8 Energy Economics of Product Design and its Environmental Impact

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Abstract

The field of Energy economics is broad and takes within its purview all the energy expended and accounts for the total amount of energy in the product. It also not only considers the optimization of the energy used to produce this product but also takes the consideration that the energy used and expended in the product while it is in use. This consideration and the consideration of the energy expended in the total supply chain to be able to produce this product gives the total amount of environmental impact of the product. This is a comprehensive way of looking and designing a green product.

Keywords: Green Product Design, Embodied Energy Economics, Green Production, Energy Economics, Lifecycle Energy Management.

Introduction

Like economics that focuses on the utilization and allotment of resources energy economics is a broad interdisciplinary field focused utilization, supply, demand, distribution and allocation of energy resources across societies. Basically, the field of energy economics studies how energy is utilized to drive economic growth and how these scarce resources, market structures and regulatory interventions shape the choices of utilization and usage of energy. Energy is one of the prime inputs in the production of industrial products and without it few if any can be produced; therefore, when there is abundance of energy the production of Industrial products is huge, creating economic expansion less inhibited, rather than scarcity slows macroeconomic output (Stern, 2011).Since energy production is a part of infrastructure development, economic growth and political systems, in order to analyse such, we need specialized models that are not the same as the tradition commodity framework.

The discipline and energy economics, historically speaking, put an emphasis on the extraction, pricing and optimal depletion of finite fossil fuels including oil coal and natural gas. This discipline was more interested in the optimal depletion of the fuel rather than looking at the entire supply chain. Recently, researchers started evaluating supply chain, global trade dynamics and how volatility in the energy sector creates impact on the macroeconomic health of the entire economy (Juhro et al., 2024). Now everybody in the economic supply chain's been able to understand the impact of using traditional fuel for economic development the environment and is moving toward sustainability and decarbonisation and the entire supply chain is in a transition movement right now.

It is only recently, realised that using fossil fuel energy input there are numerous challenges towards the environment particularly carbon emissions and pollution. Due to this reason and the market failing to understand the implications of environmental damage caused by traditional combustion energy economists evaluate the public interventions efficiency, carbon pricing and renewable energy to align market behaviour with the climate targets set (Blazquez et al., 2020). To do this it is also imperative to study the demand-side economics such as the behavioural barriers of the consumer to adopt energy-efficient technologies which tremendously affect the welfare benefits of climate policies (Gillingham et al., 2009).

Integration of green technologies in energy also bring with itself complex economic challenges. There is an economics angle of switching to green technologies where the cost benefit ratio needs to be determined and kept at a certain level. This is the reason why economists model mathematically the technical and financial feasibility of transitioning to solar, wind and or hydro resources assessing the investments required for such and the benefits it brings in and also the intermittent supply of such technologies energy into needs to be taken into consideration (Twidell& Weir, 2015). By combining mathematical models and pricing models with environmental science energy economists provides the policymakers and industrial decision-makers the analytical toolkits required to balance the economic growth ecological survival.

What is referred to as the design energy Paradox, is of a fundamental challenge in sustainable architecture, building science and industrial and Systems engineering. The design energy Paradox is about the decision-making mismatch or the decision-making and data availability mismatch in a project life-cycle. This energy design Paradox can be simply stated as the phase when the most amount of decision-making is required and impact could be done about the energy performance of the product or project is the exact time or phase when the least amount of empirical data is available about the energy performance of the project or the product (Braham, 2015). To understand the paradox, we can simply state it as the period of time when the greatest impact can be done on the energy performance of the project is the exact period when the least empirical data is available about the same. Therefore, when the data is available such design changes could not be done and when the data is not available the design is to be done.

In order to get an idea about the dilemma one can look at the project timeline split in two distinct phases:

The Early Design Phase

When the design has started, it is the time when the maximum amount of freedom is there for decisions to be made about the future of the product and/or the project. Decisions made at this stage or the conceptual stage like say for example while creating a building design there is a conceptual stage when the building's geometric massing, orientation relative to the sun ratios are to be calculated which constitutes about 80% of its operational energy footprint is when the data about the project's whereabouts is least available (Østergård et al., 2016). What is not available at the conceptual stage is the thermodynamic behaviour of the structural loads, the micro climate or the material interactions which are of paramount importance in determining the operational footprint of the energy usage of the building. Due to this reason the designers are forced to design a building with the rules of thumb, and/or historical records.

The Operational Phase

After the construction is completed, it is only then when the actual figures about the micro climate and other variables be found when there is little to none in ability of the designer to change the design in a fundamental way. These data are available through post-occupancy sensors, smart metres and others which create highly massive pool of real-world energy data. Consequently, the fundamental design flaws which is apparent now cannot be changed after the building is completed its construction or even if it could be done it is hugely expensive and cost benefit ratio is not at all good. Therefore at this period in time the inability to influence energy efficiency drops to nearly zero making the facility managers bound only marginal and superficial retrofits rather than systemic optimisations.

Green Engineering

The paradox of design and energy act as a structural bottleneck for decarbonisation. As it is apparent fundamental flaw inherent in the design of project – products and buildings the product or any design is fundamentally locked in the design phase and by the completion of the design phase any changes to the fundamental philosophy of design of that would not be done. Due to this reason engineers foresee the worst-case scenarios and design parts of the product in such a way that it works at suboptimal level for the lifetime of the product. For example, in order to guarantee the safety of any high-pressure valve the engineers might foresee and overdo the engineering of the valve which might make it cumbersome and work

ISBN: 978-93-49468-54-2

in some optimum way for the lifetime of it. This type of overengineering not only adds to the cost but also degrades the way such products work.

Furthermore, traditional methods of project management exacerbate this paradox effects. Traditionally, the energy and green consultants are brought in after the basic design philosophy and the conceptual design is completed. They are not made part of these teams. These are the reasons why when they are brought in, they can only work under certain constraint circumstances which can only alleviate the symptoms and not design solutions to the problem in the design. There are conceptual design solutions like changing the orientation of the building by certain degrees might solve an expensive window film designed for overheating problems. Such solutions cannot be given by the energy engineers because of the workflow and the time they are brought in.

Crumpling the Paradox

Let us consider a building designed as an example to understand how we can nullify the effects of the paradox. Modern engineering and other practices deploy targeted technical toolkits effectively shift that art collection to the beginning of the project timeline:

- Building information modelling BIM: these are types of software where building designers are able to understand the energy simulations of their design early in their products design (Jalaei et al., 2020).
- Predictive building energy simulation BEMS by running algorithmic sensitivity analysis during the conceptual phase virtual conditions would be created and tested in a computer before it is actually designed and developed.

Such methods are available now in the market and with the advent of artificial intelligence technology many more simulation methods available which can actually predict what can happen if certain situations arise and therefore the design flaw can be avoided by integrating it in the conceptual stage of the design.

"Eco-Efficiency"

The concept of eco-efficiency, a strategy framework guiding modern sustainable development, corporate environmental management and industrial ecology is one of the core pillars in energy economics. This concept and the idea was originally from world business Council for sustainable development (WBSCD) and it was coined in 1992 where is your succinctly defined as, “creating more goods and services with the usage of fewer resources and creating less pollution and waste” (Schaltegger& Burritt, 2005). Therefore, if we look at the concept it is about creation of goods and services of value with scars resources and less amount of pollution and waste. This addition of pollution and waste to the definition makes it more comprehensive in nature. Therefore, it fundamentally decouples the economic growth and environmental degradation and forces us to believe in work in the way of commercial profitability and ecological stewardship as interdependent goal rather than mutually exclusive goals.

Mathematically eco-efficiency can be expressed as a ratio that relates economic value to environmental impact:

$$\text{Eco-Efficiency} = \frac{Product\ or\ Service\ Value}{Environmental\ Influence}$$

Here the numerator represents the economic output such as net sales, unit production, volume that is produced as a function of economic value to the consumer's and the denominator represents the environmental inputs and outputs which not only includes the material consumption but also takes into account energy intensive operations, water depletion, greenhouse gas emissions in a comprehensive way to find out the efficiency of the production. Therefore in order to increase the efficiency of the product and production the industry has to either increase the numerator keeping the denominator constant or decrease the denominator keeping denominator constant or both (Sinkin et al., 2008).

Pillars of Eco-Efficiency

According to the environmental management frameworks enhancing eco-efficiency requires multidimensional industrial approach focused on seven primary foundation pillars:

- Minimisation of material intensity of goods and services
- Minimisation of energy intensity of production
- Reduction of toxic substances dispersion in nature
- Enhancing of recyclability of materials
- Maximisation of sustainable use of renewable resources
- Extension of durability of lifespan of products
- Increase of service intensity of goods, shifting from product ownership to service models

By integration of these practices the businesses can transform their supply chain from a linear supply chain to optimise closed-loop configurations that drastically lower operational overhead while mitigating regulatory risks associated with carbon emissions and resource scarcity (Jollands et al., 2004).

Strategic Value and Constraints

From corporate finance perspective, adoption of eco-efficiency metrics offers measurable advantages. Research has shown that eco-efficient firms enjoy a high valuation for market, reduced capital costs and superior operational resilience because of proactive mitigation of waste handling and resource volatility (Sinkin et al., 2008). This is a very comprehensive way for practical translating of abstract

ISBN: 978-93-49468-54-2

sustainability principles into something which is quantifiable that corporate executives investors and operational managers can evaluate upon time to time.

Industrial ecologists often caution that eco-efficiency is a measure of relative rather than absolute sustainability (Huppes& Ishikawa, 2005). This limitation can be very well be illustrated by the Jevons paradox or illustrated by the Rebound effect. To understand this effect let us consider a manufacturing facility improves energy efficiency by 20% and a result of it is the cost of production dropping. If the company passes on this savings that they have made to its consumers the demand of the product may skyrocket leading to increased total production volume. Consequently the absolute consumption of resources and total carbon emissions may actually increase completely erasing the gains and good effects achieved by the company through local efficiency modifications (Figge & Hahn, 2004).

Therefore, eco-efficiency is indispensable concrete and a very good way of operational baseline of reducing industrial waste and making the contemporary green engineering frameworks stress on eco-effectiveness paradigms shift toward circular designs where waste is completely nullified rather than minimised (Huppes& Ishikawa, 2005).

Embodied Energy Economics: Manufacturing Process Optimization

- **Foundational aspects of Embodied Energy Economics**

With escalation of global resource scarcity and carbon boundaries being tightened, manufacturing units worldwide are forced with intense operational and structural pressure to trasition towards sustainable programs (An et al., 2022). Traditionally traditionally energy management in industries was about prioritization of reduction of direct operational energy resources like the raw electricity consumed, fuel, or steam consumed actively on the factory floor (Mousavi et al., 2015). However in order to make a comprehensive evaluation macroeconomic, thermodynamic and otherwise requires looking beyond localised operational energy consumption to examine the concept of embodied energy (Burger et al., 2015; Dixit et al., 2015).

The term embodied energy constitutes of the total sum of energy in any form required to extract, secure or process intermediate components, transport and other capital investments required for the assets entire lifespan (Dixit et al., 2015; Liang et al., 2023). Within the discipline the embodied energy and its economics EEE, energy is not treated as a variable utility cost but as a component of value bound to physical assets, raw material imports and production chains (Liu et al., 2022).

For a manufacturing system optimisation requires a double pronged approach where minimisation of the structural embodied energy which is bound to the material inflows while concurrently maximising the efficiency of the unit process to minimise cumulative processing energy additions (Mousavi et al., 2015; Xia et al., 2023). When manufacturing processes are poorly managed, they act as sites of

ISBN: 978-93-49468-67-2

energy which compounds significantly thermodynamic inefficiency and with its comes financial inefficiencies.

Systematically optimising manufacturing units can transform operations, conversely, allowing organisations to achieve competitive economic advantage mitigate carbon risk and ensure industrial level resilience (An et al., 2022; Liu et al., 2022). This comprehensive analysis is a detailed description of the mathematical, thermodynamic, algorithmic and organisational framework that drives the optimisation of embodied energy across all industrial processes in modern era.

Theoretical Foundation and Thermodynamic Framework

- **The First and Second Laws of Thermodynamics**

Embodied energy economics relies heavily on thermodynamics and the science of thermodynamic systems theory. While the first Law of thermodynamics as given the absolute conservation of energy across all process lines it lacks the capacity to measure structural qualitative decay and structural inefficiencies. EEE, consequently, relies heavily on its Exergy analysis the second Law metrics which is all about the maximum useful work that is available or that can be drawn form a material or energy stream relative to the standard environmental reference state.

When the raw material enters the production line it is in a high-exergy state which is then systematically modified integrity by mechanical and thermal and chemical actions. The cumulative energy used across all the steps above constitute the assets structural embodied energy footprint.

Mathematically total embodied energyEE_{Total} within a product or a specific boundary of the system at any given processing stage is given by the equation:

$$EE_{Total} = \sum_{i=1}^{n} M_i . \epsilon_i + \sum_{J=1}^{m} E_{Direct,j} + \sum_{k=1}^{p} T_k . \tau_k + E_{Capital}$$

Where:

- M_i represents the mass or quantitative volume of the costs i-th material input stream.
- ϵ_i represenvts the specific upstream embodied energy intensity coefficient per unit mass of that specific material (e.g., Mj/Kg).
- $E_{Direct,j}$ represents the direct operational energy consumed by the j-th industrial unit unit-process (e.g., electricity, thermal heat, fuel consumption).
- T_k represents the mass-distance transportation metric for logistics path k, and τ_k represents the specific logistics energy intensity factor.

ISBN: 978-93-49468-54-2

- $E_{Capital}$ denotes the amortized share of the embodied energy consumed during the manufacturing, installation, and deployment of factory machinery, facility tools, and building envelopes (Dixit et al., 2015).

Multi-Level Manufacturing Systems

in order to evaluate and control this cumulative energy profile we are required to organise the manufacturing framework into a clear hierarchy. The structure maps of energy consumption is from all mechanical manufacturing areas to global supply chain areas:

- Unit process level: Hhere the focus is on the physical and chemical transformations occurring in the shop floor(as for example lathe machine, moulding cycles, CNC milling etc.). Here the target is to optimise the parameters in order to reduce direct mechanical and thermal energy demand (Mousavi et al., 2015).
- Production line or chain level: Here the focus is on the serial and the parallel interactions that workers in multiple unit process material handling systems, intermediate queueing ways and buffer stations (An et al., 2022). Here the optimisation targets idle time reduction and optimise structural view routing to achieve lower energy demand (Xia et al., 2023).
- Factory level: Combines production lines and auxiliaries facility systems including the HV AC, compressed air, central cooling system and local microgrid (An et al., 2022). Here waste recovery is the main objective of the optimisation.
- Supply chain a life-cycle level: This encompasses all other operations which encompasses, transits and the transition through vehicles, sea freight and or airfreight and all other operations which are required to maintain the supply chain (An et al., 2022). Here optimisation targets to achieve low intensity which material loops and circular economy recovery loop (Liang et al., 2023).

Quantification of Embodied Energy

In order to accurately optimise manufacturing systems require reliable measurement methodology. This field although uses many methodologies here we have detailed to methodologies for clarification:

Input-Output (IO) Economic Models

To mitigate truncation gaps in top-down economic approach utilises national input output tables. IO models transform economic transactions between industrial people into a matrix equation that represent energy distribution across the entire economy. By linkages of sector level financial flows directly to primary fuel extractions, IO model capture an extensive amount of indirect energy footprint that a bottom-up approach cannot capture (e.g., legal services, marketing, administrative support).

IO framework also lacks in physical resolution. They rely on aggregation of the industrial sector averages and urging all a linear relationship between capital expenditure and physical energy making it less effective for optimisation of specific machine configurations on shop floor (Dixit et al., 2015).

Hybrid Paradigms

In order to combine the effectiveness of both approaches more modern economics utilises hybrid quantification models (Dixit et al., 2015). Hybrid model embed highly specific process-based life-cycle analysis data into a macrolevel IO structural matrix. This method integrates maintaining physical processing resolution for localised factory floor adjustments while leveraging on top-down economic data to prevent truncation errors particularly across all capital investments and human labour structures (Dixit et al., 2015).

Quantification Methodology	Core Analytical Direction	Main Strength	Principal Technical Limitation
IO Economic Models	Top-down allocation using national economic sector matrix equations.	Complete system boundaries that capture macro-level indirect impacts.	High aggregation errors and low physical resolution.
Hybrid Paradigms	Matrix integration embedding process data into national IO tables.	Eliminates truncation errors while preserving operational precision.	Requires significant data and complex matrix computations.

Manufacturing Process Optimization Framework

- **Unit Process Level Optimization**

At the base level optimisation is about minimisation of energy investment per volume of processed material. In machining operations for example the total energy required for machining of a particular material$E_{machining}$ can be take divided into distinct functional states:

$$E_{machining} = P_{idle}.t_{idle} + P_{warm}.t_{warm} + P_{cutting}.t_{cutting}$$

Where:

- P_{idle} is the constant standby power drawn by ancillary systems (e.g., cooling pumps, CNC controllers, oil mist extractors).
- $P_{cutting}$ is the active power required to overcome material resistance and execute the transformation.

Unit-level optimization focuses on adjusting kinematic parameters—such as cutting velocity v_c, feed rate f, and axial depth of cut a_p—to maximize the Material Removal Rate MRR. Accelerating the MRR shortens the active processing time $t_{cutting}$ reducing the cumulative time-integrated draw of background standby power P_{idle} (Mousavi et al., 2015).

However the adjustments create trade-offs which are complex. Increasing of speeds particularly dynamic speeds increases the tool wear which shortens the tool lifespan and increasing of replacements required. Because manufacturing replacement for as significant manufacturing energy excessive wear of tool and replacement of it increases the embodied energy footprint of the production system. Consequently, unit level optimisation requires balancing of direct energy consumption and structural through life constraints.

Production Line Scheduling and System-Level Co-Simulation

In the production line, optimisation is directed towards interactions between multiple sequential machines (An et al., 2022). Optimising efficiency of a individual component does not automatically translate into optimal system performance. Even if a high-efficiency machine processes parts faster than machines that work after it can handle components that are created before that particular machine are kept in standby modes wasting energy (Mousavi et al., 2015).

In order to bypass this kind of problems discrete event simulation and localised dynamic models are used in conjunction with each other to optimise entire process chains (Mousavi et al., 2015). These systems run scheduling algorithms in way that the machine are kept in a state of low-power sleep mode during production gaps to optimise performance.

By restructuring scheduling cues and optimising the buffer size and capacity factories are minimising the total energy added during intermediate holding stages (Xia et al., 2023).

Synergistic Waste Heat Recovery and Facility Integration

Modern manufacturing facilities optimise the core production lines with auxiliary plant infrastructure (An et al., 2022). It is done by the method of capturing the heat from exhaust air from industrial furnaces and exothermic chemical reactions plant infrastructure's and other such judicious and intelligent usage of heat and other physical objects which can be used in other processes, which is rather was on waste energy otherwise.

In this way of judicious usage, where heat can be used for climate control in colder areas which goes otherwise wasted, we not only recover energy and use it but also reduce the total embodied energy (Liang et al., 2023).

ISBN: 978-93-49468-67-2

Advanced Computational Paradigms and Metamodeling

- **Multi-Objective Optimization Formulations**

Therefore, we can very well state that embodied energy optimisation is about balancing of conflicting industrial objectives. Minimisation of a product's embodied energy footprint often calls for increase of immediate capital costs extending cycle times and strains alternative manufacturing metrics (Yepes-Bellver et al., 2023).

Consequently, process optimisation is formulated as a multi-objective problem where not only multiple objectives are present but conflicting objectives of also present. The mathematical framework optimising the same evaluates these conflicting objectives such as minimising life-cycle cost minimising total embodied energy and minimising operational carbon footprint to find out the optimal system configuration (Yepes-Bellver et al., 2023).

- **Surrogate Modeling and Kriging Metamodels**

Evaluation of manufacturing area using complex physical simulations like that of finite element thermal models or discrete event simulations can be computationally expensive and require investment in order to optimise these processes efficiently engineers implement a bypass method which is the advanced surrogate meta-modelling techniques (Yepes-Bellver et al., 2023).

A primary tool used in this domain is the **Kriging Metamodel**, a probabilistic spatial interpolation framework that approximates complex, non-linear industrial response surfaces based on limited sampled data points (Yepes-Bellver et al., 2023).

The optimization process follows a structured sequence:

- **Initial Sampling:** The multi-variable design space is sampled using statistical techniques like Latin Hypercube Sampling (LHS) to establish a representative baseline dataset (Yepes-Bellver et al., 2023).
- **Metamodel Construction:** A Kriging surrogate model is constructed to map the relationships between input parameters (e.g., feed rates, alloy compositions, heat treatment cycles) and the targeted performance outcomes (Yepes-Bellver et al., 2023).
- **Algorithmic Optimization:** Metaheuristic algorithms—such as Non-dominated Sorting Genetic Algorithm II NSGA – II —search the surrogate surface to find optimal solutions (Yepes-Bellver et al., 2023).
- **Pareto Frontier Generation:** The optimization outputs a Pareto optimal frontier, providing engineering teams with a range of balanced solutions where no single metric (e.g., embodied energy) can be improved without degrading another (e.g., production cost) (Yepes-Bellver et al., 2023).

ISBN: 978-93-49468-54-2

Microeconomic and Macroeconomic Dimensions of embodied energy economics

- **Microeconomic Cost Dynamics and Capital Trade-Offs**

For standalone individual firms, trying to reduce the products embodied energy footprint it requires initial capital investment and long-term operational savings. Upgrading low embodied energy raw inputs and to also upgrading the present missionary of the firm to highly efficient manufacturing machinery requires significant upfront Investments.

The firms justify these investments through microeconomic life-cycle cost analysis that show that the products that are being produced will have lower variable operating cost because of reduced energy consumption and minimised regulatory carbon penalties decreasing material cost over time

- **Macroeconomic Trade Flows and Embodied Carbon Leakage**

At the level of macroeconomic scale lower embodied energy heavily influence the international trade flows (Liu et al., 2022). Upon implementation of strict carbon pricing and energy efficiency regulations by the industrialised nations manufacturing cost of high-energy industries increase.

To remain competitive in such scenario the production often migrates to regions with less restrictive environmental policies often a phenomenon known as carbon leakage (Liu et al., 2022).

This type of shift distorts the global environmental accounting. While the companies report, a lowering of operational emissions their net environmental impact is often increased due to the impact of goods from regions with higher carbon intensity and lower process efficiency (Liu et al., 2022).

To address such issues the economies are trying to implement advanced trade mechanisms such as border carbon adjustments to level the competitive landscape and incentivise global manufacturing process optimisation (Liu et al., 2022).

Conclusion

Embodied energy economics provides a comprehensive framework for improving of natural sustainability in industry and evaluation of such in comprehensive way. It is the method by the help of which we can actually understand the environmental impact and the amount of energy that has been used to develop and manufacture a particular product which can then be used to understand the environmental impact of manufacturing. By analysing the flow of energy across all the scales of operation - by that we mean from production line localised optimisation to supply chain operations by the method of embodied energy economics industrial optimisation moves well beyond the localised short-term efficiency gains (An et al., 2022; Mousavi et al., 2015).

This type of method of calculation not only helps us in the long run for environmental impact of production to supply chain but also helps us in the way to understand how to most efficiently work and deliver the most optimised products in the market in a green way. Only speaking about green marketing and green optimisation is not going to work in the long run's it is only through calculations like these we can actually impact in a quantitative manner to not only the local environment but also to the global environmental scale.

Though environmental applications of energy economics is not new, it is the application of such and strict abidance of it will save the day for the environment in the local and the environment in the global scale which at the end of the day make a tremendous impact on the society as a whole making the entire supply chain worth it.

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