	**49T53**	3.1	**69T82**	0.09	**13T15**	-0.02	**55T56**	-0.33
HUN	-114.2	-11.45	**35T39**	12.61	**49T53**	8.86	**13T15**	0.27	**69T82**	0.15	**55T56**	-0.1
IRL	-318.5	-70.87	**35T39**	40.8	**19**	12.23	**45T47**	0.32	**69T82**	0.28	**90T96**	0.25
ITA	-164	-2.75	**35T39**	271.73	**49T53**	83.01	**13T15**	12.76	**16**	2.42	**69T82**	1.45
LTU	-45	-14.52	**49T53**	11.88	**35T39**	4.32	**13T15**	0.41	**69T82**	0.11	**55T56**	-0.1
LUX	-2.3	-4.49	**49T53**	0.73	**20T21**	0.21	**35T39**	0.19	**17T18**	0.09	**69T82**	0.01
LVA	-12.9	-6.13	**35T39**	14.4	**49T53**	3.8	**19**	0.08	**69T82**	0.07	**13T15**	-0.07
MLT	-1.2	-2.87	**49T53**	0.84	**35T39**	0.32	**69T82**	0.01	**22**	0	**16**	-0.01
NLD	-14.7	-0.89	**35T39**	122.82	**49T53**	50.31	**17T18**	5.77	**13T15**	0.91	**69T82**	0.88
POL	-12.7	-0.33	**35T39**	229.97	**49T53**	97.4	**19**	13.53	**13T15**	3.3	**69T82**	1.16
PRT	70.5	6.71	**35T39**	84.76	**49T53**	19.63	**19**	6.42	**13T15**	4.6	**69T82**	0.17
ROU	41.6	2.04	**35T39**	95.1	**19**	79.31	**49T53**	31.27	**13T15**	0.77	**69T82**	0.36
SVK	-64	-11.83	**49T53**	15.06	**35T39**	13.15	**69T82**	0.14	**13T15**	-0.15	**55T56**	-0.18
SVN	-7.9	-3.87	**35T39**	10.17	**49T53**	4.22	**13T15**	0.1	**69T82**	0.06	**19**	-0.05
SWE	-278.8	-29.71	**19**	5.82	**69T82**	0.44	**13T15**	0.06	**55T56**	-0.76	**16**	-1.22

Table 7: MISTICS for lowest bioeconomy sectors for each EU Member State

	MISTICS five lowest sectors									
Country	**#1**	**Mio (€)**	**#2**	**Mio (€)**	**#3**	**Mio (€)**	**#4**	**Mio (€)**	**#5**	**Mio (€)**
AUT	**01T03**	-52.91	**20T21**	-30.51	**10T12**	-12.09	**19**	-6.59	**22**	-5
BEL	**20T21**	-86.49	**01T03**	-28.63	**10T12**	-14.73	**45T47**	-8.02	**22**	-3.47
BGR	**01T03**	-28.47	**20T21**	-6.7	**10T12**	-3.82	**19**	-2	**17T18**	-1.69
CYP	**49T53**	-0.84	**01T03**	-0.34	**13T15**	-0.05	**69T82**	0	**22**	0
CZE	**01T03**	-78.69	**20T21**	-16.9	**22**	-6.05	**10T12**	-5.59	**49T53**	-4.76
DEU	**20T21**	-311.58	**01T03**	-149.5	**10T12**	-71.69	**90T96**	-44.9	**22**	-39.91
DNK	**20T21**	-61.22	**01T03**	-36.63	**35T39**	-34.96	**45T47**	-1.56	**90T96**	-1.51
ESP	**01T03**	-275.64	**20T21**	-115.5	**10T12**	-54.02	**45T47**	-29.46	**90T96**	-16.3
EST	**01T03**	-15.69	**16**	-1.17	**10T12**	-1.11	**17T18**	-0.69	**45T47**	-0.57
FIN	**01T03**	-66.7	**20T21**	-27.45	**49T53**	-27.26	**10T12**	-3.35	**19**	-2.25
FRA	**01T03**	-415.27	**20T21**	-107.35	**10T12**	-57.25	**45T47**	-25.04	**90T96**	-8.54
GBR	**01T03**	-279.16	**20T21**	-86.35	**10T12**	-56.03	**22**	-24.37	**45T47**	-22.38
GRC	**10T12**	-11.23	**20T21**	-9.31	**19**	-8.11	**49T53**	-6.79	**13T15**	-1.38
HRV	**01T03**	-9.18	**20T21**	-4.52	**10T12**	-2.54	**22**	-1.6	**17T18**	-1.14
HUN	**01T03**	-79.99	**20T21**	-24.88	**19**	-19.13	**22**	-3.8	**10T12**	-3.5
IRL	**20T21**	-261.15	**10T12**	-74.22	**01T03**	-31.87	**49T53**	-1.94	**17T18**	-1.5
ITA	**01T03**	-355.27	**20T21**	-70.17	**10T12**	-36.29	**19**	-23.36	**22**	-18.32
LTU	**01T03**	-28.06	**20T21**	-12.53	**19**	-8.38	**10T12**	-4.9	**45T47**	-2.41
LUX	**01T03**	-1.71	**19**	-0.84	**10T12**	-0.38	**90T96**	-0.28	**22**	-0.13
LVA	**01T03**	-23.76	**20T21**	-2.39	**10T12**	-1.42	**16**	-1.32	**45T47**	-1.11
MLT	**01T03**	-1.1	**90T96**	-0.33	**10T12**	-0.29	**17T18**	-0.23	**45T47**	-0.15
NLD	**01T03**	-122.27	**20T21**	-24.19	**10T12**	-19.91	**45T47**	-14.33	**90T96**	-4.93
POL	**01T03**	-166.34	**20T21**	-70.48	**10T12**	-37.86	**22**	-25.84	**17T18**	-21.62
PRT	**01T03**	-24.99	**20T21**	-6.95	**10T12**	-6	**45T47**	-2.69	**22**	-2.07
ROU	**01T03**	-104.15	**20T21**	-24.01	**10T12**	-22	**17T18**	-3.56	**90T96**	-3.2
SVK	**01T03**	-72.46	**20T21**	-4.4	**22**	-3.29	**17T18**	-2.46	**19**	-2.43
SVN	**01T03**	-10.79	**20T21**	-8.18	**22**	-0.74	**10T12**	-0.67	**17T18**	-0.58
SWE	**01T03**	-118.02	**35T39**	-92.91	**49T53**	-29.15	**20T21**	-22.42	**10T12**	-6.94

2. Discussion and Conclusion

In this study, we quantified and compared the sustainability of bioeconomy development in the EU. We conceptualized a theoretical framework building upon Arrow et al.'s (2012) framework for assessing whether economic growth is compatible with sustaining wellbeing over time. We complemented their framework with the characteristics of bioeconomy-related investment projects: uncertainty about future rewards and losses, irreversible impacts, and flexible timing. We linked bioeconomy value added with intergenerational wellbeing and estimated irreversible effects on greenhouse gas emissions, which allowed us to apply our framework empirically to the European Union's bioeconomy. We calculated hurdle rates to describe the degree of uncertainty and flexibility of bioeconomy sectors and the maximum amount of irreversible costs as indicators of the sustainability of bioeconomy investments against irreversible environmental impacts.

We found that the hurdle rate in the bioeconomy is lower for the bio-based part than for the non-bio-based part for most countries, indicating a high potential for further sustainable investments in the transition toward an EU bioeconomy. The countries with the lowest hurdle rates for their bioeconomy are Italy, the Netherlands, and Portugal, followed closely by Austria, Belgium, Cyprus, Germany, and France. The sectorial hurdle rates show high variability within and between countries. Conventional bioeconomy sectors, such as food products, beverages, and tobacco and paper products and printing, have low hurdle rates in many countries. We recommend that policymakers prioritize investment in the bioeconomy in specific sectors, which can vary from country to country. The majority of countries have negative MISTICs for their bioeconomy, implying that bioeconomy projects need to provide irreversible benefits. However, all of the countries have bioeconomy sectors with positive

MISTICs. Our findings are consistent with the results reported by the Ecological Footprint, which showed that most EU MSs have an ecological deficit, as they have a greater footprint than biocapacity[6].

Our results show a high potential for sustainable bioeconomy investments in many European countries, with hurdle rates only slightly above 1. The most potential is frequently in conventional bioeconomy sectors, but unconventional bioeconomy sectors, such as transportation and storage and arts, entertainment, recreation, and other service activities, also show potential. When we look at individual countries, we can see that some surprising sectors have the lowest hurdle rates, such as construction in Poland. Loizou et al. (2019) also identified this as a promising bioeconomy sector with the potential to stimulate knock-on effects in the Polish economy. An expert survey also named construction and building materials a promising bioeconomy sector, along with bio-composites, food and feed additives, pharmaceuticals, and bioplastics (Stegmann *et al.* 2020). In accordance with this result, we found that the food products, beverages, and tobacco sector has a low hurdle rate in many countries and chemicals and pharmaceutical products in France, Great Britain, Lithuania, Romania, and Sweden.

Moreover, our estimation of the MISTICs revealed that Portugal, Cyprus, Greece, Romania, and Croatia are the only European countries where bioeconomy investments are sustainable without compensating for irreversible impacts. The countries with the lowest MISTICS are Ireland, Sweden, Denmark, and Finland, which performed well in other studies on bioeconomy development (D'Adamo *et al.* 2020; Ronzon *et al.* 2022). These seemingly contradictory results can be explained by the increased difficulty of augmenting investments in an already well-developed bioeconomy. Low-hanging fruits—that is, bioeconomy investment projects that provide high economic and

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[6] The data for the Ecological Footprint by the Global Footprint Network and the Ecological Footprint Initiative at York University is available at https://data.footprintnetwork.org/#/.

environmental benefits—have already been collected in these countries. However, if we consider the MISTICS on a sectorial level, we find the electricity, gas, water supply, sewerage, waste, and remediation services sector frequently as the highest. This outcome stems from the significant reduction in greenhouse gases in this sector, which is associated with increased bioeconomy value added. Bioenergy can be essential in decarbonizing electricity (IEA 2016), but it can also cause biodiversity loss, deforestation, increased demand for agricultural land, and water scarcity (GBEP 2011). The case is similar for transportation and storage, where biofuels are one of the primary ways to decarbonize the sector (IEA 2021). The MISTICs indicator can be used to evaluate the tradeoff between irreversible benefits and costs of bioenergy investments, where a positive MISTIC value reflects tolerable irreversible costs.

Comparable to this study, the World Bank published several reports with empirical results on "genuine savings" (GS) as an indicator to measure sustainable development. They provide a database that includes the latest estimates of GS for all EU MSs (and most countries in the world) termed "adjusted net savings" (ANS) based on the World Bank (2010)[7]. ANS is calculated by taking net national savings plus education expenditure minus energy depletion, mineral depletion, net forest depletion, carbon dioxide damage, and particulate emissions damage. They do not include other important sources of environmental degradation because of the lack of internationally comparable data. Contrary to our MISTICs, all but one country has positive ANS. The results show Sweden, Denmark, Ireland, and Finland as having high ANS. Greece is the only country with a negative ANS, and Portugal, Romania, and Cyprus have comparatively low values. A possible explanation for these results contradicting ours might be that we estimate the marginal effect of an additional unit of bioeconomy value added on

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[7] The data for the Adjusted Net Savings by the World Bank is available at https://databank.worldbank.org/source/adjusted-net-savings.

greenhouse gas emissions and then multiply with the change in value added. If this coefficient is negative for a sector estimated uniformly across all countries, it reduces the MISTICs for a country with the most strongly increasing value added.

Agriculture, forestry and fishing, which are the biomass-producing foundation of the bioeconomy, have the lowest MISTICS in most countries and a high hurdle rate in many countries. A combination of these two factors might explain these negative results. First, total factor productivity slightly decreased in the EU between 2004 and 2013 (Baráth and Fertő 2017), indicating a lower investment potential. Second, the sector is a major contributor to GHG emissions (Kuosmanen *et al.* 2020), and we found that increases in bioeconomy value added are related to a rise in GHG emissions. According to our results, in most countries, future investment projects in agriculture, forestry and fishing have to compensate for their irreversible costs with an increase in biodiversity or contribute to decarbonizing the sector to be sustainable.

We faced significant challenges in compiling the data needed for the empirical application of our framework. After designing our framework, we aimed to apply it to the EU bioeconomy systematically, which means that we required data available for all EU MSs, sectors, and an extended period. However, data capable of covering all bioeconomy sectors are still lacking (D'Adamo *et al.* 2020). Therefore, we could not include a social indicator for the calculation of MISTICs. Further, other indicators measuring important environmental impacts on biodiversity soil quality are not available by economic activity. As soon as additional indicators become available, future studies could quickly address this issue. Similarly, estimating option values is difficult, as they cannot be directly observed; indicators can be derived but are not yet available. These include the number of patent applications over time and public and private sector investments in the bioeconomy.

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4. Appendix A

Arrow et al. (2012) define intergenerational wellbeing $V(t)$ as the discounted flow of current and future generations' utilities U. Utility is derived through consumption $\underline{C}(s)$ at time s and of the economy's stock of capital assets $K(s)$ at time s, including manufactured goods, services provided by nature, health services, and many more.[8] The term $U(\underline{C}(s))$ is interpreted as felicity (utility flow) at date *s*. Accordingly, δ denotes the felicity discount rate. Continuous time is denoted by s and t, $s \geq t$. Consequently, intergenerational wellbeing $V(t)$ is formalized as (Arrow *et al.* 2012 p. 322):

$$V(t) = \int_t^\infty \left[U(\underline{C}(s)) e^{-\delta(s-t)} \right] ds, \delta \geq 0 \tag{A.8}$$

Arrow et al. (2012) then define sustainability as non-declining intergenerational wellbeing over time $dV/dt \geq 0$. Genuine investment is determined as a measure of changes in wellbeing, where wellbeing is a function of its determinants, namely the economy's stock of capital assets K and time t. Given that $\underline{K}(t), K(s)$ and $\underline{C}(s)$ are determined for all future times $s \geq t$ we can write that $V(t) = V(\underline{K}(t), t)$. This is a standard Ramsey model in which generations make consumption and savings. These savings are capital assets for the next generation. The variable *t* reflects the impact of time-varying factors, which we treat as exogenous. These include changes in terms of trade, technological change, unexplained population growth, and unexplained changes in institutions.

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[8] Note that the population size is fixed throughout the model. Moreover, movements in total factor productivity and the changes in international trade are exogenous. The consumption flow at time S include both marketed goods and also leisure, health services, and consumption services supplied by nature.

Supposing that $V(t)$ is differentiable in $\underline{K}$. If we take the derivative of $V(t)$ with respect to t, and by the definition of sustainability

$$\frac{dV}{dt} = \frac{\partial V}{\partial t}\frac{dt}{dt} + \frac{\partial V}{\partial K}\frac{dK}{dt} = \frac{\partial V}{\partial t} + \sum_i \frac{\partial V(t)}{\partial K_i(t)}\frac{dK_i(t)}{dt} \geq 0$$

To arrive at a measure of comprehensive wealth that accounts for certain exogenous changes (e.g., changes in the total factor of production), we need an additional shadow price. For this purpose, we take *t* as a capital asset. Now, we define $r(t)$ ($= \partial V / \partial t$) as the shadow price of time at t in order to calculate comprehensive wealth, as in Arrow et al. (2012), and $p_i(t)$ ($\equiv \partial V(t) / \partial K_i(t)$, for all i) as the shadow price of the i^{th} capital asset at time t. By letting $I_i(t)$ equal $\Delta K_i(t) / \Delta t$, genuine investment is

$$\Delta V(t) = r(t)\Delta t + \sum p_i(t) I_i(t) \Delta t. \quad \text{(A.9)}$$

Equation (A.2) shows that the changes in an economy's set of capital assets weighted at shadow prices, including time, equal the change in wellbeing. Hence, by defining genuine investment, we establish the relationship between comprehensive wealth and intergenerational wellbeing. Looking at Equation (A.2) in more detail, it shows that positive genuine investment increases wellbeing, while negative genuine investment decreases intergenerational wellbeing. Hence, positive genuine investment facilitates sustainable development.

The costs of irreversible change are implicitly captured in Arrows' genuine investment model by using shadow prices in Equation (A.2). What Equation (A.2) does not explicitly consider is the effect that uncertainty over future benefits and costs has on the number of investments that are partially or completely irreversible. The fact that sustainability is defined as non-declining wellbeing over time ($dV / dt \geq 0$) helps to formally solve the described dilemma. Considering that future benefits and costs of genuine investment will always be uncertain, we determine that $d\hat{V} / dt \geq 0$ needs to be preserved as an important property of the genuine investment model (analogous to the definition of sustainability), where $\hat{V}$ solely considers changes through **reversible investments**. Thus, we assume that genuine investments $\hat{V}(t)$ require among them investments *I* that are irreversible (to keep the model simple, we assume *I* to be time invariant). This is the difference in V and $\hat{V}$: while V includes reversible and irreversible investments, $\hat{V}$ only considers reversible investments. The valuation of $\hat{V}$ comprises uncertainty effects, since $\hat{V}$ follows a GBM. Thus, all three additional features of sustainability-related investment projects are taken into consideration: uncertainty is taken into account by letting $\hat{V}$ follow a GBM, flexibility by making use of the option value concept, and irreversibility by assigning a separate parameter *I* that explicitly reflects the effects of irreversibility.

Arrow et al.'s (2012) model requires a forecast of the economy's future after time t to well-define the intergenerational wellbeing. The forecast depends on the stock of assets at time t , advancements in technology, consumer preferences, and institutions beyond t. Given that Arrow et al. (2012) takes these time-varying factors as exogenous, we suppose $\hat{V}(t)$ following a GBM, which enables us to endogenous future prices and costs to a certain degree without explicitly modeling them.

A stochastic process fulfilling the property of non-negativity through time is GBM. By letting intergenerational wellbeing $\hat{V}$ follow a GBM, uncertainty over future intergenerational wellbeing is introduced to the model (Pindyck 2000). The GBM features a constant percentage drift (or trend) parameter α , and a constant percentage volatility (or uncertainty) parameter σ . dz shall denote the increment of a Wiener process, which is normally distributed during the time interval Δt with zero mean and variance Δt . Consequently, Equation (A.2) can be reformulated as follows:

$$d\hat{V}(t) = \alpha\left(\hat{V}(t),t\right)dt + \sigma\left(\hat{V}(t),t\right)dz \tag{A.10}$$

$$= \alpha\hat{V}(t)dt + \sigma\hat{V}(t)dz \tag{A.11}$$

The stochastic differential equation in Equation (A.3) can be simplified as Equation (A.4), since we suppose it is a GBM, so that $\alpha\left(\hat{V}(t),t\right)=\alpha\hat{V}(t)$ and $\sigma\left(\hat{V}(t),t\right)=\sigma\hat{V}(t)$, where α and σ are constants. Percentage changes in $\hat{V}$ ($\Delta\hat{V}/\hat{V}$) are normally distributed in the natural logarithm of $\hat{V}$. Absolute changes in $\hat{V}$ ($\Delta\hat{V}$) are log-normally distributed. Since Equation (4) is continuous over time but not differentiable, we need Ito's Lemma. First, we take the natural log of $\hat{V}(t)$ and by using Ito's lemma,

$$d\left(\ln\hat{V}(t)\right)=\left(\ln\hat{V}(t)\right)' d\hat{V}(t)+\frac{1}{2}\left(\ln\hat{V}(t)\right)'' d\hat{V}(t)d\hat{V}(t)=\frac{d\hat{V}(t)}{\hat{V}(t)}-\frac{1}{2}\frac{1}{\hat{V}(t)^2}\sigma^2 V$$

$$=\frac{d\hat{V}(t)}{\hat{V}(t)}-\frac{1}{2}\frac{1}{\hat{V}(t)^2}\left(\alpha\hat{V}(t)^2 dt^2+2\sigma\alpha dtdz+\sigma^2\hat{V}(t)^2 dz^2\right)$$

$$=\frac{d\hat{V}(t)}{\hat{V}(t)}-\frac{1}{2}\frac{1}{\hat{V}(t)^2}\sigma^2\hat{V}(t)^2 dt$$

since dt^2, $dtdz$ is equal to 0 and $dz(t)^2=dt$. Then, we use Equation (A.4).

$$d\left(\ln\hat{V}(t)\right)=\left(\alpha-\frac{\sigma^2}{2}\right)dt+\sigma dz(t)$$

As a next step, we integrate the above equation from 0 to t, and we get

$$\ln\hat{V}(t)=\ln\hat{V}(0)+\left(\alpha-\frac{\sigma^2}{2}\right)t+\sigma z(t)-\sigma z(0)$$

Since the increment of the GBM is normally distributed and is equal to 0 at $t=0$. Then we get

$$\hat{V}(t)=\hat{V}(0)+exp\left(\left(\alpha-\frac{\sigma^2}{2}\right)t+\sigma z(t)\right) \qquad \text{(A.12)}$$

Thus far, we have explained how uncertainty about the future level of intergenerational wellbeing $\hat{V}$ is included in our model of genuine investment. In the following paragraphs, we will analyze how the flexibility of investment timing might be taken into account. McDonald and Siegel (1986)McDonald and Siegel (1986) developed the basic model of the value of waiting to invest under uncertainty, irreversibility, and flexibility known as the real option model. Scatasta et al. (2006) are among many researchers who suggest making use of the real option model, that is, comparing the value of an immediate genuine investment decision to the option value of a postponed genuine investment decision. Therefore, we will henceforth differentiate between the value $\hat{V}$ and the option value $F\left(\hat{V}\right)$ of genuine investment projects.

The value to option to invest is a well-known concept. However, for the sake of completion of the model, we will provide the Bellman equation (for a detailed explanation, see Dixit and Pindyck, 1994, Chapters 4 and 5). Since there is no immediate payout before investment, the continuation region, where no investment is made, of the continuous time Bellman equation (Dixit and Pindyck 1994 p. 140) is:

$$\delta F = \frac{1}{dt} E\left(dF\right)$$

$$\delta F dt = E\left(dF\right)$$

where $\delta > 0$ is the discount rate. The left-hand side of the equation is the expected return of the investment, and the right-hand side is the expected capital appreciation over an interval dt. Now, by Ito's Lemma, we calculate dF and take the expected value of it $E\left(dF\right)$. If we plug into the above equation, we reach the following Bellman equation:

$$\frac{\sigma^2 \hat{V}^2}{2} F''\left(\hat{V}\right) + \alpha \hat{V} F'\left(\hat{V}\right) - \delta F = 0$$

Note that we take $\delta - \alpha > 0$, otherwise growth being larger or equal then discount rate leads the analysis to a trivial case or NPV. Moreover, the above equation satisfies the following boundary conditions (Dixit and Pindyck 1994 p. 141)

$$F(0) = 0 \quad \text{(A.13)}$$

$$F\left(\hat{V}^*\right) = \hat{V}^* - I \quad \text{(A.14)}$$

$$F'\left(\hat{V}^*\right) = 1 \quad \text{(A.15)}$$

Following Dixit and Pindyck (1994), who showed that under the assumption $\hat{V}$ follows a GBM, the option value of genuine investments *F(*$\hat{V}$ *)* shall be given by the following equation, where A_1 and A_2 are constants that have yet to be determined, and β_1 and β_2 are the two roots of the fundamental quadratic:

$$\beta_1 = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{\left[\frac{\alpha}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2(\delta - \alpha)}{\sigma^2}} > 1, \text{ and } \beta_2 = \frac{1}{2} - \frac{\alpha}{\sigma^2} - \sqrt{\left[\frac{\alpha}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2(\delta - \alpha)}{\sigma^2}} < 0 \text{ (}$$

δ denotes the exogenous discount rate:

$$F\left(\hat{V}\right) = A_1\hat{V}^{\beta_1} + A_2\hat{V}^{\beta_2} \quad \text{(A.16)}$$

Note that Equation (A.9) is subject to the boundary conditions (A.6), (A.7), and (A.8), where I represents the sunk or irreversible costs of a genuine investment project. Boundary condition (A.6) implies that $A_2 = 0$, so that Equation (A.9) can be reduced to:

$$F\left(\hat{V}\right) = A\hat{V}^{\beta_1} \quad \text{(A.17)}$$

Boundary conditions two and three concern optimal investment because is a threshold value at or above which it is optimal to invest. The second condition (Equation 7) is the value-matching condition, and the last condition (Equation A.8) is the smooth-pasting condition (Dixit and Pindyck 1994; Pindyck 2000, 2002). Boundary conditions two and three concern optimal investment because $\hat{V}^*$ is a threshold value at or above which it is optimal to invest. The second condition (Equation A.7) is the value-matching condition, and the last condition (Equation A.8) is the smooth-pasting condition (Dixit and Pindyck 1994; Pindyck 2000, 2002).

Accordingly, the sustainability criterion shall be non-declining intergenerational wellbeing under irreversibility as well as uncertainty and flexibility over time $d\hat{Y}/dt \geq 0$, with:

$$\hat{Y}(t) = F\left(\hat{V}_t, I\right) \tag{A.18}$$

Since we aim to look at irreversibility effects in more detail, we now pose the question of how much irreversible cost can be accepted (the threshold value of I, I^*) while maintaining a positive genuine investment rate $d\hat{Y}/dt \geq 0$, where I is the stock of irreversible genuine investments. Therefore, we substitute Equation (A.11) into Equations (A.7) and (A.8). By rearranging, we get the following (McDonald and Siegel 1986):

$$A = \frac{\left(\hat{V}^* - I\right)}{\left(\hat{V}^*\right)^{\beta_1}} = \frac{(\beta_1 - 1)^{\beta_1 - 1}}{[(\beta_1)^{\beta_1} I^{\beta_1 - 1}]} \tag{A.19}$$

$$\hat{V}^* = \frac{\beta_1}{\beta_1 - 1} I \tag{A.20}$$

and we have for the value of investment:

$$F(V, I) = \begin{cases} A\hat{V}^{\beta_1} \hat{V} \leq \hat{V}^* \\ \hat{V} - I > \hat{V}^* \end{cases} \tag{A.21}$$

The result in Equation (A.13) indicates that an investment will be sustainable if the actual value of project *V* is larger than $\hat{V}^*$.

5. Appendix B

Thus far, the discount rate has been exogenously introduced into the model. In this section, we discuss how to calculate the equilibrium expected rate of return on investment opportunity following the method introduced by McDonald and Siegel (1986). Note that the main difference between the two models is the cost of investment. In our model, we take the value of investment *V* as a GBM, whereas McDonald and Siegel (1986) take both the cost and the benefit as a GBM. We should also point out that our model aims to measure genuine investment (the change in intergenerational wellbeing). Thus, we define the value of an investment as the discounted flow of current and future generations, and, following Arrow et al. (2012), to measure comprehensive wealth, we show that the changes in an economy's set of capital assets weighted at shadow prices, including time, equals the change in wellbeing (Arrow et al., 2012, p.325). This approach already captures the costs of irreversible change by using shadow prices, so we take the cost of investments as time-invariant. However, to capture the uncertainty and irreversibility of benefits in the model, we take the genuine investment as GBM.

We define the option value to invest by Equations (A.9) and (A.10). Now, we follow McDonald and Siegel's (1986) approach. In the Ito derivative of Equation (A.10), the option value is:

$$\frac{dF}{F} = \beta_1\left(\alpha_{\mathrm{v}}dt + \sigma_{\mathrm{v}}dz_{\mathrm{v}}\right) + \beta_1\left(\beta_1 - 1\right)\frac{1}{2}\sigma_{\mathrm{v}}^2 dt. \qquad \text{(B.1)}$$

The only risk or unanticipated component of the return on F is the term $\beta_1\sigma_{\mathrm{v}}dz_{\mathrm{v}}$, which is a weighted average of the unanticipated components in the rate of change V. We know from asset pricing models that the risk premium earned on an asset and the riskiness of the asset are proportional.

Hence, the discount rate for future payoffs and the equilibrium expected rate of return on the investment opportunity are:

$$\delta = r + \beta_1 \left(\alpha_{\mathrm{v}}^* - r \right) \tag{B.2}$$

where α_v^* is the expected rate of return of the assets with an unexpected rate of return $\beta_1 \sigma_{\mathrm{v}} dz_{\mathrm{v}}$, r is the risk-free rate. With this, we define risk premium earned, which is the proportional increase in the riskiness of the assets, $\beta_1 \left(\alpha_{\mathrm{v}}^* - r \right)$. Finally, if we equate the required rate of return on F with the actual expected rate of return on F , then we can arrive at the following equation and solve for β_1:

$$\left[r + \beta_1 \left(\alpha_{\mathrm{v}}^* - r \right) \right] dt = E\left(\frac{dF}{F} \right) \tag{B.3}$$

$$\left[r + \beta_1 \left(\alpha_{\mathrm{v}}^* - r \right) \right] dt = \beta_1 \alpha_{\mathrm{v}} + \beta_1 \left(\beta_1 - 1 \right) \frac{1}{2} \sigma_{\mathrm{v}}^2 \ ]dt \tag{B.4}$$

$$\beta_1 = \frac{1}{2} - \frac{r - \gamma_{\mathrm{v}}}{\sigma^2} + \sqrt{\left[\frac{r - \gamma_{\mathrm{v}}}{\sigma^2} - \frac{1}{2} \right]^2 \frac{2r}{\sigma^2}}$$

where $\gamma_{\mathrm{v}} = \alpha_{\mathrm{v}}^* - \alpha_{\mathrm{v}}$, which defines the difference between the expected rate of return required by investors and actual drift.