Energy-Denominated Currencies as a Viable Pathway for Sustainable Societal Transitions

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Abstract

An energy-based system of exchange that combines the commodity and credit-clearing characteristics of currency can be adopted in parallel to or in place of fiat currencies in order to facilitate a sustainable societal transition. The universal adoption of fiat currencies and of the fractional reserve banking system coincided with access and ability to utilize energy-dense fossil fuels. Their combined effect allowed for unprecedented rates of economic expansion but the synergy of this combination switched from positive to negative due to the depletion of economically recoverable fossil fuels thus setting the stage for persistent systemic crises. An energy credit system concept that realigns the economic system to the thermodynamic limits of the physical world is described and a transition to an energy currency is postulated. The ability of energy currency to support sustainability objectives is shown to be more comprehensive than existing policy options based on a framework of sustainability principles including a debt as future consumption commitment constraint. An energy currency generally reflects the economic value-added of current activities but also addresses instances of undervalued energy services like the merit order effect for renewables.

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Keywords: energy currency; sustainable transition; energy economics; renewable energy; merit order effect; money supply.

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1 Introduction

An economy’s ability to grow is limited by its ability to increase resource availability and/or decrease resource intensity per unit of output. In other words, the rate of wealth creation is dependent on the rate of resource consumption and the value generated per unit of resource input. The dominant system of resource exchange initially used to reflect this fact as it moved from barter trade, to commodity, and then symbolic currencies. With the appearance of credit, and credit-clearing currencies, debt accumulation that did not reflect the abilities of the productive economy became possible. Given the very limited ability to grow for societies before the first industrial revolution, debt accumulation was resolved by jubilee events – periodic debt cancellations and asset redistribution.

The ability to harness fossil fuels, a high energy density resource, with increasing efficiency coincided with a socio-economic paradigm - capitalism, scientific thought, and an entrepreneurial work ethic (Weber 2002) - that on one hand allowed Europe to escape a potentially catastrophic collapse due to severe fuel shortage from extreme deforestation (Tainter 2004) and on the other to create a viable, debt-based, financial super-structure. Their combination provided a powerfully reinforcing feedback that led to the rapidly growing globalized economic system of today.

1.1 Motivation: Unsustainability of the Financial Superstructure

It is quipped that modern currency is “a belief about a belief” (Lietaer 2001) referring to the willingness of trading parties to accept money as compensation in the expectation of receiving equivalent services at a later time. In the conventional monetary system based on fractional reserve, the monetary supply is controlled, indirectly, by the interest rates set by the central bank. Low interest rates allow the expansion of debt, which in turn increases the supply of money. The problem that this system creates for itself is that its sustainability is contingent upon sufficient expansion of economic activity that maintains acceptably low default levels and this requires expanding energy inputs, a key component of the natural capital, to the economic system. At the point where natural capital becomes so constrained as not to allow the repayment of debt and thus cause defaults and economic recessions, it is likely that activity to
transition to less non-renewable resource intensive production methods may not be pursued because of the unavailability of capital thus leading to a deep societal collapse.

Consequently, the ultimate viability of the current financial system is dependent on the availability of accessible energy resources. As Douthwaite (2011) suggests, the growing supply of money in a fractional reserve banking system that sustains a higher rate of loan creation than debt repayment could be supported through “more energy [that] could be produced from fossil-fuel sources to give value to that money.” The correlation between artificially constrained energy availability (OPEC oil crises of 1973 and 1979) and economic recessions is indicative to this effect. In the 00s, the increase in money supply from loan creation resulted in asset appreciation (bubbles) and partially in increase in consumption worldwide. However, the effectively flat supply of liquid fossil fuels resulted in increasing oil prices (whether this effect was due to speculative activity is not relevant) which did not immediately register as inflation due to the increasing share of low cost production in China and other developing countries and the recycling of the developing countries export surpluses in the form of loans and investments (capital) towards the developed world. The unsustainable cycle of debt-supported consumption of energy imports either directly or embedded into products was shaken with the ongoing financial crisis and its aftershocks.

When looked from the energy thermodynamics perspective the unsustainability of an exponential growing system is self-evident and hence the calls for early transition to a steady state economy (e.g. Daly 1996 Part II Ch. 4, and Georgescu-Roegen 1993). As the availability and accessibility of fossil fuel resources become constrained either through voluntary (climate change mitigation) or through involuntary (depletion) restrictions, it is likely that the current financial edifice cannot sustain a recovery. Therefore, it is pertinent to identify and adopt mechanisms that allow a smooth transition from the current socio-economic paradigm to a more sustainable one that correctly accounts for resource constraints. Douthwaite recommends the adoption of complementary currencies, mentioning energy in passing, as a possible mechanism for instituting resilient non-traditional economic structures.

This paper focuses on the concept of using energy as currency and investigates its feasibility and impacts compared to other sustainable transition options.
1.2 Energy Economy Interactions

It has been empirically observed that energy prices impact economic activity proportionally more than their nominal economic share would imply using standard economic models (e.g. Hamilton 1983). Alternative models involving either imperfect (Rotemberg and Woodford 1996) or perfect competition and endogenous energy to capital interactions (Finn 2000) have been proposed to explain this effect. Hamilton (2009) notes the qualitative change of the 2007-2008 oil price shock that came from a physical rather than political supply constraint exacerbated by speculative activity which was in turn facilitated by the low interest rates of monetary policy. Murray and King (2012) reinforce Hamilton and note the phase transition in the inelastic behavior of oil supply since 2005 to oil price changes that may have contributed to the ongoing financial crises. In each case, energy availability is shown to be a central factor to the health of the macroeconomy.

Common and Perrings (1992) note that a self-regulating economic system should be based on consumption and production “objectives” that are sustainable. “Consumer sovereignty,” or market-based price adjusted resource valuation, is unlikely to reflect optimal valuation of the natural capital and therefore recommend external changes (price setting, property rights re-allocation etc) to manipulate the broader societal optimal capital valuation. This paper proposes that it is possible to effectively address the inability of prices to appropriately value natural capital by using natural capital availability to price economic activity based on it.

1.3 Societal Objectives and Sustainable Transition Characteristics

The societal needs that drive the implementation of a sustainable transition mechanism are also defining the mechanism’s appropriate specifications. Broadly speaking the needs can be identified over two domains: physical and economic resources. In the physical domain there are three dimensions: (i) energy availability, (ii) power capacity, and (iii) impact mitigation. The economic domain in turn would include equity, liquidity, credit availability, and accurate reflection of resource availability.

Predictably, given the abundance of fossil fuels, the physical societal objectives that have been so far considered are primarily the latter two (impact from emissions and power capacity constraints). The neglect of the first dimension
(energy availability) results in situations where the incentives set may lead to a conflict with and deterioration in that dimension. Two examples can help illustrate this:

- Mechanisms that support greenhouse gas emissions reductions by placing a price on carbon (ETS or tax) create incentives for use of carbon capture and sequestration. In conventional power plants both capture and sequestration are energy intensive processes that reduce the output efficiency of the plant by between 8 to 20% (Mokhtar et al.). In other words, the emissions constraint decreases the energy availability of the resource.

- Similarly, the mechanisms that address power capacity constraints (usually in an electricity grid, time-of-use variable pricing) intend to create peak shaving and load shifting behavior. To the extent that load shifting is addressed through energy storage (thermal or electrical) it incurs efficiency penalties thus also conflicting with energy availability.

Sections 1.1 and 1.2 though showed that energy availability should (and will inevitably) become the key to a sustainable transition.

Common and Perrings (1992) used vectors representing all resources and defined welfare over a finite planning period to include both the current resource base and the future state of the system. With these they formulated economic and ecological optimality conditions for a sustainable transition. The economic part was based on Solow’s formulation of the Hartwick rule: “a necessary condition for consumption to be maintained over time is that the efficiency rents from exploiting exhaustible resources should be re-invested in non-exhaustible assets” and assumed a condition on prices (the Hotelling rule) that states that the price of an exhaustible should be increasing at the rate of interest.

In a recent contribution extending the work on natural capital accounting, Arrow et al. (2010) define sustainable development based on maintaining, on a per-capita basis, the value of “comprehensive” wealth (capital goods, human and natural capital, knowledge etc.) or formally defined as the shadow value of all capital assets and institutions. Shadow values are derived in their analysis from the price of the goods. They utilize current prices for valuing energy
inputs (natural capital) and capital gains are also valued in current prices, which if they are low understate the impact of wealth depletion.

Both approaches contain helpful conceptualizations of the sustainability conditions for a society but they are (i) dependent on pricing for valuing wealth, (ii) assume capital substitutability, and (iii) are hard to apply specifically for a single resource. In our approach we prefer Daly’s formulation (Daly 1996) which we formalize for energy resources in Section 3.

1.4 Alternative Sustainable Transition Mechanisms

In its effectiveness to facilitate a sustainable transition, we examine the energy currency concept in the context of other sustainable transition mechanisms. These include systems that have already been implemented in various energy contexts:

- **Emissions trading schemes (ETS).** A cap is placed to reflect the maximum desirable level of emissions and permits are allocated through auctioning or other means to emitters which in turn can opt to reduce their emissions or trade in permits thus creating a market that allows the economically efficient measures for emissions reductions to be implemented. Cap and trade systems have been in place and created markets for SO\textsubscript{x} and greenhouse gases in the US, the EU, the global community through the Kyoto protocol and elsewhere with moderate to significant success in curbing emissions (cf. Ellerman and Buchner 2007).

- **Emissions tax.** In theory simpler than market-based systems, a carbon tax is a single, clear price signal imposed by a sovereign state. Unlike ETS, an upper limit is usually not set. Carbon taxes have been implemented on a sectoral basis in different regions including Australia, UK and elsewhere. (cf. Pearce 1991).

- **Feed-In Tariffs (FITs).** A mechanism creates a reliable price incentive based on a long-term off take agreement that bridges the cost disadvantage of renewable energy in the prevailing fossil-based energy system.
- **Renewable Energy Quotas (REQs).** A family of mechanisms that sets a target for penetration of renewable energy. It can be set as a global system target or be required by individual utilities thus setting the stage for a system of tradable permits like Renewable Energy Certificates. Butler and Neuhoff (2008) provide a comparative review of the FIT and REQ systems.

In addition, it is worth mentioning a system of Tradable Energy Quotas (TEQs) that has been proposed for implementation in the UK (Fleming 2005). TEQs represent entitlements to fossil-based energy that can be auctioned and traded among users which inherently presents a problem for how it incorporates renewable energy and does not act proactively to introduce it at a desired rate.

### 1.5 Approach and Outline of the Paper

Section 2 summarizes the Ergo energy credit concept and discusses how it could transition to a wider-based energy currency. Section 3 extends and formalizes four principles of societal sustainability with a focus on energy. The four principles are used to evaluate the comparative effectiveness of an energy currency system. Section 4 discusses potential impacts of an energy currency adoption on the energy systems, the societal needs that it meets, and the macro economy.

### 2 From Energy Credits to Energy Currency: Definition and Overview

An energy credit system operates on the premise that the energy input required for the provision of a product or service is compensated solely by ‘surrendering,’ i.e. withdrawing from circulation, a corresponding amount of existing credits. An energy currency extends the use of energy credits into a circulating currency that can be used to transact both energy-intensive and non energy-intensive trades. The adoption of an energy-denominated currency is likely to evolve organically as an emergent social phenomenon starting from an established energy credit base. This section examines the proposed operations of an energy credit concept and its potential to transition into a currency.
2.1 Energy Credit System: the Ergo Concept

The fundamental principle of the Ergo system, an energy credit system conceptualized by Sgouridis and Kennedy (2010), is that it should reflect as faithfully as possible the key attributes of the actual energy system in which it is implemented. Based on this principle, they proposed that ergos (energy credits) should: i) be issued against actual energy supply capacity under strict accounting rules, ii), expire upon use and have a preset, finite, validity period, iii) be traded in asymmetric markets where users that have exceeded their allocated amount can only buy ergos at the spot market price at the time of use. The Ergo system was envisioned to support communities that have to maintain a binding energy constraint (cf. Section 4.1). This subsection provides an overview of these principles.

2.1.1 Transaction Coverage

The Ergo system is designed to cover the energy component of transactions (and not material or non-energy value added). As a result, even for transactions that are purely energy consuming (e.g. electricity or hot water consumption) the non-energy component that the utility requires may still be covered by the conventional currency. Initial transactions covered would be energy intensive ones (electricity, HVAC services, hot and cold water, transportation etc).

2.1.2 Supply Side Issuance

Ergos are issued based on the total quantity of primary energy available to the community that meets its energy targets. The community (in collaboration with the producers) estimates the amount of distributable energy that will be produced in the budgeting period (an annual budget would be the norm). To differentiate between processes that need high-grade heat and those that don’t the energy budget is adjusted based on Gibbs free energy to disincentivize the use of high-grade energy sources for processes that can be accomplished to the same level of service with low-grade resources. For example, electricity or natural gas residential hot water boilers would be substituted with higher efficiency processes like combined heat and power (CHP) or heat pumps or by low-grade resources such solar flat-panel collectors.
2.1.3 Demand Side Allocation

Once the desired amount of ergos to be issued over the budgeting period is estimated, ergos have to be allocated over the budgeting period and across the user base. The time allocation could in fact match the demand pattern (i.e. higher allocation during the peak energy demand period of the year) if there is ample spare capacity and/or grid connections, but it would have to match the supply if the application is for an autonomous urban system.

Allocation frequency also depends on the expiration period – a feature inherent to ergos. The reasons for designing in an expiration are two-fold: (i) renewable energy is expensive to store over long periods – this may be less of an issue for cases with high penetration of fossil fuels or cheap storage, and (ii) the psychological effect of strong future discounting – it is unlikely that users given their full annual ergo allotment would be able to provision and plan for their consumption at the end of the year thus increasing the likelihood of running end of year deficits but they would be more likely to do so with a daily or weekly allowance. Additionally, anticipating the transition to a currency, an expiring unit, similar to a depreciating one, prevents hoarding and limits the potential for a speculative market.

Allocation among users can be equitable or follow a subscription-based system with tiered categories (akin to a cell phone plan) depending on user needs.

2.1.4 Price Setting: The Asymmetric Ergo Market Operation

The key to the success of any demand side management system lies with the ability to match the signal to the desired outcome; in this case, staying within a predefined energy budget. Every Ergo user and service provider has a dual account of ergos and conventional currency registered. As the user consumes ergos for energy services throughout the ergo validity period the cumulative consumption is registered in an asymmetric market for ergos operated by the Ergo regulator (cf. subsection 2.1.6). When the cumulative demand matches the forecasted demand profile then the price of ergos is stable. Ergo prices change as there is divergence, i.e. if ergos are retired earlier than planned then their price rises or conversely if there is a surplus their price is reduced. Since this is a function of cumulative consumption, it presents a slowly varying signal rather than the faster fluctuations of a real-time pricing system.

The Ergo system subscribers can access and monitor their ergo account through a programmable web-enabled interface that can provide information through smart devices (be it smart phones, internet apps, screens, or ambient
information devices). They have complete access to information of current and past prices, ergo balance etc and can set a trading level for when the prices of ergos on the spot market rise above her reservation price. In that case, ergos from the user’s account are sold on the market and the monetary price is deposited to the users current account. What makes the market asymmetric is the fact that the user cannot speculatively buy ergos without immediately retiring them for an energy service. In this way, there is a choice for the ergos that will be retired when prices are lower (from the user’s account or from the spot market). If the user has entirely drained her ergo account then until the new issuance becomes available she will need to buy (and immediately retire) ergos at the spot market price for her current energy needs.

Modulating the issuance, allocation and expiration are the key adjustment levers for customizing the Ergo system to address the specific energy system operational needs. Frequent issuance periods, precise supply matching and short expirations would mean a more volatile price and would address the needs of autonomous renewable-heavy systems but such price volatility may incur a political and acceptance cost. On the other hand, an Ergo system implemented in regions with higher fossil fuel penetration (be it net importer or exporter of energy) would have longer validity periods as ergos can be issued to represent reserve resource yet to be extracted.

2.1.5 Ergo Debt and Futures

Given that most initial real word applications would evolve around grid-connected communities with the option of using fossil fuels, a less restrictive approach would allow communities to balance their energy budget and meet their renewable energy targets over longer periods. To moderate price volatility, ergos could be issued on a deficit basis to effectively place an upper limit cap to the price of ergos. Since ergo issuance is transparent, this ‘energetic’ balance (debt or surplus) becomes an indication of the sustainability of the community. Debts will need to be covered in the next budgetary period through additional investment in energy generation.

To facilitate the long-term energy planning, ergo futures could be issued and traded. These are ergos that have a future activation date and represent planned generating capacity expansion or fossil fuel reserve extraction. Unlike active ergos, these are traded actively and symmetrically and therefore can be banked. Once they become active they revert to being ordinary ergos. A regulator can adjust capacity planning by monitoring the prices of ergo futures.
2.1.6 Governance

The Ergo system was envisioned to be deployed under a regulating authority that verifies the energy accounting, i.e. that it guarantees that ergos issued reflect actual energy generation and that it is liable for any ergo “deficit” that arises from energy trading with outside communities. In addition, the authority provides the energy user and producer interfaces for ergo transactions (i.e. the necessary web-enabled software, debit RFID cards, device-readers and databases for a widely-used credit system). Finally, the Ergo system is designed to be revenue neutral – i.e. it incentivizes energy budgeting by re-allocating wealth from the users that use excess energy to those that use less with the regulator acting as a market intermediary.

A version of the Ergo system could emerge through a bottom-up, peer-to-peer, dis-intermediated model. It would coalesce from energy producers that start offering ergos to pay for services (e.g. their employees), which would be redeemable in energy that they commit to produce.

2.2 From Energy Credits to Energy Currency

The transition from a credit system to a currency system could emerge organically as ergo users extend the transactions they are willing to accept ergos for. This would generally be facilitated in systems that have longer expiration dates and by extension longer issuance periods as well as in systems that allow for a significant percentage of ergo futures to be traded. The transition from an Ergo energy credit system to an energy-based currency system would be complete when the bankable ergo futures are used to price the asymmetric spot market for immediate energy delivery. The initial stages of the transition from credit to currency with limited penetration may appear inconsequential but they signal a fundamental transition away from fiat currency, which is further discussed in the following two sections.

Effectively, an energy credit system represents the rate of energy consumption for an economy while an energy currency system tracks both the rate of consumption and the amortization of the embedded energy stock in the economy (a kind of Gross Domestic Energy Product). To illustrate the above, we consider the construction of a long-term asset – e.g. a commercial building. In an energy credit system, the activities registered would only include surrendering the energy credits required during the construction period and the operating energy expenses during its
lifetime. An energy currency system, on the other hand, should in addition register the amortization, profits, and replacement investment even though these are not consuming energy directly at the time of the transaction. As a consequence, an energy credit system can only be implemented in parallel to a fiat currency while an energy currency can operate in the absence of a fiat currency. Table 1 summarizes the characteristics of the energy credit versus currency options.

Table 1: Energy Credits vs. Energy Currency

<table>
<thead>
<tr>
<th>Energy Credit</th>
<th>Energy Currency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solely ‘surrendered’ for energy portion of transaction</td>
<td>Covering all transactions</td>
</tr>
<tr>
<td>Solely parallel currency</td>
<td>Fiat currency replacement possible</td>
</tr>
<tr>
<td>Designed</td>
<td>Emergent</td>
</tr>
<tr>
<td>Energy consumption rate</td>
<td>Energy wealth or stock (energy consumption rate including embedded energy and replacement investment)</td>
</tr>
</tbody>
</table>

3 Four Applied Principles of Sustainable Energy Transitions and the case for Energy Currency

In order to evaluate the potential effectiveness of different transition mechanisms towards sustainability and compare the energy currency in that context we formalize four sustainability principles (in the form of constraints). (Daly 1996) outlined three sustainability principles that refer to the present status of resource extraction and consumption for a society. This paper formalizes their definition and adds a fourth principle addressing the issue of debt formation and the resource consumption commitment that the society is locked in if it is to be serviced without default (or effective default through inflation). While the principles can be generalized to any resource, the discussion as presented here is energy oriented. The four proposed principles are outlined as follows:

I. Renewable capital consumption is less than the long-run ecosystem carrying capacity.

II. Rate of pollution emission is less than the ecosystem assimilative capacity.

III. Non-renewable capital consumption is less than the rate of generation of renewable alternatives.

IV. Committed renewable energy investment is proportional to current consumption commitments.
Each principle is applied in an energy context in the subsections that follow and the final subsection evaluates the applicability of the energy currency concept along with alternative sustainable transition mechanisms.

3.1 Principle I: Renewable capital consumption is less than the long-run ecosystem carrying capacity

Renewable energy sources should only be exploited up to the level that their impact on the ecosystem’s ability to regenerate is not irreversible. While clearly applicable for biomass harvesting for energy purposes, it also can be applicable on other renewable energy flux harvesters (solar panels, wind-turbines, tidal turbines etc) as their installation can also be detrimental to their environment especially when scaled massively. The estimation of the carrying capacity is not a purely objective exercise and it depends on the location and intrusiveness of the technology but a maximum power level \( (Q_{\text{max}}) \) can be hypothesized. Aggregating the active (within the lifetime \( L \)) renewable energy capital investment \( (I_{\text{RE}}) \) that was completed at time \( (t) \) with nominal power intensity per unit of investment \( (P) \) and utilization factor \( (n_r) \), we can write the constraint in the form of Eq. 1.

\[
\int_{t=L}^{t} I_{\text{RE}}(t) dt \cdot P_{\text{RE}} < Q_{\text{max}}
\]

Eq. 1

3.2 Principle II: Rate of Pollution emission is less than the ecosystem assimilative capacity

Similarly to the above, emissions from the use of non-renewable, fossil-based energy sources should be contained within the ecosystem’s ability to sequester them. This is of primary significance for greenhouse gas emissions, which need to be curtailed at an annual level \( (S_{\text{max}}) \) that allows their atmospheric concentration to be lower than what is expected to entail large-scale climate disruptions (discussed stabilization targets to prevent catastrophic climate change range from 550ppm to 350ppm CO2eq but in either case, long-term stabilization implies reaching a near-zero net rate of anthropogenic emissions (Matthews and Caldeira 2008)). The operation of active fossil energy capital investment \( (I_{\text{FE}}) \) operated at full capacity for \( (FLH_f) \) hours a year with efficiency and losses \( (n_f) \), and with emissions intensity \( (s) \) should abide by a constraint in the form of Eq. 2.

\[
\int_{t=L}^{t} I_{\text{FE}}(t) dt \cdot P_{\text{FE}} \cdot \frac{FLH_f}{n_f} \cdot s < S_{\text{max}}
\]
3.3 Principle III: Non-renewable capital consumption is less than the rate of generation of renewable alternatives.

A practical application of the Hartwick Rule (cf. Section 1.3), this key principle ensures that we invest sufficient amount of non-renewable resources for the construction and deployment of renewable energy capital. Contrary to being an oxymoron, investment of non-renewable energy to manufacture and install renewable sources acts as an energy extender mechanism. The rate of deployment of renewables to sustainably maintain societal wealth depends on their energy return on energy invested (EROEI). EROEI is defined as the amount of energy generated over the lifetime of a renewable energy project (E_{RE}) over the energy input (E_{IN}) for its construction (Bardi, Lavacchi, and Yaxley 2011). Based on the definition, the net energy output (E_{NET}) of a renewable energy project is shown in Eq. 3 and the equivalency as a rate of generation (power) per unit of investment (P).

\[
E_{NET} = E_{RE} - E_{IN} = E_{RE} - \frac{E_{RE}}{EROEI} = E_{RE} \cdot \frac{(EROEI - 1)}{EROEI} \leftrightarrow P_{NET} = P_{RE} \cdot \frac{(EROEI - 1)}{EROEI}
\]

Eq. 3

The Principle III constraint presented in Eq. 4 can therefore be transformed into a lower bound for renewables investment shown in Eq. 5. We recommend that since the loss of the fossil fuels is irreversible their full calorific value should be accounted for instead of just the portion extracted of useful energy at current utilization efficiencies.

\[
l_{RE}(t) \cdot \int_{t}^{t+L} P_{NET} dt \cdot FLH_r \cdot n_r - \int_{t-L}^{t} l_{FE}(t) dt \cdot P_{FE} \cdot \frac{FLH_f}{n_f} \geq 0
\]

Eq. 4

\[
l_{RE}(t) \geq \frac{\int_{t-L}^{t} l_{FE}(t) dt \cdot P_{FE} \cdot FLH_f \cdot \frac{1}{n_r} \cdot \frac{EROEI}{EROEI - 1}}{P_{RE} \cdot L \cdot \frac{FLH_r}{n_f}}
\]

Eq. 5

3.4 Principle IV: Committed renewable energy investment is proportional to current consumption commitments

The last principle addresses the decoupling of the financial and the real world that was discussed in Section 1. It recouples the physical and the financial world by limiting the levels of committed consumption through both public
and private debt (D) to the future availability of resources. It depends on an estimate of the future economic energy intensity of the economy. Conservatively the economic energy intensity could be considered stable over the debt period and equal to the ratio of total current energy supply (E) over the value of current consumption (Y) equivalent to GDP².

\[ I_{RE}(t) \cdot \int_{t}^{t+L} P_{NET} dt \cdot FLH_{r} \cdot n_{r} - D(t) \cdot \frac{E(t)}{Y(t)} \geq 0 \]

Eq. 6

Where

\[ E(t) = \int_{t-L}^{t} I_{FE}(t) dt \cdot P_{FE} \cdot \frac{FLH_{f}}{n_{f}} + I_{RE}(t) \cdot \int_{t}^{t+L} P_{RE} dt \cdot FLH_{r} \cdot n_{r} \]

Eq. 7

3.5 Sustainable Transition Options and the Four Sustainability Principles

Having formally expressed the four sustainability principles we can examine the performance of the different sustainable transition mechanisms and compare it with the energy credit/currency concept. This is also summarized in Table 2.

Feed-in tariffs (FIT) can be designed to scale-down as we reach the limits of the renewable resource but it cannot stop further expansion inherently. Similarly, these systems cannot guarantee compliance with any of the other principles as they are primarily an ad-hoc mechanism for increasing penetration of renewables. Yet, their design allows that if their value is set correctly and in combination with the price from an ETS or emissions tax, Principle III can be addressed. Emissions trading systems excel in addressing Principle II as they are designed for that purpose but they cannot address any of the other principles on their own. An emissions (carbon) tax behaves like an ETS with the exception that is weaker in its ability to limit emissions as it poses no strict cap on them. Renewable energy targets or

² It should be noted that Eq. 6 is depicting a steady state condition. When first applied the cumulative debt should be used rather than the current year value. In that case the ratio (D/Y) is equivalent to the total debt to GDP ratio.
quotas (REQ) could be set such that they satisfy Principles I and III although not in their current, simplistic, version of a percentage target over total energy consumption.

Turning to the family of energy currency systems, the ability to address Principle IV is mainly available in the fully deployed energy currency system – in a way it is intrinsic to it. Debt is possible in the form of ergo futures which is an explicit commitment to generate this amount of energy by a given time in the future and in compliance with Principles I-III. Compliance with these principles is possible by controlling the ratio of issuance of ergos from the portfolio of energy sources (cf. Section 4.2.3).

Table 2: Comparison of Sustainable Transition Mechanisms against the Four Sustainability Principles

<table>
<thead>
<tr>
<th>Principle</th>
<th>FIT</th>
<th>REQ</th>
<th>ETS</th>
<th>Carbon Tax</th>
<th>TEQ</th>
<th>Energy Credits</th>
<th>Energy Currency</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Renewable capital consumption is less than the long-run ecosystem carrying capacity.</td>
<td>N</td>
<td>M</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>II. Rate of pollution emission is less than the ecosystem assimilative capacity.</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>M</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>III. Non-renewable capital consumption is less than the rate of generation of renewable alternatives.</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>IV. Committed renewable energy investment is proportional to current consumption commitments.</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>M</td>
<td>Y</td>
</tr>
</tbody>
</table>

Note: Y(es) indicates strong capacity for compliance with a given principle, M(aybe) indicates limited capacity depending on incentive design, and N(o) indicates no capacity to comply

4 Integration of Energy Currency In the Current Energy Economy

Having discussed the potential advantages of utilizing an energy currency for a sustainable transition, we turn to how it would be integrated in the existing energy economy nexus. This section examines the case and conditions for communities that can become potential lead adopters of an energy credit scheme and the effects that an energy currency system adoption would have on the energy system on one hand and its integration in the macro-economy on the other.

4.1 Energy Currency Lead Adopters

The lead adopters of an energy credit system that would act as a precursor to the energy currency transition would be communities with a binding energy constraint but with access to energy resources. The ideal community would
have defined boundaries, be a fossil fuel importer, have access to renewable energy resources, and would have set aggressive renewable energy targets. On the technology front, it would have existing or planned smart grid deployment and a technologically savvy population.

Sgouridis and Kennedy developed the Ergo concept for application to the Masdar City – a mid-size development aspiring to be net zero carbon near Abu Dhabi (Reiche 2010). A similarly aggressive challenge may be taken by the community of Zug in Switzerland along with other communities that are engaging in a fundamental debate on whether to strive towards creating a 2000-Watt society (Marechal, Favrat, and Jochem 2005). The concept advocates that western societies can and should move towards reducing their energy consumption drastically converging towards the estimated global average primary energy consumption per capita. This amounts to a personal 2000W limit or 17,520 kWh/person/year and implies, approximately, a 70% reduction from current energy consumption levels in Switzerland.

More broadly, any type of renewable energy target, be it 20% or 30% or 100%, once it becomes a commitment, places a limit in the actual energy available for consumption based on the capacity of renewable energy generation (existing or planned). Regions that face an energy cap due to actual capacity limitations (e.g. off-grid communities) are an extension of this case.

4.2 Energy Currency and the Energy System

Using energy as a currency translates the physical work for a process or product into comparable units that can be aggregated over the value chain. In essence, it enables a bottom-up energy audit on any activity and in the process instills energy as a measure of value. As a result, among the three physical objectives of an energy system presented in Section 1.3, energy availability becomes the focus but the objectives of power capacity and impact mitigation can also be managed through an energy currency. This section overviews the ways that the energy system is likely to be affected.

4.2.1 Energy Availability

The key outcome of an energy currency system is the rationalization of energy consumption across uses and over time and a more appropriate valuation of the non-renewable resources. As consumer products and services become
comparable against a common energetic value the consumer choice will naturally gravitate to those that have the lower energy footprint. If implemented correctly, the use of energy quality (measured by e.g. the Gibbs free energy) as a weighting mechanism will increase the use of energy grades that are fit for purpose and limit the expense of high-grade resources to deliver low-grade heat (cf. Section 1.4).

4.2.2 Power Capacity and Energy Price Volatility

The ability to handle energy variability may be considered one of the key weaknesses of an energy currency. Energy demand varies over time and with increasing penetration of renewables so does its supply. In electricity grids, this variability combined with marginal cost dispatch gives rise to the ‘merit order effect’, i.e. instances where the spot price of energy becomes zero (or even negative with priority dispatch for renewables) as baseload producers offload the costs for throttling down their generation facilities. Conversely to the merit order effect, at times where demand is higher than capacity, spot prices can justify decisions to shift energy demand through inefficient storage to meet the power capacity limit. In both cases, energy’s perceived market value is effectively variable dependent on the time of its availability being thus a less stable value representation. The same price volatility situation but with longer periods is present in the fossil fuel markets (especially for oil but also for natural gas).

Arguably though, this volatility is not reflective of real valuation – the energetic value of a kWh is the same irrespective of time of use especially for storable fuels – but rather a distortion arising from the ‘coincidence’ of underpriced fossil fuel energy and cannot be sustained during a sustainable transition. Valorizing energy through an energy currency addresses this distortion at a fundamental level and facilitates the adoption of existing technologies to adjust demand and supply much more flexibly than what current market conditions have so far permitted. Nevertheless, in instances of temporal energy scarcity the price of energy should vary reflecting this. The Ergo concept addresses this price variation through the asymmetric spot market (cf. Section 2.14) which in turn can be priced in long-term bankable ergo futures (cf. Section 2.2).
4.2.3 Impact Mitigation

The current approach towards Sustainability Principle II –limiting pollutant emissions below the ecosystem’s assimilative capacity - is a combination of FIT, ETS, and taxes. This approach effectively valorizes the negative outcome (emissions) in the hope of providing sufficient incentive for its mitigation. The energy currency approach on the other hand would valorize the positive outcome (energy delivery) but place an upper limit to the total issuance of currency such that there is compliance with Principle II (essentially forcing the adjustment of the FLH parameter of Eq. 2). More critically, as debt can only be issued through ergo futures and these need to be backed by planned installation of capacity an energy currency system allows the coupling of investment in renewables $I_{\text{RE}}(t)$ with the creation of debt $D(t)$ in Eq. 6 thus ensuring that committed future consumption will not cause an increase in emissions.

4.3 Energy Currency and the Macroeconomy

One way of assessing the potential impact of a widely adopted energy currency system is to examine the current relationship between the energy input and economic value of products and services. A consistent way to do so is to extracting the \textit{lifecycle} total energy and total economic value component from economic input-output lifecycle (EIOLCA) accounts. We use the US 243 sector model based on the 2002 producer prices (CMU-GDI 2008). Using a $1M$ activity as a base, we register the total economic value generated from each sectoral activity (i.e. the direct and indirect economic activity that includes the $1M$ seed activity) and the total (direct and indirect) weighted energy input requirement for supplying this activity. The EIOLCA model breaks energy inputs into five categories (coal, natural gas, oil, bio/waste, and non-fossil electricity), which we weight with reference to the higher quality of available energy of electricity.

The results plotted in Figure 1 show a strong correlation between energy inputs and economic value but also with a significant spread. The energy-intense activities that provide a basis for the economy (i.e. the transportation, extraction and power sectors along with some energy intense heavy-industry activities like smelting) demonstrate expectedly lower total economic value-added today as they form the basis for the other activities. With increasing energy scarcity, the correlation can be expected to tighten further providing the rationale for the adoption of an energy
currency system. Unfortunately, there is no comparable update yet available to test this hypothesis with the higher energy input costs due to the oil price increases in the last decade.

Figure 1: Correlation between Economic Value Added and Energy Input from a Lifecycle Perspective

These results indicate that to a certain degree, energy-intensity already represents fairly well the economic value added of existing activities. The introduction of an energy currency therefore would not disrupt the majority of existing price relations but it would make relatively more expensive (internalize the externalities) activities that rely on readily available cheap industrial-scale power like cement manufacturing and smelting.
5 Conclusions

Rifkin (2008) suggests that the confluence of technological progress in information technology and energy supply was instrumental in initiating distinct “revolutions” or periods of accelerated and qualitative different societal development. In this case, he identifies the Internet, distributed energy generation, and smart grids as the catalysts for the “third industrial revolution.” Energy credit and currency systems build on the very same components to realign the financial economics world with the limits of the physical world. Energy credit systems can meet the needs of communities that have defined energy constraints, renewable energy resources, and smart infrastructure. Energy currencies are likely to evolve from these pilot applications as users extend the transactions for which they accept an energy credit.

An energy currency system is fundamentally an energy accounting tool that reflects the energy availability and energy commitments of a society. It makes energy use transparent and allows users to internalize and compare the true energy costs of a product or service. We show that energy currencies can perform well across the board in responding to four sustainability principles for energy resources. They are especially adept in addressing the issues of managing the ratio of investment in renewable energy technologies so that it at least matches the rate of extraction of non-renewable energy resources (Principle III) but also to the level of committed future consumption based on debt accumulation (Principle IV). As a result, its adoption facilitates a sustainable transition before reaching the limits of energy availability and, thus, potentially preventing a hard collapse due to energy resource constraints or climate change.

The circulation of an energy currency would not drastically change the relative valuations of the majority of products and services available today as there is already a fairly consistent correlation between total lifecycle energy input and economic value added. It would affect the relative valuation of energy intensive products produced through reliably cheap energy sources (like cement and steel) but this would arguably be a cost internalization. Importantly, it would resolve the seeming paradox of zero energy costs due to the merit order effect for systems with high renewable energy penetration and baseload power producers by weighting more long-term energy availability and essentially forcing a paradigm shift from energy pricing under an abundant energy regime to one that is rationed.
6 Acknowledgments

This work was supported by the Masdar Institute and benefited from conversations with various colleagues.

7 References


