Accounting for Taste and Equity: Measuring the True Cost and Fairness of Cultural Value Using Emergy Analysis

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Accounting for Taste and Equity: Measuring the True Cost and Fairness of Cultural Value Using Emergy Analysis

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Abstract

This study applies emergy analysis as a framework to quantify both the environmental impact and social equity dimensions of music production. Using David Byrne's 2004 album *Grown Backwards* as a case study, I integrate economic data with emergy calculations to estimate total environmental resource consumption across the album's full lifecycle. Findings reveal that 98.77% of total emergy derives from the energy-intensive production and distribution of physical media. I introduce a novel "return on emergy" ($\boldsymbol{\rho}$) metric to evaluate distributional fairness among stakeholders. The analysis shows that the record label's return on emergy per labour hour is approximately 28 times higher than the artist's, highlighting a significant structural imbalance in benefit distribution. This research contributes to sustainability and equity discourse in cultural production, offering a holistic framework for assessing the true cost and fairness of cultural value in the digital age. Methodologically, it provides a replicable template for applying emergy analysis to cultural products; substantively, it introduces the $\boldsymbol{\rho}$ metric and generates new empirical findings about the environmental and distributional implications of cultural production systems.

Keywords: Emergy analysis, Cultural value, Sustainability, Social equity, Music industry, Environmental impact, JEL: Q50 · Z11 · L82

1 Introduction

The music industry has experienced profound transformation driven by technological change and shifting consumption patterns [1]. These shifts have reconfigured the industry's economic landscape and prompted growing scrutiny of the environmental costs of music production and consumption [2]. At the same time, questions about the fairness of how cultural value is distributed among creators and intermediaries have intensified [3].

Traditional economic metrics are poorly suited to capturing either the full environmental footprint or the social equity dimensions of cultural products. This study applies emergy analysis, developed by Odum [4], as a framework for addressing both limitations simultaneously. Emergy analysis converts diverse resource inputs—from raw materials to human labour—into a common unit of solar emjoules, enabling comprehensive assessment of a product's total environmental support [5]. Crucially, I extend this framework to social equity by introducing a novel "return on emergy" (ρ) metric that relates each stakeholder's labour input to their financial return, both expressed in energy terms.

Through comprehensive analysis of David Byrne's 2004 album *Grown Backwards*, this research addresses four questions: (1) Can emergy analysis provide meaningful insights into music production's resource use and environmental impact? (2) How does emergy compare with traditional economic measures in assessing cultural products? (3) How can emergy analysis shed light on social equity in cultural value distribution? (4) What are the implications for sustainability and fairness policy in the music industry?

This study serves dual purposes. Methodologically, it provides a detailed template for applying emergy analysis to cultural products, documenting data sources, calculations, and boundary decisions to enable replication across different albums, artists, and genres. Substantively, it introduces and operationalises a novel equity metric and generates new empirical findings about the environmental and social costs of music production during the physical-to-digital transition. While the case study is historically specific—anchored in 2004—both the methodological framework and the conceptual innovation of equity-based emergy metrics are designed for broader application.

2 Theoretical Framework

This study integrates cultural value, economic value, environmental impact, and social equity as interconnected dimensions of cultural production [6]. Cultural value encompasses aesthetic, symbolic, and social significance—inherently subjective and multidimensional. Economic value reflects monetary worth as expressed through market mechanisms such as sales figures and streaming revenues. Environmental impact, measured through emergy analysis, represents the ecological cost embedded in a product's full resource history [4]. Social equity concerns the fairness with which benefits, costs, and opportunities are distributed among stakeholders [3].

These dimensions interact continuously in the music industry. Cultural value drives music creation and shapes consumer behaviour, generating economic value. Economic incentives in turn influence production and distribution methods with environmental and equity consequences. When recognised, these environmental and social impacts can feed back into cultural perceptions and economic decisions.

Emergy analysis converts diverse inputs—from raw materials to human labour—into a common unit (solar emjoules), enabling comprehensive comparison of a product's total environmental support [5, 7]. The ρ metric builds on this foundation: it operationalises the relationship between stakeholder labour input (converted to emergy) and financial return (also converted to emergy), drawing on Odum's foundational principle that energy flows underlie economic value [4]. The framework synthesises perspectives from cultural economics [6], systems ecology [7], cultural labour studies [3], and environmental music analysis [2].

3 Literature Review

3.1 The Evolution of the Music Industry in the Digital Age

The music industry has undergone profound transformation propelled by technological advancement and shifting consumer behaviour. Wikström's comprehensive account [1] charts the industry's journey from physical media dominance to the current streaming-centric landscape, documenting how digitalisation has fundamentally reshaped the entire value chain of production and consumption, from artist discovery to revenue models.

Leyshon [8] investigates the "softwarisation" of the music industry, showing how digital technologies have democratised production and distribution while simultaneously precipitating what he terms a "crisis of value." The sheer abundance of available music challenges traditional notions of scarcity and worth, complicating the assignment of both cultural and economic value.

The shift towards streaming as the dominant mode of music consumption has further complicated the economic landscape. Aguiar and Waldfogel [9] find that while streaming has contributed to overall industry growth, it has also concentrated revenue distribution among top artists, raising critical questions about the economic viability of niche genres and emerging creators.

Marshall [10] argues that while record labels' traditional functions have been disrupted, they continue to play pivotal roles in artist development and marketing, with power dynamics between artists and labels shifting only gradually. The digital transformation has also had profound implications for copyright and intellectual property frameworks [11], which have struggled to adapt to the realities of digital reproduction and distribution. These changes form the essential backdrop against which any analysis of cultural value, environmental impact, and social equity must be situated.

3.2 Alternative Methodologies for Assessing Cultural and Environmental Value

The limitations of traditional economic metrics in capturing the holistic impact of cultural products have spurred exploration of alternative methodologies. Life Cycle Assessment (LCA), ecosystem services frameworks, and contingent valuation methods have each been adapted to address the unique challenges posed by the music industry, reflecting a growing recognition that cultural value is complex and multidimensional.

Brennan and colleagues [2, 12] have traced the environmental consequences of vinyl and CD manufacturing and compared physical and digital delivery formats, providing crucial per-unit benchmarks: physical CDs require 27 MJ and produce 3.2 kg CO_2; digital albums require 8 MJ and produce 0.4 kg CO_2; digital singles require 0.8 MJ and produce 0.04 kg CO_2. Devine [13] has further exposed the hidden energy costs of digital music consumption, complicating assumptions about the ecological neutrality of streaming.

Ecosystem services frameworks, adapted from environmental economics, attempt to quantify the diverse benefits that cultural products provide to society—including aesthetic enrichment, spiritual experience, social cohesion, and cultural heritage preservation [14]. Contingent valuation methods use survey techniques to elicit individuals' willingness to pay for non-market goods, such as the continuation of public music programmes [15]. While each of these methodologies offers valuable insights, none integrates environmental and equity analysis within a single systems framework.

3.3 Environmental Sustainability of Music Production

Growing environmental awareness has brought increasing scrutiny to the ecological sustainability of music production and distribution. Vinyl records' resurgence, while culturally significant, carries substantial environmental costs: PVC production releases considerable greenhouse gases [16, 17], and the manufacturing process involves toxic chemicals and generates wastewater [18]. CDs, composed of polycarbonate and aluminium, have a marginally lower environmental impact but pose significant recycling challenges [19].

Digital streaming eliminates the need for physical media but introduces diffuse and growing energy demands. Powering data centres and facilitating data transfer for streaming services generates considerable carbon emissions [20], and Unruh et al. [21] provide a sobering account of the hidden environmental costs of digital lifestyles more broadly. While streaming's per-transaction emissions are lower than those of physical media, the sheer volume of data transferred makes the aggregate impact significant.

Bottrill et al. [22] provided an early comprehensive assessment of the UK music industry's carbon footprint, documenting that in 2009 the industry's energy mix was approximately 85% non-renewable and 15% renewable. This finding is used as a proxy for the 2004 production context examined in this study, providing essential context for understanding the environmental intensity of music production during the transitional period under analysis.

These studies offer valuable insights into the environmental dimensions of music production and consumption but typically focus on physical and digital distribution channels, with less attention to the production process itself and the broader social and economic dimensions of music ecosystems. This study addresses that gap by employing emergy analysis to provide a more comprehensive assessment of music production's environmental and social sustainability.

3.4 The Promise of Emergy Analysis

Emergy analysis, as conceived by H.T. Odum [4], offers a promising methodology for assessing the true cost and value of cultural products. By enabling fine-grained understanding of the relationships between cultural production and its ecological foundations, it provides a bridge between economic valuation and environmental impact assessment [5].

The methodology has been successfully applied to diverse systems—from agricultural production [23] to wastewater treatment [24]—demonstrating its versatility and robustness. Most relevant to this study, Abel [25] demonstrated that emergy analysis can quantify cultural production, calculating transformities across a global hierarchy of human labour and cultural outputs and establishing a framework for treating creative work within systems ecology. Recent methodological advances have further extended the framework's applicability [26, 27], highlighting its adaptability across diverse and complex systems. Despite this, emergy analysis has not previously been applied to music production, and its potential for illuminating equity within cultural systems remains unexplored.

3.5 Equity and Fairness in the Music Ecosystem

The music industry is characterised by pronounced power asymmetries, compensation disparities, and instances of artist exploitation [3, 28]. Critical scholarship has examined the precarious labour conditions of many cultural workers, the unequal bargaining power between individual artists and large corporate intermediaries, and the difficulty of securing fair compensation in the digital economy. Hesmondhalgh [3] provides a comprehensive analysis of cultural work, documenting how creative labour is systematically undervalued despite being central to the generation of cultural value.

Streaming platforms have intensified these equity concerns. Marshall [10] documents the controversies over artist royalties from on-demand streaming services, revealing how new distribution models can entrench or exacerbate existing inequities rather than resolve them. Per-stream royalty rates remain notoriously low, and revenue distribution continues to favour established artists and corporate intermediaries over emerging creators.

Quantitative, systems-based methodologies capable of measuring disparities in benefit distribution relative to contributions remain scarce. The ρ metric proposed in this study is designed to address this gap. It offers a potential means of quantifying equity by comparing the emergy invested by different stakeholders—artists, labels, platforms—against the emergy they receive in the form of economic benefits, complementing existing qualitative critiques with empirical, energy-based measurement.

3.6 Research Gap

Existing literature comprehensively addresses the digital transformation of the music industry, the challenges of quantifying cultural value, the environmental consequences of music production and consumption, and the structural inequities of creative labour. Methodologies such as LCA and contingent valuation offer valuable but partial insights. Emergy analysis emerges as a holistic, proven tool with extensive applications in other sectors but extremely limited use in cultural production.

A significant gap exists for a framework that integrates environmental, economic, and social equity dimensions to quantify cultural production's 'true cost' and assess its fairness. No existing study has applied emergy analysis to a music album with the dual aim of measuring its comprehensive environmental resource base and analysing the equity of value distribution among contributors using an energy-based metric. This study addresses that gap directly, bridging divides between economic valuation, environmental impact assessment, and social equity analysis in the music industry context.

4 Methodology

4.1 Case Study Selection

David Byrne's 2004 album *Grown Backwards* was selected on the basis of the exceptional transparency of its financial documentation. Byrne [29] provides an unusually detailed account of the album's economic structure, including a full breakdown of the $225,000 advance, sales figures (127,000 physical CDs, 8,000 digital albums, 74,000 digital singles), revenue distribution, and stakeholder payments—data that are rarely available in music industry studies.

This study is intended to function as an exemplar and template for future investigations into emergy flows and environmental impacts across popular music ecosystems. By carefully documenting methodology and findings, I aim to provide a replicable roadmap for applying similar approaches to other albums, artists, and genres.

The 2004 release date, while not reflecting the most current industry practices, captures the industry at a key transitional moment between physical and digital dominance. This period offers valuable insight into the ecological and economic implications of that shift. The detailed financial snapshot provides a clear baseline for analysing value distribution among stakeholders and serves as a useful comparative benchmark against which more recent, streaming-dominated models can be assessed.

4.2 System Boundary and Data Collection

The system boundary encompasses the full lifecycle of *Grown Backwards* from inception to consumption, based on sales and usage data to 2010. This includes:

1. Creative development (songwriting, arranging, pre-production)
2. Recording and production (tracking, mixing, mastering)
3. Manufacturing of 127,000 physical CDs (raw materials, disc and packaging fabrication)
4. Distribution (logistics for physical CDs and digital infrastructure)
5. Marketing and promotion
6. Retail operations (physical and digital)
7. Consumer use (energy required to play the album on various devices)

Key exclusions are: vinyl production (comparable data are unavailable from Byrne [29]), consumer playback device lifecycles (these constitute a separate and complex analytical system), live performance (treated as a separate product system), and long-term cultural impact beyond point of sale.

Primary data are drawn from the detailed financial records and sales figures in Byrne [29]. Labour hours were estimated using a multi-method approach: (1) fee-based estimation (dividing known fees by industry-standard hourly rates), (2) project timeline estimation (based on standard practices for major-label productions), and (3) cross-referencing against expert knowledge of standard industry timelines.

Secondary data sources include energy consumption and CO_2 emission coefficients from Weber et al. [30], providing per-unit data: physical CDs (27 MJ, 3.2 kg CO_2), digital albums (8 MJ, 0.4 kg CO_2), and digital singles (0.8 MJ, 0.04 kg CO_2). Transformity values are taken from Ingwersen [31]: electricity (3.71×10^5 sej/J) and human labour (6.74×10^6 sej/J). The money transformity (1.55×10^{12} sej/\$) corresponds to the U.S. emergy-to-money ratio for 1990 USD, as tabulated in Odum [4] and applied throughout Brandt-Williams [32]. Although this value pre-dates the 2004 album release, it is the closest well-documented benchmark in the published emergy literature and is used here as a standard reference value. Material transformities, including plastic (1.0×10^7 sej/g), are sourced from Bottrill et al. [22]. Studio energy consumption data come from the U.S. Energy Information Administration's Commercial Buildings Energy Consumption Survey [33] (22.5 kWh per square foot annually), with an average studio size of 1,000 sq. ft. [34]. The 85/15 non-renewable/renewable energy mix from Jones et al. [35] is used as a proxy for 2004 conditions.

4.3 Emergy Analysis

The analysis follows a systematic, multi-step process adhering to established emergy accounting protocols [4, 36].

Step 1: Inventory Analysis. All energy and material flows were quantified. Physical CD production energy was calculated as: 127,000 units × 27 MJ/CD = 3,429,000 MJ [30]. Digital sales energy used coefficients of 8 MJ/album and 0.8 MJ/single. Studio electricity was estimated from a 1,000 sq. ft. studio operating over a two-month recording period, yielding 3,750 kWh total energy use.

Step 2: Conversion to Emergy. All quantified flows were converted to solar emjoules using specific transformity values. Energy flows in joules were multiplied by the electricity transformity (3.71×10^5 sej/J) [31]. Labour hours were converted to joules assuming human metabolic power output of 100 J/s during work, then multiplied by the labour transformity (6.74×10^6 sej/J) [31]. Material flows (e.g., plastic in CD cases) were multiplied by the appropriate material transformity [22].

Step 3: Classification and Summation. Converted emergy values were classified by input type (renewable, non-renewable, purchased) and process stage. All emergy inputs were summed to calculate Total Emergy (U):

$$U = \sum_i \text{Emergy}_i \tag{1}$$

where i represents all identified resource flows.

4.4 Economic Analysis

The economic analysis is drawn directly from Byrne [29] and includes: (1) revenue breakdown, categorising income into retail revenue ($1,097,600) and label gross revenue ($1,372,000), totalling $2,469,600 gross revenue; (2) cost analysis, examining the full breakdown of Byrne's $225,000 advance into studio expenses ($54,000), musician fees ($85,500), engineer fees ($38,250), arranger fees ($15,750), and other costs ($31,500); (3) profit calculation, determining Byrne's net income ($58,000 from $276,000 revenues minus $218,000 costs) as a percentage of total gross revenue (2.35%); and (4) stakeholder financial mapping, quantifying revenue distribution among all major stakeholders.

4.5 Social Equity Analysis: The Return on Emergy (ρ) Metric

To assess benefit distribution quantitatively, I introduce the "return on emergy" (ρ) metric, adapting the financial concept of return on investment to an emergy basis. The metric evaluates the efficiency with which stakeholders convert invested labour emergy into captured economic emergy.

Theoretical Foundation. The metric rests on the systems ecology principle that energy flows underlie all economic value [4]. A distributionally equitable system would show reasonable alignment between the emergy a stakeholder contributes (primarily through labour) and the emergy they receive in return. Significant deviations from this alignment indicate potential inequity.

Calculation Methodology. For each major stakeholder i:

Step 1: Emergy Investment (EI_i)—the stakeholder's labour contribution converted to emergy:

$$EI_i = \left(LH_i \times 3{,}600\ \mathrm{s\,hr^{-1}} \times 100\ \mathrm{J\,s^{-1}}\right) \times \tau_L \tag{2}$$

where LH_i is the estimated labour hours for stakeholder i, 360,000 J/hr is the assumed human metabolic power output during work, and $\tau_L = 6.74 \times 10^6$ sej/J is the labour transformity [31].

Step 2: Emergy Returns (ER_i)—the stakeholder's financial gain converted to emergy:

$$ER_i = P_i \times \tau_M \tag{3}$$

where P_i is the profit or fee in USD for stakeholder i, and $\tau_M = 1.55 \times 10^{12}$ sej/\$ is the money transformity for 1990 USD [4, 32].

Step 3: Return on Emergy ($\rho_{\mathrm{total},i}$):

$$\rho_{\mathrm{total},i} = \frac{ER_i}{EI_i} \tag{4}$$

This dimensionless ratio indicates how many units of economic emergy are returned per unit of labour emergy invested.

Step 4: Per-hour normalisation ($\rho_{\text{hour},i}$):

$$\rho_{\text{hour},i} = \frac{\rho_{\text{total},i}}{LH_i} \tag{5}$$

This final metric, expressed in sej return per sej invested per hour, provides a standardised measure of value-capture efficiency that enables fair comparison across stakeholders with different total hours worked.

The analysis covers six stakeholder groups for which both financial data and labour hour estimates could be robustly derived: (1) David Byrne (artist), (2) musicians (session players), (3) engineer/mixing, (4) arranger/copyist, (5) producer, and (6) record label management/administration. Financial data are taken directly from Byrne [29]; labour hour estimates are derived using the methods described in Sect. 4.2.

5 Results

5.1 Total Emergy Inputs

Total emergy input for *Grown Backwards* was 1.334146×10^{18} sej, representing the cumulative environmental support required throughout the album's lifecycle—a quantifiable measure of the "ecological memory" embedded in the cultural product [4].

Table 1 Breakdown of total emergy inputs for *Grown Backwards*

Component	Emergy (sej)	% of total
Energy use (CD manufacturing & distribution)	1.317866×10^{18}	98.77
Human labour (creative & technical)	1.1277×10^{16}	0.85
Studio electricity	5.0085×10^{15}	0.38
Total (U)	1.334146×10^{18}	100.00

The overwhelming dominance of energy use (98.77%), attributable almost entirely to the manufacture, packaging, and global distribution of 127,000 physical CDs, confirms that the environmental burden of album production in this era was located not in the creative process but in the industrial systems required to replicate and disseminate the finished product at scale [2, 30]. Studio electricity and human labour together account for only 1.23% of the total emergy budget.

5.2 Energy Use and CO_2 Emissions

Total primary energy consumption associated with the album's production and distribution was 3,552,200 MJ. Corresponding CO_2 emissions, based on emission factors for the relevant energy mix [30], were estimated at 412.56 metric tonnes.

The stark contrast in emissions between physical and digital formats underscores the significant potential environmental benefit of digital distribution. Digital sales,

Table 2 CO_2 emissions by distribution method

Method	Units sold	Energy (MJ)	CO_2 (t)	% of total
Physical CDs	127,000	3,429,000	406.40	98.51
Digital sales[a]	82,000	123,200	6.16	1.49
Total	—	3,552,200	412.56	100.00

[a] Album-equivalents; singles converted at a 10:1 ratio [30].

representing approximately 12% of total album-equivalent units sold (82,000 digital equivalents versus 127,000 physical CDs), contributed only 1.5% of total CO_2 emissions. This finding provides robust quantitative support for the environmental rationale behind the industry's shift towards digital formats, confirming previous comparative assessments [13, 30].

5.3 Economic Analysis and Value Distribution

Total gross revenue generated by *Grown Backwards* was $2,469,600, comprising retail revenue ($1,097,600, 44.5%) and label gross revenue ($1,372,000, 55.5%).

Table 3 Stakeholder financial outcomes

Stakeholder	Amount (USD)	% of gross revenue
David Byrne (Artist)		
Total revenues received	$276,000	11.2
Cost of making record	$218,000	8.8
Net profit	$58,000	2.35
Record label		
Gross revenue	$1,372,000	55.5
Net profit	$271,656	11.0
Other allocations		
Marketing/promotion	$370,440	15.0
Retail profit	$123,480	5.0
Publishing royalties	$123,480	5.0
Other expenses	$1,333,584	54.0

Byrne's net profit of $58,000 represents only 2.35% of total gross revenue, illustrating the modest financial return to the primary creative artist despite the album's commercial success. This provides concrete evidence for the economic structure critiqued by scholars of creative labour [3]: a large proportion of generated value is captured by intermediaries and overheads rather than flowing back to the creator.

The breakdown of Byrne's $225,000 advance reveals the resource allocation during production: musician fees ($85,500, 38%), studio expenses ($54,000, 24%), engineer/mixing fees ($38,250, 17%), arranger/copyist fees ($15,750, 7%), and other expenses ($31,500, 14%). Over 62% of the advance was allocated directly to human creative and technical labour, reflecting the labour-intensive nature of professional music production [1].

5.4 Social Equity Analysis: Return on Emergy

Labour hour estimates for the six key stakeholders were: David Byrne (1,230 hours, based on creative development, recording, production oversight, and project management), session musicians (850 hours, estimated from $85,500 in fees at approximately $100/hr), engineer/mixing (380 hours, from $38,250 in fees), arranger/copyist (160 hours, from $15,750 in fees), producer (420 hours, from a $42,000 royalty), and record label management (500 hours, estimated to cover project management, A&R, marketing coordination, and administration).

Table 4 Return on emergy (ρ) by stakeholder

Stakeholder	Profit/fee (USD)	Labour (h)	Labour emergy (sej)	Economic emergy (sej)	ρ_{total}	ρ_{hour}
Record label	$271,656	500	1.213×10^{15}	4.075×10^{17}	335.8	0.672
Arranger	$15,750	160	3.88×10^{14}	2.36×10^{16}	60.8	0.380
Engineer	$38,250	380	9.22×10^{14}	5.74×10^{16}	62.2	0.164
Producer	$42,000	420	1.019×10^{15}	6.30×10^{16}	61.8	0.147
Musicians	$85,500	850	2.062×10^{15}	1.28×10^{17}	62.1	0.073
David Byrne	$58,000	1230	2.984×10^{15}	8.70×10^{16}	29.1	0.024

The record label's ρ_{hour} (0.672) is approximately 28 times that of David Byrne (0.024), meaning the label converts each hour of labour into economic emergy at 28 times the rate of the primary artist. The intermediary thus captures disproportionately high returns relative to its estimated labour input, while the artist—whose labour generated the core cultural and economic value of the product—receives the lowest return on labour investment of all stakeholders analysed.

Expressing values relative to Byrne as a baseline of 1.0 reveals the inverted value-capture structure in stark terms: record label (28.0×), arranger/copyist (15.8×), engineer/mixing (6.8×), producer (6.1×), musicians (3.0×), David Byrne (1.0×). Specialised support roles are compensated 3–16 times more efficiently per labour hour than the lead artist, and the corporate intermediary captures value 28 times more efficiently.

5.5 Comparative Context

To contextualise these findings, the same per-unit calculations were applied to Robbie Williams' *Greatest Hits* (2004), which sold approximately 2.3 million CDs—nearly 20 times the physical sales of *Grown Backwards* [37]. This yields an estimated total emergy of approximately 2.30×10^{19} sej, roughly 17 times higher than the present case study. This extrapolation underscores the significant scaling effect of commercial success on environmental impact, and situates this study's case within the broader range of industry resource intensities.

6 Discussion

6.1 Interpreting Environmental Costs

Total emergy of 1.334146×10^{18} sej quantifies the substantial biophysical support required to produce and distribute a moderately successful album in the mid-2000s. While specific to this case, it serves as a powerful heuristic for understanding the often-hidden ecological footprint of cultural goods.

The overwhelming concentration of emergy in physical media manufacture and distribution (98.77%) challenges narratives of dematerialisation in the digital age [8]. It confirms that the environmental impact of the music industry during this transitional period was intrinsically tethered to the material economy of fossil fuels, petrochemical plastics, and globalised logistics [2, 30].

The finding that direct studio electricity and human labour together constitute only 1.23% of total emergy is particularly instructive. It shifts the locus of environmental concern from the creative studio to the industrial systems of mass manufacturing and distribution, suggesting that sustainability efforts should prioritise material efficiency, circular economy principles for physical goods, and logistics decarbonisation over a narrower focus on greening the recording process itself.

The stark contrast in CO_2 emissions between physical and digital formats (406.4 vs. 6.16 tonnes) provides robust quantitative support for the environmental rationale behind the industry's digital transition. However, this finding must be contextualised carefully. While digital distribution eliminates the burdens of physical replication and shipping, it introduces a diffuse but growing energy demand from data centres, network infrastructure, and consumer devices [13, 21]. The per-unit advantage of digital is clear, but the aggregate impact of streaming—characterised by continuous data transmission and energy-intensive server infrastructure—presents a complex scaling challenge. The environmental promise of digitalisation is not absolute, but conditional on the progressive greening of digital infrastructure.

6.2 The Equity Paradox

The ρ analysis reveals a profound and systemic paradox. While human labour constitutes only a tiny fraction of total environmental emergy (0.85%), its distribution exposes severe economic inequities. The central finding—that the record label's ρ_{hour} (0.672) is approximately 28 times greater than David Byrne's (0.024)—presents a stark quantitative illustration of the value-capture disparity at the heart of the industry. This inversion, in which the corporate intermediary reaps disproportionately high returns relative to its labour input while the originating artist receives the lowest return on labour investment of any stakeholder analysed, provides empirical support for long-standing qualitative critiques of power imbalances in the creative industries [3, 28].

The performance of supporting roles adds further nuance. Specialised technical and creative contributors—arrangers, engineers, and producers—achieved ρ_{hour} values 6–16 times higher than Byrne's. This suggests that the prevailing economic model functioned more equitably for contracted, fee-for-service expertise than for the entrepreneurial artist who bears overarching creative risk, provides the foundational intellectual property, and invests years in embodied skill development. The artist's role—encompassing non-contractual hours of ideation, career-building, and personal investment—appears systematically undervalued by a system optimised for transactional labour. This misalignment between the source of cultural value and the capture of economic value represents a structural feature of the music industry, one that the transition to streaming has arguably reinforced through further revenue concentration and reduced per-stream royalties [9, 28].

The ρ metric thus serves as a valuable diagnostic tool, moving equity discussions from qualitative critique to quantitative, systems-based assessment. It reveals not merely that disparities exist, but where and to what magnitude they are most acute within the production network.

6.3 Methodological Contributions and Limitations

This study makes two methodological contributions. First, it demonstrates the applicability of emergy analysis to a complex cultural product, providing a replicable template for assessing the full environmental resource base of music albums and other creative works. Second, it extends the emergy framework by introducing the ρ metric—a novel, quantitative tool for analysing social equity within production ecosystems, bridging ecological economics and critical cultural studies. By converting both labour input and financial output into a common energy-based unit, the ρ metric offers a systems-level view of value distribution that complements traditional financial and qualitative analyses.

Findings must be interpreted in light of several limitations:

Temporal specificity: The analysis is a historical snapshot (2004 production, 2010 sales data). The industry's energy mix, manufacturing efficiency, and primary revenue models have evolved considerably, particularly with the rise of streaming. The 85/15 non-renewable/renewable energy ratio used as a 2004 proxy is certainly outdated. Similarly, the money transformity applied here (1.55×10^{12} sej/\$) reflects the U.S. emergy-to-dollar ratio for 1990 [4, 32], the closest well-documented value in the published emergy literature; by 2007 this ratio had risen to approximately 1.95×10^{12} sej/\$ [38], suggesting that the 1990 figure may slightly underestimate the emergy cost of money at the time of the album's release.

Case study specificity: A major-label release by a respected and well-documented artist may not be representative of independent, DIY, or streaming-era production contexts, which may have substantially different economic and environmental profiles.

Methodological boundaries: The exclusion of vinyl production (due to data constraints) omits a high-impact format. The system boundary also excludes the lifecycle of consumer playback devices, which represents a substantial part of the full environmental cost of music consumption.

The ρ metric: While innovative, the metric is a simplified proxy. It quantifies the efficiency of converting labour into economic value but does not capture non-monetary rewards such as artistic recognition, career capital, or creative fulfilment—dimensions that are important to many cultural workers and that may partially offset monetary disparities from the perspective of individual wellbeing, even while the structural inequity persists.

Future research should address these limitations through longitudinal studies tracking changes in emergy intensity and equity metrics, comparative analyses across genres and formats (particularly streaming and vinyl), expanded system boundaries including device lifecycles, and refinement of the equity framework to integrate non-monetary dimensions of value.

6.4 Policy Implications

The integrated findings suggest that policies aimed at fostering a sustainable cultural sector must address ecological and social fronts simultaneously, as environmental and equity costs are intertwined.

On the environmental side, the results indicate that policy attention should focus on the supply chain rather than the studio. Concrete recommendations include: incentivising renewable energy in manufacturing plants and data centres through tax breaks or grants; developing and certifying sustainable alternatives for physical media materials and packaging; incorporating environmental impact assessments (including emergy or carbon footprint calculations) into major-label album budgets and cultural grant applications; and supporting R&D and industry partnerships to improve energy efficiency in streaming data storage and transmission.

On the equity side, the ρ findings support structural reforms to rebalance value capture. Potential pathways include: reforming royalty structures through strengthened collective bargaining and advocacy for more favourable streaming royalty rates; standardising rights-reversion clauses to return copyrights to artists after defined periods; supporting artist cooperative and fan-funded models that align ownership with creative contribution; mandating clearer royalty reporting from labels and platforms; and integrating both sustainability and equity metrics into the criteria for public cultural funding.

The true cost of cultural value is a compound measure. It encompasses not merely market price or carbon footprint, but also the social cost of inequitable value distribution. A music industry that is genuinely sustainable must harmonise its relationship with the natural environment while ensuring that its economic structure justly rewards the creative labour at its centre.

7 Conclusion

This study demonstrates that emergy analysis provides a powerful, integrative framework for quantifying the environmental costs and illuminating the social equity dimensions of cultural production. Through detailed analysis of *Grown Backwards*, it moves beyond traditional economic valuation to reveal the complex interplay between artistic creation, industrial resource use, and economic value distribution.

The environmental findings are unequivocal: the production and distribution of physical music media at the turn of the digital age demanded substantial ecological investment, with 98.77% of total emergy attributable to energy-intensive manufacturing and logistics systems. This underscores that cultural products, experienced as intangible art, are materially grounded in biophysical flows with significant environmental consequences. The stark per-unit advantage of digital formats provides clear environmental rationale for the ongoing digital transition, while simultaneously sounding a cautionary note about the growing—if decentralised—energy appetite of digital infrastructure.

More innovatively, extending emergy analysis to social equity through the ρ metric quantifies persistent structural imbalances. The analysis reveals that the label captured economic returns approximately 28 times more efficiently than the primary artist per labour hour, crystallising with quantitative precision the long-standing qualitative critiques of creative industry fairness.

The theoretical and methodological contribution lies in deliberate synthesis. By bridging ecological economics, cultural valuation, and social equity analysis, this study proposes and operationalises a holistic, tripartite framework for assessing cultural value's 'true cost' across its interconnected economic, environmental, and social dimensions. This challenges siloed thinking and posits that sustainable, resilient cultural sectors cannot be built by addressing environmental impacts in isolation, nor by pursuing economic growth without regard for ecological limits and equitable reward.

While historically specific and subject to acknowledged limitations, this case study's primary value lies in its role as a methodological template and catalyst for broader inquiry. Detailed documentation provides a clear roadmap for future researchers to apply, adapt, and critique this framework.

The central question—can we measure cultural value's true cost?—can be answered affirmatively, but only by significantly expanding what 'cost' means. A genuinely complete accounting must encompass market price, hidden environmental burden, and the social cost of inequitable distribution. As the music industry and the wider cultural sector navigate the intertwined challenges of digital disruption and climate crisis, embracing multifaceted, systemic assessment will be essential to building creative ecosystems that are economically viable, culturally vibrant, ecologically sustainable, and socially just—industries that truly account for taste, and for the planetary and human resources that make it possible.

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Declarations

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Consent for publication Not applicable.

Data availability All data used in this study are available from published sources cited in the manuscript. Detailed calculations are provided in the appendices. Raw calculation spreadsheets and supplementary materials are available from the author upon reasonable request.

Materials availability Not applicable.

Code availability Not applicable.

Author contribution Single-author study. M.McL. conceived the study, collected and analysed the data, and wrote the manuscript.

Appendix A Detailed Emergy Calculations

Table A1 Physical CD production emergy

Item	Value
Energy per CD [30]	27 MJ
CDs produced [29]	127,000
Total energy	3,429,000 MJ
Transformity [31]	3.71×10^5 sej/J
Emergy (CDs)	1.272459×10^{18} sej

Table A2 Digital sales emergy

Item	Value
Energy per digital album [30]	8 MJ
Digital albums sold [29]	8,000
Energy per digital single [30]	0.8 MJ
Digital singles sold [29]	74,000
Total energy (digital)	123,200 MJ
Transformity [31]	3.71×10^5 sej/J
Emergy (digital)	4.57072×10^{16} sej

Appendix B Return on Emergy Calculations

Constants:

- Labour transformity: 6.74×10^6 sej/J [31]
- Human metabolic power output: 100 J/s $= 360{,}000$ J/hr
- Emergy per labour hour: 2.4264×10^{12} sej/hr
- Money transformity (1990 USD): 1.55×10^{12} sej/$ [4, 32]

Table A3 Studio electricity emergy

Item	Value
Annual energy per sq. ft. [33]	22.5 kWh
Studio size [34]	1,000 sq. ft.
Recording duration	2 months
Energy (2 months)	3,750 kWh
Conversion to joules	1.35×10^{10} J
Transformity [31]	3.71×10^{5} sej/J
Emergy (studio)	5.0085×10^{15} sej

Table B4 Total labour emergy

Item	Value
Total labour hours (estimated)	4,645 hr
Human metabolic power output	100 J/s
Total metabolic energy	1.6722×10^{9} J
Transformity [31]	6.74×10^{6} sej/J
Total labour emergy	1.1277×10^{16} sej

Example calculation—David Byrne:

$$EI_{\text{Byrne}} = 1{,}230 \text{ hr} \times 2.4264 \times 10^{12} \text{ sej hr}^{-1} = 2.984 \times 10^{15} \text{ sej} \tag{B1}$$

$$ER_{\text{Byrne}} = \$58{,}000 \times 1.55 \times 10^{12} \text{ sej } \$^{-1} = 8.7 \times 10^{16} \text{ sej} \tag{B2}$$

$$\rho_{\text{total,Byrne}} = \frac{8.7 \times 10^{16}}{2.984 \times 10^{15}} = 29.15 \tag{B3}$$

$$\rho_{\text{hour,Byrne}} = \frac{29.15}{1{,}230} = 0.024 \tag{B4}$$

References

[1] Wikström, P.: The Music Industry: Music in the Cloud, 2nd edn. Polity Press, Cambridge (2013)

[2] Brennan, M., Devine, K.: The cost of music. Popular Music **39**(1), 43–65 (2020)

[3] Hesmondhalgh, D.: The Cultural Industries, 4th edn. SAGE Publications, London (2019)

[4] Odum, H.T.: Environmental Accounting: Emergy and Environmental Decision Making. Wiley, New York (1996)

[5] Brown, M.T., Ulgiati, S.: Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. Ecol. Model. **178**(1–2),

201–213 (2004)

[6] Throsby, D.: Determining the value of cultural goods: how much (or how little) does contingent valuation tell us? J. Cult. Econ. **27**(3–4), 275–285 (2003)

[7] Odum, H.T., Odum, E.C.: Modeling for All Scales: An Introduction to System Simulation. Academic Press, San Diego, CA (2000)

[8] Leyshon, A.: Reformatted: Code, Networks, and the Transformation of the Music Industry. Oxford University Press, Oxford (2014)

[9] Aguiar, L., Waldfogel, J.: As streaming reaches flood stage, does it stimulate or depress music sales? Int. J. Ind. Organ. **57**, 278–307 (2018)

[10] Marshall, L.: 'Let's keep music special. F—Spotify': on-demand streaming and the controversy over artist royalties. Creative Ind. J. **8**(2), 177–189 (2015)

[11] Towse, R.: Economics of music publishing: copyright and the market. J. Cult. Econ. **41**(4), 403–420 (2017) https://doi.org/10.1007/s10824-016-9268-7

[12] Brennan, M., Archibald, P.: The economic cost of recorded music: Findings, datasets, sources, and methods. Technical report, University of Glasgow (2019). http://eprints.gla.ac.uk/183249/

[13] Devine, K.: Decomposed: The Political Ecology of Music. MIT Press, Cambridge, MA (2019)

[14] Crossick, G., Kaszynska, P.: Understanding the value of arts and culture: the AHRC cultural value project. In: Cultural Value and Cultural Policy. Arts and Humanities Research Council, Swindon, UK (2016)

[15] Noonan, D.S.: Contingent valuation and cultural resources: a meta-analytic review of the literature. J. Cult. Econ. **27**(3), 159–176 (2003)

[16] The Guardian: Back on the record: the environmental cost of vinyl's revival. The Guardian. Accessed 15 August 2024 (2020)

[17] Forde, E.: Nightmares on wax: the environmental impact of the vinyl revival. The Guardian. Accessed 15 August 2024 (2020)

[18] Baker, S.: Vinyl as event: Record Store Day and the value-vibrant matter nexus. Media Int. Aust. **173**(1), 45–58 (2019)

[19] The Conversation: Are CDs recyclable? And other ways to reduce the environmental impact of your music collection. The Conversation. Accessed 15 August 2024 (2023)

[20] Recording Arts: The environmental cost of streaming music. Recording Arts.

Accessed 15 August 2024 (2023)

[21] Unruh, G.C., Kiron, D., Kruschwitz, N., Reeves, M., Rubel, H., zum Felde, A.M.: The environmental footprint of digital technologies. MIT Sloan Manage. Rev. **60**(4), 1–5 (2019)

[22] Bottrill, C., Liverman, D.M., Boykoff, M.: Carbon soundings: greenhouse gas emissions of the UK music industry. Environ. Res. Lett. **5**(1), 014019 (2010)

[23] Chen, B., Chen, G.Q.: Emergy-based energy and material metabolism of the Yellow River basin. Commun. Nonlinear Sci. Numer. Simul. **14**(3), 923–934 (2009)

[24] Vassallo, P., Paoli, C., Fabiano, M.: Emergy required for the complete treatment of municipal wastewater. Ecol. Eng. **35**(5), 687–694 (2009)

[25] Abel, T.: Human transformities in a global hierarchy: emergy and scale in the production of people and culture. Ecol. Model. **221**(17), 2112–2117 (2010)

[26] Lou, B., Ulgiati, S.: Identifying the environmental support and constraints to the Chinese economic growth: an application of the emergy accounting method. Energy Policy **55**, 217–233 (2013)

[27] Amaral, L.P., Martins, N., Gouveia, J.B.: A review of emergy theory, its application and latest developments. Renew. Sustain. Energy Rev. **54**, 882–888 (2016)

[28] Hesmondhalgh, D.: Is music streaming bad for musicians? Problems of evidence and argument. New Media Soc. **23**(12), 3593–3615 (2021) https://doi.org/10.1177/1461444820953541

[29] Byrne, D.: How Music Works. McSweeney's, San Francisco, CA (2012)

[30] Weber, C.L., Koomey, J.G., Matthews, H.S.: The energy and climate change implications of different music delivery methods. J. Ind. Ecol. **14**(5), 754–769 (2010)

[31] Ingwersen, W.W.: Emergy as a life cycle impact assessment indicator: a gold mining case study. J. Ind. Ecol. **15**(4), 550–567 (2011)

[32] Brandt-Williams, S.L.: Handbook of Emergy evaluation: Folio #4—Emergy of Florida agriculture. Technical report, Center for Environmental Policy, University of Florida, Gainesville, FL (2002). Revised September 2002

[33] U.S. Energy Information Administration: Commercial buildings energy consumption survey (CBECS). Technical report, U.S. Department of Energy (2018)

[34] Recording Academy: Recording Studio Standards and Specifications. Recording

Academy. Industry data (2018)

[35] Jones, C., Comfort, D., Hillier, D.: The carbon footprint of the UK music industry in 2009. Technical report, Julie's Bicycle, London (2010)

[36] Brown, M.T., Ulgiati, S.: Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. **9**(1–2), 51–69 (1997)

[37] NME: 30 biggest selling CDs of the past 30 years. NME. Accessed 12 August 2024 (2019)

[38] Campbell, D.E., Lu, H., Walker, H.A.: Relationships among the energy, emergy, and money flows of the United States from 1900 to 2011. Frontiers in Energy Research **2**, 41 (2014) https://doi.org/10.3389/fenrg.2014.00041