ENERGY'S PLACE IN ECONOMIC THEORY

by

BENJAMIN LEIVA

(Under the Direction of Octavio Ramirez)

ABSTRACT

Energy has no place in economic theory despite that (i) goods are material rearrangements and (ii) humans can only rearrange matter with energy transfers. These principles can be implemented by modifying conventional neoclassical consumer and producer problems. The point of departure is the statement of an autarkic consumer's energy budget constraint, which implies that Pareto Efficiency requires energy surplus maximization and energy transfer minimization. The resolution of these problems provides insights into the role of energy in economic growth, price formation, the importance and limits of efficiency, and other economic phenomena. This approach broadens the understanding of economics, reconciles economics with natural sciences, interprets previous results relating energy and economics, and provides a basis for a general reinterpretation of economics as the interplay between human desires and thermodynamic processes.

INDEX WORDS: Energy prime movers, economic theory, growth theory, embodied energy, prices, sustainability, inequality

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B.S., Universidad de Chile, 2012

A Dissertation Submitted to the Graduate Faculty
of The University of Georgia in Partial Fulfillment
of the
Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2019

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May 2019

Dedication

To Aylan and all future Aylans we have already failed

* * *

Preface

The motivation of this dissertation is that current economic paradigms seem unable to overcome the two capital challenges of the XXI century: achieving sustainability and curtailing extreme inequality. The dissertation's inception came by reading a diagram of a trophic structure in an ecology book: if energy governs the structure and functioning of all living systems, how can it be entirely absent from economic theory? Might this be the missing element that makes economic theory often seem shallow and useless to address the major challenges of our time?

This dissertation places energy at the center of economic theory by recognizing the essential relation between energy transfers and change. As energy transfers require energy goods and prime movers, such variables become the protagonists of a general reinterpretation of economic theory covering growth, price formation, and other areas such as distribution. This reinterpretation is an incursion into a new way of thinking about economics heavily rooted in both marginal analysis and natural science. The objective of such journey is to enhance our understanding of economic systems, and to explore a potentially fruitful approach to sustainability and inequality.

My own journey has been bittersweet. On one hand I have been lucky to enjoy unwavering support from my advisers, family, friends, and government to make all the “mistakes” necessary while exploring new paths. This support has allowed me to marvel on the coherence and insights from understanding energy’s ubiquitous presence in our lives, economies, and societies. On the other hand I have been disappointed with the lack of professionalism of the peer review process and how it stifles innovation, and by the prevalence of academics (Nobel laureates included) that think and act as apologist of established wisdom. Through them I have experienced Keynes’ remarks that the true difficulty of new ideas lies in escaping from old ones.

— Benjamin Leiva

Acknowledgments

I am grateful to my major adviser, Octavio Ramirez, and the members of my committee: John Schramski, Jeffrey Mullen, Greg Colson, and Craig Landry for their years of support; to Jose Gonzalez for teaching me physics; to Maria Fernanda Terraza for her patience and advice; to my parents for their intellectual and emotional support; to the Government of Chile through CONICYT for their financial support; to Joseph Ramos, Mona Ahmadiani, Diego Vivanco, Pablo Troncoso, Tomas Gonzalez, and Joaquin Gana for their suggestions; and to the friends that made my time in Athens memorable.

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Introduction and Literature Review

> The concepts that find application in all branches of science involving measurement are space, time, and energy (...). That energy deserves a place beside them follows from the fact that because of the laws of its transformation and its quantitative conservation it makes possible a measurable relation between all domains of natural phenomena (...). In the last analysis everything that happens is nothing but changes in energy.
>
> — Wilhelm Ostwald
>
> (in Lindsay, 1976)

Energy has no place in economic theory. Since Adam Smith and throughout all influential schools of thought, the conceptual constructions of how economies work have emphasized desires and aspirations, capital and labor, technology and shocks, institutions and trade, but never energy. Mainstream economists mention this “substance” as no more than an example to illustrate oligopolies and rents, and energy economists consider energy as simply another input alongside capital and labor within *ad hoc* extensions of producer theory. Those considering a more fundamental role for energy are generally viewed as fringe elements of the profession (Alessio, 1981).

And yet it moves. Energy deserves a place in economic theory because i) production is a material rearrangement process (Ryan and Pearce, 1985; von Mises, 1949; Marshall, 1920), and ii) humans can only rearrange matter with energy transfers. This second fact is the piece of the puzzle generally ignored: energy is neither a substance nor a thing, but a property of things determining their potential for change. Energy transfers are what allows the cosmos to evolve, civilizations to rise, and all living beings to exist (Smil, 2007), as without them all is dark, silent, and still. The rearrangement of raw materials into new desired forms — the essence of all productive processes — is done by systems capable of transferring energy such as laborers, engines, and computers. These prime movers, alongside the energy goods that energize them, are the protagonists of production because in the quest of material rearrangements, there is no substitute for energy transfers. Prime movers and energy goods can be substituted (e.g. laborers for engines and rice for oil) (Smil, 2017; Hanna and Oliva, 2015; Burke, 2013; Renshaw, 1963), and energy can be transferred with varying efficiency (Warr et al., 2010; Ayres and Warr, 2005; Ayres et al., 2005), but energy must be transferred for humans to enact any material change.

This dissertation builds a theoretical framework that places energy at center stage of economic theory while observing the formality of marginal analysis and the subjective drive of economic activity. At its core is the modeling of the behavior of consumers and producers with modifications to their conventional problems. The modifications center the means available to humans around energy transfers given that energy is a property of nature determining physical systems' potential for change, and that energy transfers are the only way humans can rearrange matter. By highlighting energy transfers as a process requiring an array of inputs (only some of which are energy goods), the framework recognizes energy's prominence in nature while avoiding energy reductionism. Such approach enhances the study of economics, of the relation between economics and energy, and fosters a better dialogue between economics and natural science.

After the development of general energetics in the late 1800s by Rankine, Clausius, Ostwald, Mach, and others, calls were made from the natural sciences for a better consideration of energy within economics. Lotka (1925) stated that "The life contest, then is primarily a competition for available energy", and Soddy (1933) argued that "the flow of energy should be the primary concern of economists". Few listened, and for the next 40 years the profession was dominated by the developments of the Modern Program, Macroeconomics, Monopolistic competition, Econometrics, and among others, Game Theory (Warsh, 2006).

The oil shocks of the 1970's led studies about energy and the economy to be published in influential economic journals (e.g. Berndt and Wood, 1979), yet such interest proved shallow and short-lived. Despite the shocks' effects, economic theory has yet to acknowledge what energy is and the role it plays in the functioning of all physical systems. For example, labor and capital are conceptualized independently from energy, as if humans and machines could do something without energy goods energizing them. Also, growth is theorized with no reference to the energy throughput powering it, as if the world economy was an enormous perpetual motion machine.

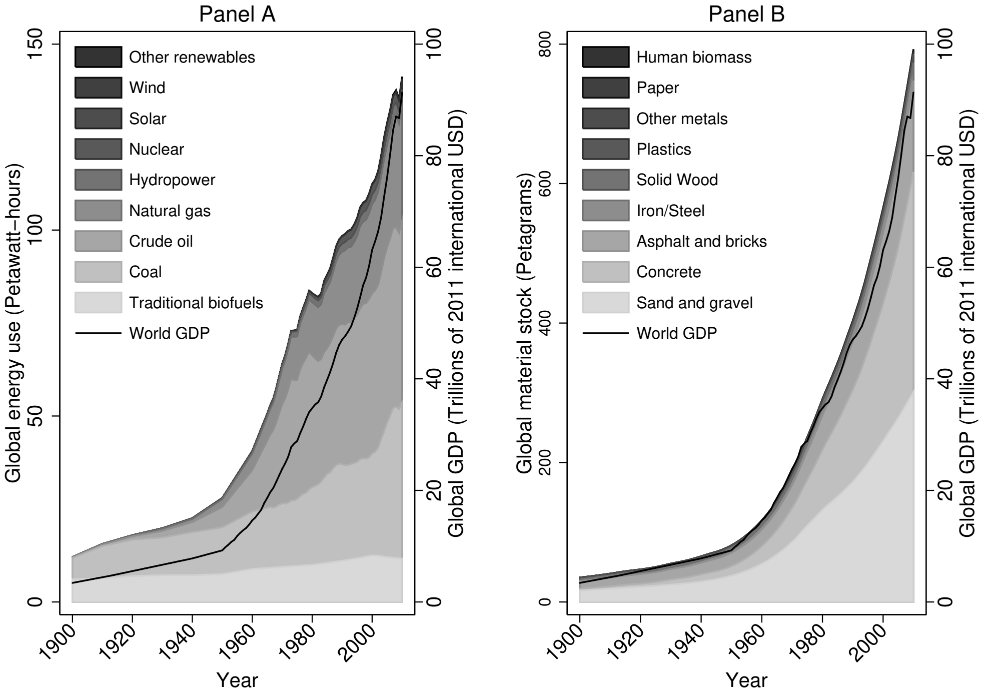

Figure 1: Global energy use, material stock, and GDP. Own elaboration with data from Our World in Data and Krausmann et al. (2017).

But perpetual motion machines do not exist, and the functioning and expansion of any economy is exquisitely dependent on the energetic flux enabling the production of everything. Panel A of Figure 1 involves more than a simple correlation between energy use and GDP due to the intrinsic association between humanity's capacity to transfer energy and to modify the world as desired. This relation is strict because i) production is a material rearrangement process, and ii) humans can only rearrange matter by transferring energy. Panel B underscores the material basis of energy transfers, as all inputs enabling energy transfers are physical: energy goods providing energy content, prime movers with power rates[1], supporting inputs enabling prime movers' energy transfers, and raw materials to be rearranged.

The complexity and centrality of energy transfer processes has been detailed in broad historical accounts (Smil, 2017; Weissenbacher, 2009; Cook, 1976). All major developments of the human enterprise are associated with new energy goods and prime movers, but in the context of intricate environmental conditions, social institutions, cultural traits, knowledge, and chance. For example, the transition from agricultural to industrial societies was based on the use of coal, followed by oil, gas, and electricity, but was critically dependent on the invention of the steam engine and turbine, internal combustion engine, induction motor, and other prime movers capable of transferring the energy content of those energy goods with sufficient efficiency to do useful things. The invention of these prime movers required not only specific materials such as steal and refined copper, but social institutions such as private property, cultural traits such as the acceptance of profit, knowledge such as thermodynamics, and a considerable amount of luck as evidenced by the winding paths of Diesel and Tesla.

From the perspective of means as energy transfers, the ignorance about the nature and role of energy is one of economics' most pressing and rarely discussed problems. How can energy be absent from the study of production if production has and will always be done by energy transfers? Given this, how can energy be absent from economic theory? Such theory without energy is like thanksgiving

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[1] Power rates are the rates of energy transfer, which determine prime movers' raw capacity to transfer the energy content of energy goods.

without turkey: you can do it, but there is clearly something missing. Adam Smith's neglect is understandable as he died 30 years before Carnot unveiled the basics of thermodynamics, yet such disregard has no justification with the theory and evidence available today (Brown et al., 2011).

Besides a conceptual and historical shortcoming, the omission of energy by economic theory creates practical problems. Some are localized, such as the controversies regarding the elasticity of substitution between capital and energy (Koetse et al., 2008; Apostolakis, 1990), the misunderstandings about the relation between energy use and GDP (Ozturk, 2010; Payne, 2010), and the misleading distinction between agricultural and energy industries. Other problems are much broader, such as the neglect of marginal net energy returns for understanding growth processes (Aghion and Howitt, 2009; Solow, 1956), and the belief in unbounded efficiency gains due to the neglect of thermodynamic limits.

These conceptual and practical problems make the absence of energy in all influential schools of thought an uncomfortable reality, and change the question *if* energy should have a place in economic theory to *how* to provide it. This dissertation implements the idea of means as energy transfers by modifying the conventional problems with which neoclassical economics studies behavior. Energetics is brought in to the consumer problem by stating that utility maximization for an autarkic agent is subject to an energy budget constraint, and to the producer problem by noting that given such constraint, Pareto-efficiency requires energy surplus maximization and energy transfer minimization. Agents are argued to be bounded by an energy budget constraint *as if* they were aware of it, even when in practice they may not. For autarkic agents this is trivial, but under exchange energy budget constraints are argued to be socially represented by money budget constraints. This derives from the development of nominal prices as social representations of the marginal energy transfers required to produce goods.

Marginal energy transfers as goods' opportunity costs does not imply an energy theory of value. Energy goods are not the only relevant input because marginal energy transfers contain direct energy transfers and a measure of prime movers' opportunity cost. Furthermore, marginal energy transfers are duly influenced by efficiency changes, uncertainty, and inter and intra temporal preferences. In fact, marginal energy transfers as goods' opportunity costs sustains the pursue of human ends as the central driver of economic activity because the concept itself does not exist in isolation from utility maximization.

Thought this approach is entirely novel, an extensive interdisciplinary literature has studied the relation between energy, economics, and society. Bioeconomics (Gowdy and Mesner, 1998; Odum and Odum, 1976; Georgescu-Roegen, 1971), biophysical economics (Hall and Klitgaard, 2012; Cleveland et al., 1999), and dissipative structure theory (Prigogine and Stengers, 1984; Nicolis and Prigogine, 1977) conceive societies as highly organized systems requiring constant energy throughput to revert entropy increase. Social metabolism (Muradian et al., 2012; Haberl et al., 2011) and energy-focused historical accounts (Smil, 2017; Weissenbacher, 2009) study human action through energy goods, prime movers, and what enables their energy transfers. Exergy analysis studies the expansive and reinforcing effects of efficiency enhancements (Warr et al., 2008; Ayres et al., 2003), the Energy Return Over Investment (EROI) literature the fundamental constraint placed by net energy returns on long run growth (Hall, 2017; Hall et al., 2014), and the energy transitions literature the determinants and prospects of broad changes in energy bases (Court et al., 2018; Fouquet, 2010).

Energy economists have also studied the relation between energy and economics, but either without theory (e.g. Bruns et al., 2014) or with *ad hoc* extensions of producer theory called KLEM models (e.g. Berndt and Wood, 1979). The most common atheoretical studies address the causal relation between GDP and energy use, and the most common KLEM models the elasticity of substitution between energy and capital. The rest of the field is mainly concerned with energy markets (excluding food for some arbitrary reason), which are studied with conventional economic methodology. Paradoxically, the study of energy markets has little to no regard to their energetic nature, focusing instead on externalities, innovation, and failure of market organization.

The implementation of means as energy transfers using neoclassical methods provides a theoretical framework that enhances the consideration of energy by economics, and dialogues seamlessly with the other perspectives relating energy, economics, and society. Such framework interprets how energy influences growth (Chapter 1), price formation (Chapter 2), and motivates further empirical research on how energy influences price formation (Chapter 3). The framework also provides insights into the relation between EROI and interest rates, energy surplus and inequality, and sustainability (only sketched out in this dissertation). These insights are derived alongside the Law of Demand and other conventional results, thus implying an approach best understood as a generalization of neoclassical economics. Ultimately, the framework provides a richer understanding of economics, society, and ourselves as an interplay between human desires and thermodynamic processes.

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Chapter 1

A theoretical framework to consider energy transfers within growth theory

Abstract

Growth theory has rarely considered energy despite its invisible hand in all physical systems. We develop a theoretical framework that places energy transfers at centerstage of growth theory based on two principles: (1) goods are material rearrangements and (2) such rearrangements are done by energy transferred by prime movers (e.g. workers, engines). We derive the implications of these principles for an autarkic agent that maximizes utility subject to an energy budget constraint and maximizes energy surplus to relax such constraint. The solution to these problems shows that growth is driven by positive marginal energy surplus of energy goods (e.g. rice, oil), yet materializes through prime mover accumulation. This perspective brings under one framework several results from previous attempts to insert energy within growth theory, reconciles economics with natural sciences, and provides a basis for a general reinterpretation of economics and growth as the interplay between human desires and thermodynamic processes.

Keywords: Energy; prime movers; economic theory

JEL Codes: D11, D21, O13, Q40

Nomenclature

x_l	Prime mover of type l
p_l	Power rate of l
P	Aggregate power level
ϵ_l	Direct energy transferred by l
ω_l	Total energy transferred by l
r_l	x_l's maximum rate of accumulation
Q_e	Quantity of energy good e
δ_e	Energy content of energy good e
γ_e	Marginal embodied energy of good e
γ_e^A	Average embodied energy of good e
PES	Primary Energy Sources
E	Total energy surplus
α_e	Marginal energy surplus of energy good e
ϕ_l	Mg. energy surplus of prime mover l
λ	Marginal utility of energy surplus
φ	Proportion of useless energy surplus
ζ	Energy good equilibrium
Q_n	Quantity of non-energy good n
Λ_n	Energy assignment of non-energy good
Θ	Over-assignment of energy surplus
ρ	Total efficiency
Ψ_k	Minimum γ_k of any good k
η_k	Quantity elasticity of γ_k^A

1.1 Introduction

Energy has rarely been part of the narratives developed by economists to study economic growth (Galor, 2011; Aghion and Howitt, 2009; Beinhocker, 2006; Galor and Weil, 2000; Lucas, 1990; Romer, 1990; Solow, 1956). Although this omission has been justified on energy's low cost share in production (Kümmel et al., 2015; Denison, 1985; Perry, 1977), it is surprising given that growth theory traditionally began with descriptions of the material conditions of production (Perrings, 1987), and energy's invisible hand in all physical systems was unveiled by natural scientists over a century ago (Ostwald, 1892; Boltzmann, 1886; Maxwell, 1872). Such omission also stands against the extensive documentation of the role played by energy — and the systems that use it — in human history (Smil, 2016; Rees, 2012; Gillett, 2006; White, 1943; Odum, 1971; Cottrell, 1955; Lotka, 1925).

Attempts to consider energy within growth theory have stemmed from scholars focused on the physical conditions of an economy and on energy transitions. The former stress that energy is the potential to do work and that production upgrades the organization of matter with free energy (Herrmann-Pillath, 2015; Lindenberger and Kümmel, 2011; Warr et al., 2008; Gillett, 2006; Ayres et al., 2003; Cleveland et al., 1984; Georgescu-Roegen, 1971). The latter argue that growth theories such as Solow (1956) and Galor and Weil (2000) can include energy to explain major evolutionary transitions, and show that energy has an important role in explaining growth (Court et al., 2018; Kander and Stern, 2014; Fröling, 2011; Tahvonen and

Salo, 2001). However, none of them consider that *energy transfers* are the essence of all productive processes.

How can energy transfers be placed at the center of growth theory? This paper aims to do this by articulating marginal analysis — economists' canonical methodology — with key insights from physics. Our model highlights the relevance of consumers' energy budget constraint, the centrality of prime movers to transfer energy, and the existence of marginal embodied energy curves for all goods. Also, this approach brings under one general framework an array of results derived by previous attempts to insert energy within growth theory, like the importance of energy in growth and the constraint that the energy surplus secured by energy sectors imposes on the existence of non-energy sectors. Lastly, by informing economists' canonical modeling technique with some of physics' key concepts, the paper contributes to the dialogue between economics and natural science.

1.2 The energy budget constraint

We first present the energy budget constraint (equation (1.3)), which is our point of departure from traditional theory. The rationale behind this constraint lays on two principles: (1) goods are material rearrangements of raw materials that satisfy an agent's desires, and (2) material rearrangements are done by energy transfers. The former principle is a natural implication of Lavoisier's Law, as the impossibility of creating matter implies that production can only create order.

The latter principle is supported by the broad consensus among natural scientists that material change requires energy transfers.[1]

Under these principles, production is the process of transferring energy to rearrange raw materials into final goods, and therefore depends primarily on the two main components of energy transfers. The first are the energy goods from where energy is transferred. These have energy content (i.e. joules per gram) and must be compatible with one or more prime movers, yet can be as diverse as rice, oil, and electricity. The second are the prime movers that trigger the transfers. These have power rates (i.e. watts) and must be compatible with one or more energy goods, yet can be as diverse as peasants, engineers, diesel engines, and computers.

The indivisible centrality of these two components for production (Weissenbacher, 2009; White, 1943; Debeir et al., 1991; Cottrell, 1955) highlights the conceptual shortcoming of modelling output as a function of labor, capital, and energy (e.g. Berndt and Wood (1975)). The services provided by labor and machinery during production are the energy they transfer to rearrange matter. All other inputs support that process. Thus, substitution is possible across energy goods and prime movers, yet there are no substitutes for energy and power themselves. Higher efficiency can reduce the magnitude of energy transfers required to yield a given output, but there always exists a physical minimum (e.g. stoichiometric requirement in ammonia synthesis).

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[1] In the case of a mechanical change, the second principle is a natural implication of Newton's second law, as material rearrangements require a change in acceleration of particles and therefore a transfer of energy.

Accordingly, growth is the increase in the capacity to transfer energy, and can be studied with its constraints. The first one is the "energy budget constraint", which restricts the goods to be consumed by an agent such that the total energy transferred in their production is no greater than the agent's energy income. In the case of a simple autarkic agent, this constraint is

$$\boldsymbol{\gamma}_N^{A'}\boldsymbol{Q}_N + \boldsymbol{\gamma}_\epsilon^{A'}\boldsymbol{Q}_\epsilon = G \leq \boldsymbol{\delta}_\epsilon'\boldsymbol{Q}_\epsilon, \tag{1.1}$$

where $\boldsymbol{Q}_N = [Q_1, \ldots, Q_N]'$ and $\boldsymbol{Q}_\epsilon = [Q_1, \ldots, Q_\epsilon]'$ are the quantities of non-energy and energy goods to be consumed, $\boldsymbol{\gamma}_N^{A'}$ and $\boldsymbol{\gamma}_\epsilon^{A'}$ are their respective average embodied energies, and G is the total energy transferred. Average embodied energy is the total (direct plus indirect) energy transferred on average to produce a unit of a good.[2] $\boldsymbol{\delta}_\epsilon = [\delta_1, \ldots, \delta_\epsilon]'$ are energy good's energy contents which stem from Primary Energy Sources (PES), and I is the agent's energy income.

This constraint must hold regardless if the agent is aware of it because energy must be available to be transferred, and therefore can be used to model an autarkic agent's behavior. Focusing on a single period, a world without uncertainty, and assuming the agent's preferences can be represented by a quasiconcave, continuous, and twice-differentiable utility function that is strictly increasing on non-energy goods, the agent's primary objective is to maximize

$$U = U(\boldsymbol{Q}_N), \tag{1.2}$$

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[2] For discussions on the concept of embodied energy see Huettner (1982); Costanza (1981); Bullard and Herendeen (1975); IFIAS (1974) and Chapman (1974). Here we overlook the issues of system boundaries and co-products, and assume that all energy transfers can be uniquely allocated between all goods.

subject to the energy budget constraint in (1.1). Rearranging such constraint as

$$\boldsymbol{\gamma}_N^{A'}\boldsymbol{Q}_N \leq E, \tag{1.3}$$

yields FOCs from maximizing (1.2) subject to (1.3) choosing quantities as

$$\frac{U_n}{\lambda} = \gamma_n, \qquad \forall\, n \in N \tag{1.4}$$

where $E = \boldsymbol{\delta}_\epsilon'\boldsymbol{Q}_\epsilon - \boldsymbol{\gamma}_\epsilon^{A'}\boldsymbol{Q}_\epsilon$ is the agent's energy surplus, U_n is good n's marginal utility, λ is the marginal utility of energy, $\gamma_n = \gamma_n^A(1+\eta_n)$ is good n's marginal embodied energy, and $\eta_n = \frac{\partial \gamma_n^A}{\partial Q_n}\frac{Q_n}{\gamma_n^A}$ is the quantity elasticity of average embodied energy. A good's marginal embodied energy is the total energy transferred to produce one more unit. The equilibrium condition in (1.4) states that the Marginal Rate of Substitution (MRS) between good n and energy equals the good's marginal embodied energy. This does not mean that energy provides utility *per se*, but that more utility can be derived from one more joule due to the additional consumption it enables of utility-yielding non-energy goods.

Equation (1.4) can be used to derive tangency conditions between any two goods, which together with the energy budget constraint yield energetic-Marshallian demand functions $Q_n^*(\boldsymbol{\gamma}_N, E)$ and the marginal utility of energy surplus $\lambda^*(\boldsymbol{\gamma}_N, E)$. Replacing the demand functions back in (1.4) yields the unambiguous proposition that (a) if the marginal embodied energy of a non-energy good increases, *ceteris paribus*, its optimal level of consumption will fall, and that (b) if the marginal embodied energy of a non-energy good increases, *ceteris paribus*, the optimal level of another non-energy good will increase (details in appendix A).

1.3 Energy surplus maximization

The energy budget constraint as expressed in (1.3) implies that for Pareto-efficiency, utility maximization requires energy surplus maximization. This secondary objective can be stated as

$$\max_{\boldsymbol{Q}_\epsilon} E = \sum_{e=1}^{\epsilon} [\delta_e Q_e - G_e] \tag{1.5}$$

where Q_e is the quantity produced of energy good e and G_e is the total energy transferred to produce such quantity. However, this objective function is subject to a "prime mover constraint" of the form

$$\sum_{n=1}^{N} x_{l,n} + \sum_{e=1}^{\epsilon} x_{l,e} \leq \bar{x}_l, \qquad \forall\, l \in L \tag{1.6}$$

where $x_{l,n}$ is the quantity of prime mover of type l used in the production of non-energy good n and $\bar{x}_l$ is the agent's endowment of that prime mover type. Thus, the constraint restricts the employment of prime mover l to the agent's endowment. Energy surplus maximization is also subject to an "energy usability constraint"

$$\sum_{l=1}^{L} \varepsilon_l \sum_{n=1}^{N} x_{l,n} \geq E, \tag{1.7}$$

where $\varepsilon_l = \int_t^{t+1} p_l$ is the direct energy transferred by each unit of prime mover l during the period under study given its power rate p_l, which we assume constant for all prime movers of the same type. This constraint ensures that the agent does not produce useless energy surplus by forcing all energy surplus to be usable by prime movers employed in the production of utility-yielding non-energy goods.

The energy usability constraint highlights that energy does not provide utility *per se*, but only through the capacity to produce other goods. This sets a distance with energy theories of value as suggested in Costanza (1980) and Hannon (1973), while simultaneously recognizing the role of energy in production.

Merging the constraints in (1.6) and (1.7) yields a Lagrangian of the form

$$\mathcal{L}_e = (1-\varphi)\sum_{e=1}^{\epsilon}[\delta_e Q_e - G_e] + \varphi\sum_{l=1}^{L}\varepsilon_l \bar{x}_l - \varphi\sum_{l=1}^{L}\varepsilon_l\sum_{e=1}^{\epsilon} g_{-l,e}(Q_e, \boldsymbol{x}_{-l,e}) \tag{1.8}$$

where $\varphi \in [0,1)$ is the proportion of useless energy surplus to unconstrained maximum energy surplus, which is a measure of aggregate prime mover scarcity ($\varphi = 0$ implies that all prime movers are readily available). Also, $g_{-l,e}(Q_e, \boldsymbol{x}_{-l,e})$ is the technical requirements of production function and $x_{-l,e}$ are all prime movers used in the production of good e apart from l. The FOCs choosing quantities are

$$\delta_e = \gamma_e + \alpha_e, \qquad \forall\, e \in \epsilon \tag{1.9}$$

where $\alpha = \frac{\varphi}{1-\varphi}\frac{\sum_{l=1}^{L}\varepsilon_l\sum_{e=1}^{\epsilon} g'_{-l,e}}{L}$ is energy good e's marginal energy surplus, $g'_{-l,e}$ is the marginal technical requirements of production function, and L is the quantity of prime mover types. This expression relates to the Energy Return Over Investment (EROI) literature (see Hall, 2017) as a good's marginal energy surplus is directly related to its marginal EROI (mEROI).[3]

Equation (1.9) also shows that whenever $\alpha_e > 0$, the agent optimally leaves energy surplus "on the table" despite such surplus being the explicit constraint

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[3] Dividing (1.9) by γ_e yields $\text{mEROI}_e = 1 + \alpha_e/\gamma_e$, where $\text{mEROI}_e = \delta_e/\gamma_e$.

for utility maximization. This happens because of the underlying prime movers constraints that makes additional energy surplus useless. Thus, the equimarginal principle $\delta_e = \gamma_e$ only holds under no prime mover constraints.

The integral of α_e over the optimal production range for all energy goods yields the maximum useful energy surplus, such that if the optimal supply of good e is Q_e^* (computed using (1.9) and x_l^* found below), the optimal solution to (1.5) is

$$E^* = \sum_{e=1}^{\epsilon} \int_0^{Q_e^*} \alpha_e dQ_e. \tag{1.10}$$

Figure 1.1 represents the equilibrium conditions specified in (1.9) and the solution obtained in (1.10). The black line is the agent's maximum willingness to transfer energy to produce one more unit, which is horizontal at the good's energy content up to the quantity that saturates the agent's aggregate power level $P = \sum_{l=1}^{L} p_l x_l$, and then falls vertically as the good's energy becomes useless. The Marginal Embodied Energy Curve (MEEC) indicates the marginal embodied energy at each level of production, which can be downward-sloping at some intervals due to efficiency gains from increasing returns to scale, yet will eventually be upward-sloping as the agent is forced to tap increasingly inconvenient PES. This dynamic has been documented for the production of natural resources since Ricardo and Malthus (Backhouse, 2004), and has been specifically modeled for energy goods in Court and Fizaine (2017) and Dale et al. (2011). The intersection between these two curves yields the optimal production Q_e^* at marginal embodied energy γ_e, total energy transfer G_e^*, and energy surplus E_e^*. The marginal energy surplus α_e is the vertical distance between δ_e and γ_e.

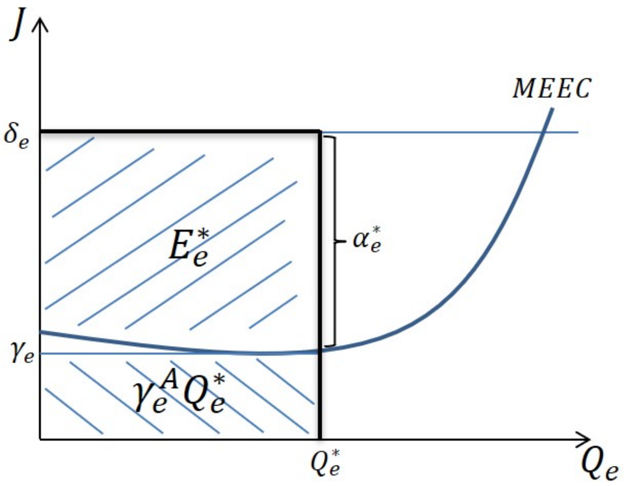

Figure 1.1: Equilibrium conditions in the production of an energy good

The logic behind the energy budget constraint in (1.3) should now be clear. The agent's energy income covers the energy transfers required to produce such income, and only the excess can be used to produce non-energy goods.[4] Accordingly, the optimal production of energy goods is independent from the agent's preferences. This result is set with the assumption that energy goods are not part of the utility function, yet its relevance rests with the energy budget constraint's logic. On the other hand, non-energy goods' optimal production depends on the agent's preferences. How energy is allocated to produce them is shown in appendix B.

The Lagrangian in (1.8) can also be specified using prime movers as $Q_e = f_e(\boldsymbol{x}_e)$, where $f_e(\cdot)$ is a concave-from-above, continuous, and twice-differentiable production function, and $G_e = \sum_{l=1}^{L} \omega_l x_{l,e}$, where $x_{l,e}$ is the quantity of prime

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[4] Although the dualism embedded in modeling energy sectors underpinning the existence of non-energy sectors broadly recalls Physiocracy and Fei and Ranis (1963) model of development, the idea is closer to the model in Fizaine and Court (2016).

mover l used in the production of the good and $\omega_l = \varepsilon_l + d_l\gamma_l^A$ is the total energy transferred by each unit of the prime mover. Note that ω_l contains direct energy transfers ε_l and indirect ones that depend on the prime mover's average embodied energy γ_l^A and depreciation rate $d_l \in (0,1)$. Solving the Lagrangian with this alternative specification yields FOCs choosing prime movers as

$$\delta_e f_{l,e} = \omega_l + \phi_l, \qquad \forall\, l \in L \tag{1.11}$$

where $f_{l,e}$ is prime mover l's marginal productivity in the production of good e and $\phi_l = \frac{\varphi\varepsilon_l}{1-\varphi}$ is prime mover l's marginal energy surplus. Equation (1.11) implies that a prime mover's marginal energy income covers the prime mover's total energy transfers and leaves a surplus, which is key to growth dynamics as shown in the next section.

Equation (1.11) can be used to derive tangency conditions that specify optimal production conditions for any two prime movers and any two energy goods. The former conditions depend on the prime movers' marginal productivities on the same good and total energy transfers, while the latter conditions depend on each prime mover's marginal productivity on different energy goods and such goods' energy contents. Also, replacing back the optimal prime mover derived demands in (1.11) yields the unambiguous proposition that (c) if the energy content of an energy good increases, *ceteris paribus*, its optimal level of production increases (details in appendix C).

1.4 Growth

Growth is driven by positive marginal energy surplus of energy goods, yet materializes with prime mover accumulation. Despite securing α_e if Q_e^* is increased by one unit, such marginal surplus is useless to the agent due to prime mover constraints and therefore does not lead to greater production by itself. Yet, $\alpha_e > 0 \implies \phi_l > 0$ because $\alpha_e = \frac{1}{L}\sum_{l=1}^{L} \phi_l g'_{-l,e}$. If $\phi_l > 0$, the agent has incentives to produce more prime movers for the following period, which relaxes its prime mover constraint, and leads to higher production of energy goods, securement of energy surplus, production of non-energy goods, and therefore to higher utility.

Formally modeling prime mover accumulation requires at least a two-period model that surpasses the scope of this paper. Nonetheless, such accumulation can be conceptualized with a modified logistic model used for population growth of the form

$$\frac{dx_l}{dt} = r_l tanh(\phi_l) x_l, \qquad \forall\, l \in L \tag{1.12}$$

where $\frac{dx_l}{dt}$ is the increase of prime mover of type l, r_l is its maximum unitary rate of accumulation, and $tanh$ is the hyperbolic tangent function. Equation (1.11) implies that under large ϕ_l the $tanh \to 1$, and the prime mover type accumulates at an unconstrained rate. Yet, ceteris paribus, as the prime mover accumulates, ϕ_l and $tanh$ fall such that accumulation slows down. Under no prime mover constraints, $\phi_l = 0$ and $tanh(0) = 0$ such that accumulation stops.

Figure 1.2 represents the increase in the production of energy good e from accumulating prime movers. As in Figure 1.1, at $t = 0$ demand is perfectly elastic at δ_e up to the quantity that saturates the agent's aggregate power level P^0, where it falls vertically. As prime movers accumulate given $tanh(\phi_l) > 0 \; \forall \; l$, prime mover constraints are relaxed such that at $t = 1$ the agent produces Q_e^{1*} and additionally secures E^{1*}. This increases the agent's utility, yet the good's marginal energy surplus is even higher and therefore $tanh(\phi_l) > 0$. At $t = 2$, a higher aggregate power level leads to the production of Q_e^{2*} where the good's marginal embodied energy increases to γ_e^2, but this increase is small enough for $\alpha_e > 0$. Finally, at $t = 3$ the production of Q_e^{3*} implies $\alpha_e = 0$ and $tanh(0) = 0$. In brief, when energy goods are relatively abundant (i.e. their marginal embodied energy and marginal EROI is high) prime movers place the constraint on growth, yet when energy goods are scarce they become the constraint (Stern, 2011).

The agent's long-run equilibrium or steady-state ζ is guaranteed to exist if the MEEC is at least eventually upward-sloping.[5] In ζ no more prime movers can be accumulated, and therefore the agent can be said to have maximized its aggregated power level as suggested in Odum (1995) and Lotka (1925). Also, in ζ no additional energy surplus can be harnessed given the energy flows governing production, and therefore utility cannot be further increased by the mechanisms discussed up to here.

Yet, there are secondary components of energy transfers that move ζ constantly. Efficiency enhancements shift the MEEC downward and push ζ to the right (see

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[5] Long-run economic equilibrium is a thermodynamic disequilibrium (**?**), which implies that economies are systems that evolve towards states far from thermodynamic equilibrium (**?**).

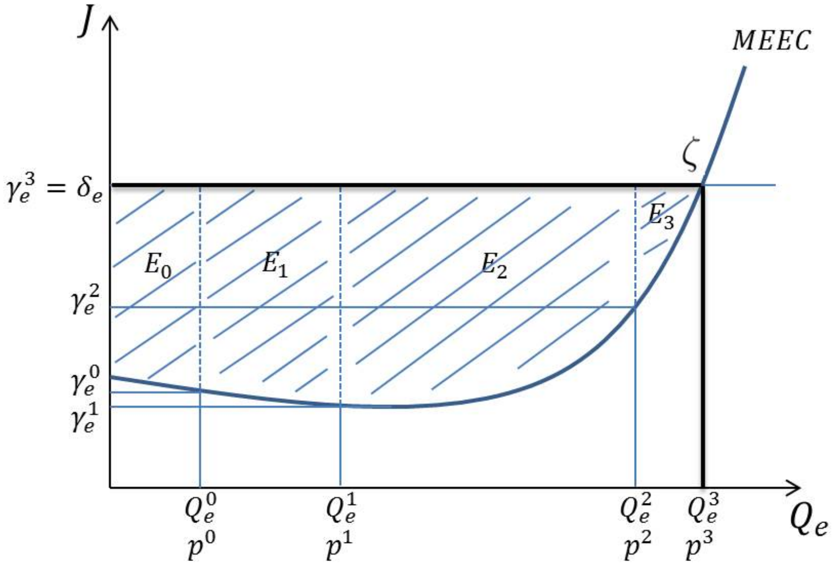

Figure 1.2: Growth dynamics driven by energy good's marginal energy surplus

appendix D for a discussion on efficiency), depletion of Primary Energy Sources (for non-renewable energy goods) shifts the MEEC upwards and push ζ to the left, and changing weather and security conditions affect the MEEC and can move ζ in either direction. Also, the invention or discovery of new prime movers (e.g. steam engines) and energy goods (e.g. electricity) can dramatically shift existing MEECs, and by creating entirely new ones, lead to long new growth spells. This is the underlying narrative in the historical accounts in Weissenbacher (2009), White (1943), Cook (1976), and Smil (2017).

1.5 Conclusion

Our results show that energy goods' positive marginal energy surplus drives growth by incentivizing prime mover accumulation and enabling higher utility levels.

Growth processes cannot be understood independently from the energy goods energizing them. Yet, the relevance of such goods must be stated in relation to the prime movers transferring their energy contents and agents' desires to rearrange matter. The focus on energy transfers using canonical economic methodology offers an alternative to conventional growth theories that recognizes energy's prominence as suggested by natural science, while avoiding energy determinism. This framework, when applied to a setting with exchange, markets, and prices, provides a theoretical explanation of the observed proportionality between market prices and embodied energies. Monetary values as social expressions of underlying energy dynamics suggest a general reinterpretation of economics as an interplay between human desires and thermodynamic processes.

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Appendices

A Utility maximization

The Lagrangian and FOCs of utility maximization subject to the energy budget constraint are

$$\mathcal{L} = U(\boldsymbol{Q}_N) + \lambda[E - \boldsymbol{\gamma}_N^{A'}\boldsymbol{Q}_N] \tag{A1.1}$$

$iA) : \frac{\partial \mathcal{L}}{\partial Q_n} = U_n - \lambda\gamma_n = 0 \qquad \forall\, n \in N$

$iiA) : \frac{\partial \mathcal{L}}{\partial Q_n} = E - \boldsymbol{\gamma}_N'\boldsymbol{Q}_N = 0.$

This setting is mathematically like conventional utility maximization, where money-income is replaced with energy surplus and market prices with marginal embodied energies. Thus, all results will only be stated and interpreted, as the mechanics can be found in Silberberg & Suen (2001) or similar. The tangency condition between any two goods $n = \{a, b\}$ implies that for optimal consumption the MRS between them equalize their relative marginal embodied energies

$$\frac{U_a}{U_b} = \frac{\gamma_a}{\gamma_b}. \tag{A1.2}$$

Replacing (A1.2) in (iiA) yields the Energetic-Marshallian demand functions $Q_n^*(\boldsymbol{\gamma}_N, E)$, as well as the marginal utility of energy surplus $\lambda^*(\boldsymbol{\gamma}_N, E)$.

Furthermore, setting $N = 2$ for goods $n = \{a, b\}$, totally differentiating the FOC, and applying Kramer's rule yields

$$\frac{\partial Q_a^*}{\partial \gamma_a} = \frac{\lambda \begin{vmatrix} U_{aa} & -\gamma_b \\ -\gamma_b & 0 \end{vmatrix}}{\begin{vmatrix} U_{aa} & U_{ab} & -\gamma_a \\ U_{ba} & U_{bb} & -\gamma_b \\ -\gamma_a & -\gamma_b & 0 \end{vmatrix}} - Q_a^* \frac{\partial Q_a^*}{\partial E}. \tag{A1.3}$$

Proposition (a): If the marginal embodied energy of a non-energy good increases, ceteris paribus, its optimal level of consumption will fall.

Such procedure also yields

$$\frac{\partial Q_b^*}{\partial \gamma_a} = \frac{\lambda \begin{vmatrix} U_{ba} & -\gamma_b \\ -\gamma_a & 0 \end{vmatrix}}{\begin{vmatrix} U_{aa} & U_{ab} & -\gamma_a \\ U_{ba} & U_{bb} & -\gamma_b \\ -\gamma_a & -\gamma_b & 0 \end{vmatrix}} - Q_a^* \frac{\partial Q_b^*}{\partial E}. \tag{A1.4}$$

Proposition (c): If the marginal embodied energy of a non-energy good increases, ceteris paribus, the optimal level of another non-energy good will increase.

B Allocation of energy surplus

To analyze production of non-energy goods, we define an energy assignment Λ_n as the maximum energy assigned by an agent to produce a unit of Q_n. These assignments do not provide genuine energy surplus, but allocate the one secured with energy goods to the production of non-energy goods. Moreover, Λ_n is endogenous to agent's preferences (shown below), as opposed to energy content which is an intensive property of energy goods. With a given $\Lambda_n \forall n$, the agent can be though to maximize quasi-energy surplus as

$$\max_{\boldsymbol{Q}_N} \mathcal{E}_N = \sum_{n=1}^{N} [\Lambda_n Q_n - G_n] \tag{B1.1}$$

subject to: $\sum_{n=1}^{N} x_{l,n} + \sum_{e=1}^{\epsilon} x_{l,e} \leq \bar{x}_l, \qquad \forall\, l \in L$

$\mathcal{E}_N + G_N \leq E$

The first restriction is the same prime mover constraint shown for energy goods, while the second one specifies that the total energy assigned to non-energy sectors must be less than the agent's total energy surplus. Replacing, the corresponding Lagrangian is

$$\mathcal{L}_n = \sum_{n=1}^{N}[\Lambda_n Q_n - G_n] + \sum_{l=1}^{L} \phi_l(\bar{x}_l - \sum_{n=1}^{N} x_{l,n} + \sum_{e=1}^{\epsilon} x_{l,e}) + \Theta(E - \mathcal{E}_N - G_N), \tag{B1.2}$$

where $\Theta \in [0,1)$ is a measure of the agent's energy surplus scarcity and ϕ_l is the marginal quasi-energy surplus of prime mover l. Replacing x_{ln} with g_{-ln} and rearranging the Langrangian yields the following FOCs with respect to quantities

$$iB): \frac{\partial \mathcal{L}_n}{\partial Q_n} = (1-\Theta)[\Lambda - \gamma_n] - \frac{1}{L}\sum_{l=1}^{L} \kappa_l g'_{-ln} - \Theta\gamma_n = 0. \qquad \forall\, n \in N$$

Rearranging (iB) yields

$$(1-\Theta)\Lambda_n = \gamma_n + \nu_n, \tag{B1.3}$$

where $\nu_n = \frac{1}{L}\sum_{l=1}^{L} \kappa_l g'_{-ln}$ is the good's marginal quasi-energy surplus. Solving the Lagrangian with respect to prime movers shows that a prime mover's marginal productivity times the non-energy good's "effective energy assignment" $(1-\Theta)\Lambda_n$ covers the prime mover's energy transfer and leaves a surplus

$$(1-\Theta)\Lambda_n f_{ln} = \omega_l + \kappa_l. \tag{B1.4}$$

The surplus κ_l is like ϕ_l for energy goods, but represents a quasi-energy surplus as non-energy goods do not provide energy income. Given that $(1-\Theta)\Lambda_n$ is independent from l, the MRTS between any two prime movers $l=\{1,2\}$ equals their relative adjusted energy transfers, hence

$$\frac{f_{1n}}{f_{2n}} = \frac{\omega_1+\kappa_1}{\omega_2+\kappa_2}. \tag{B1.5}$$

Given Θ is identical for all goods and ω_l is identical for all prime movers of type l regardless of the good they produce, then for any non-energy goods $n=\{a,b\}$ the relative marginal productivity of a prime mover on two goods equals the inverse of the good's relative energy assignments

$$\frac{f_{la}}{f_{lb}} = \frac{\Lambda_b}{\Lambda_a}. \tag{B1.6}$$

Setting $L=2$ for prime movers $l=\{1,2\}$ the following refutable hypotheses can be found

$$\frac{\partial Q_n^*}{\partial \Lambda_n} = \frac{-\Lambda_n(f1^2 f_{22} - 2f_1 f_2 f_{12} + f_2^2 f_{11})}{\Lambda_n(f_{11}f_{22} - f_{12}^2)} > 0. \tag{B1.7}$$

Proposition (d): If the energy assignment of a non-energy good increases, ceteris paribus, its optimal level of production increases.

Equilibrium for non-energy goods is found by combining (iA) and (B1.3). Doing so shows that effective energy assignments equal the MRS between good n and energy in general, adjusted by prime mover scarcity

$$(1-\Theta)\Lambda_n = \frac{U_n}{\lambda} + \nu_n. \qquad \forall\, n \in N \tag{B1.8}$$

C Production of energy goods

As δ_e is independent from l, the MRTS between any two prime movers $l = \{1, 2\}$ equals their relative adjusted energy transfers, hence:

$$\frac{f_{1e}}{f_{2e}} = \frac{\omega_1 + \phi_1}{\omega_2 + \phi_2}. \tag{C1.1}$$

Given ω_l is identical for all prime movers of type l regardless of the good they produce, then for any energy goods $e = \{a, b\}$ the relative marginal productivity of a prime mover on two goods equals the inverse of the good's relative energy contents

$$\frac{f_{la}}{f_{lb}} = \frac{\delta_b}{\delta_a}. \tag{C1.2}$$

Setting $L = 2$ for prime movers $l = \{1, 2\}$ the following refutable hypotheses can be found

$$\frac{\partial Q_e^*}{\partial \delta_e} = \frac{-\delta_e(f1^2 f_{22} - 2f_1 f_2 f_{12} + f_2^2 f_{11})}{\delta_e(f_{11} f_{22} - f_{12}^2)} > 0. \tag{C1.3}$$

Proposition (c): If the energy content of an energy good increases, ceteris paribus, its optimal level of production increases.

Lastly, if an agent seeks to equalize a prime mover's marginal energy income from the production of an energy good with the same prime mover type's effective quasi-energy income from the production of a non-energy good, then $\phi_l = \kappa_l$ and

$$\frac{f_{le}}{f_{ln}} = \frac{(1 - \Theta)\Lambda_n}{\delta_e}. \tag{C1.4}$$

D Efficiency

When an agent transfers G_k to produce Q_k, only a fraction W^u is used to do useful work, i.e. to rearrange matter. Given the First Law of Thermodynamics[6] $G_k = W^p + W^h$, where W^p is physical work and W^h is waste heat, and $W^p = W^u + W^n$, where W^u and W^n are useful and non-useful work respectively (Figure 1.3). Note that W^u is the minimum work required to produce Q_k, which is specific to context. Moreover, by the Second Law of Thermodynamics[7] $W^h > 0$, and if agents are not entirely diligent $W^n > 0$.

The agent's first-law and organizational efficiencies are $\frac{W^p}{G_k}$ and $\frac{W^u}{W^p}$, both between zero and one, and their product is the total efficiency $\rho_k = \frac{W^u}{G_k}$. Higher ρ_k improves f_k as fewer prime movers are required to produce a given quantity, yet ρ_k has a hard limit at unity given the First Law of Thermodynamics and is less than one given the Second Law of Thermodynamics.

Figure 1.3 illustrates an agent's energy flow. Energy enters the agent's system with the production of energy goods, and leaves it in the form of waste heat and embodied in goods. By modifying the embodied energy of all goods, efficiency of energy transfers profoundly influences energy surplus and the amount of non-energy goods that can be produced with a given surplus.

Pareto-efficiency requires energy transfer minimization in the production of all goods. For energy-goods, maximizing energy surplus requires minimizing energy

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[6] Energy is neither created nor destroyed.

[7] All energy transfers are subject to inefficiencies

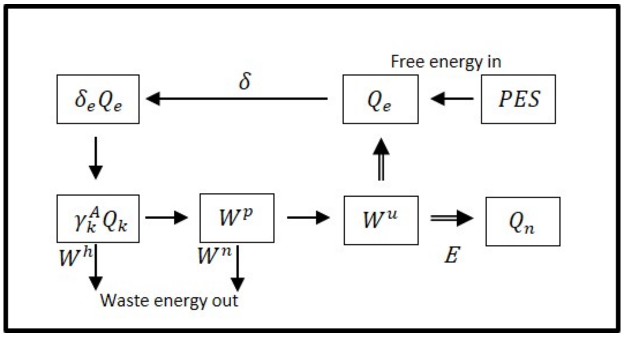

Figure 1.3: An agent's energy flow

transfers per duality. For non-energy goods, this objective provides the minimum possible marginal embodied energies.

Assuming first law-efficiencies are fixed, the agent minimizes energy transfers by increasing organizational efficiencies. Further assuming all prime movers are being used effectively, then the agent can only choose which prime movers to combine to achieve whatever target of production $\bar{\boldsymbol{Q}}$ is set. As energy transfer minimization for energy goods is the dual of energy surplus maximization, the negative of the Lagrangian in (1.8) for energy goods after dropping constants is

$$\mathcal{L} = (1-\varphi)\sum_{e=1}^{\epsilon}[\sum_{l=1}^{L}\omega_l x_{le}] - \varphi\sum_{l=1}^{L}\varepsilon_l(\bar{x}_l - \sum_{e=1}^{\epsilon}x_{le}) + \sum_{e=1}^{\epsilon}\Psi_e[\bar{Q}_e - f_e(\boldsymbol{x}_e)], \quad \text{(D1.1)}$$

where Ψ_e is good e's minimum γ_e. The FOCs are

$iD) : \frac{\partial \mathcal{L}_e}{\partial x_{le}} = (1-\varphi)\omega_l + \varphi\varepsilon - \Psi_e f_{le} \qquad \forall\, l \in L$

$iiD) : \frac{\partial \mathcal{L}_e}{\partial \Psi_e} = \bar{Q}_e - f_e(\boldsymbol{x}_e) \qquad \forall\, e \in \epsilon$

Rearranging (iD) shows that a good's minimum marginal embodied energy adjusted by prime mover scarcity times a prime mover's marginal productivity equals that prime mover's energy transfer plus consumer's energy surplus.

$$\frac{\Psi_e}{1-\varphi} f_{le} = \omega_l + \phi_l. \tag{D1.2}$$

Combining (1.11) and (D1.2) shows that an energy good's minimum marginal embodied energy equals its "useful energy content"

$$\Psi_e = (1-\varphi)\delta_e. \tag{D1.3}$$

Furthermore, as Ψ_e is independent from l, the MRTS between any two prime movers $l = \{1, 2\}$ must equal their relative adjusted energy transfers, which leads to the same tangency condition in (C1.1) for energy goods. Optimal technical conditions of production across goods are found given $\omega_l + \phi_l$ is independent from e. For any two energy goods $e = \{a, b\}$ the relative marginal productivity of a prime mover equals the inverse of their relative minimum γ_e

$$\frac{f_{la}}{f_{lb}} = \frac{\Psi_b}{\Psi_a}. \tag{D1.4}$$

At its optimum, G_e yields the energetic cost function $G_e^*(\boldsymbol{\omega}, \boldsymbol{\kappa}, \varphi, \bar{Q}_e)$ and Shephard's Lemma can be used to recover x_l^* and Ψ_e^*. Also, G_e^* allows computing optimal γ_e^{*A} and γ_e^*. On another hand, replacing the tangency conditions into (iiD) to solve the system of equations yields optimal derived demands $x_e^*(\boldsymbol{\omega}, \boldsymbol{\kappa}, \varphi, \bar{Q}_e)$, as well as good e's minimum marginal embodied energy $\Psi_e^*(\boldsymbol{\omega}, \boldsymbol{\kappa}, \varphi, \bar{Q}_e)$. Setting $L = 2$ for prime movers $l = \{1, 2\}$ leads to the refutable hypothesis

$$\frac{\partial x_1^*}{\partial(\omega_l + \phi_l)} = \frac{-f_1^2}{\begin{vmatrix} f_{11} & f_{12} & f1 \\ f_{21} & f_{22} & f_2 \\ f1 & f2 & 0 \end{vmatrix}} < 0. \tag{D1.5}$$

Proposition (e): If the energy income of a prime mover increases, ceteris paribus, its use will fall.

Such procedure also yields

$$\frac{\partial x_2^*}{\partial(\omega_l + \phi_l)} = \frac{f_1 f_2}{\begin{vmatrix} f_{11} & f_{12} & f1 \\ f_{21} & f_{22} & f_2 \\ f1 & f2 & 0 \end{vmatrix}} > 0. \tag{D1.6}$$

Proposition (f): If the energy income of a prime mover increases, the use of a substitute will increase.

Lastly, energy transfer minimization for non-energy goods follows equivalently. The Lagrangian

$$\begin{aligned} \mathcal{L}_n = & (1-\Theta)\sum_{n=1}^{N}[\sum_{l=1}^{L}\omega_l x_{ln}] - \sum_{l=1}^{L}\kappa_l(\bar{x}_l - \sum_{n=1}^{N} x_{ln} - \sum_{e=1}^{\epsilon} x_{le}) - \Theta(E - \sum_{n=1}^{N}\sum_{l=1}^{L}\omega_l x_{ln}) \\ & + \sum_{n=1}^{N}\Psi_n[\bar{Q}_n - f_n(\boldsymbol{x}_n)], \end{aligned} \tag{D1.7}$$

and the FOC with respect to prime movers

$$iiiD) : \tfrac{\partial \mathcal{L}_n}{\partial x_{ln}} = \omega_l + \kappa_l - \Psi_n f_{ln} = 0 \qquad \forall\, l \in L$$

follow the same logic above. As ($iiiD$) implies that the good's minimum γ_n times the prime mover's marginal productivity equals the prime mover's energy transfer plus consumer's quasi-energy surplus

$$\Psi_n f_{ln} = \omega_l + \kappa_l. \tag{D1.8}$$

Combining (B1.4) and (D1.8) shows that a non-energy good's minimum γ_n equals its "effective energy assignment"

$$\Psi_n = (1 - \Theta)\Lambda_n. \tag{D1.9}$$

Chapter 2

Why are prices proportional to embodied energies?[1]

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[1] Leiva, B. Submitted to *Biophysical Economics and Resource Quality*, 01/29/19.

Abstract

The observed proportionality between nominal prices and average embodied energies cannot be explained with conventional economic theory. A model is presented that places energy transfers as the focal point of scarcity based on the idea that (i) goods are material rearrangements, and (ii) humans can only rearrange matter with energy transfers. Modified consumer and producer problems for an autarkic agent show that the opportunity cost of goods is given by their marginal energy transfers, which depend on subjective and objective factors. Under perfect competition, nominal prices arise as social manifestations of goods' marginal energy transfers. The relation between the latter and average embodied energies explains the proportionality under study.

Keywords: Energy; embodied energy; prices; prime movers; economic theory

JEL Codes: D11, D21, O13, Q40

Nomenclature

Q_{ft}	Demand of final good f during t
Q_{et}	Demand of energy good e during t
Q_{lt}	Demand of prime mover l during t
τ^A_{kt}	Average energy transfer of any good k
τ_{kt}	Marginal energy transfer of good k
η_k	Quantity elasticity of average embodied energy of k
μ_k	Quantity elasticity of average energy transfer of k
E_t	Energy surplus
λ	Marginal utility of energy surplus
β_{ti}	i-period discount factor at t
ψ_{kt}	Direct energy transfers on k
θ_{kt}	Average power scarcity cost of mg. k
Γ_{kt}	Embodied energy of prime movers producing k
x_{lkt}	Quantity of l producing k
$\tilde{x}_{lt}$	Endowment of l
ε_l	l's direct energy transfer
p_l	l's power rate
ϕ	l's power scarcity cost/energy surplus
d_l	l's depreciation rate
g'_{lkt}	Marginal req. of production function
δ_e	Energy good e's energy content
Θ_t	Over-assignment of energy surplus
Λ_{ft}	Energy assigned per unit of f
p^c	Commodity price
p_k	Real price of any good k
P_k	Nominal price of any good k
τ_m	Mg. energy transfer of real money
τ_n	Syn. energy transf. of nom. money
Q_m	Quantity of real money
Q_n	Quantity of nominal money

2.1 Introduction

Nominal prices and average embodied energies seem to be directly proportional (Gutowski et al., 2013; Liu et al., 2008). Economic theory cannot explain this proportionality because if energy is like any other input (as conventional theory suggests), energy's cost share should be systematically high, yet estimates are consistently below 10% (Ayres et al., 2013; Csereklyei et al., 2016; Lindenberger and Kümmel, 2011).

Other interpretations are unavailable with neoclassical micro theory and all leading macro theories because energy is not part of their core constructs (Jehle and Reny, 2011; Mas-Colell et al., 1995; Samuelson and Nordhaus, 2004; Silberberg and Suen, 2001). Such omission is surprising considering the accepted truths that (i) goods are material rearrangements (Ryan and Pearce, 1985; von Mises, 1949), and (ii) humans can only rearrange matter with energy transfers. Together, these ideas suggest that means are energy transfers, as supply depends on the factors that influence energy transfers: primarily the energy goods that provide energy (e.g., rice, oil) and prime movers that transfer it (e.g., workers, engines), and secondarily whatever other factors that influence energy transfers processes (e.g., water, information, social norms, the environment).

The only available alternative to economic theory that could interpret the proportionality between nominal prices and average embodied energies is an energy theory of value (Costanza, 1980; Hannon, 1973; Odum, 1971). Yet, such theory creates more problems than it solves. Imposing that economic value is defined by the energy spent producing goods severely reduces or ignores the role of intra and inter-temporal preferences, other inputs, and technological progress (Huettner, 1982; Alessio, 1981; Hertzmark, 1981; Huettner, 1976; Webb and Pearce, 1975). Furthermore, energy's relevance cannot be understood independently from the prime movers that transfer it to rearrange matter, e.g., a barrel of oil is useless without an engine that can transfer its energy content to produce a good.

Hence, why are nominal prices proportional to average embodied energies? This paper attempts to theoretically explain such proportionality following conventional economic rationale. The starting point is an autarkic agent that maximizes utility subject to an energy transfer constraint. Such constraint, justified with the idea that means are energy transfers, is the point of departure from conventional theory. Given this constraint, the paper shows how maximizing consumer and producer behavior reveals marginal energy transfers, what influences their magnitudes, and that under exchange nominal prices arise as their social representation. The proportionality under study follows given the relation between marginal energy transfers and average embodied energies.

The remainder of the paper is as follows (Fig. 2.1): Section 2.2 lays out a model in which a multi-period autarkic agent maximizes utility subject to an energy transfer constraint, and given such constraint, solves an array of optimization problems that must be solved for Pareto-efficiency. Section 2.3 extends the autarkic setting to analyze how exchange leads to commodity prices, and then convenience leads to the appearance of real and nominal prices as representations of marginal energy transfers. The relation between marginal energy transfers and average embodied energies enables a theoretical interpretation of the proportionality under study. Section 2.4 provides a discussion on these results and Section 2.5 concludes.

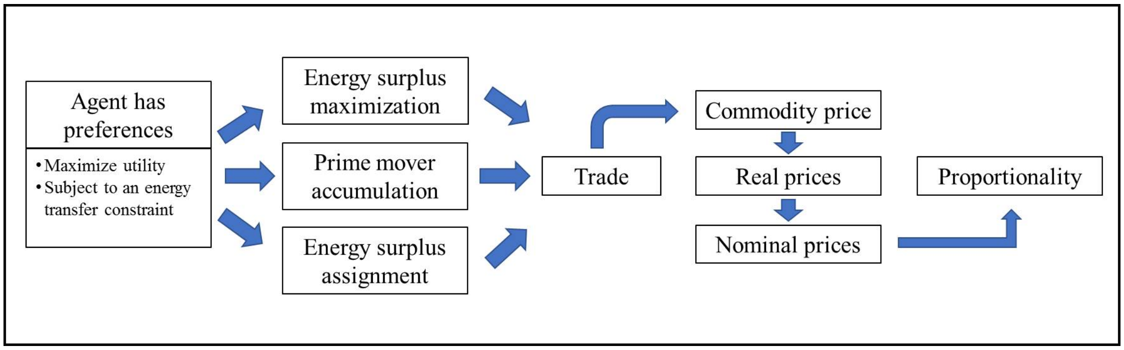

Figure 2.1: Methodological overview

2.2 A revised theory of choice

The point of departure from traditional theory is the consideration of means as energy transfers. Accordingly, utility maximization for an autarkic agent is subject to an energy transfer constraint, and given such constraint, an array of secondary optimization problems must be solved for Pareto-efficiency. This section discusses why means are energy transfers, and solves both primary and secondary optimization problems.

Means are energy transfers because humans can only act by rearranging matter, and they can only rearrange matter with energy transfers. Even if ends are immaterial such as reputation, power, or love, they can only be obtained with material rearrangements such as the writing of a seminal paper, the conquest of a territory, and the shipment of flowers. As stated by Adams (1982), “Every event in history can occur only insofar as there is available whatever amount of energy (i.e., work) is necessary to carry it out. We can think thoughts wildly, but if we do not have the wherewithal to convert them into action, they will remain thoughts".

The proposition that means are energy transfers requires two clarifications. One is that it is teleological, as energy transfers are means only insofar as they do material rearrangements in accordance to human ends. Such rearrangements are economic goods (goods hereafter), which excludes free goods that have not been touched by human action such as freely available clean air, and material rearrangements that do not serve human purpose such as an AC unit in the arctic.

The second clarification is that energy transfers are a process, not an object. The inputs enabling energy transfers can be categorized as energy goods providing energy (e.g., rice, oil), prime movers transferring such energy (e.g., laborers, engines), raw material being rearranged (e.g., hardwood, copper), and supporting inputs that enable such rearrangements (e.g., water, infrastructure). Thus, humanity can be constrained by its ability to transfer energy even when more energy reaches earth from the sun in an hour than what humanity currently uses in a year. Energy transfers are mostly limited by prime mover availability and the incapacity to transfer sunlight into energy goods at an energy surplus, but in general they can be constrained by the scarcity of any input.

The constraining role of scarce inputs does not contradict that energy transfers are the focal point of scarcity. Inputs are scarce in relation to the amount needed to do such transfers and can be substituted according to their relative convenience. On the contrary, there are no substitutes for energy transfers as the way humans alter their surroundings, and therefore outputs are scarce in relation to the amount of energy transfers they require. In a hypothetical world where more energy transfers could be done than those required for bringing about and maintaining Eden, the economic problem would cease to exist. This is why human progress is associated with the capacity to transfer energy (Weissenbacher, 2009; Cook, 1976; White, 1943). Early societies could only transfer the energy content of some types of biomass with the human body, while modern ones complement such transfers with the energy content of oil, uranium, electricity etc. transferred by diesel engines, steam turbines, computers, and a host of other prime movers.

2.2.1 Utility maximization

Consider a multi-period autarkic agent that faces no uncertainty and has preferences represented by a quasiconcave, continuous and twice-differentiable utility function of the form

$$U = U(\boldsymbol{Q}_{F1}, \ldots, \boldsymbol{Q}_{FT}), \tag{2.1}$$

where T is the agent's planning horizon and $\boldsymbol{Q}_{Ft} = [Q_{1t}, \ldots, Q_{Ft}]'$ are final goods demanded in period t. Energy goods and prime movers are excluded from the utility function as a simplifying assumption and all goods are assumed perfectly divisible. The agent's primary objective is to maximize U subject to each period's energy transfer constraint

$$\boldsymbol{\tau}_{Ft}^{A\prime}\boldsymbol{Q}_{Ft} \leq E_t \qquad \forall\, t \in T \tag{2.2}$$

where $\boldsymbol{\tau}_{Ft}^{A\prime} = [\tau_{1t}^{A}, \ldots, \tau_{Ft}^{A}]'$ are final goods' average energy transfers representing the average opportunity cost of producing each unit,[2] and E_t is the energy surplus secured in t. This constraint is real because it is a physical imperative that the energy transferred in the production of final goods (the left-hand side) does not exceed the energy surplus from where energy is transferred (the right-hand side). Moreover, the constraint is reasonable despite being unobservable and arguable unknown because this is an autarkic agent for which an observable monetary constraint does not exist. The relevant Lagrangian at $t = 1$ is

$$\mathcal{L}_f = U(\boldsymbol{Q}_{F1}, \ldots, \boldsymbol{Q}_{FT}) + \sum_{t=1}^{T} \lambda_t (E_t - \boldsymbol{\tau}_{Ft}^{A\prime} \boldsymbol{Q}_{Ft}), \tag{2.3}$$

where λ_t is the marginal utility of energy surplus in period t. The FOCs to choose optimal quantity of final good f are

$$\frac{U_{ft}}{\lambda_t} = \tau_{ft} \qquad \forall\, f \in F, t \tag{2.4}$$

where $\tau_{ft} = \tau_{ft}^{A}(1 + \mu_f)$ is good f's marginal energy transfer, i.e. the minimum energy transfer required to produce one more unit of the good, and $\mu_f = \frac{\partial \tau_f^A}{\partial Q_f} \frac{Q_f}{\tau_f^A}$ is the quantity elasticity of average energy transfer. Given that average and marginal energy transfers are exogenous for the agent *as a consumer*, the FOCs show that the agent adjusts consumption levels such that in equilibrium the MRS between a final good and energy surplus equals the good's marginal energy transfer. Thus, marginal energy transfers reflect ratios between final goods' contribution to the agent's ends (U_{ft}), and the marginal utility of its energy surplus (λ_t). The latter

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[2] A formal definition of energy transfers is provided in section 2.2.2. The problems of system boundary and co-products are overlooked by assuming that all energy transfers can be uniquely allocated among goods.

represents the general intensity of the agent's desires: if λ_t is high then desires are strong, and an additional Joule of energy can substantially increase utility.

The agent's intertemporal preferences are defined by the time-shape of discount factors, where the i-period discount factor at t is endogenously defined as

$$\beta_{ti} = \frac{\lambda_{t+i}}{\lambda_t}, \qquad \forall\, t, i \tag{2.5}$$

and represents the MRS between energy surplus during $t + i$ and t. Given this definition of β_{ti}, ratios of (2.4) shows that optimal demand for good f i-periods apart must observe

$$\frac{U_{ft+i}}{U_{ft}} = \beta_{ti} \frac{\tau_{ft+i}}{\tau_{ft}}, \qquad \forall\, t, i \tag{2.6}$$

which is consistent with Euler's equation despite the endogenous discount factor. β_{ti} could be greater than unity (Hurd, 1989; Hotz et al., 1988; Hansen and Singleton, 1983) because the relative magnitudes of λ_t depend on the relative magnitudes of E_t, or in other words, because an agent's time preference depends on the time-shape of his income stream (Fisher, 1930). If $\beta_{ti} < 1\ \forall\, i$, which is consistent with the growth of energy surplus over time, then β_{ti} is non-increasing in i, and typically decreasing. Yet, β_{ti} can increase (or decrease) over t while decreasing over i.

2.2.2 Marginal energy transfers

Minimizing direct energy transfers in the production of any good $k \in K$ is a Pareto-efficient condition to maximize utility because it is required to minimize the left-hand side of the energy budget constraint in (2.2). The resolution of this problem (detailed in appendix A) shows that good k's marginal energy transfer is

$$\tau_{kt} = \psi_{kt} + \theta_{kt}, \qquad \forall\, k \in K, t \tag{2.7}$$

where $\psi_{kt} = \frac{1}{L_k}\sum_{l=1}^{L_k} \varepsilon_l g'_{lkt}$ is the average direct energy transfers required to produce one more unit of good k, and $\theta_{kt} = \frac{1}{L_k}\sum_{l=1}^{L_k} \phi_{lt} g'_{lkt}$ is the average power scarcity cost in the production of an additional unit of good k. Power scarcity costs arise due to limited prime movers, and thus marginal energy transfers account for both energy goods and prime movers. Moreover, L_k is the quantity of prime mover types producing good k, and for any type l, $\varepsilon_l = \int_t^{t+1} p_l dt$ is the direct energy transfer, p_l is the effective power rate, $g'_{lkt} = f_{lk}^{-1}$ is the marginal requirements of production function (with f_{lk} the marginal productivity in the production of good k), and ϕ_{lt} is the power scarcity cost. A prime mover's power scarcity cost derives from its limited availability, and is measured in Joules as it reflects the energy surplus that could be secured with an additional unit (details in appendix B).

Equation (2.7) shows that marginal energy transfers are endogenous for the agent as a producer, and depends on prime movers' power rate, productivity, and scarcity. Marginal energy transfer change upon changes in ε_l due to variations in effective power rates, in g'_{lkt} due to changes in management or the environment, and in ϕ_{lt} due to shifts in demand for l in the production of any good. In a world with uncertainty, new prime movers and energy goods introduced in a period t_1 would shock the values of $\tau_{kt\geq t_1}$ by modifying $g'_{lkt\geq t_1}$ and $\phi_{lt\geq t_1}$ respectively.

2.2.3 Equilibrium magnitudes

Marginal energy transfers are defined by (2.7), but in equilibrium they equal expressions that vary according to the nature of good k. These expressions are derived from three distinct optimization procedures. Their resolution, alongside energy transfer minimization, is a Pareto-efficient condition for utility maximization. The first optimization procedure is energy surplus maximization, which is required to maximize the right-hand side of the energy transfer constraint in (2.2). The resolution of this problem (details in appendix B) shows that in equilibrium the marginal energy transfer of energy good $e \in \epsilon \in K$ is

$$\tau_{et} = \beta_{t1}\delta_e, \qquad \forall\, e \in \epsilon, t \tag{2.8}$$

where β_{t1} is the one-period ahead discount factor during t and δ_e is good e's energy content in Joules.[3] Equation (2.8) implies that energy goods' marginal energy transfers are influenced by their energy content and the agent's intertemporal preferences, as in equilibrium the agent equates energy goods' opportunity cost to the discounted energy income they provide.

The second procedure is optimal prime mover accumulation, which is required to minimize the left-hand side of the energy transfer constraint in (2.2). The resolution of this problem (detailed in appendix D) shows that in equilibrium the marginal energy transfer of prime mover l is

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[3] We overlook other features of energy goods, such as density and cleanness. For a discussion on energy goods see Cleveland et al. (2000), Podobnik (2005), Stern (2010), Bhattacharyya (2011), and Smil (2016).

$$\tau_{lt} = \phi_{lt} + \sum_{i=1}^{T} \beta_{ti}\phi_{lt+i}d_l^{i-1}, \qquad \forall\, l \in L, t \tag{2.9}$$

where β_{ti} is the ith-period ahead discount factor during t and $d_l \in (0,1)$ is l's linear depreciation rate. Given that ϕ_{lt} can be interpreted as prime movers' marginal energy surplus (details in appendix B), equation (2.9) implies that at equilibrium, the opportunity cost of prime movers — i.e. their marginal energy transfer — equals the flow of discounted energy surplus that they generate. By extension, the opportunity cost of all assets is the present value of the flow of energy surplus that they generate, or as (Fisher, 1930) puts it "The value of any property is its value as a source of income and is found by discounting that expected income". Furthermore, although prime movers produce the energy goods that build energy surplus, with the relation going from the former to the latter, the value of such prime movers is determined by the energy surplus they secure, with the relation going from the latter to the former. In short, "Income values produce capital values" (Fisher, 1930).

The third and last optimization procedure is optimal allocation of energy surplus, which is required for the quantities produced and demanded of final goods to be equal. The resolution of this problem (detailed in appendix D) shows that in equilibrium the marginal energy transfer of final good f is

$$\tau_{ft} = (1 - \Theta_t)\Lambda_{ft}, \qquad \forall\, f, t \tag{2.10}$$

where $\Theta_t \in [0,1)$ is a measure of the agent's over-assignment of energy surplus during t, and Λ_{ft} is the energy assigned by the agent to the production of each unit of final good f. Equation (2.10) implies that final goods' marginal energy transfer is influenced by their energy assignments and excess of energy assignments.

Using equations (2.4) and (2.10) shows that effective energy assignments are

$$(1 - \Theta_t)\Lambda_{ft} = \frac{U_{ft}}{\lambda_t}, \qquad \forall\, f, t \tag{2.11}$$

where the right-hand side is the MRS between a final good and energy surplus. Thus, the agent chooses consumption levels such that the endogenous marginal utility of final goods leads to a MRS with respect to energy surplus equal to the good's exogenous marginal energy transfer. Also, the agent chooses production levels such that the endogenous marginal energy transfer of final goods equal the goods' exogenous effective energy assignments. Equilibrium is reached when effective energy assignments equal the MRS between final goods and energy surplus.

2.3 A revised theory of price

Under autarky no nominal prices exist. This section allows exchange to take place between previously autarkic agents, and shows how nominal prices arise as social representations of marginal energy transfers through exchange and competition. Furthermore, the section formally relates nominal prices to average embodied energies.

Agents have incentives to engage in exchange because, in general, doing so further increases their utility. Exchange leads to gains from trade from the lowering of average energy transfers, which relaxes their energy transfer constraints. These gains follow conventional Ricardian logic.

2.3.1 Commodity prices

Assume two previously autarkic agents exchange two goods and consume them in the same quantities as under autarky. Also assume exchange takes place in a single period such that the time subscript can be omitted. If "agent 1" exchanges q_B units of good B for q_C units of good C with "agent 2", the gains from trade (GT) are

$$GT = \int_{q_C^E}^{q_C^A} \tau_C^1 dq_C - \int_{q_B^A}^{q_B^E} \tau_B^1 dq_B + \int_{q_B^E}^{q_B^A} \tau_B^2 dq_B - \int_{q_C^A}^{q_C^E} \tau_C^2 dq_C - TC \tag{2.12}$$

where q_k^A and q_k^E are the quantities produced of good $k = B, C$ under autarky and exchange respectively, and TC are transaction costs due to transportation, etc. The positive terms are savings from reduced production and the negative ones are spending from increased production. When $GT > 0$ there are unambiguous gains from trade because aggregate production and consumption of both goods is the same under exchange as under autarky, but at lower average energy transfers. Gains from trade are a "release" of energy surplus that the agents can use to produce other goods. If under autarky $\tau_B^1 < \tau_B^2$ and $\tau_C^1 > \tau_C^2$ ($\tau_B^1 < \tau_B^2$ and $\tau_C^1 < \tau_C^2$) there are absolute (relative) comparative advantages.

For the unambiguous gains from trade to benefit both agents, the rate of exchange of goods q_B/q_C (i.e. their commodity price) must remain between agents' reservation values. Such values are τ_C^1/τ_B^1 for agent 1 and τ_C^2/τ_B^2 for agent 2. The commodity price that will govern this exchange is between agents' reservation values, yet nothing more is known as both agents are monopolies of the good they produce, and monopsonies of the other one. The exact commodity price will depend on site-specific features such as negotiating abilities.

Changes in marginal and average energy transfers alter each agent's entire schedule of production and consumption. As shown in Figure 2.2, the intersection between a good's demand and marginal energy transfer curve (METC) yields equilibrium production and consumption under autarky. The agent in the left diagram has a relatively lower METC, and under exchange produces more relative to autarky. Faced with a higher marginal energy transfer $\tau^{E'} > \tau^{E}$, this agent will demand less and produce more. The difference are exports (E). The agent in the right diagram, faced with a lower marginal energy transfer $\tau^{I'} < \tau^{I}$, will produce less and demand more. The difference are imports (I). Under exchange, the marginal energy transfer of both agents is the same $\tau^{E'} = \tau^{I'}$ if $TC = 0$.

Without the assumption that the agents' consumption remains the same after exchange there are still unambiguous gains for both agents if $GT > 0$ and if the rate of exchange of goods is between agents' reservation values. If an agent willingly reduces the consumption of a good as compared to autarky, doing so must provide the agent with another good that yields more utility.

The optimal rate of exchange of goods is given by maximizing (2.12) choosing q_B and q_C. For any good $k = B, C$ the FOC is

$$\tau_k^I = \tau_k^E + MTC_k, \tag{2.13}$$

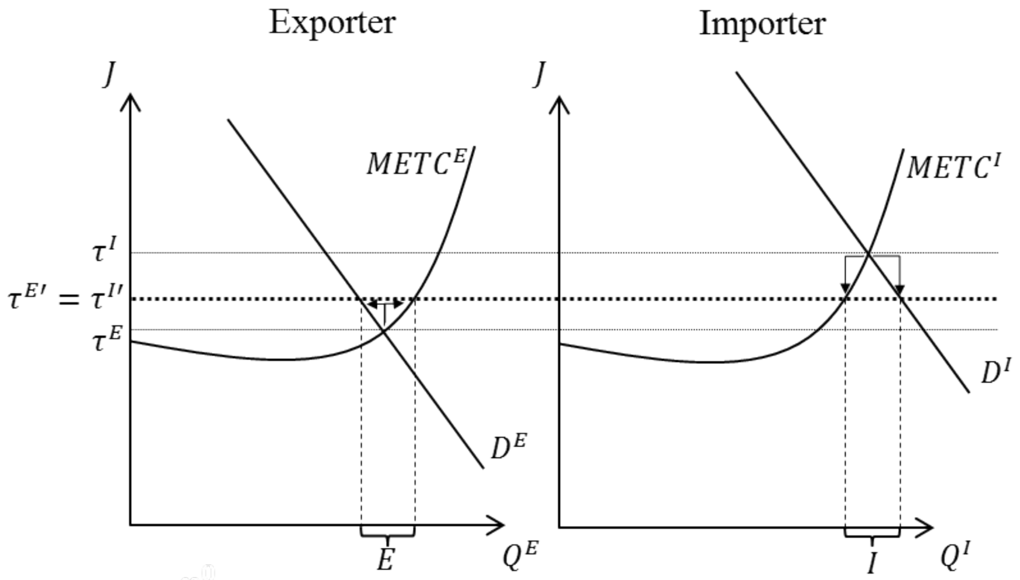

Figure 2.2: Changes in demand and supply due to exchange

where τ_k^I and τ_k^E are the marginal energy transfers of the importing and exporting agent respectively, and MTC_k is good's k marginal transaction cost. This condition sets the patterns of trade: until (2.13) is observed, agents with relatively lower marginal energy transfers will export a good, while those with relatively higher ones will import it. If $TC = 0$ (assumed hereafter), the optimal quantity exchanged by the agents equalizes the marginal energy transfer of each good between agents (Figure 2.2).

If "agent 1" trades q_B^* for q_C^* with "agent 2", under (2.13) the exchange implies

$$\tau_B q_B^* = \tau_C q_C^*, \tag{2.14}$$

such that the agents are exchanging equivalent energy magnitudes at the margin. Cross multiplying (2.14) yields the commodity price

$$\frac{q_B^*}{q_C^*} = p^c = \frac{\tau_C}{\tau_B}, \tag{2.15}$$

such that the quantity of good B traded per unit of good C (i.e. the commodity price of C) is given by the inverse of their relative marginal energy transfers. The conditions in (2.13) and (2.14) and the price associated with it in (2.15) materializes through competition. Adding more agents to the exchange of goods B and C makes negotiation abilities and other site-specific features progressively irrelevant. As monopolistic and monopsonistic positions are lost, Nash equilibrium brought about by tâtonnement leads to the collapse of the range of possible commodity prices at the ratio of marginal energy transfers under exchange τ_C/τ_B.

2.3.2 Real and nominal prices

Even a modest number of K goods make barter impractical. Agents convene on using real money (i.e. commodity money or general equivalent) to solve this problem (Schumpeter, 1954; Menger, 1892). If compliant with certain characteristics (Einzig, 1966), real money solves the problem of double coincidence of wants as a medium of exchange, facilitates savings as a store of value, enables debt as a unit of deferred payments, and reduces the number of commodity prices from $K!$ to $K-1$ as a unit of account (Schumpeter, 2014; Smithin, 2014; Karimzadi, 2013).

Despite acquiring such attributes, real money is first and foremost a good such as cowries, cows, or gold (Cribb, 1986), and therefore has its own marginal energy transfer τ_m. Given (2.15), the commodity price of commodity k in terms of real money, i.e. its real price, is

$$p_k = \frac{\tau_k}{\tau_m}, \tag{2.16}$$

which can have complex movements as both τ_k and τ_m can be simultaneously changing. For example, τ_m can increase due to depletion of gold deposits, and τ_k can fall due to innovations reducing energy transfers or investments reducing prime mover constraints.

Given the hurdles inherent in using real money (Karimzadi, 2013), societies further facilitate exchange by adopting nominal money as a representation of real money (Poor, 1969). Nominal money, also called representative money or currency, does not derive its rate of exchange with other goods from its own marginal energy transfer. Nominal money such as pesos, dollars, and euros have a "synthetic energy transfer" established by applying (2.15) between real and nominal money. The synthetic energy transfer of nominal money, i.e. its purchasing power, is

$$\tau_s = \frac{\tau_m Q_m}{Q_n}, \tag{2.17}$$

where Q_m and Q_n are respectively the total quantities of real and nominal money in an economy. Given (2.15), the real price of commodity k in terms of nominal money, i.e. its nominal price, is

$$P_k = \frac{\tau_k}{\tau_s}, \tag{2.18}$$

which holds for all goods regardless if they are final, energetic, or prime movers. Thus, when agents engage in exchange using nominal money and prices, it is unknown and irrelevant to them that marginal energy transfers are defined according to (2.7) and expressed according to (2.18). The same is true regarding how marginal energy transfers of energy goods, prime movers, and final goods are influenced according to (2.8), (2.9), and (2.10) respectively. Under the cloak of nominal prices all goods appear equal.

The common nominal component of all nominal prices also contribute to their mimetization. Inverting, logging, and differentiating (2.17) shows the rate of decrease of the purchasing power of nominal money, i.e. inflation, as

$$\pi = d\ln(\frac{Q_n}{Q_m}) - d\ln(\tau_m) \tag{2.19}$$

where $\pi = d\ln(1/\tau_s)$. Logging and differentiating (2.18) shows the rate of change of nominal prices as

$$d\ln(P_k) = d\ln(\tau_k) + \pi, \tag{2.20}$$

and replacing with (2.19) yields

$$d\ln(P_k) = d\ln(p_k) + d\ln(\frac{Q_n}{Q_m}). \tag{2.21}$$

Both expressions show that all nominal prices are affected by the same common nominal component π or $d\ln(Q_n/Q_m)$. Equation (2.21) shows that nominal prices experience more complex movements than real prices, as the former contains the latter and is additionally influenced by the rate of growth of the ratio of nominal money to real money. In fact, $d\ln(Q_n/Q_m)$ can lead to drastic changes in nominal prices (e.g., expansive monetary policies or trade deficits under the gold standard) even when changes in the real component is zero, i.e. $d\ln(p_k) = 0$. Logically, if most of these variables remain stable, then nominal and real prices can be mostly stable. Thus, equation (2.21) interprets the existence of waves of price equilibriums and price revolutions as documented in Fischer (1996), although such interpretation exceeds the scope of this article.

Caution must be taken when nominal money is replaced with fiat money and therefore τ_s stops being defined by (2.17). In such context, τ_s starts depending on the trust that agents have on the issuer of fiat money and the equations specified with τ_s loose validity. The extent of this loss exceeds the scope of this paper, as it relates to the old and ongoing debate between Chartalism (Wray, 2012) and Metallism (Menger, 1892).

The ratios of real prices offset the variability in real prices that stem from the marginal energy transfer of real money. Considering commodities A and $C \in K$ with real prices $p_B = \tau_B/\tau_m$ and $p_C = \tau_C/\tau_m$ shows that their relative real price equals the ratio of their marginal energy transfers

$$\frac{p_B}{p_C} = \frac{\tau_B/\tau_m}{\tau_C/\tau_m} = \frac{\tau_B}{\tau_C}. \tag{2.22}$$

Similarly, relative nominal prices offset the variability in nominal prices that stem from the purchasing power of nominal money, and they also offset the effect of fiat money. Considering nominal prices $p_B = \tau_B/\tau_s$ and $p_C = \tau_C/\tau_s$ shows that their relative nominal price also equals the ratio of their marginal energy transfers

$$\frac{P_B}{P_C} = \frac{\tau_B/\tau_s}{\tau_C/\tau_s} = \frac{\tau_B}{\tau_C}. \tag{2.23}$$

2.3.3 The proportionality between prices and embodied energies

Equations (2.18) and (2.23) do not directly interpret the proportionality under study because they contain marginal energy transfers instead of average embodied energies. Yet, they come close as both concepts are tied by the direct energy transfers required to produce goods. Good k's marginal embodied energy can be decomposed as

$$\gamma_k = \psi_k + \Gamma_k, \tag{2.24}$$

where ψ_k is good k's marginal direct energy transfer as described in (2.7) and Γ_k is the average energy transfers used to build the prime movers producing the marginal unit of k. Thus, marginal energy transfers and embodied energies coincide regarding direct energy transfers yet differ regarding indirect transfers. Embodied energies are backward-looking by considering as indirect transfers the energy used in the past to produce the prime movers doing direct transfers (Chapman, 1974; IFIAS, 1974). Energy transfers are forward-looking by considering as indirect transfers the power scarcity of prime movers doing direct transfers. As this measure is determined by prime movers' potential to provide energy surplus in the future and has no relation to the past, energy transfers recognize that "bygones are forever bygones".

Given (2.7) and (2.24), marginal energy transfers and embodied energies are related as

$$\tau_k = \gamma_k + (\theta_k - \Gamma_k), \tag{2.25}$$

such that they differ according to the difference between prime movers' potential to provide energy surplus and the energy transferred to produce them. Another reason equations (2.18) and (2.23) fail to interpret the proportionality under study is because they contain marginal values, while estimates of embodied energies are of average embodied energies or of random samples of the marginal embodied energy curve. As in either case the most reasonable assumption is that available estimates are averages, then replacing (2.18) with (2.25) and noting that $\gamma_k = \gamma_k^A(1+\eta_k)$ leads to nominal prices as

$$P_k = \frac{\gamma_k^A(1+\eta_k) + (\theta_k - \Gamma_k)}{\tau_s}, \tag{2.26}$$

where $\eta_k = \frac{\partial \gamma_k^A}{\partial Q_k}\frac{Q_k}{\gamma_k^A}$ is good k's industry-wide quantity elasticity of average embodied energy. Equation (2.26) interprets the proportionality under study by indicating a noisy positive relation between nominal prices and average embodied energies. The noise is due to differences between the energy transferred to produce prime movers and their potential to provide energy surplus, differences between marginal and average values, and inflation.

To control for the effect of inflation, the ratio of (2.26) for any two commodities A and $B \in K$ is

$$\frac{P_A}{P_B} = \frac{\gamma_A^A(1+\eta_A) + (\theta_A - \Gamma_A)}{\gamma_B^A(1+\eta_B) + (\theta_B - \Gamma_B)}. \tag{2.27}$$

2.4 Discussion

The proportionality between market prices and average embodied energies can be understood by recognizing energy transfers as the means available to human ends. Nominal prices represent marginal energy transfers, and such transfers are related to average embodied energies. The proportionality under study is noisy due to the differences between energy transfers and embodied energies, the difference between marginal and average embodied energy, and inflation.

The model presented is mostly consistent with conventional economic theory. Economics is the study of human behavior as a relationship between ends and scarce means (Robbins, 1932); means are simply energy transfers. Production is not creation but transformation through arrangement (Ryan and Pearce, 1985; von Mises, 1949; Marshall, 1920); arrangements are simply argued to be a material process associated with energy transfers. Production consists of the rendering of services by human agencies (Friedman, 1962; Knight, 1935); services are simply specified as energy transfers and human agencies as prime movers. The cost of a service in producing a good is the other goods it could produce (Stigler, 1987); the Joule only measures the quantity of goods that are being sacrificed. In summary, we can recognize means as energy transfers and agree with all fundamental laws of neoclassical microeconomics (Rappaport, 1998).

Disagreements between conventional theory and this model stem from energy's place in economics. While energy is ignored by the former, the latter recognizes that energy transfers are the means by which humans act. This leads to several divergences, the two most important being the understanding of the limiting factors of production and growth, and the acceptance of a physical unit of value. These novelties signal where this perspective provides new insights into economic phenomena. The first one suggests that growth is constraint by whatever hinders the capacity to transfer more energy, and therefore highlights the importance of prime mover accumulation, efficiency enhancements, and energy goods' energy surplus (see Chapter 2). The second suggests that by measuring the opportunity cost of goods in Joules, market prices can be interpreted as social manifestations of underlying energy magnitudes. Although controversial for economists, this proposition simply observes that "Energy is the only universal currency: one of its many forms must be transformed to another in order for stars to shine, planets to rotate, plants to grow, and civilizations to evolve" (Smil, 1999).

This perspective does not support an energy theory of value or an energy transfer theory of value. First, means as energy transfers does not imply valuations that are independent from human ends. Material rearrangements become goods and energy transfers means only if they further human ends. Furthermore, marginal energy transfers are goods' opportunity cost, and therefore a comparison that respects the chief notion that nothing can be valuable without reference to something else. Whatever marginal energy transfers are revealed in a given economy, they are specific to the ends sought by the unique human beings constituting it, and on the factors influencing the scarcity of energy transfers in a given place and time. Second, although nominal prices represent marginal energy transfers, such magnitudes depend on an array of variables apart from direct energy transfers and the scarcity of prime movers. Marginal energy transfers of final goods also depend on the MRS between goods and energy surplus, and those of energy goods and prime movers on the agent's time preferences. If anything, this perspective harmonizes objective and subjective schools of economic value by recognizing human ends as the driver of economic activity, and energy transfers as the means to fulfill them.

Further clarifications are in order on why this perspective does not support an energy theory of value, and how it responds to the issues put forth in Alessio (1981), Hertzmark (1981), Huettner (1976, 1982), and others. First, this perspective highlights energy transfers and not energy as the ultimately scarce resource, and notes that energy transfer are processes done by prime movers using energy goods while supported by a host of other factors such as water, infrastructure, social norms, etc. Second, there is nothing in the model requiring the scarcity of energy goods to intensify over time. This is likely to happen, and is required for a long run equilibrium to exist, but a society that manages to produce ever more energy goods at constant marginal energy transfers will simply grow indefinitely. Third, there is no suggestion that a pure physical energy analysis is superior to a monetary analysis. On the contrary, monetary magnitudes are expressions of underlying energy flows, and thus conventional economic analysis is energy analysis in disguise. Fourth, price levels and relative prices are not dependent on supply alone, as marginal energy transfers depend on intra and inter-temporal preferences. Fifth, time preferences heavily weight on the marginal energy transfers of energy goods and prime movers. Sixth, marginal energy transfers take into consideration all inputs required to produce a good, not only the energy goods and prime movers used in production. If an input (e.g., water) becomes scarce in some place and time, this means that more energy transfers are required to obtain it, which affects the marginal energy transfers of all goods using it. Seventh, technology plays a major role influencing marginal energy transfers and the magnitude of energy surplus. The disruptions of discoveries and inventions such as electricity and the induction motor are not analyzed because uncertainty was ruled out, not because they cannot fit within the model.

The model provides several secondary results. Energy transfers as a forward-looking measure of energy flow contrasts with the conventional backward-looking concept of embodied energy, and thus has stronger economic intuition. Similarly, a prime mover's marginal energy transfer (and nominal price) equals the discounted future energy surplus it will generate. Moreover, an endogenous discount factor and its relation to EROI provides a new perspective on interest rates as the bridge between a society's impatience and opportunity. Lastly, the logical sequence leading to the use of real and nominal money provides a definition of inflation that is partially different to its conventional understanding.

Recognizing means as energy transfers has consequences that exceed the interpretation of the proportionality under study. Viewing nominal prices as representations of marginal energy transfers adds a new layer to microeconomic analysis. This is irrelevant if nominal prices are given, yet has implications when they are unreliable or nonexistent as with market power and nonmarket valuation. Furthermore, this layer provides a new micro-foundation for macroeconomics, with implications for the understanding of growth, interest rates, inflation, and inequality. Proper accounts of these implications are future research avenues.

The model's limitations provide other topics for further research. Excluding energy goods and prime movers from agents' utility functions implies a relatively low loss of generality, yet their inclusion would yield a more general framework. More generality could also be obtained with the inclusion of institutional and environmental factors that influence economies and markets. Although such factors only stimulate or obstruct the fundamental tendencies that the current model describes, a complete description of nominal prices should consider them. Finally, the model is set up without uncertainty, market power, or other prominent features of real world economies. Given the use of conventional economic rationale, extensions considering choice under uncertainty, game theory, and monopolies/oligopolies should follow seemly.

2.5 Conclusion

Nominal prices are proportional to average embodied energies because marginal energy transfers measure goods' opportunity costs, and because energy transfers and embodied energies are related concepts of energy flows. These results derive from recognizing energy transfers as the means available to human purpose, the relevance of an autarkic agent's energy transfer constraint, and the role that prime movers play in production. These deviations from standard theory are the basis to interpret the proportionality under study, and to include energy within neoclassical micro theory. Understanding nominal prices as social representations of underlying marginal energy transfers provides a new layer to microeconomics and a new micro-foundation to macroeconomics, with implications for interest rates, inflation, growth, and among others, inequality. At a broader level, such understanding suggests a perspective of economics as an interplay between human desires and thermodynamic processes.

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Appendices

A Energy transfer minimization

This secondary objective for the agent takes the form

$$\min_{\boldsymbol{x}_{kt}} \boldsymbol{\varepsilon}'\boldsymbol{x}_{kt}, \qquad \forall\, k, t \tag{A2.1}$$

subject to the productive targets

$$f_{kt}(\boldsymbol{x}_{kt}) = \bar{Q}_{kt}, \qquad \forall\, k, t \tag{A2.2}$$

and the prime mover constraints

$$\sum_{k=1}^{K} x_{lkt} \leq \tilde{x}_{lt}, \qquad \forall\, l, t \tag{A2.3}$$

where $\boldsymbol{\varepsilon}'\boldsymbol{x}_{kt}$ is the direct energy transferred to produce Q_{kt}, $\bar{Q}_{kt}$ is the target of production of good k during t, and $f_{kt}(\cdot)$ is a concave from above, continuous, and twice-differentiable production function. Also, $\boldsymbol{x}_{kt} = [x_{1kt}, \ldots, x_{Lkt}]'$ is the set of prime movers used to achieve such production and $\tilde{x}_{lt}$ is the agent's availability of prime mover l during t.

The objective and production functions only include prime movers because — in an autarkic setting — prime movers contain all other inputs. Supporting inputs (e.g., desks, warehouses, transmission lines) are subsumed by a given prime mover endowment because $\tilde{x}_{lt}$ includes everything required to transfer energy. Energy inputs (e.g., rice, gasoline, electricity) are accounted for by prime mover's $\boldsymbol{\varepsilon}$ as prime mover's energy transfer is a transferal of energy goods' energy content. Furthermore, there are no intermediate inputs because the agent runs the entire productive chains, and raw materials need not be considered as they are spontaneous material arrangements that the agent finds in nature. Finally, the opportunity cost of prime movers themselves is factored in through prime mover constraints as shown below.

The minimization of $\boldsymbol{\varepsilon}'\boldsymbol{x}_{kt}$ given $\bar{Q}_{kt}$ and $\tilde{x}_{lt}$ $\forall\ l, t$ is done by modifying conventional cost minimization procedures described in Silberberg & Suen (2001) or similar. The relevant Lagrangian at $t = 1$ is

$$\mathcal{L}_k = \sum_{t=1}^{T}\sum_{k=1}^{K} \lambda_t \boldsymbol{\varepsilon}'\boldsymbol{x}_{kt} + \sum_{t=1}^{T}\sum_{k=1}^{K} \lambda_t \tau_{kt}[\bar{Q}_{kt} - f_{kt}(\boldsymbol{x}_{kt})] - \sum_{t=1}^{T}\sum_{l=1}^{L} \lambda_t \phi_{lt}(\tilde{x}_{lt} - \sum_{k=1}^{K} x_{lkt}), \tag{A2.4}$$

where each good's marginal energy transfer appears as the Lagrange multiplier associated with its productive target constraint because it is goods' opportunity cost. Each energy flow is multiplied by its corresponding marginal utility of energy because the primary objective of the agent is to maximize utility, not some energy flow *per se*. The FOC to choose the optimal quantity of prime mover l to produce good k in period $t > 0$ is

$$\tau_{kt} f_{lkt} = \varepsilon_l + \phi_{lt}, \tag{A2.5}$$

where f_{lkt} is the marginal productivity of prime mover l in the production of good k in period t, and ϕ_{lt} is its power scarcity cost in that period. Multiplying (A2.5) by g'_{-lkt} (the inverse of f_{lkt}) and averaging over l yields the expression for marginal energy transfer in (2.7).

The resolution of the Lagrangian in (A2.4) involves a system of $L^2 \times K^2 \times T^3$ equations and unknowns (the λ_t are exogeneous for the agent *as a producer*). This system, even in its simpler versions (e.g., $L = 2$; $K = 2$; $T = 3$), has no closed form solution under conventional functional forms of the production function. Numerical approximations are required to obtain optimal prime mover demands, marginal energy transfers, and power scarcity costs.

B Energy surplus maximization

This secondary objective for the agent takes the form

$$\max_{\boldsymbol{Q}_{et}} E_t = \sum_{e=1}^{\epsilon} (\delta_e Q_{et-1} - D_{et}), \qquad \forall\, t \tag{B2.1}$$

subject to the prime mover constraints

$$\sum_{k=1}^{K} x_{lkt} \leq \tilde{x}_{lt}, \qquad \forall\, l, t \tag{B2.2}$$

where Q_{et-1} is the quantity of energy good e produced in period $t-1$ and available in t and $Q_{e,0}$ is the initial endowment of the good. The relevant Lagrangian at $t = 1$ is defined as

$$\mathcal{L}_e = \sum_{t=1}^{T} \lambda_t [\sum_{e=1}^{\epsilon} (\delta_e Q_{et-1} - D_{et}) + \sum_{l=1}^{L} \phi_{lt} (\tilde{x}_{lt} - \sum_{k=1}^{K} x_{lkt})], \tag{B2.3}$$

where the multiplication of each energy flow by its corresponding marginal utility of energy responds to the idea that energy surplus maximization is a Pareto-efficient condition for utility maximization.

Noting that $x_{lkt} = g_{lkt}(Q_{kt}, \boldsymbol{x}_{-lkt})$, the FOC to choose the optimal quantity of energy good e in period $t > 0$ indicates that energy goods' marginal energy transfers equals their discounted energy income

$$\tau_{et} = \beta_{t1}\delta_e. \qquad \forall\, e \in \epsilon \tag{B2.4}$$

Given $\beta_{t1} = \frac{\lambda_{t+1}}{\lambda_t}$, equation (B2.4) implies that the utility the agent derives from producing an additional unit of an energy good in period $t+1$ $(\lambda_{t+1}\delta_e)$ equals the utility forgone due to its production in $t(\lambda_t\tau_{et})$. Also, the condition implies that all energy goods have the same marginal Energy Return Over Energy Investment ($\text{mEROI}_{et} = \delta_e/\tau_{et}$) $\forall\, e, t$, yet not necessarily the same average Energy Return Over Energy Investment ($\text{aEROI}_{et} = \delta_e/\tau_{et}^A$). This definition of mEROI implies that $\beta_{t1} = \frac{1}{mEROI_{et}}\ \forall\, e$, and thus a relation between the agent's time preferences, interest rate, and opportunities to increase energy transfers in the future.

The resolution of the Lagrangian in (B2.3) involves a system of $L \times \epsilon \times T^3$ equations and unknowns. The equations representing the FOC with respect to ϕ_{lt} are identical to the ones in the previous section, and thus provide no additional information. This system can be solved by considering ϕ_{lt} exogeneous and the optimization based on energy transfers instead of direct energy transfers and prime mover constraints. The system yields optimal production of energy goods and the agent's entire schedule of energy surplus.

Prime movers' power scarcity cost is their marginal energy surplus, which is found replacing $Q_{et} = f_{et}(\boldsymbol{x}_{e,t})$ in (B2.3). Deriving such expression with respect to any prime mover x_{let}, and averaging over e shows that prime mover l's power scarcity cost is

$$\phi_{lt} = \beta_{t1} \frac{1}{\epsilon} \sum_{e=1}^{\epsilon} (\delta_e f_{let} - \varepsilon_l), \qquad \forall\, l \tag{B2.5}$$

where the right-hand side is l's discounted marginal energy surplus secured on average across all energy goods. This surplus provides the incentive for the agent to accumulate prime movers.

C Optimal prime mover accumulation

This secondary objective for the agent takes the form

$$\max_{Q_{lt}} \mathcal{E}_L = \sum_{l=1}^{L} (\phi_{lt} Q_{lt} - D_{lt}), \qquad \forall\, t \tag{C2.1}$$

subject to the prime mover constraints

$$\sum_{k=1}^{K} x_{lkt} \leq \tilde{x}_{lt}, \qquad \forall\, l, t \tag{C2.2}$$

where $\mathcal{E}_L$ is a quasi-energy surplus that indicates the energy balance between energy income and transfers associated with prime mover production. $\mathcal{E}_L$ is a *quasi*-surplus because prime movers do not provide an energy income directly. Therefore, *quasi*-surpluses are transferals of energy surplus from energy sectors to non-energy sectors. Noting that prime mover endowment is

$$\tilde{x}_{lt} = \sum_{i=0}^{t-1} d_l^i Q_{lt-1-i}, \qquad \forall\, l, t \tag{C2.3}$$

where Q_{lt-1-i} is the quantity of prime mover l produced in period $t-1-i$, and Q_{l0} is its initial endowment, then replacing (C2.3) in (C2.2) and including λ_t as done above for all energy flows implies that the relevant Lagrangian at $t=1$ is

$$\mathcal{L}_l = \sum_{t=1}^{T} \lambda_t [\sum_{l=1}^{L} \phi_{lt} Q_{lt} - D_{lt} + \phi_{lt} (\sum_{i=0}^{t-1} d_l^i Q_{lt-1-i} - \sum_{k=1}^{K} x_{lkt})]. \tag{C2.4}$$

The FOC to choose the optimal quantity of prime mover l in period $t > 0$ indicates that, in equilibrium, l's marginal energy transfer equals the average contemporary surplus secured by all prime movers type plus the discounted net sum of the energy surplus l provides over its lifetime

$$\tau_{lt} = \phi_{lt} + \sum_{i=1}^{T} \beta_{ti} \phi_{lt+i} d_l^{i-1}. \qquad \forall\, l, t \tag{C2.5}$$

Given $\beta_{ti} = \frac{\lambda_{t+i}}{\lambda_t}$, the condition equates the utility the agent derives in all future periods from producing an additional unit of a prime mover in t $(\lambda_t \phi_{lt} + \sum_{i=1}^{T} \lambda_{t+i} \phi_{lt+i} d_l^{i-1})$ to the utility forgone due to its production in that period $(\lambda_t \tau_{lt})$. The condition also yields prime mover's optimal production in each period, prime movers endowment for the next one, and the agent's aggregate power rate $P_t = \sum_{l=1}^{L} p_l \tilde{x}_{lt}$.

The resolution of the Lagrangian in (C2.4) involves a system of $L \times T$ equations and unknowns. This system can be easily solved based on energy transfers instead of direct energy transfers and prime mover constraints. The system yields optimal production of prime movers and the agent's entire schedule of power.

D Optimal allocation of energy surplus

This secondary objective for the agent takes the form

$$\max_{Q_{ft}} \mathcal{E}_F = \sum_{f=1}^{F} (\Lambda_{ft} Q_{ft} - D_{ft}), \qquad \forall\, t \tag{D2.1}$$

subject to the prime mover constraints

$$\sum_{k=1}^{K} x_{lkt} \leq \tilde{x}_{lt}, \qquad \forall\, l, t \tag{D2.2}$$

and the energy assignment constraint

$$\sum_{f=1}^{F} \Lambda_{ft} Q_{ft} \leq E_t, \qquad \forall\, t \tag{D2.3}$$

where $\mathbf{\Lambda}_t = [\Lambda_{1t}, \ldots, \Lambda_{Ft}]'$ is the unitary energy assigned by the agent to the production of final goods. The last constraint binds the total energy assigned in the production of all final goods to the agent's energy surplus. The relevant Lagrangian at $t = 1$ is

$$\begin{aligned} \mathcal{L}_f = & \sum_{t=1}^{T} \lambda_t \sum_{f=1}^{F} (\Lambda_{ft} Q_{ft} - D_{ft}) + \sum_{t=1}^{T} \sum_{l=1}^{L} \lambda_t \phi_{lt} (\tilde{x}_{lt} - \sum_{k=1}^{K} x_{lkt}) \\ & + \sum_{t=1}^{T} \lambda_t \Theta_t (E_t - \sum_{f=1}^{F} \Lambda_{ft} Q_{ft}), \end{aligned} \tag{D2.4}$$

where $\Theta_t \in [0, 1)$ is a measure of the agent's over-assignment of energy surplus during t. The FOC to choose the optimal quantity of good f during t shows that in equilibrium marginal energy transfers of final goods equal effective energy assignment

$$\tau_{ft} = (1 - \Theta_t)\Lambda_{ft}. \qquad \forall\, f, t \tag{D2.5}$$

This solution ensures that, $\boldsymbol{\Lambda}_t$, the agent produces the maximum amount of final goods while complying with energy assignment and prime mover constraints. The resolution of the Lagrangian in (D2.4) involves a system of $L \times F \times T^3$ equations and unknowns. The system yields optimal production of final goods and the schedule of over-assignment of energy.

Chapter 3

Further evidence on the proportionality between prices and embodied energies: The case of food[1]

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[1] Leiva, B. and Mullen, J. To be submitted to *Economic Letters.*

Abstract

The evidence on the proportionality between prices and embodied energies is limited. This study explores if such proportionality holds for foodstuff and interprets it theoretically. Results show that the proportionality consistently holds at the aggregate and national level, and that it is entirely consistent with theory. In levels, the proportion is mainly dominated by the effect of inflation, and in ratios by relative returns to scale, marginal productivities, and investment requirements.

Keywords: Embodied energy; prices; food

JEL Codes: Q11, Q40

Nomenclature

P_k	Price of good k
γ_k^A	Average embodied energy of good k
η_k	Quantity elasticity of average embodied energy in the production of k
θ_k	Partial opportunity cost of the prime movers producing k
Γ_k	Average marginal embodied energy of prime movers used in the marginal unit of k
τ_s	Purchasing power of nominal money
ϕ_k	Prime mover l's power scarcity cost
γ_l	Prime mover l's marginal embodied energy
L_k	Quantity of prime mover types used in the production of good k

3.1 Introduction

Average embodied energy (EE) is the total energy required on average to produce a good. Some authors have suggested that goods' prices and EE should be proportional given the role of energy in the functioning of societies and economies (Cottrell, 1955; Hannon, 1973; Odum, 1971; Soddy, 1933). Such proportionality has been reported at the national level using input-output techniques by Costanza (1980) and Costanza and Herendeen (1984), and at the commodity level using process analysis byLiu et al. (2008) and Gutowski et al. (2013).

This literature is yet too limited to conclude that the proportionality holds in general. For example, Liu et al. (2008) and Gutowski et al. (2013) only study intermediate goods, and do not analyze if the proportionality holds at the country level. Does this proportionality hold for foodstuff, which are generally final goods? Does it hold for different countries? Furthermore, can the proportionality under study be interpreted with the theoretical relation specified by Chapter 2?

This is the first article to consolidate all published estimates of EE of foodstuff (to the best of the authors' knowledge), pair them with corresponding prices in space and time, and see if there is a positive correlation between them that holds for different countries. Also, this is the first attempt to use the theoretical construct developed in Chapter 2 to interpret the proportionality between prices and EE, and relative prices and relative EE using conventional economic rationale.

3.2 Model and data

3.2.1 Model

Chapter 2 suggests that under perfect competition and no uncertainty, the nominal price of any good k is

$$P_k = \frac{\gamma_k^A(1+\eta_k) + (\theta_k - \Gamma_k)}{\tau_s}, \tag{3.1}$$

where γ_k^A is good k's average EE, η_k its quantity elasticity of average EE, and τ_s is the purchasing power of nominal money. Moreover, $\theta_k = \frac{1}{L_k}\sum_{l=1}^{L_k}\frac{\phi_l}{f'_{lk}}$ is the partial opportunity cost of the prime movers producing an additional unit of good k, with ϕ_{lt} representing prime mover l power scarcity cost and f'_{lk} the marginal productivity function. Lastly, $\Gamma_k = \frac{1}{L_k}\sum_{l=1}^{L_k}\frac{\gamma_l}{f'_{lk}}$ is the average marginal EE of prime movers used in the marginal unit of k, γ_l is the marginal EE of prime mover l, and L_k is the quantity of prime mover types used in the production of good k. Prime movers are systems capable of transferring energy to rearrange matter, such as workers, engines, and computers.

As τ_s is the purchasing power of nominal money, $d\ln(1/\tau_s)$ is inflation. A small but persistent inflation rate over a long period dramatically reduces τ_s. For example, with an average yearly inflation rate of 4%, the USD's purchasing power fell by 85.9% during 1950-2000. Given (3.1), a small τ_s, *ceteris paribus*, implies that any good's price will be larger than what its average EE alone suggests. The relation between these variables should have a slope greater than one if the effect of τ_s dominates over the effects of η_k, θ_k, and Γ_k.

To control for τ_s, the ratio of (3.1) for any two commodities A and B is

$$\frac{P_A}{P_B} = \frac{\gamma_A^A(1+\eta_A) + (\theta_A - \Gamma_A)}{\gamma_B^A(1+\eta_B) + (\theta_B - \Gamma_B)}. \tag{3.2}$$

Lower η_k implies that average EE decreases more or increases less as quantity increases, and thus higher returns to scale. For any pair of industries producing goods A and B, the higher the relative returns to scale η_A/η_B, *ceteris paribus*, the lower the relative price P_A/P_B compared to what relative EE alone suggest.

Rewriting $\theta_k - \Gamma_k$ as $\frac{1}{L_k}\sum_{l=1}^{L_k}\frac{\phi_l - \gamma_l}{f'_{lk}}$ shows that the sign of such difference depends on the sign of $\phi_l - \gamma_l$. If $\phi_l > \gamma_l \; \forall \; l$, for any pair of industries producing goods A and B, the higher the relative average marginal productivity, *ceteris paribus*, the lower the relative price compared to what relative EE alone suggest. If $\phi_l < \gamma_l \; \forall \; l$ the relation is reversed. If $\phi_l - \gamma_l$ changes sign by l the relation will depend on the weighted sum of such difference by marginal productivity across all prime movers.

Arguably, relative returns to scale and average marginal productivity move together, which implies that if $\phi_l > \gamma_l \; \forall \; l$ the relation between relative prices and relative EE unambiguously has a slope less than one. If $\phi_l < \gamma_l \; \forall \; l$ the relation depends on the relative magnitudes of relative returns to scale and relative $\theta_k - \Gamma_k$. Thus, although it is theoretically possible for the relation between relative prices and relative EE to have a slope greater than one, it is more likely for them to have a slope less than one. This recalls the relation between Marshallian demand and own price, which cannot be unambiguously established yet is expected to be negative.

3.2.2 Data

We consolidate data from seven papers that estimate the EE of foodstuff for different countries and pair those estimates with their corresponding prices in space and time. The countries and sources of the data are listed in Table 3.1, and a complete description is available in the accompanying Data in Brief.

Table 3.1: Observations and sources

Country	Embodied Energy		Price	
	Observations	Sources	Observations	Sources
Brazil	23	Veiga et al. (2015)	15	FAOSTAT (2016b)
			15	FAOSTAT (2016a)
Great Britain	16	Williams et al. (2006)	12	FAOSTAT (2016b)
			12	Crucini et al. (2005)
Italy	8	Vittuari et al. (2016)	6	FAOSTAT (2016b)
			5	Crucini et al. (2005)
Netherlands	75	Coley et al. (1998)	13	FAOSTAT (2016b)
			50	Crucini et al. (2005)
Netherlands(2)	107	Kok et al. (1993)	17	FAOSTAT (2016b)
			17	FAOSTAT (2016a)
			107	Kok et al. (1993)
Sweden	151	Carlsson-Kanyama et al. (2003)	16	FAOSTAT (2016b)
			41	FAOSTAT (2016a)
			50	centralbyråns (2008)
United States	8	Pimentel (2009)	7	FAOSTAT (2016b)
			7	FAOSTAT (2016a)
			5	NASS (2018)

For each EE data point we collected two or three price data points. For expositional purposes we only present results using price data from FAO in USD, which we deflate to express in constant year 2000 values. This price series was prioritized because it allows a meaningful comparison between countries, and thus the presentation of aggregated and country-specific results. Results using the other price data sets are available in the appendix.

The data have four caveats to consider. First, average EE values carry measurement errors due to the inherent difficulties in estimating them (Chapman, 1974; IFIAS, 1974; Frischknecht et al., 2015). Second, actual data are proxies for average EE as they are random samples from country-specific marginal EE curves of goods. Third, there are some temporal disconnects between EE and prices due to data availability. For example, the EE for the Netherlands is for the years 1995-1998, yet price data for pork and lamb started in the year 2002. Fourth, in a few cases the items in the EE and price datasets were not exactly equivalent. For example, the EE for Pasta for Italy was paired to the average price data between spaghetti and macaroni. For a complete description of temporal disconnects and item approximations see the Data in Brief.

3.3 Results and discussion

Figure 3.1 shows the relation between prices and EE for all countries. Both panels show a positive relation in levels and ratios, and a OLS line that yields $R^2 = 0.5$ (Table 3.2). In levels the slope is 24.33 ($SE = 4.26$), significantly greater than unity and consistent with theory per equation (3.1). This pattern is also present in the results of Liu et al. (2008) and Gutowski et al. (2013). In ratios the slope is 0.23 ($SE = 0.04$), significantly lower than unity and different from zero, which is consistent with the most plausible scenario from theory per equation (3.2).

Figure 3.2 shows that the proportionality between prices and EE is not an artifice of aggregation. A higher and lower-than-unity slope in levels and ratios respectively, is found for Great Britain, USA, Italy, Netherlands, and

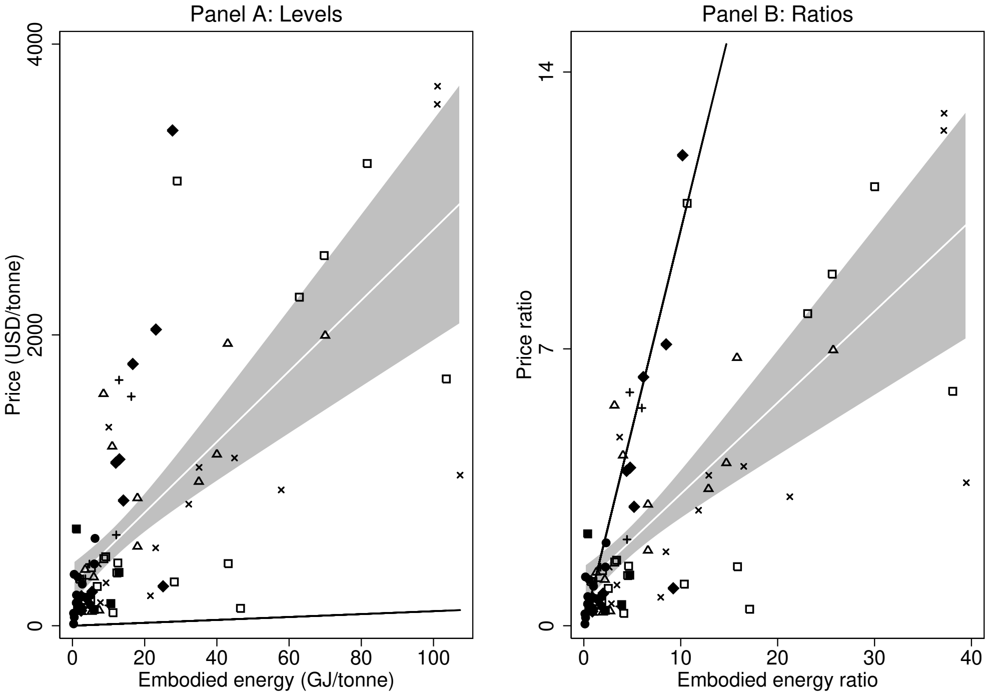
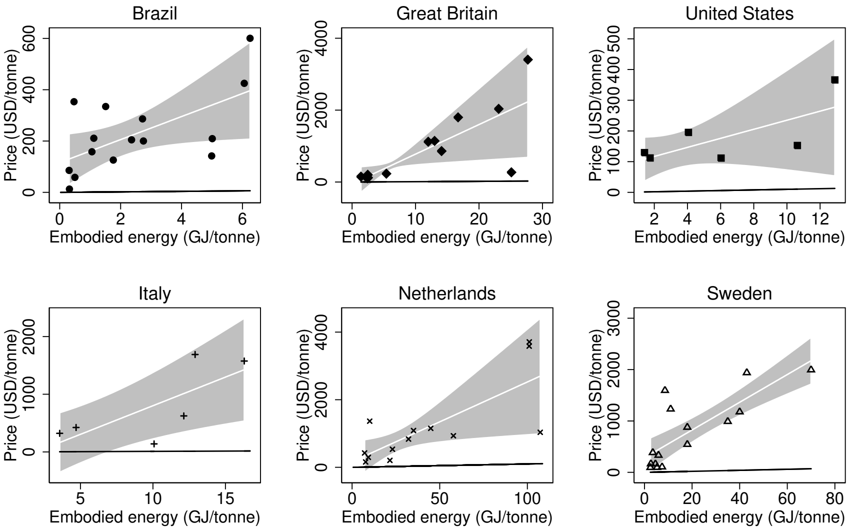


Figure 3.1: EE and prices in USD for all countries in levels and ratios.
White and black lines are the OLS and 45-degree lines respectively.
Shaded areas are 95% CI. Ratios are in terms of potatoes.
Each marker symbol is a different country.

Netherlands(2). For Brazil and Sweden the proportionality in ratios is also found, but the OLS and 45-degree lines intersect far from the origin.

The results for Brazil and Sweden are inconsistent with theory as they imply that the relation between relative prices and EE shifts by the level of relative prices. For Brazil this anomaly is driven by tomatoes and onions. Without them the slope increases and the constant is no different from zero at the 95% confidence level. For Sweden the constant is no different from zero at the 95% confidence level even with the outliers (fresh strawberries and wild berry jam).

Panel A: Levels



Panel B: Ratios

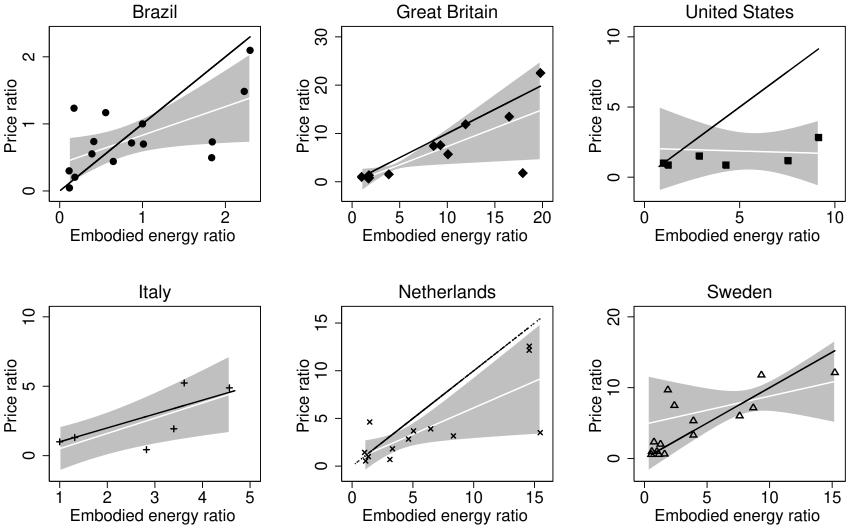


Figure 3.2: EE and prices in USD for each country in levels and ratios. White and black lines are the OLS and 45-degree lines respectively. Shaded areas are 95% CI. Ratios are in terms of potatoes.

Table 3.2: Regresion results

Country	n	Levels			Ratios			R^2
		Cons.	Slope	P-value	Cons.	Slope	P-value	
All	84	285.24	24.44	< 0.001	0.99	0.23	1	0.50
		(73.36)	(4.27)		(0.26)	(0.04)		
Brazil	15	116.02	44.86	0.021	0.41	0.43	0.996	0.38
		(50.31)	(19.45)		(0.18)	(0.18)		
Great Britain	12	-45.52	82.25	0.014	-0.30	0.76	0.779	0.58
		(203.52)	(32.13)		(1.35)	(0.29)		
United States	6	87.55	14.74	0.024	0.68	0.16	0.999	0.59
		(33.94)	(8.13)		(0.26)	(0.09)		
Italy	6	-190.68	99.19	0.009	-0.59	1.09	0.967	0.54
		(230.46)	(25.42)		(0.71)	(0.28)		
Netherlands	13	165.92	23.59	0.017	0.56	0.55	0.967	0.58
		(273.50)	(9.29)		(0.93)	(0.22)		
Netherlands(2)	17	209.35	24.20	0.002	0.65	0.15	1	0.47
		(198.69)	(6.59)		(0.62)	(0.04)		
Sweden	15	285.36	26.97	< 0.001	1.73	0.75	0.971	0.62
		(155.19)	(4.23)		(0.94)	(0.12)		

Note: P-value is the probability of observing a slope less or equal to unity.
Standard errors in parenthesis.

The use of other price series yields mostly consistent results. The price data from FAO in Local Currency Units (LCUs) (Figure 3.3 in the appendix) shows the same results as with USD, even though the series is not deflated for inflation. In ratios, Brazil and Sweden have intersecting lines, but Sweden has many observations driving it. Italy has both lines perfectly aligned. The price data from other sources (Figure 3.4 in the appendix) shows the same results except for a flat OLS line for the USA, and an OLS line for ratios with a slope great than unity for the Netherlands and Italy. For the Netherlands, the null that the slope in ratios is less or equal to one has P-value = 0.132. For Italy the slope is significantly greater than one (P-value = 0.009) and for the USA is not significantly different from zero, yet for both countries the number of observations is very small.

The consistency of results provides strong support that either $\phi_l > \gamma_l \ \forall \ l$ or that if $\phi_l < \gamma_l \ \forall \ l$ the effect of relative returns to scale dominates. The consistency is also remarkable given the problems with the data. They mostly hold despite measurement errors, temporal disconnects, item approximations, and small sample sizes. Future work should focus on estimating average EE and collecting appropriate price data simultaneously. While the problems of estimating EE are well-known (Chapman, 1974; IFIAS, 1974; Frischknecht et al., 2015), special attention should be given to the temporal consistency of the inputs with which EE are estimated. Also, further study of this proportionality requires extensive estimations of EE (of foodstuff and other goods) in all countries except for the few European ones where broad estimations have already been done. The methods presented in van Engelenburg et al. (1994) and Ciceri et al. (2010) seem particularly fit for such a task.

3.4 Conclusion

Prices and embodied energies of foodstuff are consistently proportional at aggregate and national levels. The shape of the proportionality is consistent with the theoretical relation between these variables. These results contribute to the confirmation that prices and embodied energies are proportionally related, thus supporting the perspective that energy plays a more fundamental role in economic systems than what conventional theory recognizes. Despite the evidence shown in this study further effort is required to conclude that the proportionality holds generally over space, time, and types of goods.

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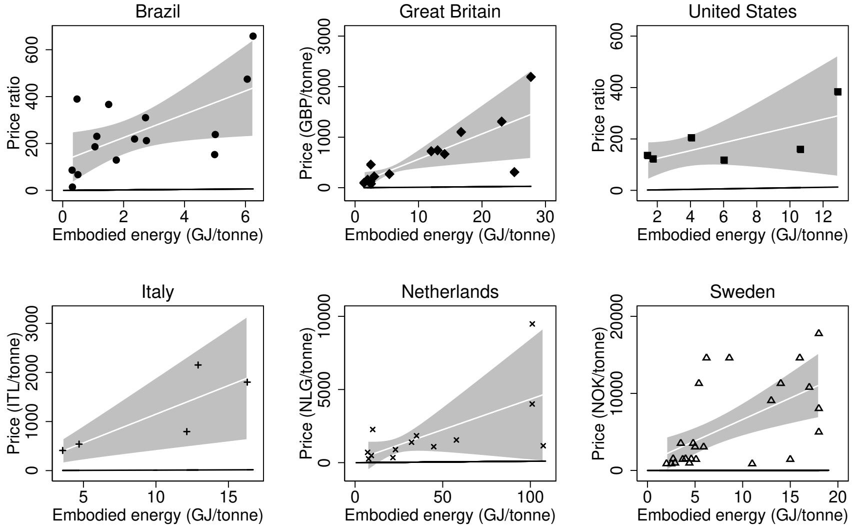
Appendix

Panel A: Levels



Panel B: Ratios

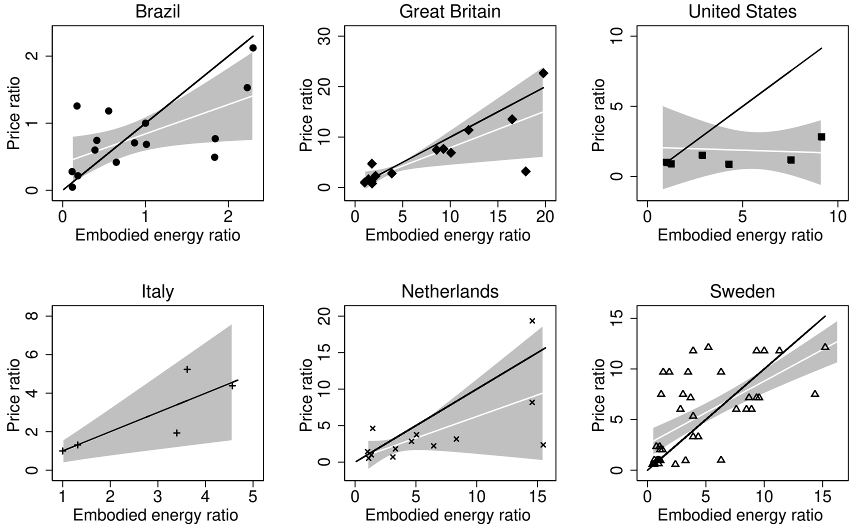
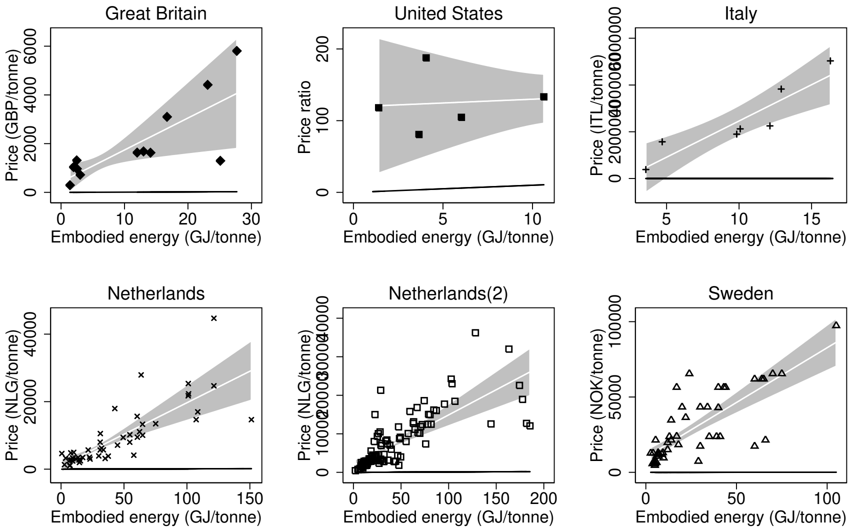


Figure 3.3: EE and prices in LCU for each country in levels and ratios. White and black lines are the OLS and 45-degree lines respectively. Shaded areas are 95% CI. Ratios are in terms of potatoes.

Panel A: Levels



Panel B: Ratios

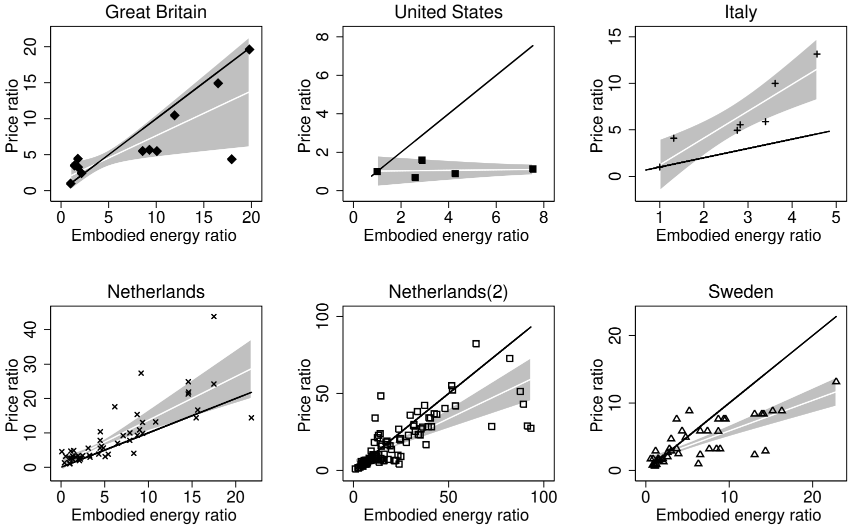


Figure 3.4: EE and prices with various data for each country in levels and ratios. White and black lines are the OLS and 45-degree lines respectively. Shaded areas are 95% CI. Ratios are in terms of potatoes.

Conclusion

This dissertation has three central results. First, energy goods' positive marginal energy surplus drives growth by incentivizing prime mover accumulation and enabling higher utility levels. Second, nominal prices are proportional to average embodied energies because marginal energy transfers measure goods' opportunity costs, and energy transfers and embodied energies are related concepts of energy flows. Third, prices and embodied energies of foodstuff are consistently proportional at aggregate and national levels as predicted by theory.

These results follow from the understanding that regardless of their subjective ends, humans can only rearrange matter with energy transfers. Means as energy transfers is the intellectual basis to include energy in economic theory as an autarkic agent's consumer constraint, the objective function in production, and what is being "spent" during production by prime movers. From this setup, marginal analysis and Ricardian logic leads to market prices as social representations of underlying marginal energy transfers, and to the visible portion of economic systems.

Such approach lays in stark contrasts with the conventional modeling of energy as another input alongside capital and labor. Yet, the perspective maintains basic economic rationale as human desires are the original driver of economic activity and valuations are relations between goods that cannot exist in isolation. The approach is best understood as a generalization of conventional economic theory that specifies what are the means available to achieve whatever ends, or in other words, what allows human action. The idea that the Joule is the unit of value but not valuable by itself enables a dialogue between economists, natural scientists, and historians that promises a better understanding of economics itself. For starters, nominal prices as social expressions of energy flows entails a new layer to microeconomics and a new micro-foundation for macroeconomics, with implications for price formation, growth, interest rates, inflation, and among others, sustainability and inequality.

Regarding sustainability, the perspective implies that a society can only sustain itself by securing a non-decreasing energy income stream. Achieving this will make-or-break our civilization's stability as it transitions from a fossil energy base currently providing 80% of our energy income towards a renewable one. Moreover, maintaining and expanding our prosperity will depend on energy income *and* energy surplus. Securing the latter is poised to be a bigger challenge in the current energy transition given the relatively high energy surplus of fossil fuels against renewables. Dangerous human intervention in the biosphere, usually associated with sustainability concerns, will undermine our civilization's capacity to sustain itself by feeding into higher energy transfers to produce all goods.

Regarding inequality, the perspective highlights the surplus nature of energy surplus. Unlike the portion of energy income assigned to reproduce prime movers' productive capacity (i.e. total energy transfers), the distribution of energy surplus does not have economic rationale. By definition, energy surplus does not respond to effort. Thus, who commands it and why? Around energy surplus follows a profound and inescapable study of a society's class struggle. Profound because the distributional issues of oppressor and oppressed, of elites battling over power, and of rent-seeking are anchored on a general theory of economics based on natural science. Inescapable because energy surplus is not an anomaly of imperfect markets that goes away with more competition or better regulation, but a fundamental feature of complex societies that underscores their prosperity and welfare.

This perspective on energy's place in economic theory is set to help understand an ever-more complex, big, and therefore dangerous economic system. This dissertation merely sets the field — hopefully a fertile one — to explore the implications of such approach. From this vantage point, there are many discoveries awaiting from the recognition of economics as a science subsumed under the principles of physics, chemistry, and biology, which arises by the interplay between human desires and thermodynamic processes.

Previous publications

- **Leiva, B.**, & Liu, Z. (2019). Energy and economic growth in the USA two decades later: replication and reanalysis. *Energy Economics* (Forthcoming).
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- **Leiva, B.** (2013). The big gift: copper in Chile, institutional framework and rent. Undergraduate thesis. Available at http://www.tesis.uchile.cl/handle/2250/111643.

Data in brief

Data article

Title: *Data on embodied energy and price of foodstuff*

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Affiliation: The University of Georgia

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Abstract

This data in brief contains information on embodied energy estimations of foodstuff and their corresponding market prices. All data are publicly available. The data is cross-sectional, covers six countries, and contains 277 observations. The data is concentrated between 1990-2016, although it varies for different countries. The data are analyzed, interpreted, and discussed in Chaper 3.

Specifications Table

Subject area	*Energy Economics*
More specific subject area	*Relation between prices and embodied energies*
Type of data	*Table*
Data format	*Filtered*
How data was acquired	*Data comes from an array of primary sources that are publicly available*
Data accessibility	*Data accompanies this article, and all root sources are publicly available*

Value of the data

- The data consolidates in one dataset all available estimates of embodied energy of foodstuff
- The data relates embodied energy estimates of foodstuff with their corresponding market prices
- The data is useful to analyze the proportionality between embodied energies and market prices

Data

The data contains the embodied energy estimations and corresponding prices of foodstuff for seven countries and dozens of goods. The countries, dates, and number of observations are shown below. The number of observations of market prices are conditional on observing a product's embodied energy.

- Brazil. Years 1980-2000.

  Embodied energy: 23 data points from Veiga et al. (2015) in GJ/tonne.

  Prices: 15 data points from FAOSTAT (2016a) in BRL/tonne and 15 data points from FAOSTAT (2016b) in USD/tonne.

- United Kingdom. Years 1992-2005. Embodied energy: 16 data points from Williams et al. (2006) in GJ/tonne. Prices: 12 data points from Crucini et al. (2005) in GBP/tonne and 12 from FAOSTAT (2016b) in USD/tonne.

- United States. Years 1980-2006. Embodied energy: eight data points from Pimentel (2009) in GJ/tonne. Prices: Five data points from NASS (2018), seven data points from FAOSTAT (2016a) in USD/tonne, and seven data points from FAOSTAT (2016b) in USD/tonne.

- Italy. Year 2016. Embodied energy: eight data points from Vittuari et al. (2016) in GJ/tonne. Prices: Five data points from Crucini et al. (2005) in ITL/tonne, and six from FAOSTAT (2016b) in USD/tonne.

- Netherlands. Years 1995-1998. Embodied energy: 75 data points from Coley et al. (1998) in GJ/tonne. Prices: 50 data points from Crucini et al. (2005) in NLG/tonne and 13 data points from FAOSTAT (2016b) in USD /tonne.
- Netherlands 2. Years 1995-1998. Embodied energy: 107 data points from Kok et al. (1993) in GJ/tonne. Prices: 107 data points from Kok et al. (1993) in NLG/tonne, 17 data points from FAOSTAT (2016b) in USD/tonne, and 17 data points from FAOSTAT (2016a) in NLG/tonne.
- Sweden: Year 2000. Embodied energy: 151 data points from Carlsson-Kanyama et al. (2003) in GJ/tonne. Prices: 50 data points from centralbyråns (2008) in NOK/tonne, 41 data points fromFAOSTAT (2016a) in NOK/tonne, and 16 data points from FAOSTAT (2016b) in USD/tonne.

Materials and methods

When time series of prices were available, the price included in the dataset is the average for the years were the embodied energy data is concentrated. For example, the embodied energy for Brazil is estimated with data between 1980 and early 2000, with the majority concentrated during the 90s. Therefore, the price data chosen is the average between 1991-1999.

The price data from FAOSTAT (2016b) in USD/tonne allows the study of all countries together. The series was deflated using the US CPI such that the data are expressed in constant 2000 dollars. The US CPI is from the US Bureau of Labor Statistics. This data is called USD in the dataset.

The price data from FAOSTAT (2016a) in LCU/tonne includes a few goods that are not available with the data in USD/tonne. This data also allows the comparison with other datasets in LCU for several countries. The series is in current values. This data is called LCU in the dataset.

United States

Price data for the United States in LCU and USD is average from the years 1997-2006. Both series differ only because the former and latter are in current and constant USD respectively.

Brazil

Price data for Brazil in LCU is the average from the years 1994-1999 due to hyperinflation until 1993. Embodied energy for castor bean is the average of two available estimates. The price data is proxied with castor oil.

United Kingdom

Price data for the United Kingdom in LCU for beans considers average between Green and dry beans. Wheat bread is proxied with wheat. Pig is only for 2004-2005 due to data availability.

Italy

Price data from Crucini et al. (2005) is for the year 1998. The pairing of embodied energies to prices, when the goods are not named exactly equal, are the following: “Apples” to a mix of all available types. “Industrial bread” to an average of all available types. “Pasta” to spaghetti and macaroni. “canned beans” to a mix of green beans and different peas. canned tomatoes to tinned tomatoes.

Netherlands

Price data from FAOSTAT (2016a) in LCU is the average for the years 1995-1998. The pairing of embodied energies to prices, when the goods are not named exactly equal, are the following: “Apples and pears” to the simple average between them. “Leafy green veg” to “lettuce and chicory”. “Beef, veal and dishes” to “Meat, Cattle”, and in 2001 given data availability. “Chicken and turkey dishes” to the simple average between them. “Pork and dishes” to “meat, pig”, and in 2002 given data availability. “Lamb and dishes” to “meat, sheep”, and in 2002 given data availability. “White bread” is proxied with “wheat”.

Price data from Crucini et al. (2005) is for the year 1998. The pairing of embodied energies to prices, when the goods are not named exactly equal, are the following: “Other salad vegs” to a broad mix of cucumber, red radish, celery, yellow onions, spring onions, mushrooms, asparagus, brussels, broccoli, and mixed vegetables. “Other whitefish and dishes” to a mix of cod, whiting, haddock, and plaice. “Other fruit” to a broad mix including from coconut to cherries in the dataset. “Whole-grain and hi-fibre cereals” to Infant cereal-flour base, cornflakes, rice crispies (embodied energy is taken as the average between ”whole grain and hi-fibre cereals” and ”other cereals”). “Spirits” to 75% ABV, and “Liquers” to 40% ABV. “Oily fish (inclu. canned)” to a mix of sardines, herrings, salmon (not smoked), tuna, mackerel, and trout. “Pasta” to spaghetti and macaroni. “Other sugars” to caster sugar and sugar lumps. “Sugar” to granulated sugar. “Other breads” to grey bread (wheat), grey bread (rye), and mixt bread (neither wrapped nor sliced). For wine, a density of 985 kg/m3 was assumed. For spirits, a density of 842 kg/m3 was assumed. For liquers, a density of 916 kg/m3 was assumed

Netherlands 2

Price data from Kok et al. (1993) is for the year 1993. For fruit juices and other non-alcoholic beverages, a density of 1135 kg/m3 was assumed. For beer, a density of 1060 kg/m3 was assumed. For wine, a density of 985 kg/m3 was assumed. For distilled beverages, a density of 916 kg/m3 was assumed.

Price data from FAOSTAT (2016a) in LCU is the average for the years 1991-1993. The pairing of embodied energies to prices, when the goods are not named exactly equal, are the following: "Wholemeal bread" to "wheat". "Endive and lettuce" to "Lettuce and chicory". "Other cabbage varieties" to "Cabbages and other brassicas". "Other fresh vegetables" to "Vegetables, fresh". "Fresh beef" to "Meat, cattle", with data from 2001 due to data availability. "Pork" to "Meat, pig", with data from 2002 due to data availability. "Poultry" to "Meat, chicken" with data from 2003 due to data availability. "Horsemeat" to "Meat, horse" with data from 2003 due to data availability. Onions data from 2002 due to data availability.

Price data from FAOSTAT (2016b) in USD is the average for the years 1991-1993. "Wholemeal bread" to "wheat", with data from 1994 due to data availability. The pairing of embodied energies to prices, when the goods are not named exactly equal, are the following: "Endive and lettuce" to "Lettuce and chicory". "Other cabbage varieties" to "Cabbages and other brassicas". "Other fresh vegetables" to "Vegetables, fresh nes", with data from 1994 due to data availability. “Fresh beef” to “Meat, cattle”, with data from 1997 due to data availability. “Pork” to “Meat, pig”, with data from 1997 due to data availability. “Horsemeat” to “Meat, horse”. “Poultry” to “Meat, chicken”. Potato data from 1993 due to data availability. Apple data from 1993 due to data availability. Pear data from 1995 due to data availability. Strawberry data from 1995 due to data availability

Sweden

Price data from centralbyråns (2008) is for the year 2001 due to data availability.

Acknowledgements

I want to acknowledge the work of the many scholars that performed that arduous task of estimating embodied energies. They did the heavy-lifting that enabled this dataset to be built.

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