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A Simple Physics-Based Model of Growth-Based Economies Dependent on a Finite Resource Base

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Abstract: Mainstream economics describes virtual wealth with theory that is at odds with the physical laws that govern a nation's physical resources. This confusion fundamentally prevents the realization of "sustainable" economies. The relation between debt and the metabolism of a country (measured by GDP or power consumption) appears to follow a diffusion relationship, in which debt encodes the temporal evolution of an economic potential. Debt enables the production of resources and the realization of a country's economic wealth potential (the sum of its environmental, geological, and societal endowments, among others). Any economic scheme dependent on finite stocks of free energy for growth must eventually collapse, and as such cannot be considered sustainable. Our simple debt–diffusion model is shown to closely match the trajectories of 44 different economies.

Keywords: diffusion; debt; free energy; Cartesian economics; limits to growth

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1. Introduction

About 100 years ago, Nobel laureate in chemistry, Frederick Soddy started to examine the physical underpinnings of the economy [1]. Despite orthodox economics largely ignoring his contributions, he set the foundation for the study of wealth–money interactions incorporated by econophysics and ecological economics today [2]. Since the time of Soddy, we have moved ever closer to the "spaceship earth" concept introduced by Kenneth Boulding, which refers to an economy in which the earth no longer has unlimited resources or capacity to absorb pollution [3]. In this view, designing our economic systems to be compatible with long-term resource constraints is paramount.

Debt is a "lien on future energy use" [4,5], and represents a claim on future resources [6]. In the present circumstances, it is more crucial than ever to comprehend the physical ramifications of debt and how it might prolong the current growth-based economic paradigm. To these ends, we have developed a simple physics-based model based on the well-known process of diffusion that seems to capture the general evolution of many contemporary economies.

We would like to emphasize that the main aim of this paper is to bring attention to the similar debt–power consumption trajectories exhibited by most economies. We hope to show that the humble diffusion model can explain this relationship (debt essentially enables random walks of economic activity); however, given the complex nature of human economies, there are many ways to expand this analysis (e.g., to interacting economies, in-depth analysis of particular economies, etc.) that we leave for future work. This paper provides a bird's-eye view of the problem.

Economic activity within a country can be thought of as a self-organized complex system in which individual firms maximize profit and the country itself seeks to maximize GDP. Each and every economic activity requires free energy (exergy) to complete. This is the societal metabolism that leads to a tight coupling between GDP and primary energy consumption [7]. GDP can be substituted for primary power in our theory as long as inflation is considered and GDP is calculated consistently. We use GDP when developing the model and primary power consumption in the empirical portion.

To comprehend the world's journey to an end of economic growth, we must understand the physical basis of wealth. According to Soddy, wealth is embodied useful free energy or exergy ([8] p. 108). Exergy or available energy, is the fraction of energy that is useful, i.e., can do work relative to the environment; see [9,10] for more technical details and applications to natural resources. For most of humankind's existence, this useful energy was derived from solar flows [1]. Since the industrial revolution [11], however, we have supplemented these daily flows with an extraordinary amount of ancient chemical exergy from fossil fuel accumulations. During the exponential increase in energy production and consumption, it appeared that human ingenuity was the only limiter to wealth creation [1]. However, with resource availability plateauing, one can see how arrogant this attitude has been [12,13].

The nature of the availability of "land" (note that "land" in this context is the source of any and all natural resources) as the driving force behind economic well-being was recognized by thinkers such as Thomas Paine and Henry George [14,15]. This view was later focused on the finite nature of energy resources by M. King Hubbert, who discovered that resource extraction could be modeled by a Gaussian curve [16] or its logistic approximation [17,18].

By the 1970s, awareness of rapidly deteriorating resource availability was widespread, especially among systems scientists, ecologists, and activists [19–21]. However, even after 50 years, a seemingly impenetrable facade of normality persists. The concept of peak resources is often dismissed, despite the thermodynamic necessity of an end to growth. It is worth acknowledging that the persistence and survival of "growth" ideologies in the face of looming humanitarian and ecological catastrophe is partly due to technological advances in unconventional extraction that have produced additional Gaussians to describe global fossil fuel production [18]. Moreover, the fossil fuel-driven "green" revolution has delayed the inevitable population crash [13,22–24]. This being said, the unconventional energy and material sources supporting this temporary stay of decline are heavily dependent on debt [25]. Following this thought, we posit that the disconnect between economics and physics can be explained partially by "creative accounting", globalization, and the increasing reliance of societies on debt to fuel ecological overshoot. Economic growth (growth in utilized wealth) is commonly measured by Gross Domestic Product, or GDP. GDP has a significant correlation with power consumption, as every economic transaction dissipates free energy [6]. Although correlated with power, GDP is a political artifact. Given the commonly accepted paradigm of uninterrupted growth, some countries are expanding the sectors they include in the calculation. An example is Italy, which now includes prostitution and illicit drug sales [26] in their GDP. Because GDP is a nonconservative index variable, we focus on power consumption as the metric for a country's utilized wealth.

Through the beginning of the twentieth century, prominent economists such as MacCleod and Schumpeter recognized the ability of banks to create money through loans [27,28]. Economic theories have become convolved since that time, with several theories of money creation emerging, including fractional reserve banking and banks merely acting as financial intermediaries. Both of these banking practices have made their way into economic textbooks as fact [27]. In this view, non-central banks act solely as intermediaries that are unable to create money themselves. Werner et al. show that this view is incorrect, as banks create money "out of thin air" during the loan creation process [27,29]. This observation is important because a very small percentage of the monetary supply of a country is in the form of physical currency. In England, for example, 97% is in the form of bank deposits which are born in the loan creation process [30] (note that these are not funds "deposited" by clients saving with a bank, but are added to the bank's balance sheet when they issue loans; see Figure 1).

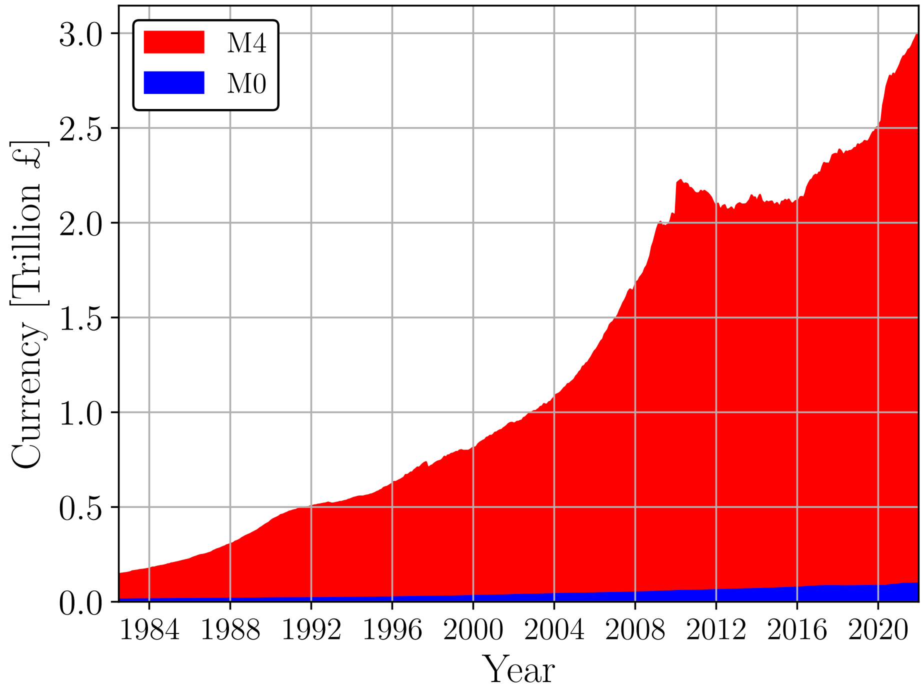


Figure 1. Money creation by the Bank of England; M0 money is the physical money (narrow) money supply, M4 includes virtual (broad) money. Data from the Bank of England [31,32].

Nonphysical money can be exchanged for goods and services, which are limited by a finite resource base. However, unlike the physical resources, the money supply itself grows. The most obvious ramification of money creation is inflation (as long as the created money is not inflating nonphysical wealth assets). In addition, however, it seems that human faith in the value of money can lead to economic development past that which is economically feasible; the money is exchanged for resources and GDP grows, but the underlying debt will never be repaid. This shifts resource consumption forward in time [4–6]. There are limits to the ability of debt to drive GDP growth, with increasing levels of debt required to finance the same amount of GDP growth [4,6]. Eventually, an economic system's productivity will go to zero and this system will stall or collapse.

Orthodox economics has long been interested in the influence of debt levels on GDP growth, particularly public debt. Following the 2008 financial crisis, Reinhart and Rogoff examined debt/GDP ratios in brackets according to their debt/GDP ratio and concluded that there was a threshold impact of debt on growth [33]. Others have questioned the assumptions of their method and failed to find evidence for a specific debt threshold that impacts growth across countries [34,35]. Chudik, et al. did find evidence for (i) a significant negative relation between rising debt/gdp ratio and growth and (ii) consistent growth of the debt/GDP ratio having a long-term impact on growth [35]. While we additionally incorporate private debt, the results of Chudik et al. are in general consistent with our model. Moreover, by linking GDP with societal metabolism and power, we offer a physical explanation for this phenomenon.

Because orthodox economic models fail to incorporate the physics of the underlying resource base, they are incapable of dealing with the forced shrinking of the global economy in this century. The major implication of the diffusion model we present here is that it predicts the "death" of an economy if its growth remains unchecked in relation to its resource endowment. We hope that this novel model will prove useful in the quest to bridge economics and physics and talk sensibly about more sustainable resource-constrained futures. Because we are concerned with the physical component of sometimes fuzzy economic concepts, we devote the next section to considering the physical quantities that back the economic variables in our model.

2. Physical Quantities Backing Economic Variables

2.1. Wealth and Production

Despite its provable fallacies [36], the Cobb–Douglas production function has been widely used in aggregate neoclassical economics to model production output considering labor, capital and technology. One of the key problems with the "Humbug Economy" Cobb–Douglas models is that they ignore chemical free energy from fossil fuels in the economic process, a factor that dwarfs the inputs of human labor. There have been some recent works that redefine GDP in terms of exergy and incorporate it into the production function [37]. These models should be contrasted with neoclassical economics ("the world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe", Robert Solow [38]). Since ignoring natural resource inputs in economic theory has supported outlandish concepts, such as infinite growth on a finite planet, alternative models informed by physics and ecology need to be adopted.

Our analysis builds on the work of many other scientists who have crossed over to the field of economics and attempted to rectify the mismatch between the economic laws and their physical foundations. One of the first scientists to make this crossover was Nobel Laureate Chemist Fredrick Soddy, whose lectures and book [1,8] delved into the nature of money, debt, and wealth. Additionally, much of our thinking is shaped by the works of Georgescu-Roegen [12], Mirowski [39], and Yakovenko [40].

Wealth is a broad term that may encompass items with very different physical properties. Going back to Aristotle, many economists and intellectuals have defined wealth in terms of its exchangeability. This definition encompasses credit and labor. The inclusion of credit violates the principle of "ex nihilo nihil fit", that is, that nothing can come out of nothing. Additionally, modern orthodox definitions of wealth rarely have a solid link to physical underpinnings, as in "wealth is a stock of assets that can generate future income and well-being" [41], and tend to be measured in terms of monetary value (or Chrematistics) [42].

We follow Soddy in defining wealth as "... a form, product, or result of a draft upon the flow of available energy consists of the special forms, products, or results which empower and enable human life" ([8] p. 109). Furthermore, this wealth is "derived from the daily revenue of solar energy, through the operations of agricultural culture. The accessories of life, clothes, houses and fuel, as well as its comforts and luxuries, are derived in great part by the augmentation of this revenue out of a capital store of energy preserved from bygone geological times" ([1] p. 12).

Here it is important to clarify the stock vs. flow nature of wealth and note that this depends on the boundaries of our system. Are we measuring the flow of wealth into society, or are we concerned with the wealth present inside the system (accounting for the inflow and decay)? Intuitively, if free energy is consumed in the creation of wealth, and if we are considering the product that is located inside our system, then wealth must be a stock. However, the time derivative is useful, and Soddy often makes reference to this flow of wealth: e.g., "Life depends from instant to instant on a continuous flow of energy, and hence wealth, the enabling requisites of life, partakes of the character of a flow rather than a store" ([1] p. 12), and "the wealth of the community is its revenue, which, in the last analysis, is a revenue of energy available for the purposes of life. That being given, in sufficient amount and in form capable of being utilized by the existing knowledge of the time, everything requisite for the life of the society can be maintained. It is impossible to save or store this *flow* [emphasis added] to any appreciable extent" ([8] p. 13).

Of course, humanity can attempt to store this flow energy physically in batteries or behind dams, or by capital accumulation; however, capital decays, and storage is vastly insufficient. Infrastructure and capital development, rather than being seen as wealth itself, are seen in the Soddian framework as "aids and accessories in the maintenance and increase of wealth out of the available revenue of energy" ([1] p. 14). To illustrate our view of wealth, we diagram the earth system as a heat engine, with earth having developed processes to consume the available solar energy while expelling waste heat at the temperature of the cosmic background radiation, see Figure 2. The input into this system is wealth, or "available energy usefully directed" [1] (p. 13). In modern times, the renewable flows of solar energy have been dwarfed by the contribution of fossil energy (Figure 3). Importantly, the rates of solar energy flows and the utilization of fossil stocks are finite; thus, so too are our economies.

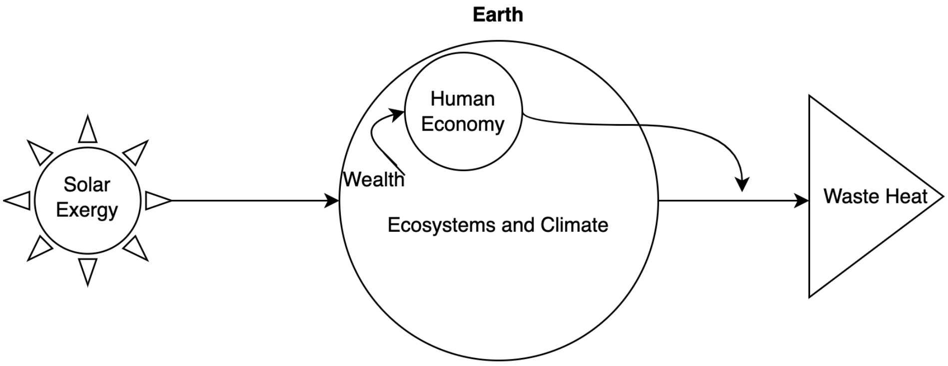


Figure 2. Earth's climate and ecosystems are powered by incoming solar radiation. A portion of the solar free-energy is captured by humans, who expropriate some of the Net Primary Productivity of the planet through agriculture, fisheries, solar panels, wind turbines, or hydropower dams. This revenue is what we consider wealth. Wealth cannot be stored for extended periods of time, and when used to build capital it requires future wealth to maintain. Geologically, some wealth has temporarily been stored in producible coal and hydrocarbon accumulations (stocks) that are fast being depleted by our global civilization.

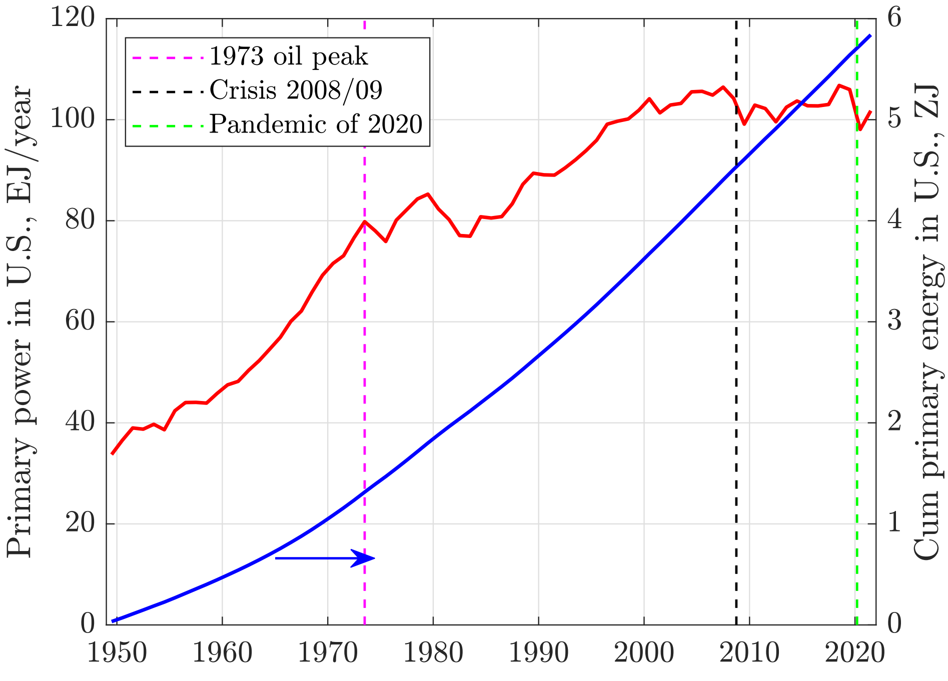


Figure 3. Primary power (red) and cumulative primary energy use (blue) in the US. Notice the astronomical amount of mostly fossil energy already burned in the US; 1 ZJ = 10^{21} Joules.

2.2. Capital

Capital is animated by free energy, and requires energy and other resources to be maintained (Figure 4). Wealth (excess free-energy) obtained in any given year cannot be stored permanently within stocks of capital. The spatial component of our model considers the capital development of an economy (Figure 5). At the top of the *y*-axis in Figure 5 is the financial and speculative layer of the economy, which is largely nonproductive. The economic potential, consisting of energy per unit GDP, navigates this space in a random walk. As the economic lifecycle progresses, a greater portion of the GDP is generated in the financial sector of the economy. The Quantity Theory of Credit developed by Werner differentiates between lending towards the real and financial sectors of the economy [43]. Financial sector lending may include real estate, construction firms, and non-bank financial institutions [43]. It can also be used to subsidize consumption, and has a tendency to produce asset bubbles [43]. We consider this the economy's imaginary metabolism; see Figure 5. Due to the coarse nature of the data we utilize in our analysis, we do not include this imaginary metabolism in our analysis; however, it may be responsible for deviations from our model predictions.

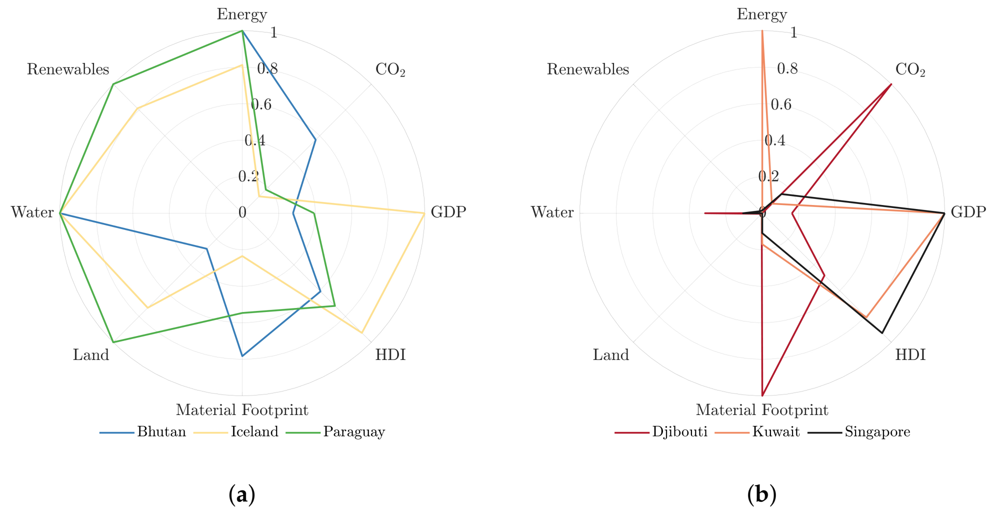


Figure 4. Eight-dimensional (octagonal) mapping of the sizes of different economies: (**a**) the resilient countries fill large areas of the octagon; (**b**) for the *vulnerable* countries, only small areas of the octagon are filled. Reference year: 2015. Reproduced from Figure 4 in [44].

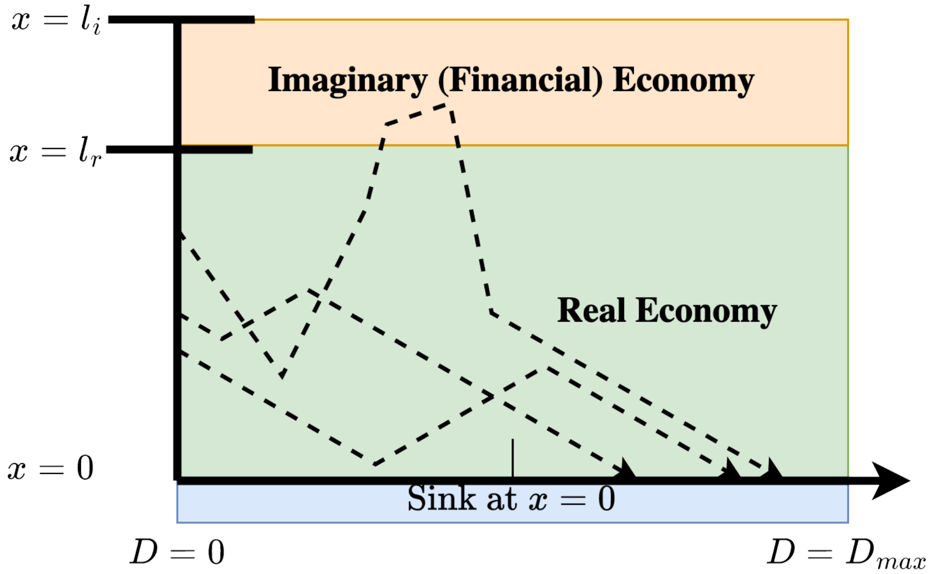


Figure 5. The gradient of an economic potential (ψ) generates random walks (dashed lines) in real and imaginary economic space ($L = l_r + l_i$, $x \in [0, L]$). This behavior is what gives rise to our continuous diffusion model in Figure 6. We consider cumulative GDP to be the integral of the flux of ϕ into the sink at $x = 0$. Note that in our analysis we do not differentiate lending to the financial vs. real sectors of the economy; this a possible extension of the present work.

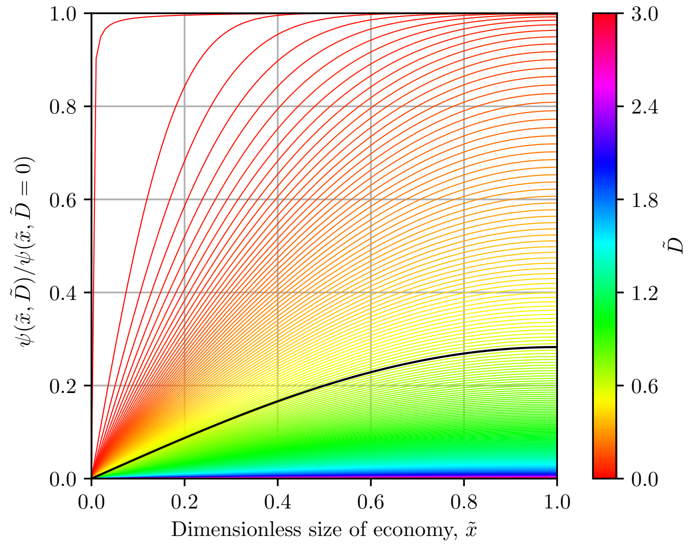


Figure 6. Normalized economic potential vs. the dimensionless size of economy. At $\tilde{D} = 0$, the economic potential is evenly distributed (top of the plot in Red); as the amount of debt grows, economic potential is consumed at the $\tilde{x} = 0$ boundary. The other boundary $\tilde{x} = 1$ is insulated. When $\tilde{D}$ approaches two, most of the economic potential is depleted; this can also be seen as the model plateau in Figure 7.

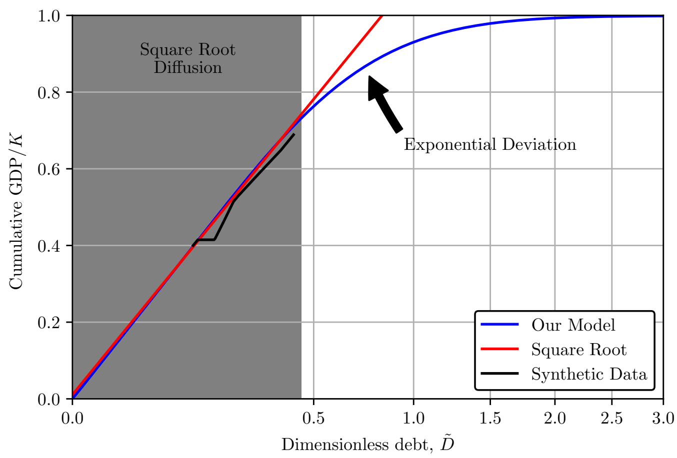


Figure 7. The y-axis is the cumulative GDP or cumulative power consumption, which is the integral of the sink at $x = 0$. The x-axis is $\tilde{D}$ (note the x-axis has a square root scale). In blue is our diffusion model with a finite economic potential, ψ, which leads to the deviation from the steady-state square root diffusion pattern (the shaded area). The trajectory in black shows an example of the deviations from the square root behavior that are present in the country data we analyzed.

2.3. Debt

A discussion of money and debt easily becomes drawn into the ideological trappings of various schools of economic thought. We aim to stick to the physical relationship that appears between human systems of debt accumulation and the physical energy resources that support these economies. We refrain from discussing the future implementation of more egalitarian or environmentally-sound economic systems, but show that the current paradigm of debt creation and resource consumption is completely unsustainable.

The terms "credit" and "debt" are interchangeable, and denote a right of action of the creditor against the debtor for a given amount [28] (p. 18). If someone is given a written promise to pay, i.e., a bill of exchange, against another (a form of credit), this item may circulate in the economy and has the same function as money; in fact, most of the money currently in existence was loaned into existence via banks. When banks take a deposit, they do not segregate the money and keep it in custody for a client; rather, they provide an abstract right of action against the bank for a certain sum of money [28] (p. 18). This money is denoted as a liability on the bank's balance sheet [45]. When a bank loans money, no funds are subtracted from the assets of the bank; the 'amount payable' of a loan amount is merely reclassified as a customer deposit [45]. Because customer deposits are considered part of the monetary supply, the amount of debt and the amount of money has increased in the economy "out of thin air". It should also be noted that because these bank deposits are not for any specifically marked money, bank credit requires faith in the bank to fulfill the right of action [28] (p. 18).

In exchanges, discounting barter and the melting of bullion, money is just a marker or a claim on wealth, and is not itself wealth [8] (p. 80.) A national currency is a token that can be exchanged for some portion of a country's national wealth; as such, money is not part of a nation's wealth but its debt [8] (p. 82). Soddy ([8], p. 137) defines virtual wealth as the total amount of money possessed by a community, representing the wealth that the community prefers to be owed rather than owned. If physical wealth is not expanding through resource exploration or colonization, then an increase in the monetary supply decreases the ratio of real to virtual wealth.

With the recognition that money itself plays a key role in economic relations, there has been an effort to understand and classify types of money creation. There are three general systems of organizing and funding enterprises within an economy: first, through private groups such as banks or credit unions; second, through the process of legislation and tax collection; and the third, through equity investments. This third option operates somewhat differently in that virtual wealth accumulated by companies or individuals is reinvested in other companies for shares or equity. This process does not directly involve the creation of money (horizontal or vertical), and we do not include it in our model or analysis. However, while the purchase of stock itself is not considered part of GDP or as contributing to the power consumption of the economy, the transferred funds can be utilized by the receiving company to obtain real wealth.

Horizontal money is created ex nihilo by banks during the loan-making process. This is how the vast majority of money in the modern economy (97% in the UK and 92% in the US [46]) enters the system [46] (p. 9). Note that this is not a new phenomenon; MacCleod wrote in 1889 that 98% of the commerce in the UK was carried out by circulating debts ([28] p. 54). If this money is spent at a different bank, reserves may be created ex nihilo by the central bank to cover the payment [46].

The second system directs public projects by legislation and covers payments through vertical money funded by the treasury. A portion of this money is recouped through the taxation process. When the government budget exceeds income through taxes, governments may fill the gap with the issuance and auctioning of government bonds, which they may later partially recoup through taxation ([47] loc. 630). Central banks may also create money ex nihilo to pay for the bonds.

It is important to note that compound interest charged on loans procured through the horizontal monetary system requires an ever-expanding monetary supply in order to cover any debts that come due; some recent models have suggested that interest is compatible with a slow-growth or no-growth economy, yet this depends on the behavior of economic agents, i.e., no saving is allowed [48–50]. Additionally, Yakovenko has discussed how debt stabilization itself is a fallacy and why the growth of debt can be considered an irreversible process that is further destabilized by interest [40]). A growing debt/monetary supply is built into our current financial system [5]. If an economic contraction occurs and the monetary supply shrinks, governments must increase the supply at all costs, including unconventional policy options such as Quantitative Easing (QE), in order to prevent the entire system from collapsing; the alternative is debt jubilee or default, which has been common throughout history in non-growing economies [49].

Defining boundary conditions is important to establish our criterion of monetary conservation. Yakovenko considers vertical money creation as money raining down onto an economy from the economic sky, such as solar radiation that enters Earth system through its external boundary and adds energy into the planetary system. As in the Earth example, and following [40] (Section 2.4), "horizontal" transactions among the agents within the system do not change the total amount of money; however, new money flows across the boundary into the system in "vertical" transactions between the system and the state.

The creation of money through bank loans originates a debt obligation (negative money) equal to the amount of money (positive deposit) being created [40] (Section 2.7) and [51].

Debt/money creation in "horizontal" transactions does not violate the conservation principle because when a loan is issued, the sum of the debt obligation (negative money) and new deposit (positive money) cancel out; thus, the total money in the system remains conserved [51].

Following Yakovenko's reasoning [40], we assert that the dimensionless "money" (or abstract ledger digits) is conserved in general and in detail, although not all monetary transactions are time-reversible (see his Section 2.2). In contrast to money, goods and services are not conserved; however, the energy and materials (mass, chemical compounds) that go into creating them are. The second law of thermodynamics governs the direction of physical time, with which this wealth becomes less available or useless, and applies to real wealth but not monetary virtual wealth ([8], p. 102 and [12]).

There are close links between the monetary and material layers of an economy. Any time we spend a unit of currency (here, a US dollar or British pound), someone has to burn something, plough soil, cut a tree, or dig something up, or perhaps all of the above; the exception to this is when currency is used to purchase an existing asset class, such as stocks or land. When large amounts of money are introduced into circulation, such as during QE, these assets tend to inflate. "Burning" here denotes the use of primary energy to underwrite essentially all monetary transactions. This energy still comes mostly from fossil fuels. Any economic activity whatsoever is rooted in a physical conversion of earth resources (minerals, fossil fuels, biodiversity, soil, water, air) into products and services [44], Figure 4. Energy is an enabler of all human activities. Services also cost resources and energy, mostly imported from elsewhere in the world [52]. Thus, a comprehensive "service economy" is a privilege of the rich, who import someone else's resources and environment in exchange for money.

3. Materials and Methods

3.1. Preliminaries

Each national economy has a unique maximum "size" or "techno-ecological footprint" that is a function of a country's surface area, energy resources, population, water resources, soil, forests, biodiversity, climate (geography and topography), access to oceans, natural resources, technological advancement, political system, appropriation of the ecosystem services of other countries (mostly by China, the US, and the EU), and so on. In another paper [44], we parameterized the "sizes" of 160 countries over 20 years using an eight-dimensional mapping algorithm (see Figure 4). With our parameterization, each economy has an ultimate size L that is already a dimensionless real number. We then define the dimensionless "economic space" variable as $\tilde{x} = x/L \in [0, 1]$.

In this space, an economy consumes the available free energy as the heats of combustion of fossil fuels and biofuels, electricity from renewables, all material inputs (including food, clean water, and clean air), labor, services, and so on. Each class of these inputs has different physical units; however, behind them there is always free energy relative to the prevailing environmental conditions, or "exergy" [53]. A vast majority of this free energy is in geological accumulations and can be consumed only once over the human timescale [12,22].

In this model, we assume that the economic potential behaves like a single resource endowment with no or negligible replenishment. Soils and forests are depleted more than they are replenished, and the solar exergy entering the system (flow) is small in comparison to the exergy from depleting stocks [13,22,23,54]. Each time a transaction is made in the economy or product is produced, some amount of free energy is consumed. Economists sum the monetary value of these outputs as the Gross Domestic Product (GDP). Note that if the "imaginary" economy made up of financial assets becomes large, then GDP and power consumption start to diverge.

Given this description of a human economy, our "economic growth potential" ψ is the free energy embodied in everything that enters the economy as a function of the cumulative debt D available to this economy from its "inception" at $D = 0$. In summary, debt that generates credit on the other side of the ledger is cumulative and encodes time in the economy; soon, we will rescale this debt to $\tilde{D}$.

Initially, the economic space available to a country is filled uniformly with the highest possible level of free energy $\psi(\tilde{D} = 0, \tilde{x}) = \psi_i$ available to that country. This free energy endowment is consumed with increasing debt ($\tilde{D} > 0$) or depleted by the free energy diffusing into a sink at $\tilde{x} = 0$, which is a human economy. From this point of view, cumulative economic growth is proportional to the cumulative consumption of free energy available to a country.

GDPs are the closely related but imperfect measures of the cumulative consumption of free energy in a given year. Consistent with our assumptions, we take the liberty of using them interchangeably.

Economic growth potential is depleted by human activities that consume the available free energy endowment and create more population, goods, and services, in short, GDP$[\psi(\tilde{D}, \tilde{x})]$/CPI. In our model, we assume that the cumulative GDP is an integral of the free energy extraction at $\tilde{x} = 0$ integrated over all debt. For the time being, we consider that $\psi(\tilde{x} = 0, \tilde{D} > 0) = \psi_0$ = const; however, in reality we expect ψ_0 to be a function of time. As diffusion dissipates the potential ψ over a finite space $\tilde{x}$, the GDP reaches an upper asymptote GDP$_{\max}$. Thus, in the end the efficiency of debt conversion to GDP approaches zero. This is the limit of the readily available high-free energy resources. The other boundary of the economy at $\tilde{x} = 1$ is insulated in this paper. The economy can be thought of as an insulated rod with one open end in which the heat can flow out (we have included a comparison of heat diffusion and economic potential diffusion in Figure A1). This ensures that the economic potential is not replenished; see the spatial evolution of ψ in Figure 6.

An obvious weakness of our model is the absence of a GDP destructor that will make GDP decline despite debt/credit when resources are lacking or when the environment is degraded. This would be equivalent to the introduction of another sink or sinks at $\tilde{x} \geq 0$ and $\tilde{D}_j > 0$, $j = 1, 2, \ldots$. These sinks would annihilate the available free energy without increasing GDP. Conversely, we could model a sudden change of GDP by changing the level of the "drawdown potential" ψ_0. This would be analogous to a technology that increases the efficiency of the economy. We leave these superposition solutions for later.

3.2. Model

This is a simplistic model of an economy that generates surplus and GDP by issuing credit = debt. We assume that given this economy's total endowment (geography, topography, biodiversity, mineral resources, fertile soil, water supply, climate, insolation, wind, population, political systems, education, R&D, military, alliances, trading, etc.), it will ultimately reach a maximum size L we normalize to one. Given all endowments, this economy has an initial growth potential ψ_i, we normalize to one. This economy has a beginning, with no debt ($D = 0$) and no GDP, as well as infinite debt ($D \to \infty$) and GDP at its maximum value in "constant" or "real" dollars. Therefore, the GDP of this economy varies between zero and some GDP$_{\max}$. Debt serves as the temporal dimension of the economy's evolution. Given rate of issuance, this debt can be inverted into the "elapsed time on debt". Our growth potential obeys the following diffusion equation:

$$\frac{\partial \psi}{\partial D} = \alpha \frac{\partial^2 \psi}{\partial x^2} \tag{1}$$

where α is the growth potential's diffusivity. We assume that α is a constant for each economy determined from financial data. We define the characteristic debt diffusion scale τ such that

$$\begin{aligned} \tau &= \frac{1^2}{\alpha}, \\ \tau\alpha &= 1, \end{aligned} \tag{2}$$

because the characteristic "length" L of the economy is already renormalized to 1. Note that L needs to be known explicitly in order to differentiate among the different countries and their trajectories [44]. We now express debt in the units of τ:

$$\tilde{D} = \frac{D}{\tau}. \tag{3}$$

With all other normalizations in place, the governing equation is

$$\frac{\partial \tilde{\psi}}{\partial \tilde{D}} = \frac{\partial^2 \tilde{\psi}}{\partial \tilde{x}^2}. \tag{4}$$

The initial condition and boundary conditions are

$$\begin{aligned} &\tilde{\psi}(x, \tilde{D} = 0) = \tilde{\psi}_i = 1, \\ &\tilde{\psi}(x = 0, \tilde{D} > 0) = \tilde{\psi}_0 = 0, \\ &\frac{\partial \tilde{\psi}}{\partial \tilde{x}}\Big|_{\tilde{x}=1} = 0. \end{aligned} \tag{5}$$

The right boundary condition means that no additional GDP is generated by the economy at its maximum size.

The well-known solution [55] (§3.4, Equation (5), p. 101, $x \to 1 - x$) is

$$\begin{aligned} &\tilde{\psi}(x, \tilde{D}) = 0 + 2\sum_{n=0}^{\infty} e^{-\tilde{D}n_1^2/4} \cos\frac{n_1(1-x)}{2}\frac{2}{n_1}\sin\frac{n_1}{2}, \\ &n_1 = (2n+1)\pi. \end{aligned} \tag{6}$$

We assume that the cumulative GDP at the debt level $\tilde{D}$ is the summation of yearly GDP from the start of the economy:

$$\begin{aligned} &\mathrm{GDP_{cum}} = K\int_0^{\tilde{D}} \frac{\partial \tilde{\psi}(\tilde{D}')}{\partial \tilde{x}}\Big|_{\tilde{x}=0} \mathrm{d}\tilde{D}', \\ &\mathrm{GDP_{cum}} = 4K\sum_{n=0}^{\infty} \frac{1}{n_1}(1 - e^{-\tilde{D}n_1^2/4})\frac{2}{n_1}\sin^2(\frac{n_1}{2}). \end{aligned} \tag{7}$$

To make clear the assumptions of the model, in addition to the boundary conditions outlined above, we assume (a) conservation of energy and mass, (b) conservation of money, and (c) closed economies.

The last assumption is quite significant. We do not consider the "offshored" power consumption embodied in imports, nor do we consider the exporting of economic potential. Additionally, we do not consider the political relationships between countries, which may grant emergency loans, resources, etc., nor do we consider the use of currencies beyond the borders of a country, for example, the black market for USD in Argentina or the use of USD to facilitate global trade. We aim to provide the simplest model that still adequately describes the data, and our results seem to broadly validate these assumptions. In a more sophisticated analysis, we may look for examples where these assumptions break down and interference occurs between countries.

4. Results and Discussion

Obtaining comparable debt statistics internationally is difficult. There are two main databases that contain compiled debt statistics across economies: the International Monetary Fund's Global Debt Database [56], and the Bank for International Settlements (BIS) Database [57]. Here, we use the BIS data, as debt is reported in USD along with local currencies. Non-financial debt is reported for the general government (GG), households (HH), and non-financial corporations (NFC). We would prefer to use the nominal value in order to avoid the speculation involved in market rates; however, nominal debt is only reported for general government debt. For household debt ("households and non-profit institutions serving households") and non-financial corporations, only market rates are available. These three categories are summed for a total debt statistic. We calculate this total in both local currency and USD.

We plot cumulative power consumption from BP [58] against the aggregate debt statistics, measuring debt in both the local currency and USD (Appendix A.3). Note that for Saudi Arabia these lines overlap, as the Saudi currency is pegged to the US dollar, which is used to price most of crude oil and gas in the world.

Local currencies follow the square root function much more closely than when measured via USD. The countries also vary in how closely they follow a single square root function. Figure 8 shows the R-squared values for a single square root fit. These graphs are shown in the Appendix A. Note that we used all data points for each fit; for countries with multiple slopes or with significant exponential damping, a more sophisticated analysis involving subsections of the time series may provide better fits. The R-squared values, fit parameters, and time series lengths for each country are provided in the Appendix A.

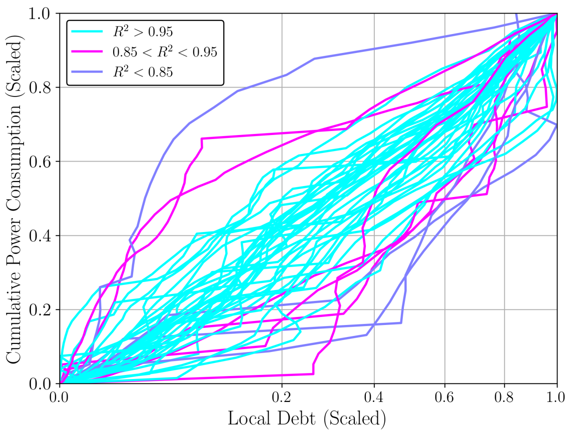
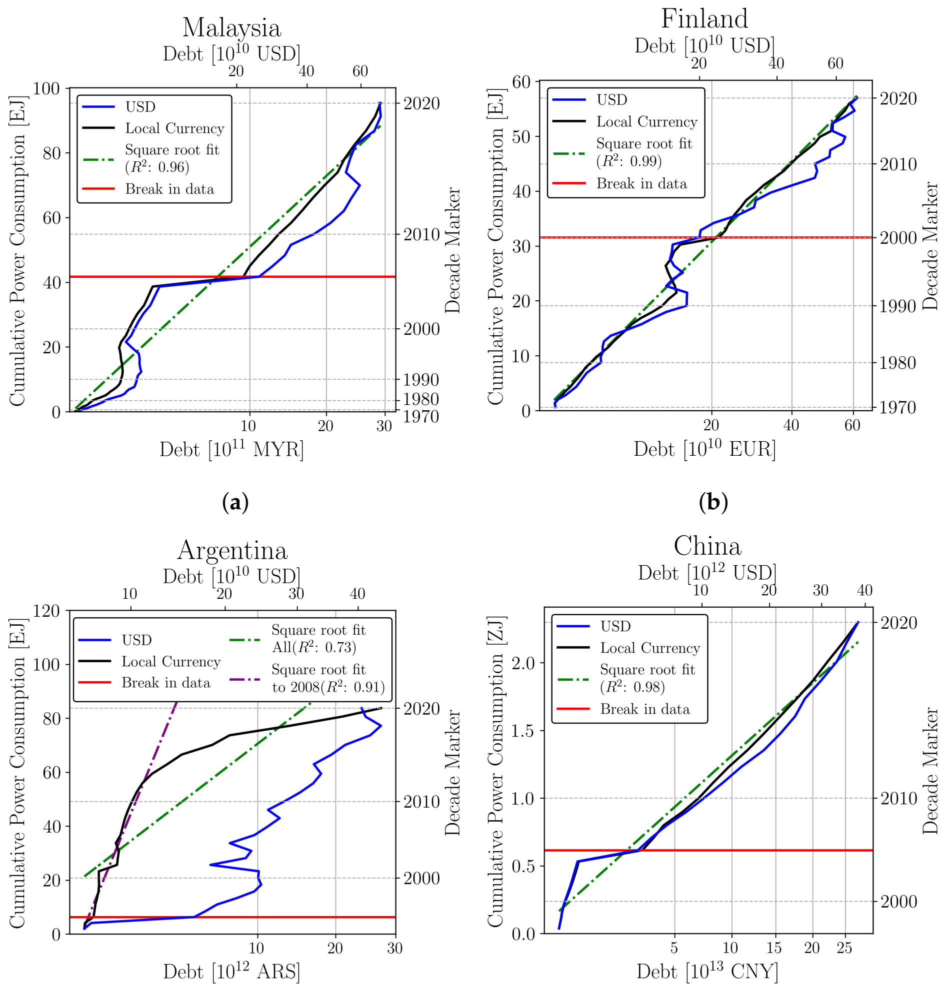


Figure 8. Goodness of fit of GDP in local currency vs. debt for various countries; note that the x-axis has a square root scale.

We hypothesize that deviations from the square-root-of-debt diffusion behavior tend to be associated with changes in economic policy or economic crises, or alternatively are indicative of faults in the underlying data. It is important to note that the availability of the components of the aggregate debt series (HH, GG, and NFC) might have different temporal availability. This can lead to deviations in the square root pattern that are artifacts. An example of this is the plot for Malaysia (Figure 9a). In these instances, care needs to be taken in the interpretation or other sources must be referenced to ensure that deviations from the square root are not caused by the missing debt series. Deviations might also occur where lending to the "imaginary" economy subsidizes asset bubbles. Although we have not differentiated between the "real" and "imaginary" sectors in this analysis, this is a logical next step.



(**d**)

Figure 9. (**a**) The Malaysian power–debt diffusion graph contains a horizontal artifact caused by the unavailability of Household and Non-Financial Corporation Debt in the BIS data series prior to the break (Red). (**b**) During the 1990s, power consumption increased rapidly in Finland, with little debt increase. Note that this period was preceded by rapid borrowing. Following the 1990s, the debt–power relationship returned to a square root function. General Government debt is not included before the break (Red). (**c**) Argentina's economy was following the square root diffusion pattern ($R^2 = 0.91$) until 2008, at which point there was exponential deviation from the curve, signifying the devaluation of the local currency. At the same time, use of the US dollar became more widespread [59]. (**d**) China's power consumption vs. debt follows a square root function closely. The R^2 fit is 0.98.

Steep increases in slope from the square root seem to be associated with economic crises. This phenomenon appeared in Finland during the 1990s, aligning with their banking crisis (Figure 9b) [60] and in Japan coinciding with the "Lost Decades" of economic stagnation. The curves for Greece, Portugal, and Hungary also steepen after the 2007 financial crisis, during which the IMF and European Financial Stability Facility conducted bailouts for some European countries [61]. Removal of "bad" debt from the system likely follows this trajectory, whether through default or through the purchase of debt from an outside agency (IMF or Federal Reserve) in exchange for vertical money (see [40], Section 2.8 for more on schemes to remove bad debt from the system). Examining the conditions under which this phenomenon appears and the circumstances in which the economic trajectory returns to the square root diffusion will be an interesting extension of the present work.

Exponential deviation from the square root function is occurring in Argentina (Figure 9c) and to a more limited extent in South Africa and Turkey. In these countries, the issuance of debt is having diminishing returns. A number of countries are currently following the square root relationship very closely, and strong deviations do not appear as of yet; these are India, Brazil, Finland, New Zealand, Indonesia (limited data), Sweden, China, the UK, Mexico, Australia, Singapore, Chile, Canada, France, and Luxembourg.

Deduction of the time horizon that individual currencies have before they enter the exponential deviation (decline) phase will require a quantification of the initial economic potential, and will likely be complicated by the interactions among economies. However, this deduction seems to be a natural next step that can help to generate more concrete policy recommendations. Given that most countries are at or nearing peak fossil fuel production, the exponential deviation phase could be expected well within the next 50 years for most economies [62,63].

Our analysis highlights that money creation is directly related to resource utilization, an area that is often overlooked in environmental policy. This paper is one of *many* in the post-growth literature that disputes the economic dogma of infinite growth on a finite planet. In general, policymakers may look for alternatives to the absolutely unsustainable GDP-maximizing system of today in the ecological economics literature, and hopefully bring them into the mainstream. These ideas are not new, and much of the environmental literature of the 1970s has just as much relevance today. For inspiration, we recommend reading the seminal *Blueprint for Survival*, first published in 1972 [21].

5. Conclusions

The majority of the world's countries for which we have data appear to still follow an early part ($\tilde{D} < 1$) of the diffusion relationship between cumulative power consumption or cumulative GDP and debt in local currency, which encodes time. The countries we examined are at different parts of the characteristic curve shown in Figure 7, the midsection of which is a simple square root debt growth. Additionally, given that every country participates to some extent in the global economy, these diffusion relationships may be impacted by economic events outside of the nation's boundaries. On the microscale, we posit that this diffusion relationship arises due to random walks of economic activity, as depicted in Figure 5.

The basics of the disconnect between our monetary system and the economic laws on one side and the physical reality on the other were described at length by Nobel Laureate Fredrick Soddy in what he termed Cartesian Economics [1,8]. Following in his footsteps, we have shown that the relation between debt and economic metabolism (GDP or power) resembles a diffusion relationship. This relation exists particularly in times where the linkages between money and its underlying resources are frayed. Increases in the money supply through the creation of debt can temporarily spur economic activity, but require continual economic expansion to maintain. Because the earth is finite, this borrowing from the future is akin to a Ponzi scheme that must collapse. While our model shows a leveling and then shrinking of GDP in line with physical resource availability, orthodox economic theory only allows for growth. At some point in time, all economies must deviate from steady state diffusion due to the depletion of the economic potential ψ, although when this will be requires considerable further research. In times of crisis, some economies seem to deviate vertically, such as Greece, while other such as Argentina follow the predicted exponential deviation (see Figure 7). The ultimate trajectory might depend on how closed the economy is and whether it maintains adherence to current growth-based economics. Open economies that can be propped up by trade connections and foreign currency might exhibit different behavior. To examine this question, countries that have experienced collapse related to currency inflation or resource consumption could be examined to see how closely they follow the exponential deviation. We suspect that this would depend on whether economic activity transitions to alternative currencies, for example the use of the USD in Argentina, as well as the strength of trade connections and the level of resource depletion in an economy.

We acknowledge that there are many ways in which our model could be extended and that there are numerous mechanisms that this model does not explicitly account for, e.g., trade, reinvestment of income, debt defaults, and efficiency improvements. However, in our view the strengths of this model lie in its simplicity and that it appears to predict the trajectories of economies of many disparate countries. The verification of this model is likely to be a long-term project, and might require progress in the way that economic interactions are treated as well as in the quantification of ψ_0. In the future, we hope to further develop the theory behind economic diffusion, in particular by exploring the meaning of the spatial variable 'x' and examining whether the incorporation of other mechanisms such as trade can help to explain deviations from the square root of debt diffusion process.

Author Contributions: Conceptualization, T.P.; methodology, T.P. and P.M.; data curation, P.M.; writing—original draft preparation, P.M.; writing—review and editing, T.P.; visualization, P.M. and T.P.; supervision, T.P.; project administration, T.P.; funding acquisition, T.P. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1. Model Figures

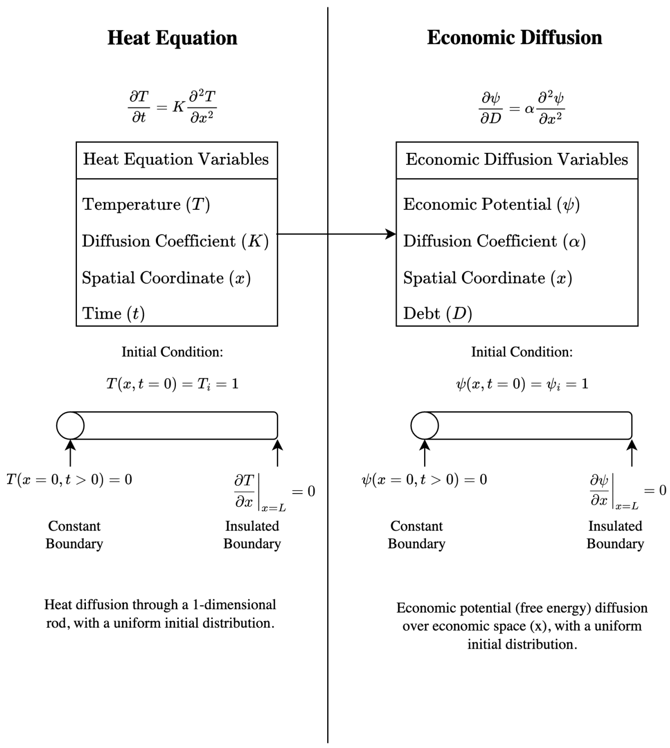

Figure A1. A comparison of the heat equation through a one-dimensional rod with the same boundary conditions as our economic diffusion model.

Appendix A.2. Square Root Fit

Table A1. The coefficients of the square root fit ($\text{Power}_{\text{cum}} = a_0\sqrt{\text{debt}} + a_1$) are shown in the graphs of the following section, along with the R-squared value and number of years for which data are available. Note that some countries may experience exponential damping and are not expected to follow the square root through the entirety of the diffusion process.

Country	A0	A1	R^2	Number of Years
Brazil	27.7	−40.2	0.996	27
United States Of America	0.7	−0.3	0.994	56
Australia	31.1	−20.6	0.994	44
Colombia	4.0	−9.2	0.994	25
Sweden	9.4	−16.2	0.992	41
Finland	7.9	−4.6	0.991	51
Canada	77.6	−52.0	0.991	52
Luxembourg	0.9	−1.0	0.991	26
Czechia	8.7	−29.2	0.990	26
France	60.6	−90.4	0.989	44
India	121.5	−2.1	0.987	40
Chile	6.3	−11.2	0.987	19
Singapore	7.5	−26.2	0.986	31
Mexico	16.1	−23.3	0.982	31
China	0.4	0.0	0.981	26
Indonesia	16.2	−49.2	0.979	20
Turkey	16.8	14.3	0.978	35
South Korea	44.0	−15.8	0.977	56
United Kingdom	59.9	50.5	0.976	55
Russian Federation	59.7	−15.6	0.975	24
Germany	106.7	−141.9	0.975	51
Norway	8.4	−5.9	0.975	46
Belgium	8.9	−17.7	0.971	41
New Zealand	3.8	−6.5	0.971	32
Poland	20.3	−16.7	0.969	26
Thailand	31.8	−59.2	0.965	30
Netherlands	32.4	−63.9	0.965	31
Malaysia	16.7	−2.0	0.962	54
Hong Kong Sar	3.8	−10.4	0.961	31
Denmark	4.3	−14.9	0.956	27
Portugal	4.3	−2.9	0.956	42
Spain	34.2	−23.0	0.954	41
Israel	8.4	−18.1	0.953	29
Italy	45.8	24.3	0.952	56
Austria	6.7	−29.5	0.923	26
Ireland	1.5	−3.9	0.923	21
Japan	0.2	−0.2	0.917	56
Argentina (To 2008)	53.7	−10.7	0.914	29
Hungary	5.7	9.2	0.906	56
South Africa	22.7	28.0	0.883	56
Saudi Arabia	67.1	−152.2	0.864	23
Euro Area	0.4	−0.9	0.829	24
Greece	4.3	−6.2	0.812	27
Switzerland	2.8	−12.9	0.784	26
Argentina (All)	16.9	17.1	0.727	29

Appendix A.3. Cumulative Power Consumption Graphs

For each country or economic unit analyzed, we show the debt time series in local currency (right plot) and USD (center plot) obtained from the Bank for International Settlements Database. The left plot shows cumulative power consumption against debt measured in local currency and USD. The square root fit uses all local currency data points. Note that as the nominal value government debt data for South Korea are not available, the market value is used instead; also note that several countries (e.g., Hungary and Israel) are clearly bimodal, and as such two linear square root of debt fits would be a better choice.

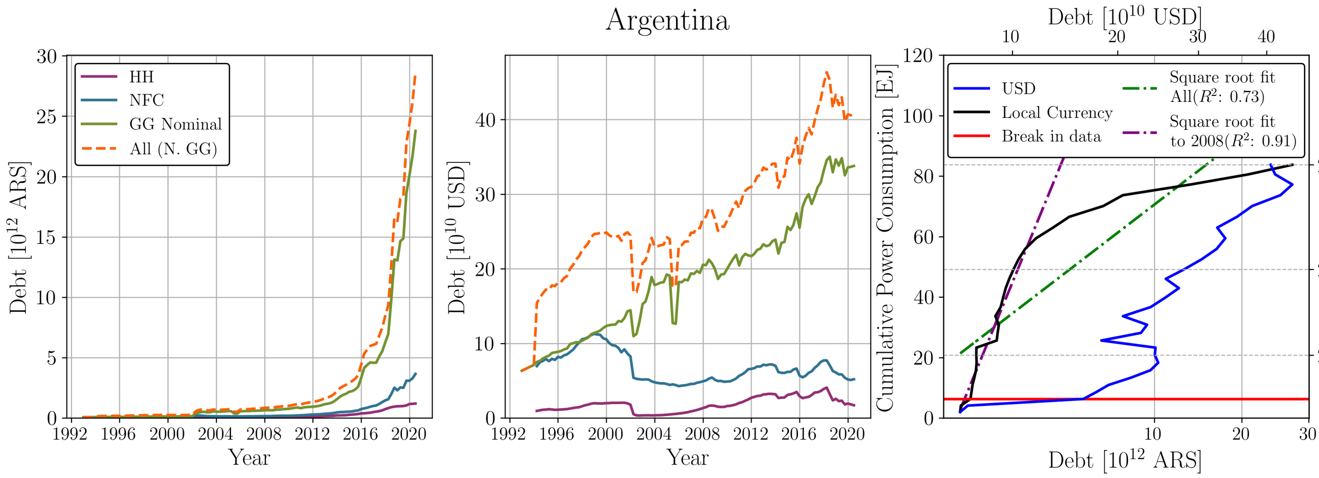

Figure A2. Argentina BIS debt time series and cumulative power consumption vs. debt.

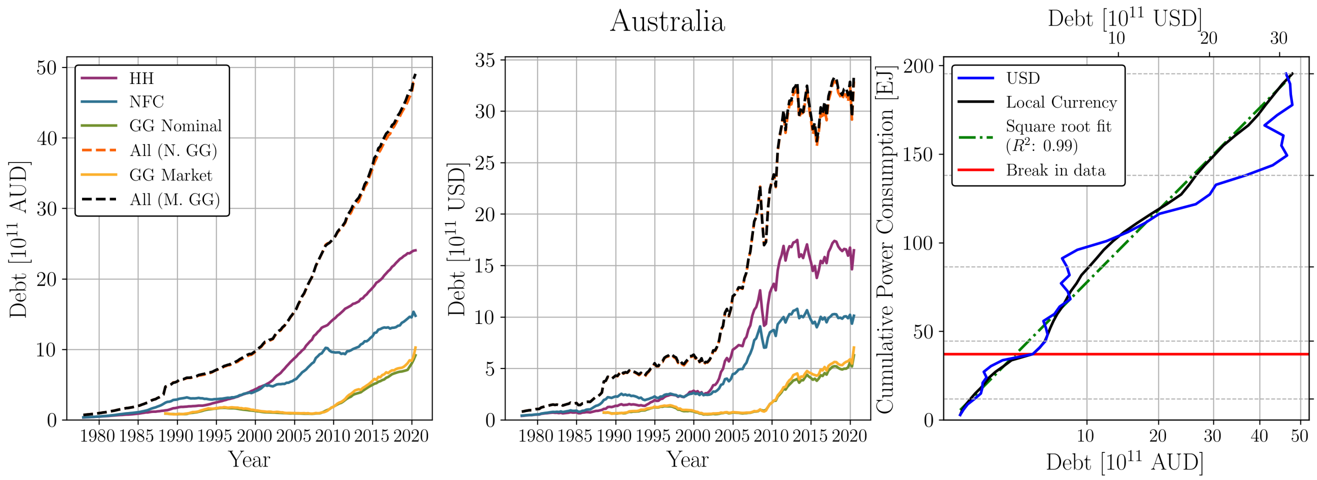

Figure A3. Australia BIS debt time series and cumulative power consumption vs. debt.

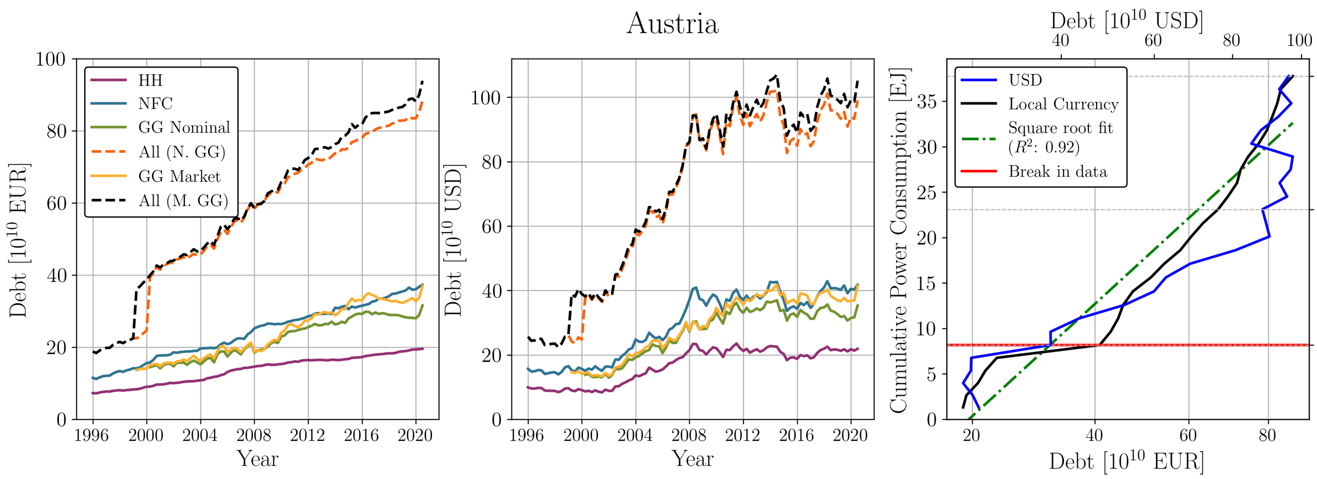

Figure A4. Austria BIS debt time series and cumulative power consumption vs. debt.

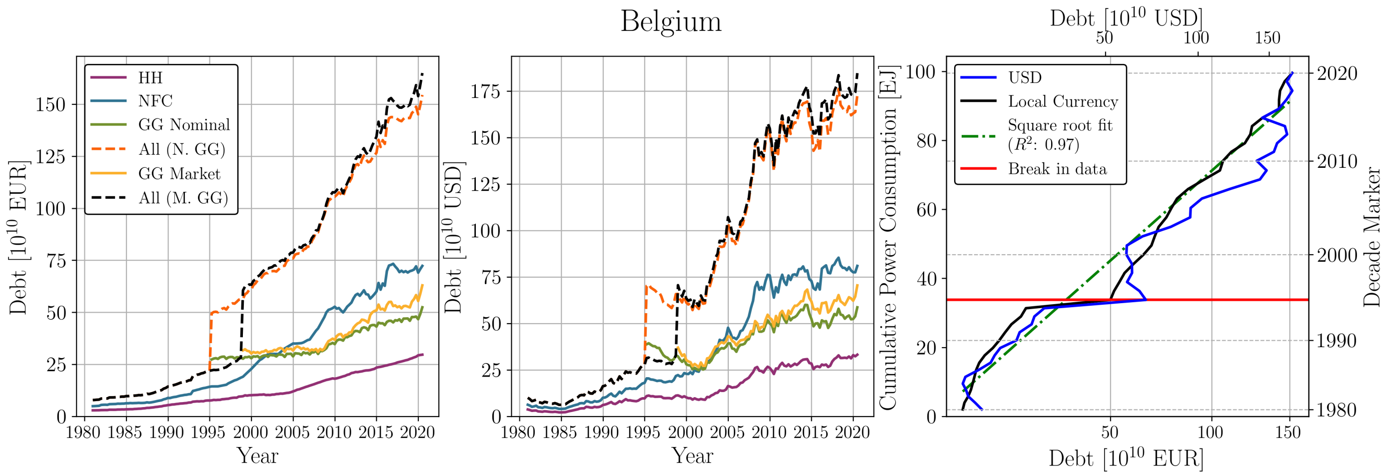

Figure A5. Belgium BIS debt time series and cumulative power consumption vs. debt.

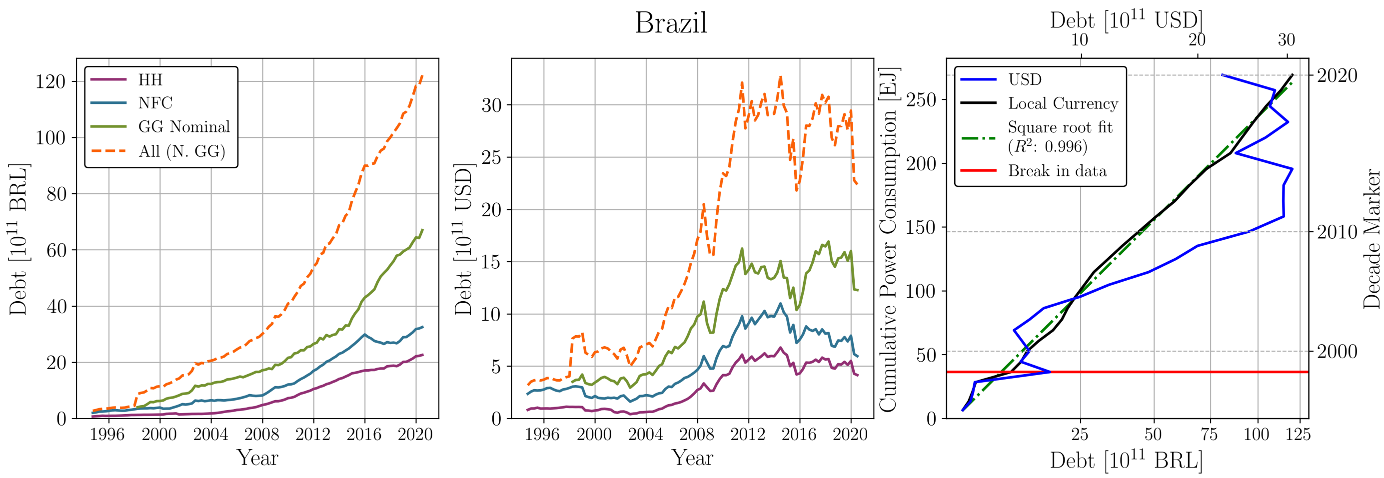

Figure A6. Brazil BIS debt time series and cumulative power consumption vs. debt.

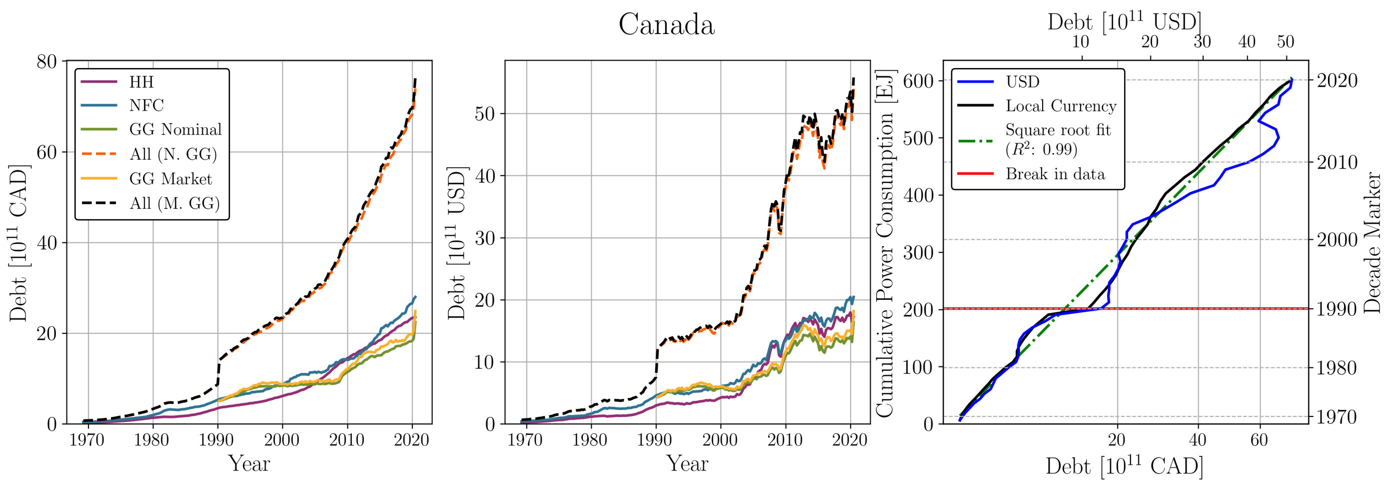

Figure A7. Canada BIS debt time series and cumulative power consumption vs. debt.

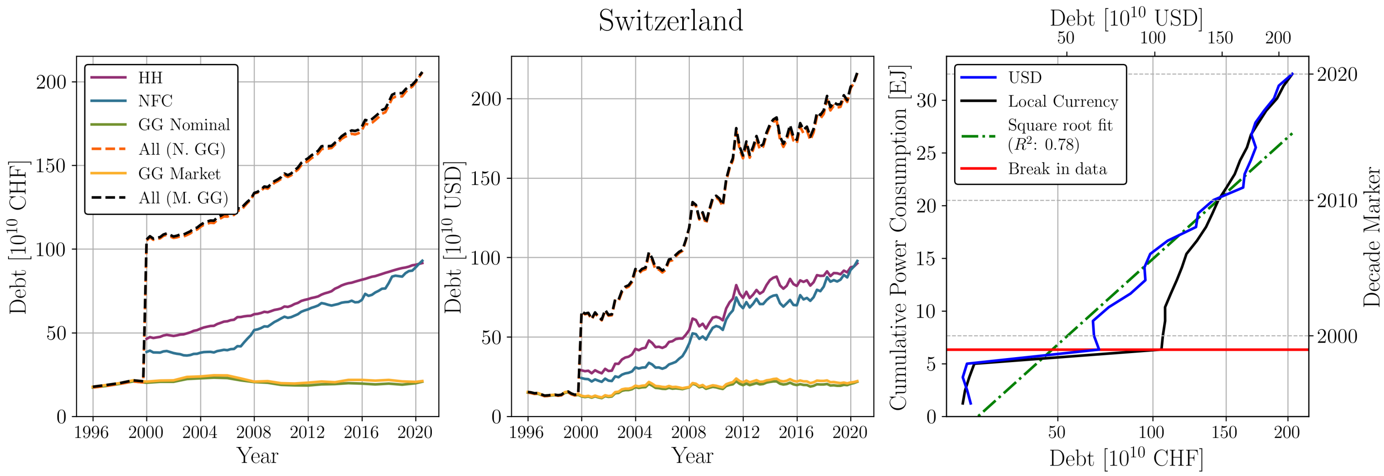

Figure A8. Switzerland BIS debt time series and cumulative power consumption vs. debt.

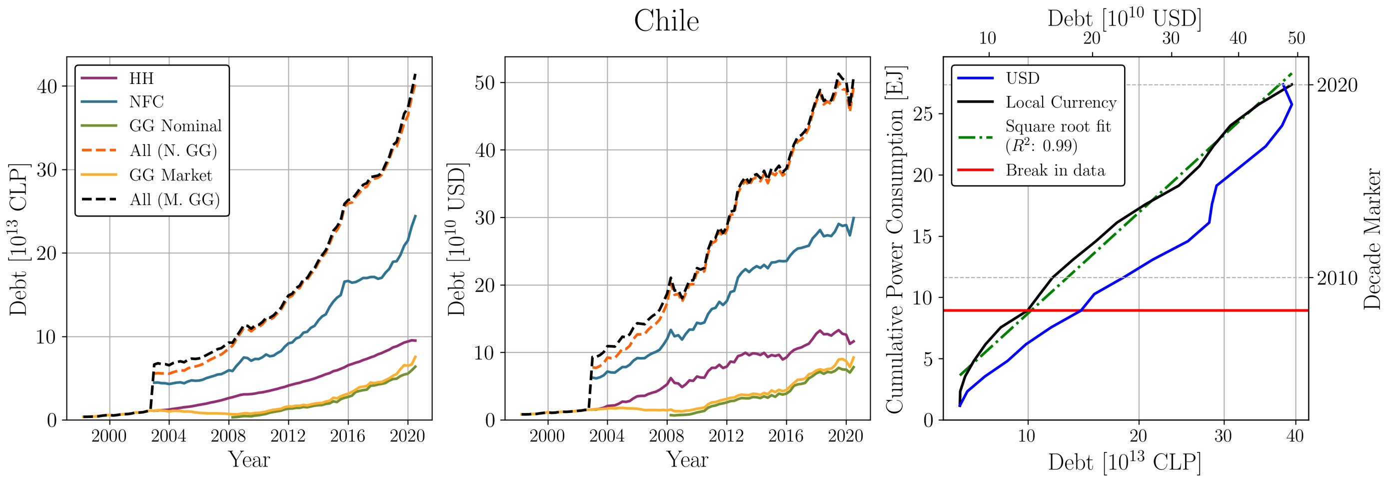

Figure A9. Chile BIS debt time series and cumulative power consumption vs. debt.

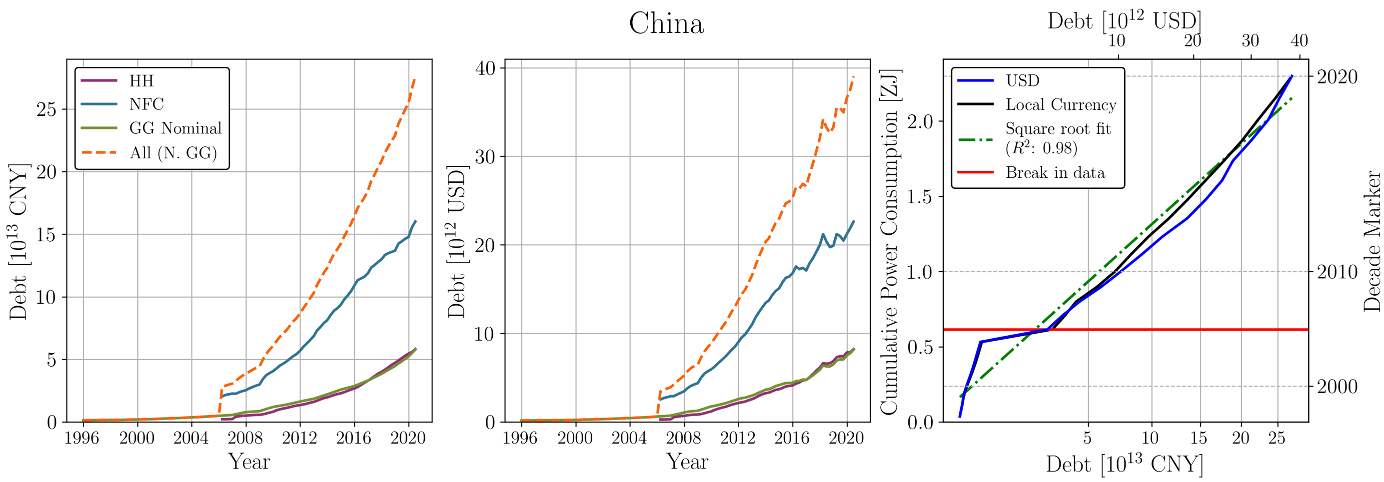

Figure A10. China BIS debt time series and cumulative power consumption vs. debt.

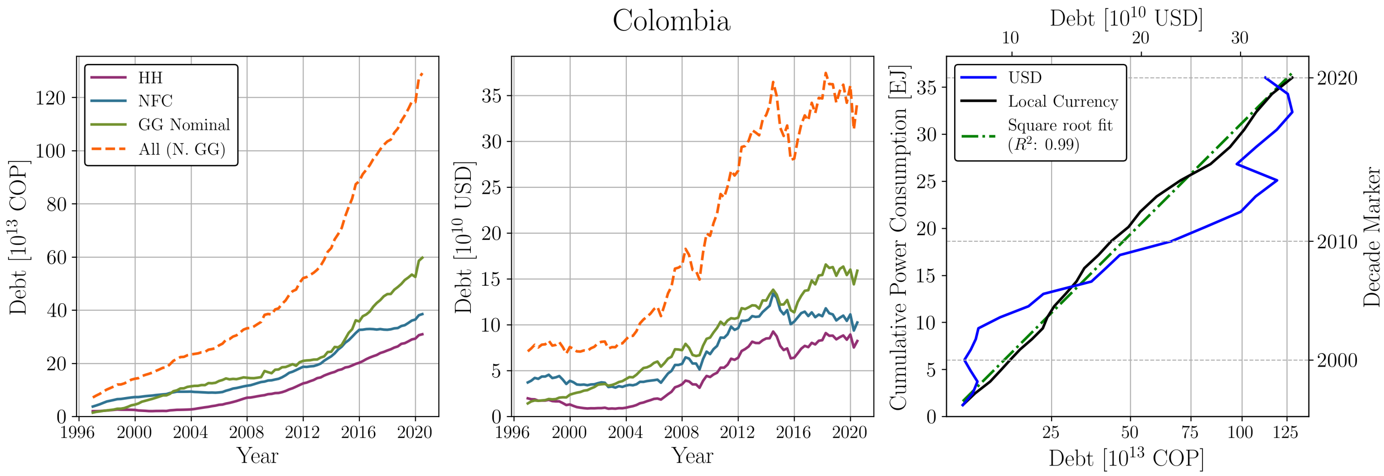

Figure A11. Colombia BIS debt time series and cumulative power consumption vs. debt.

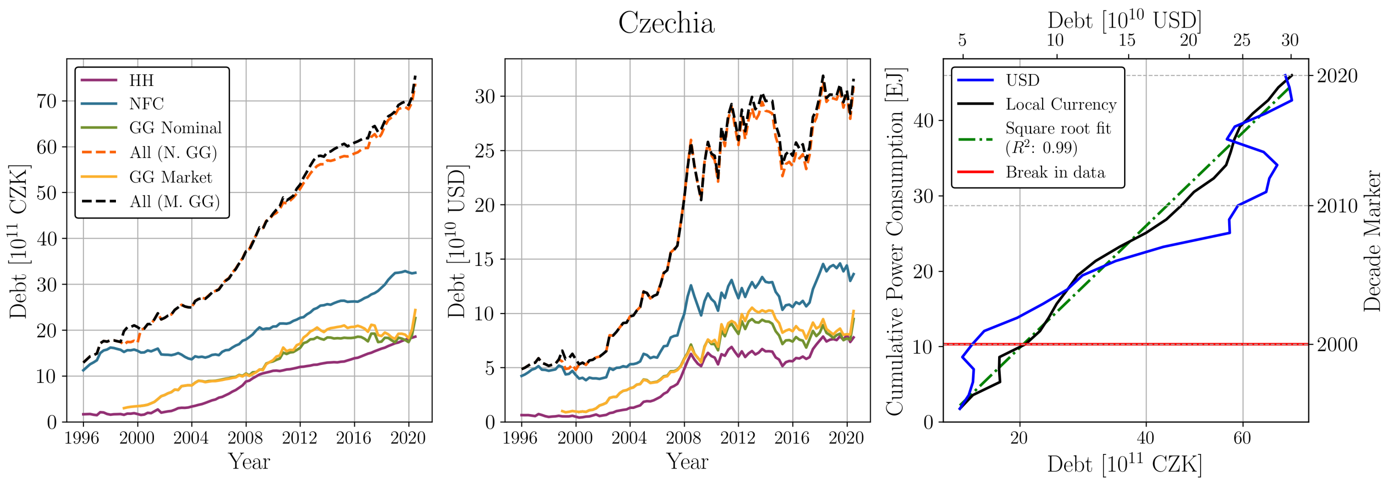

Figure A12. Czechia BIS debt time series and cumulative power consumption vs. debt.

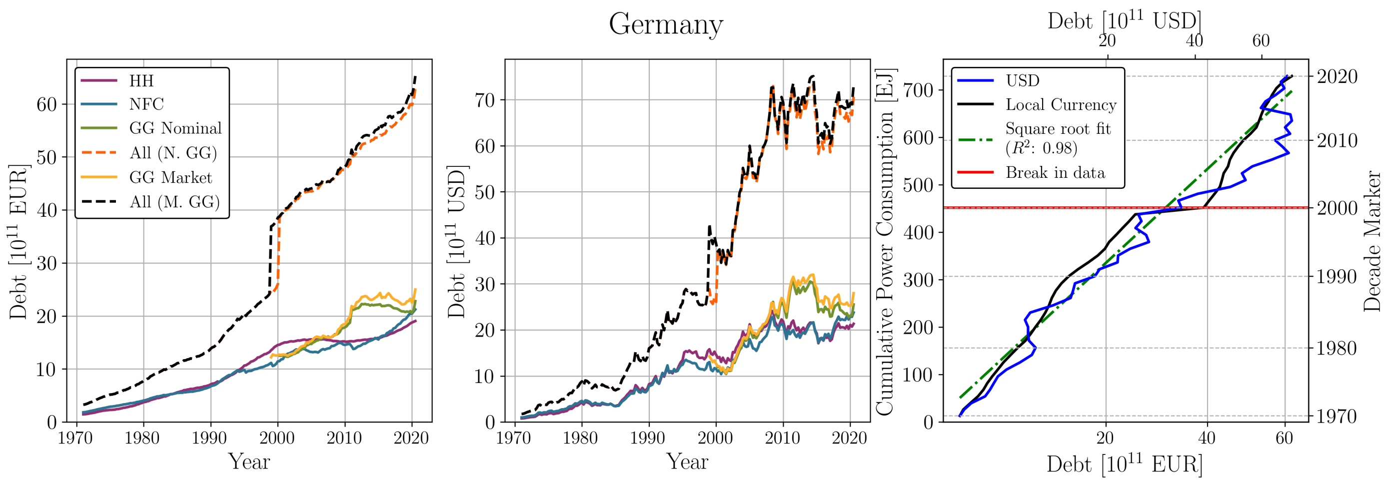

Figure A13. Germany BIS debt time series and cumulative power consumption vs. debt.

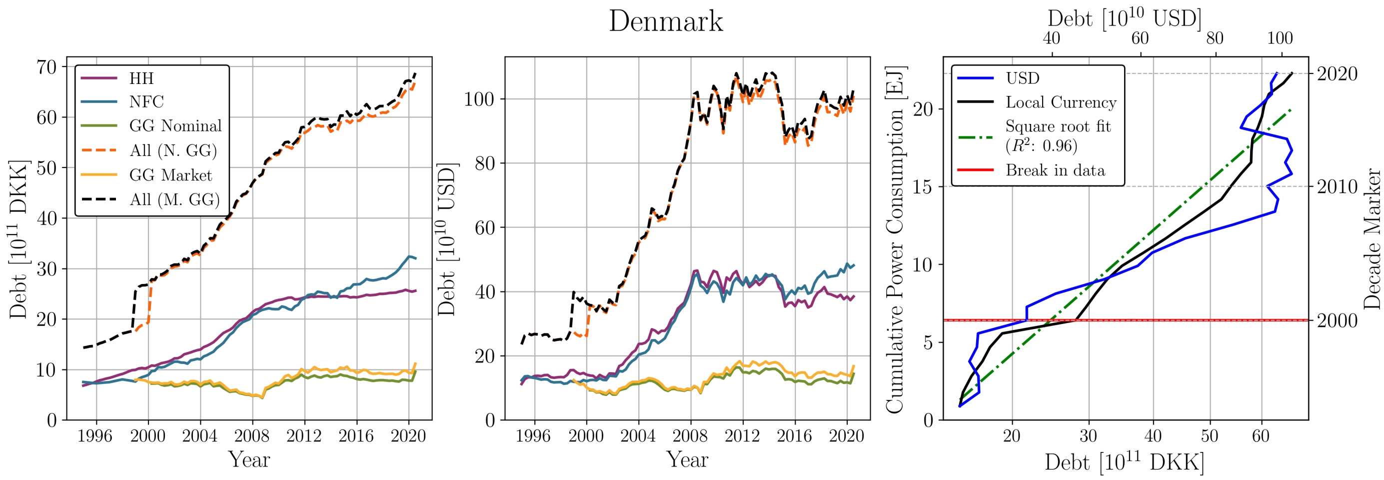

Figure A14. Denmark BIS debt time series and cumulative power consumption vs. debt.

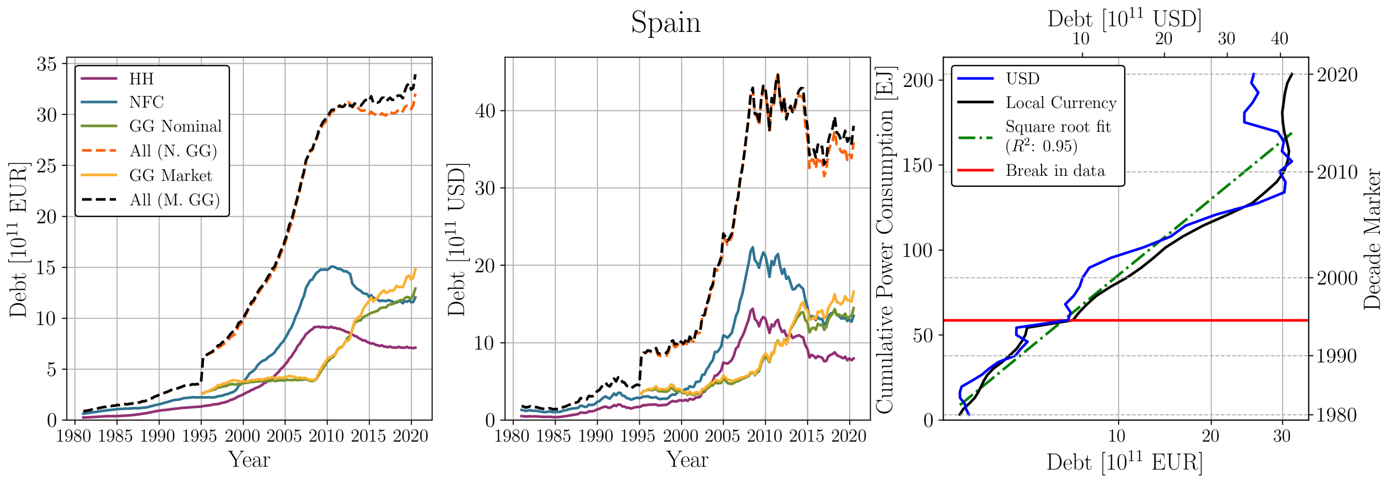

Figure A15. Spain BIS debt time series and cumulative power consumption vs. debt.

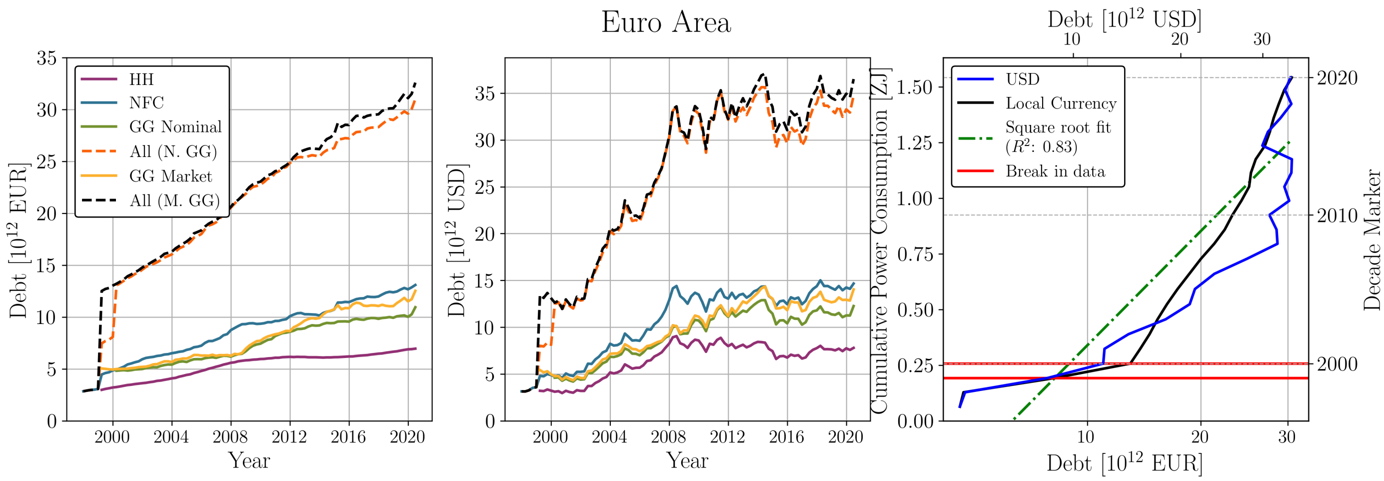

Figure A16. Euro Area BIS debt time series and cumulative power consumption vs. debt.

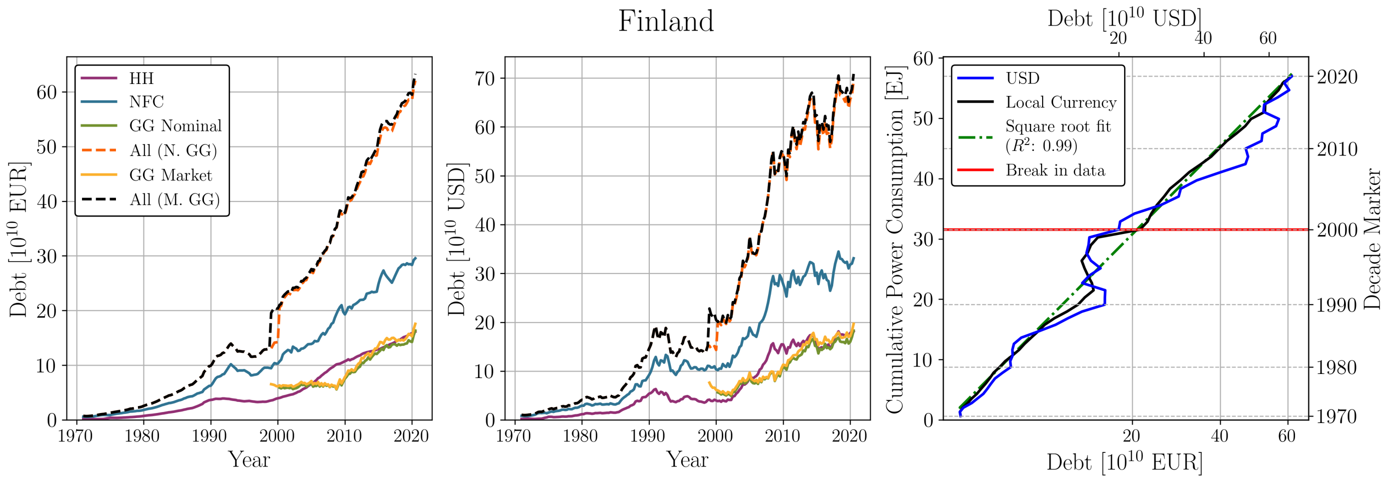

Figure A17. Finland BIS debt time series and cumulative power consumption vs. debt.

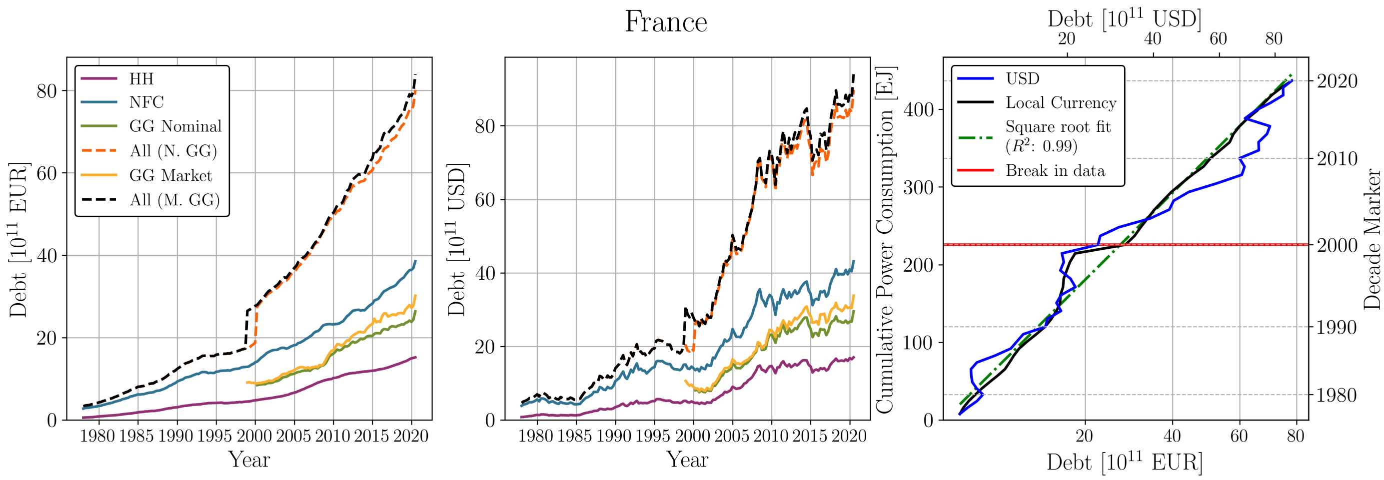

Figure A18. France BIS debt time series and cumulative power consumption vs. debt.

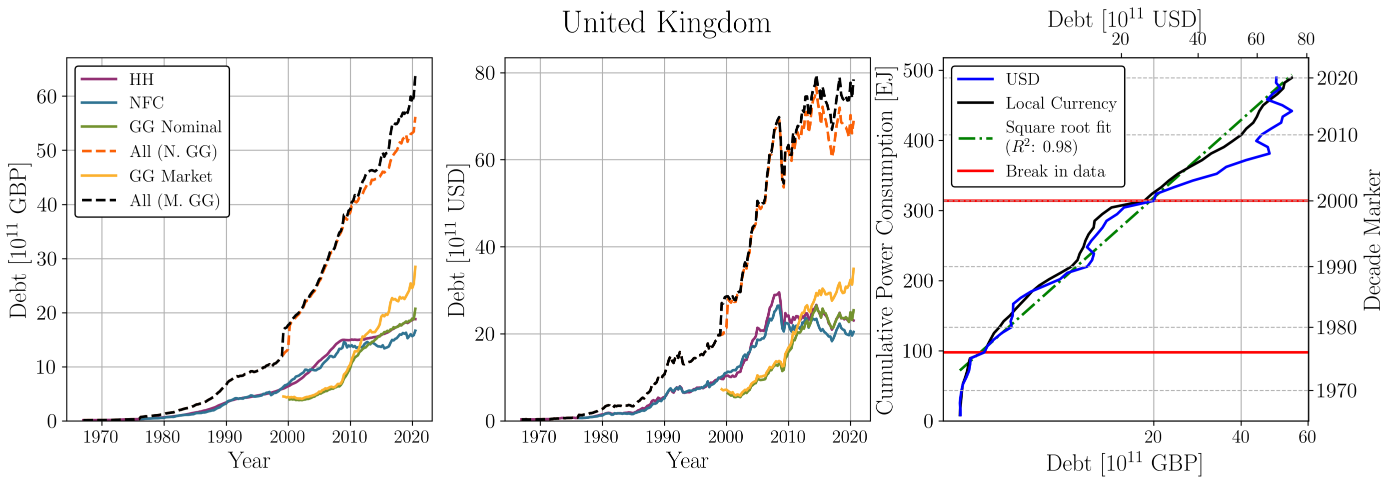

Figure A19. United Kingdom BIS debt time series and cumulative power consumption vs. debt.

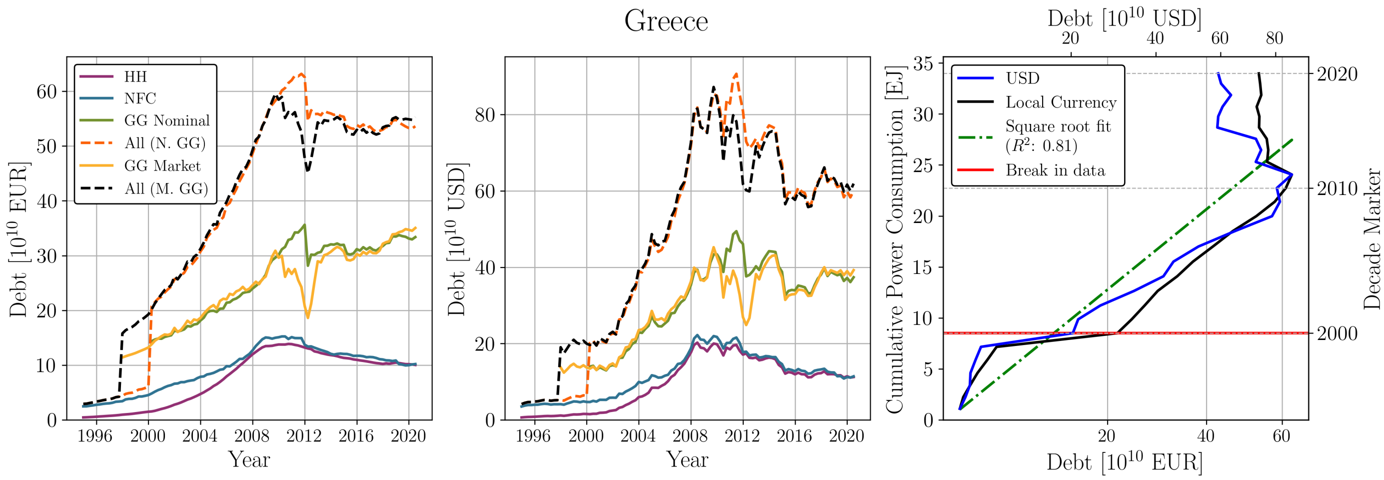

Figure A20. Greece BIS debt time series and cumulative power consumption vs. debt.

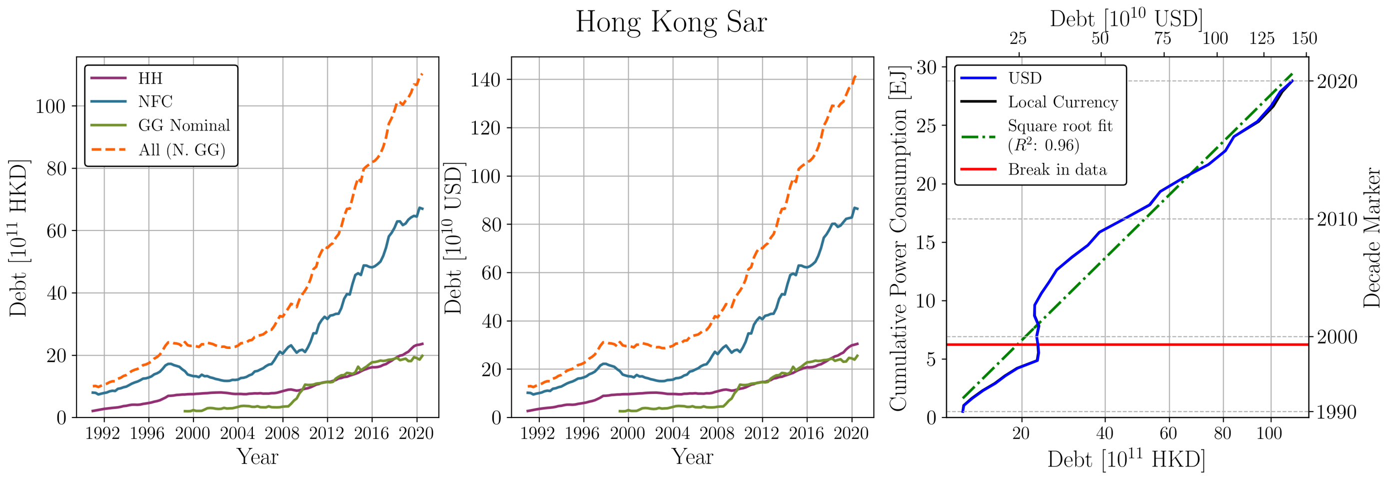

Figure A21. Hong Kong Special Administrative Region BIS debt time series and cumulative power consumption vs. debt.

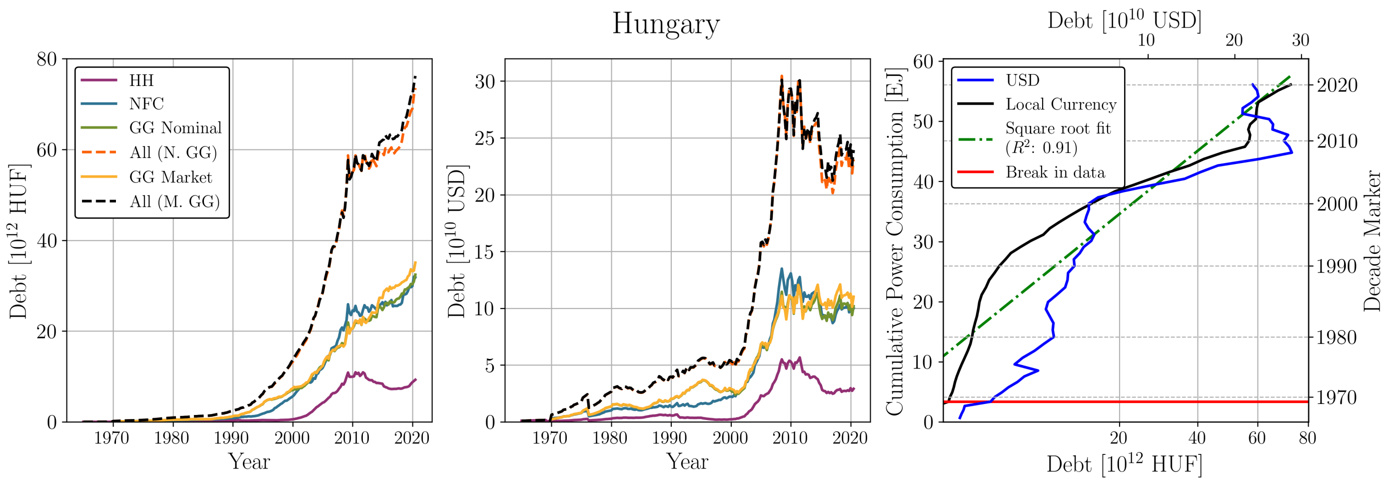

Figure A22. Hungary BIS debt time series and cumulative power consumption vs. debt.

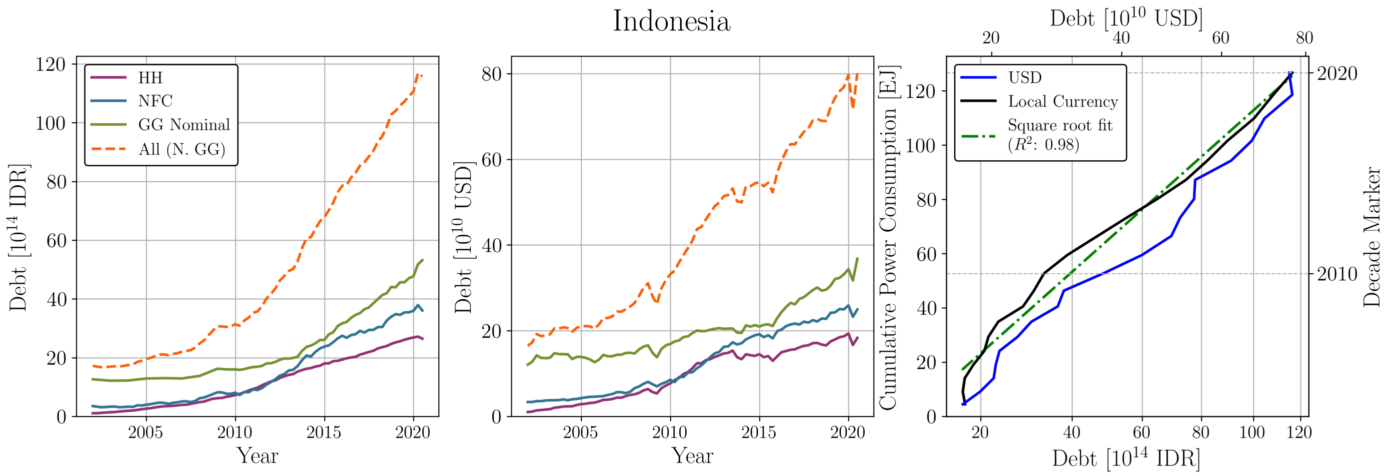

Figure A23. Indonesia BIS debt time series and cumulative power consumption vs. debt.

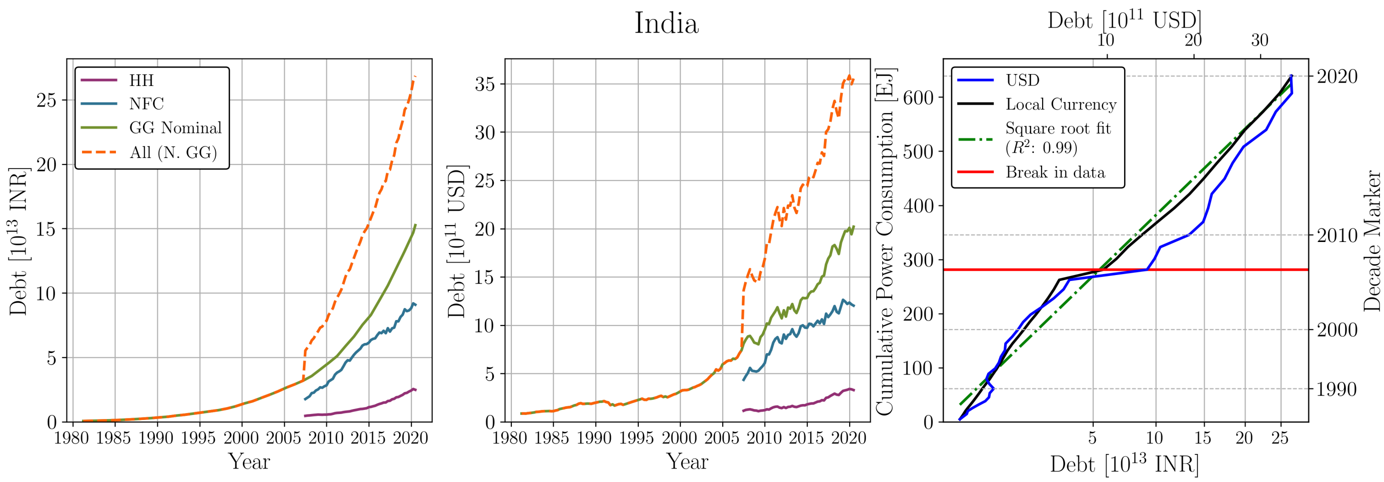

Figure A24. India BIS debt time series and cumulative power consumption vs. debt.

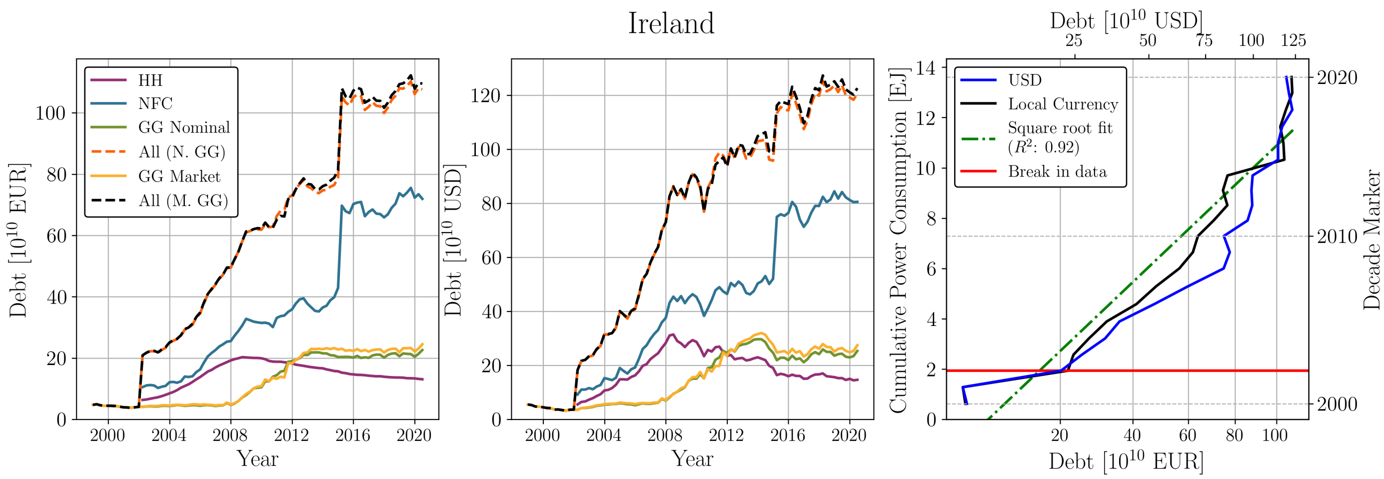

Figure A25. Ireland BIS debt time series and cumulative power consumption vs. debt.

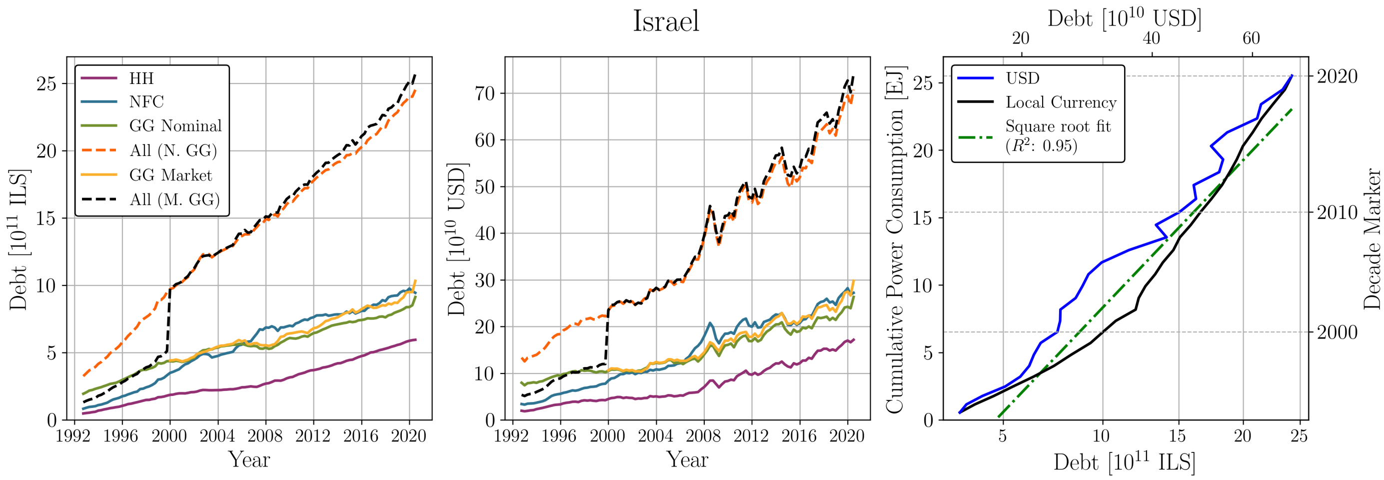

Figure A26. Israel BIS debt time series and cumulative power consumption vs. debt.

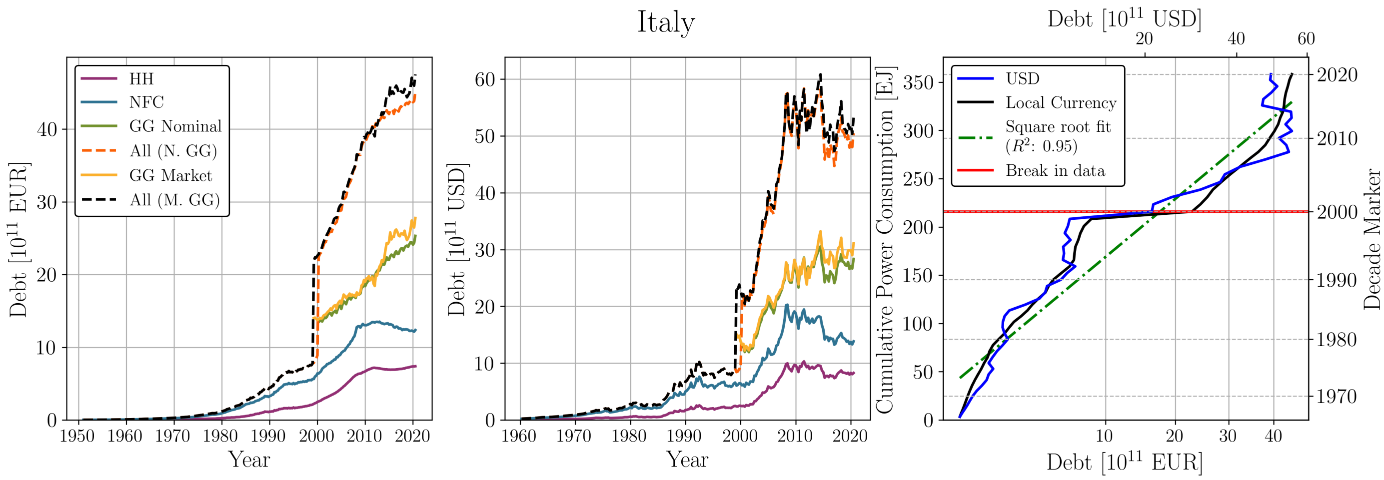

Figure A27. Italy BIS debt time series and cumulative power consumption vs. debt.

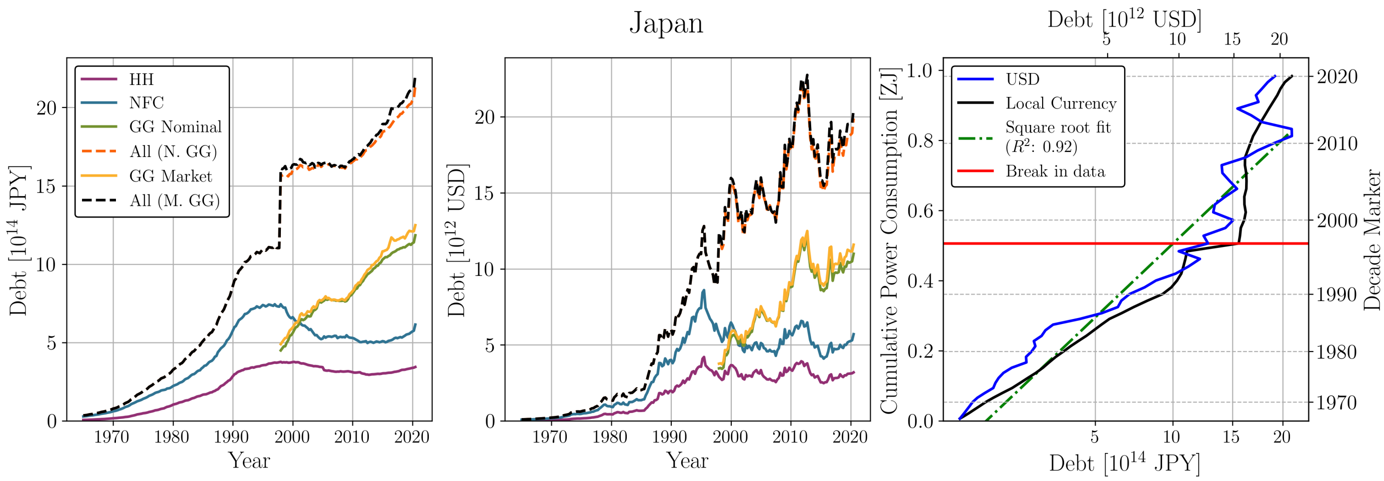

Figure A28. Japan BIS debt time series and cumulative power consumption vs. debt.

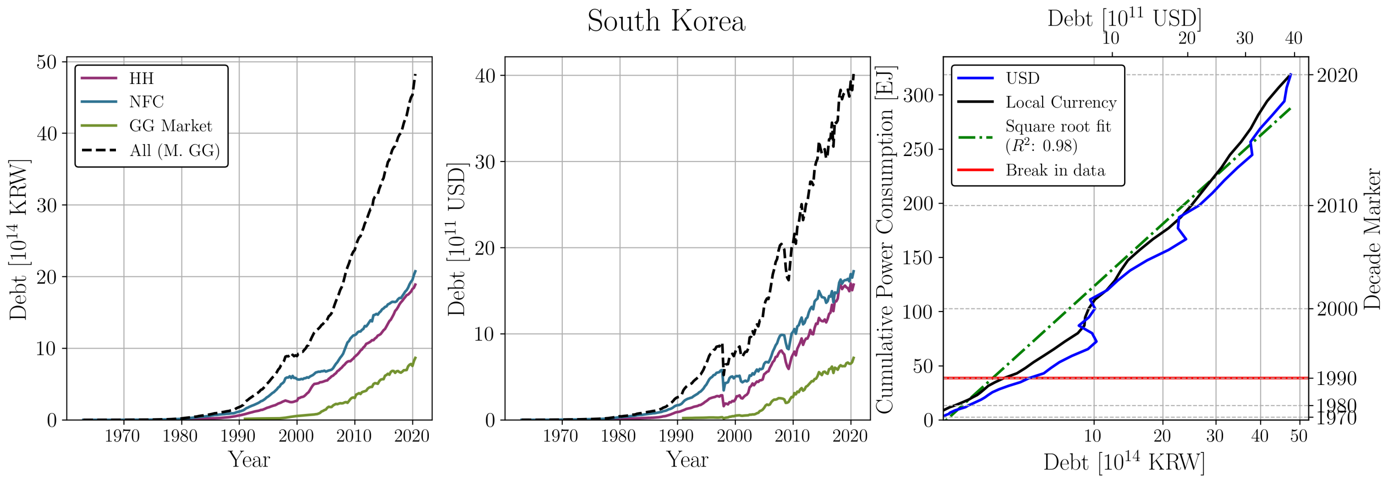

Figure A29. South Korea BIS debt time series and cumulative power consumption vs. debt.

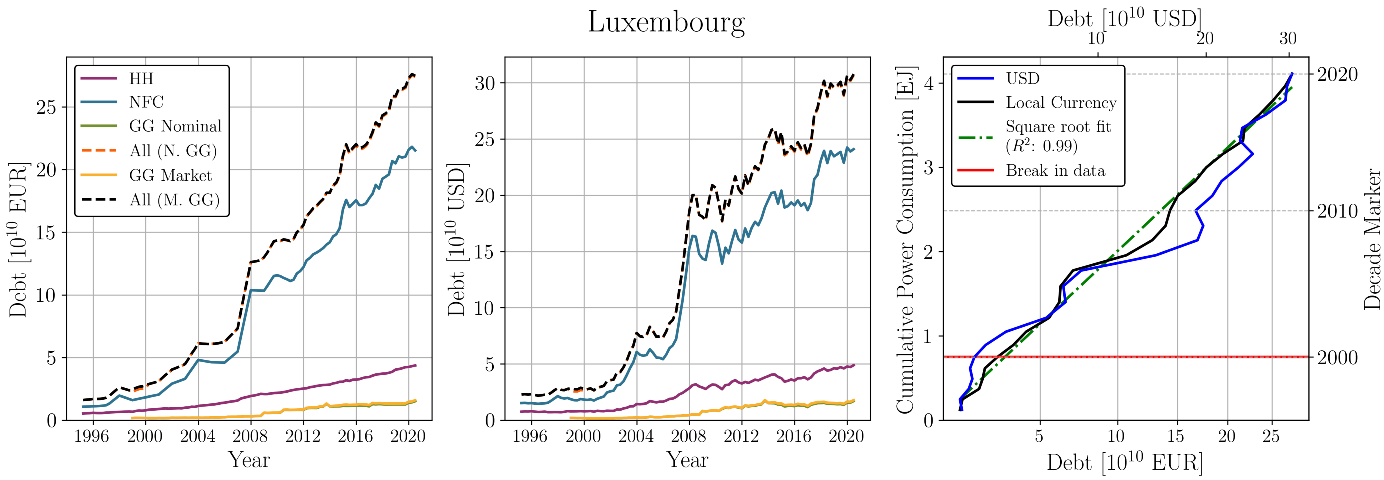

Figure A30. Luxembourg BIS debt time series and cumulative power consumption vs. debt.

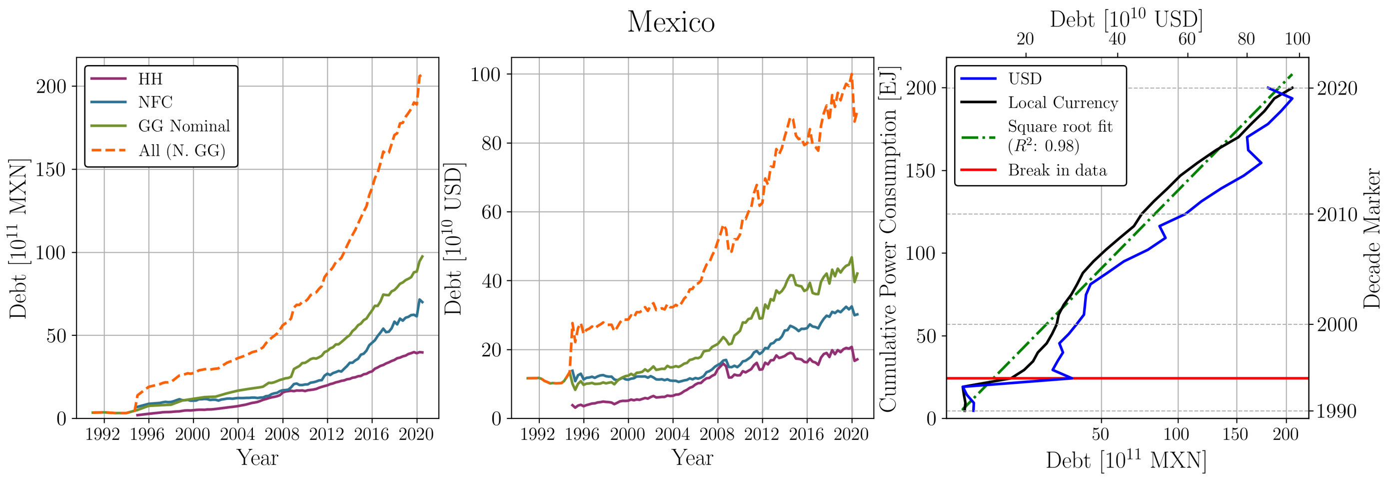

Figure A31. Mexico BIS debt time series and cumulative power consumption vs. debt.

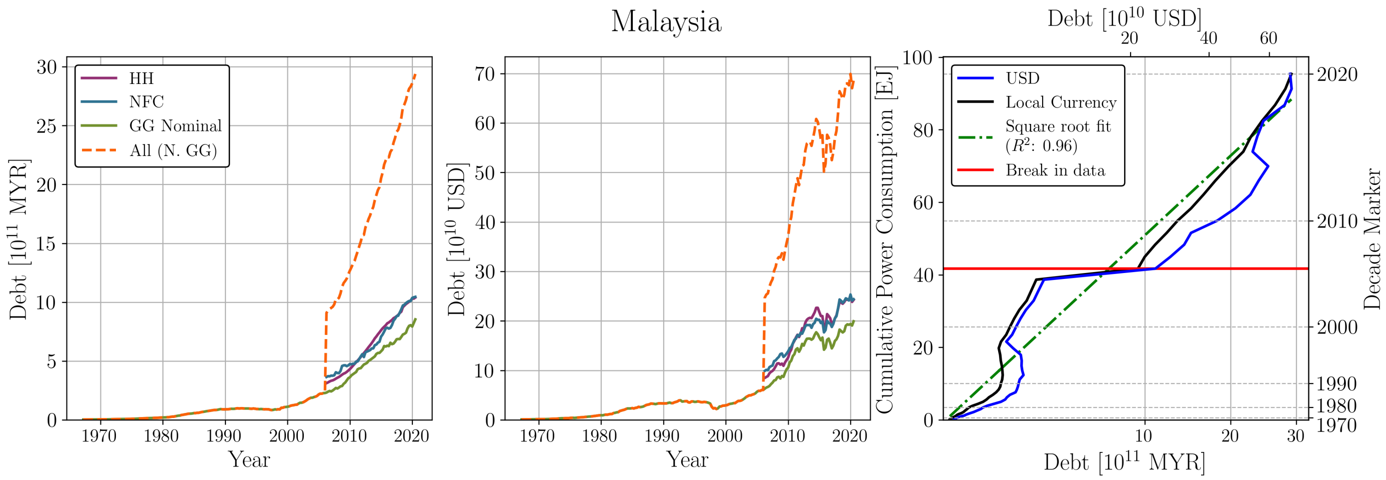

Figure A32. Malaysia BIS debt time series and cumulative power consumption vs. debt.

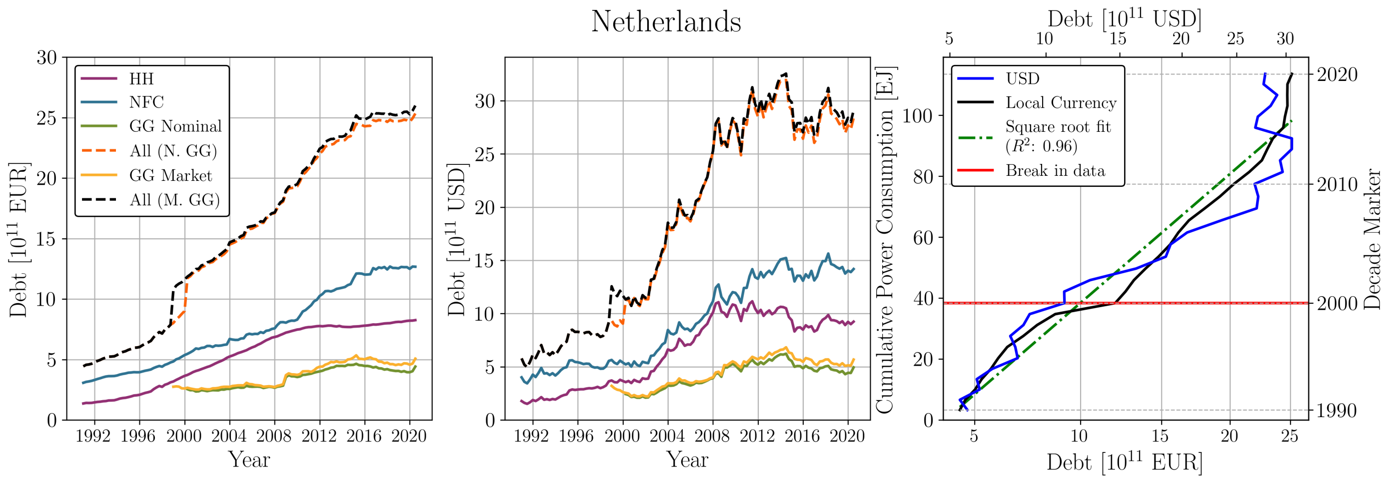

Figure A33. Netherlands BIS debt time series and cumulative power consumption vs. debt.

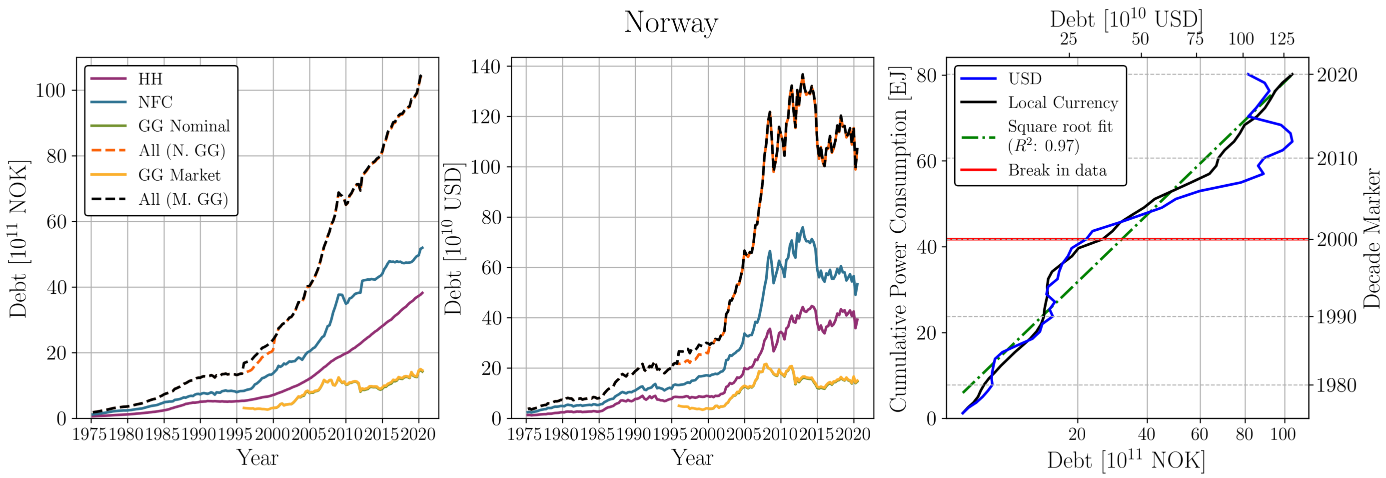

Figure A34. Norway BIS debt time series and cumulative power consumption vs. debt.

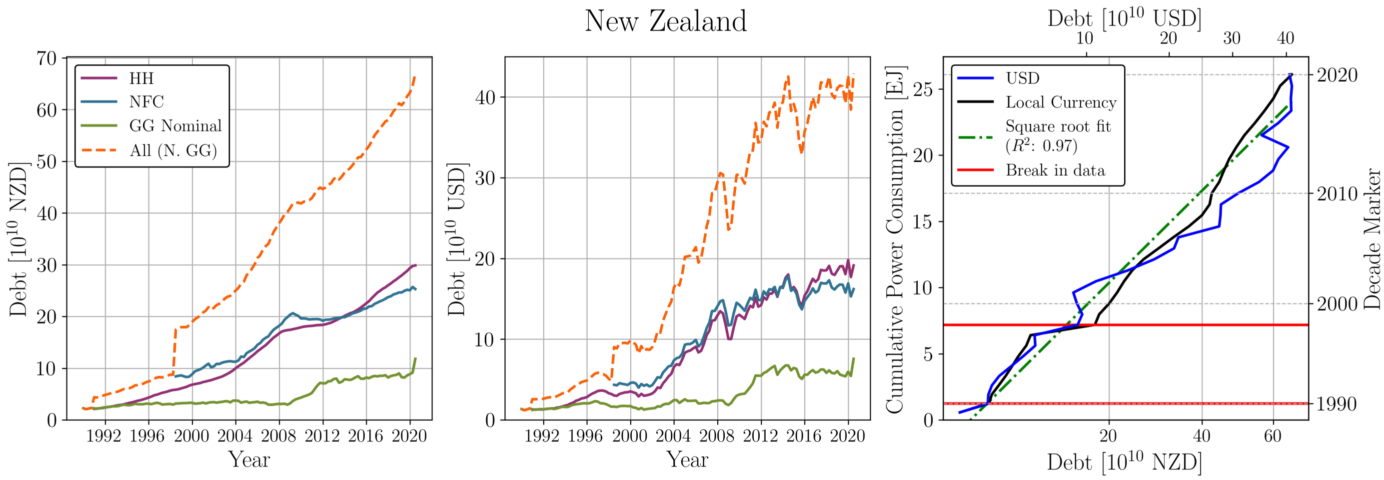

Figure A35. New Zealand BIS debt time series and cumulative power consumption vs. debt.

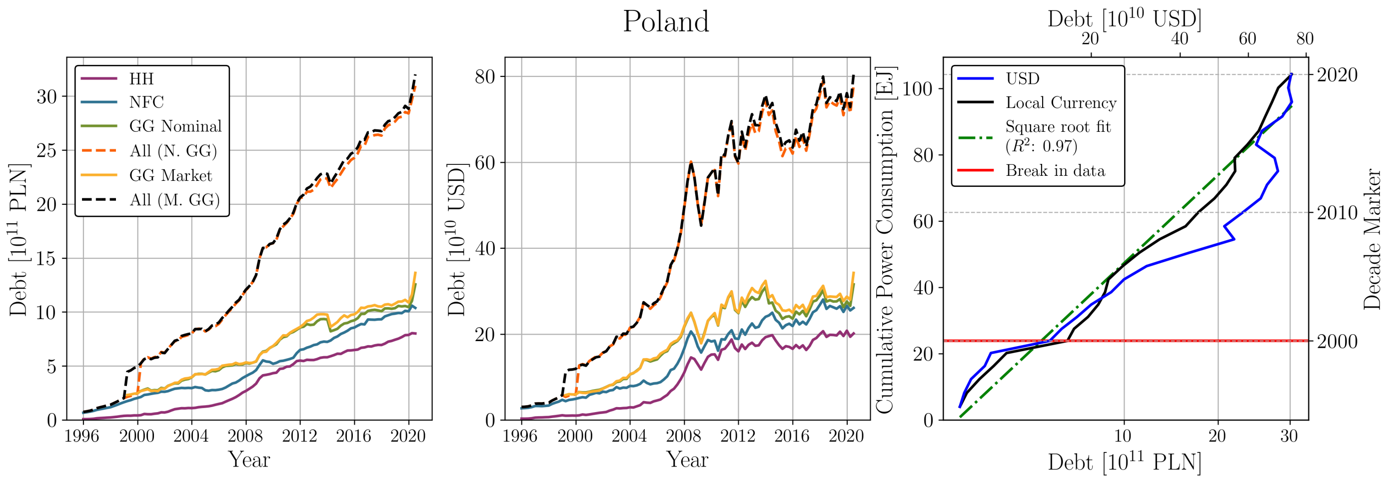

Figure A36. Poland BIS debt time series and cumulative power consumption vs. debt.

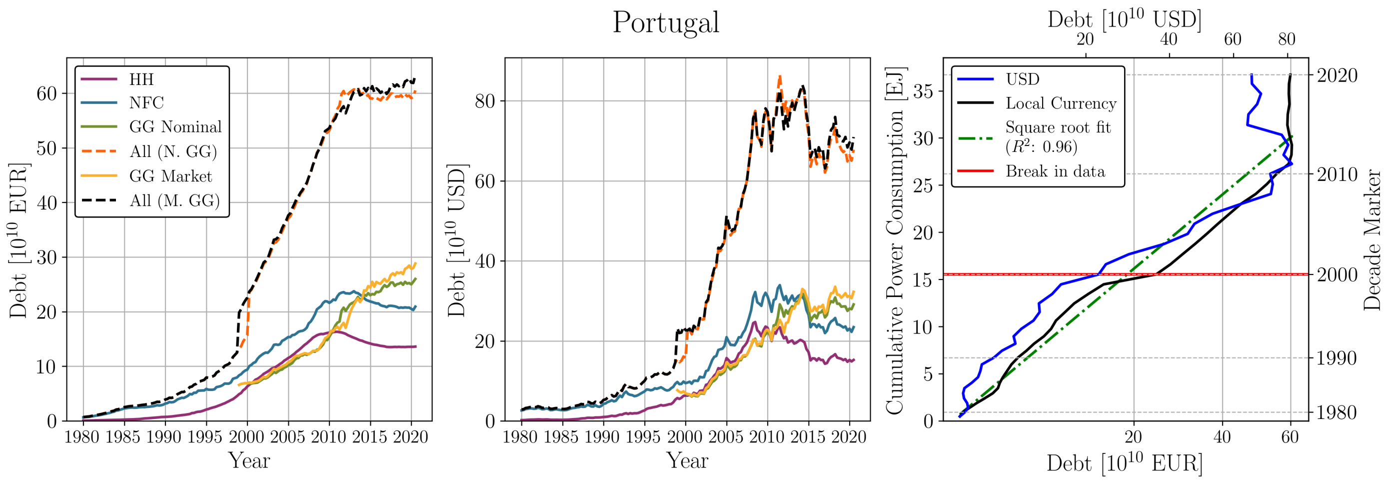

Figure A37. Portugal BIS debt time series and cumulative power consumption vs. debt.

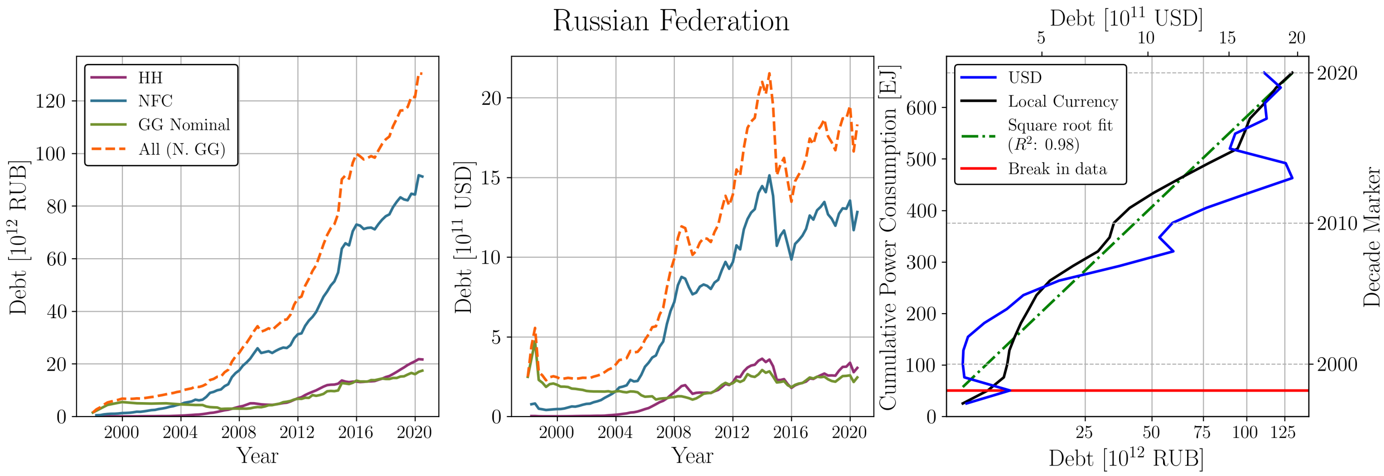

Figure A38. Russian Federation BIS debt time series and cumulative power consumption vs. debt.

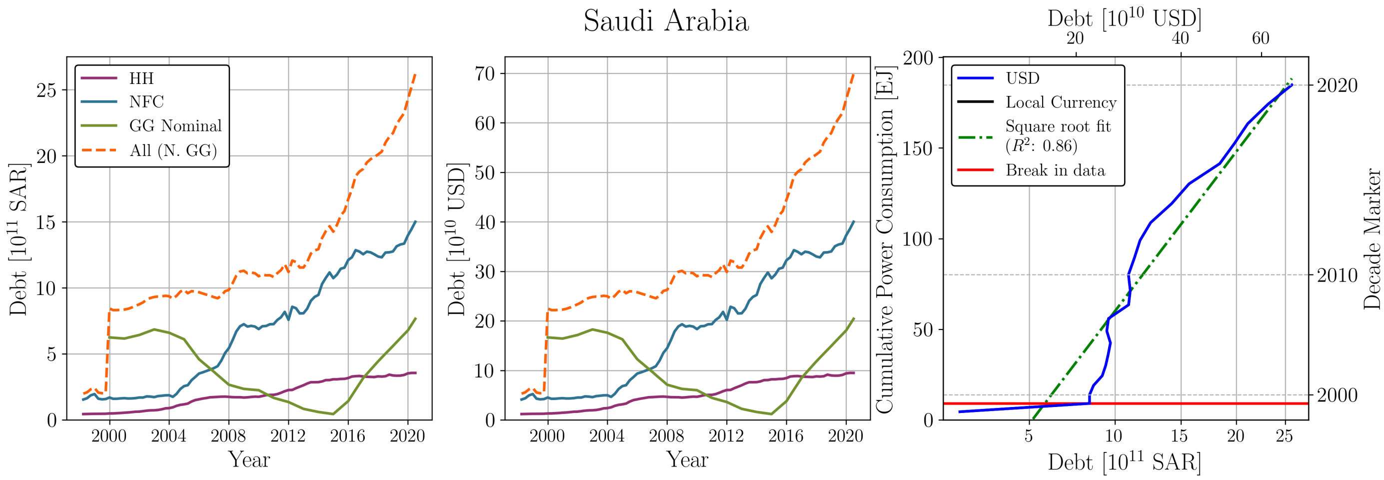

Figure A39. Saudi Arabia BIS debt time series and cumulative power consumption vs. debt.

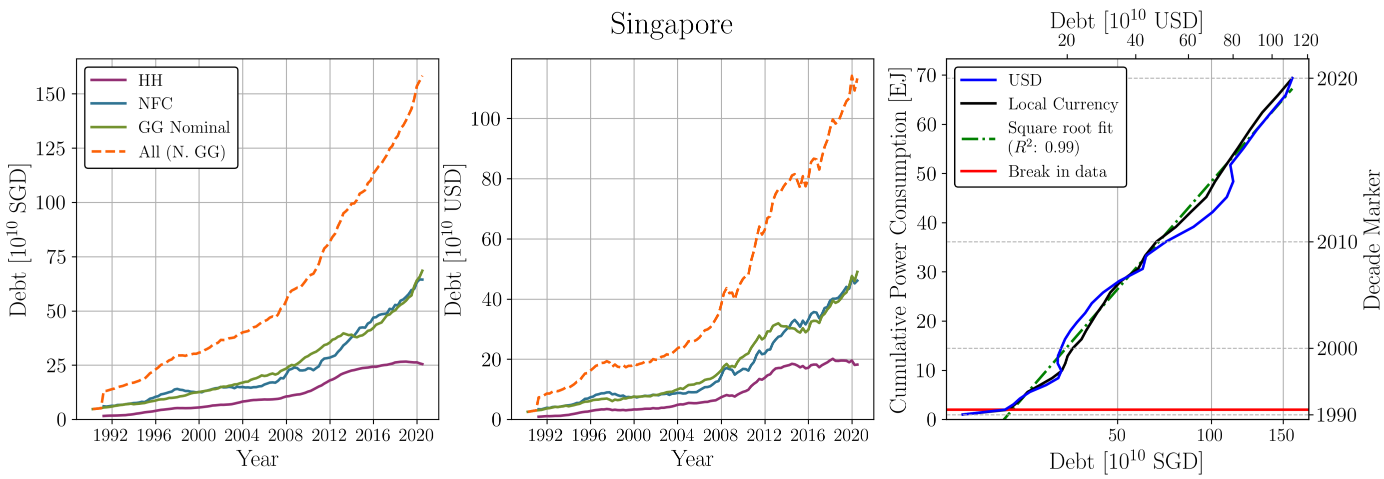

Figure A40. Singapore BIS debt time series and cumulative power consumption vs. debt.

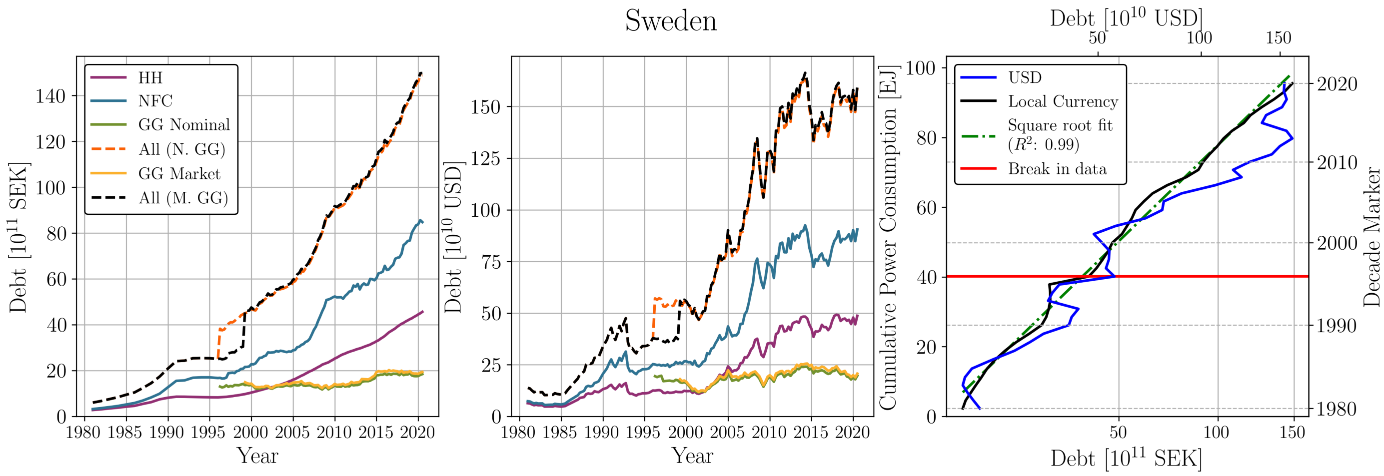

Figure A41. Sweden BIS debt time series and cumulative power consumption vs. debt.

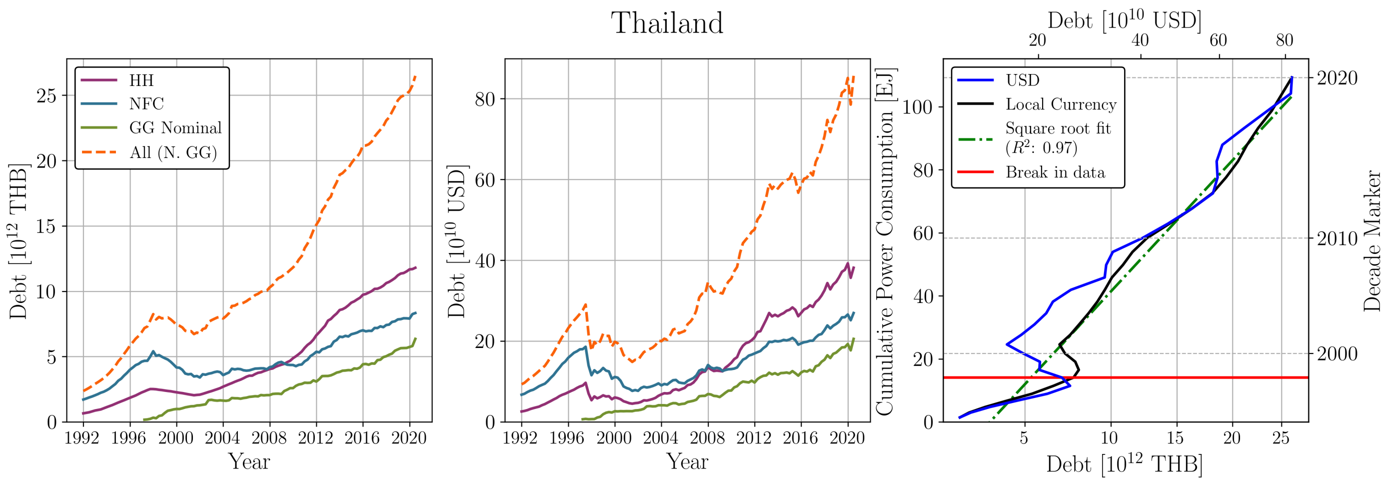

Figure A42. Thailand BIS debt time series and cumulative power consumption vs. debt.

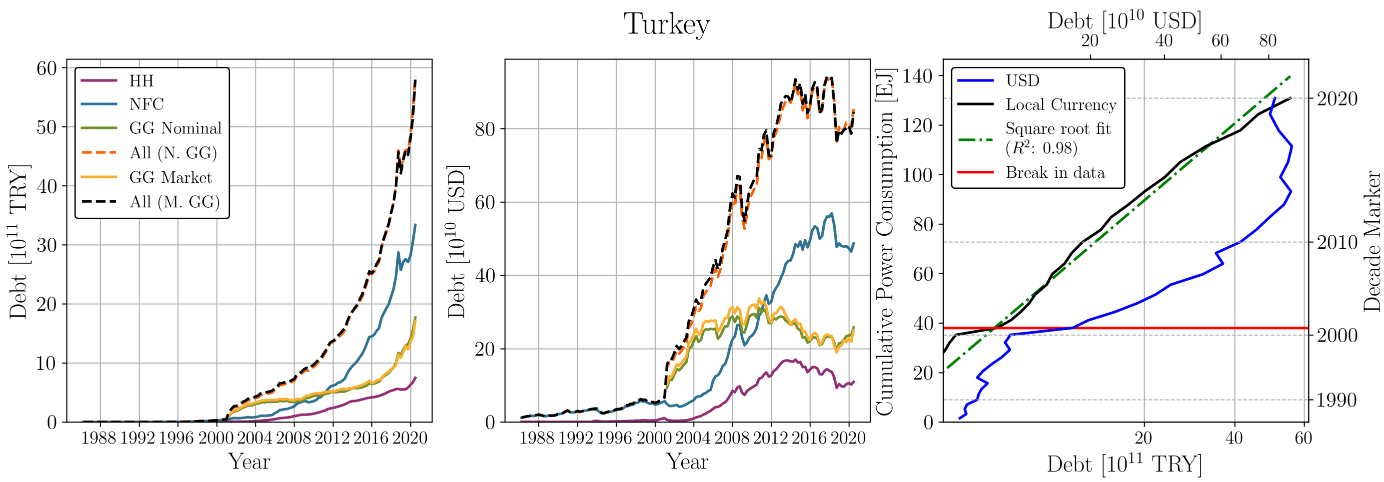

Figure A43. Turkey BIS debt time series and cumulative power consumption vs. debt.

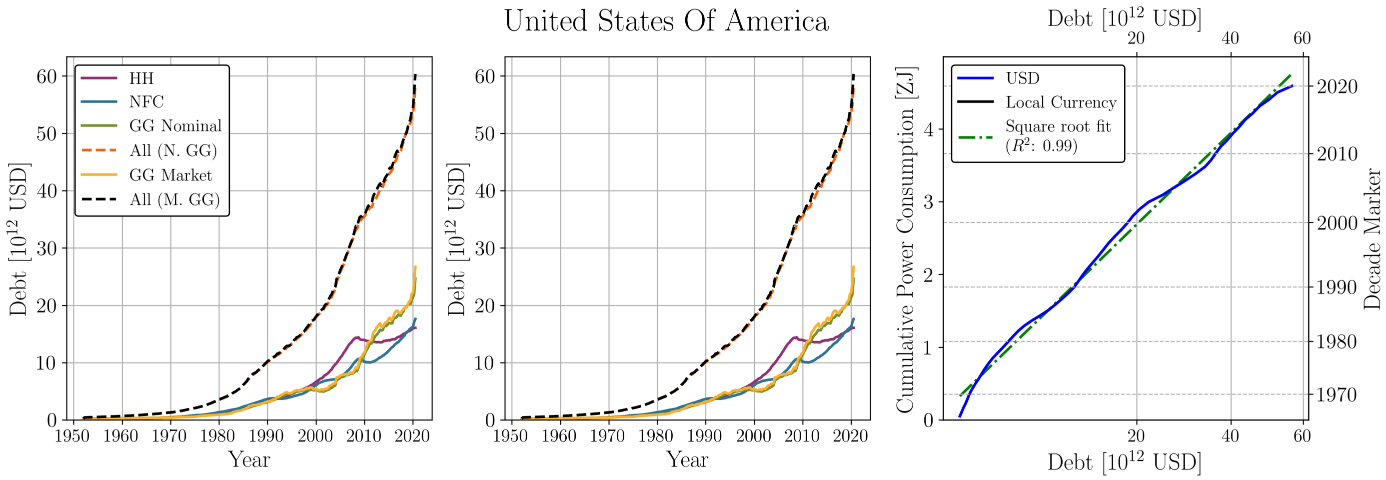

Figure A44. United States of America BIS debt time series and cumulative power consumption vs. debt.

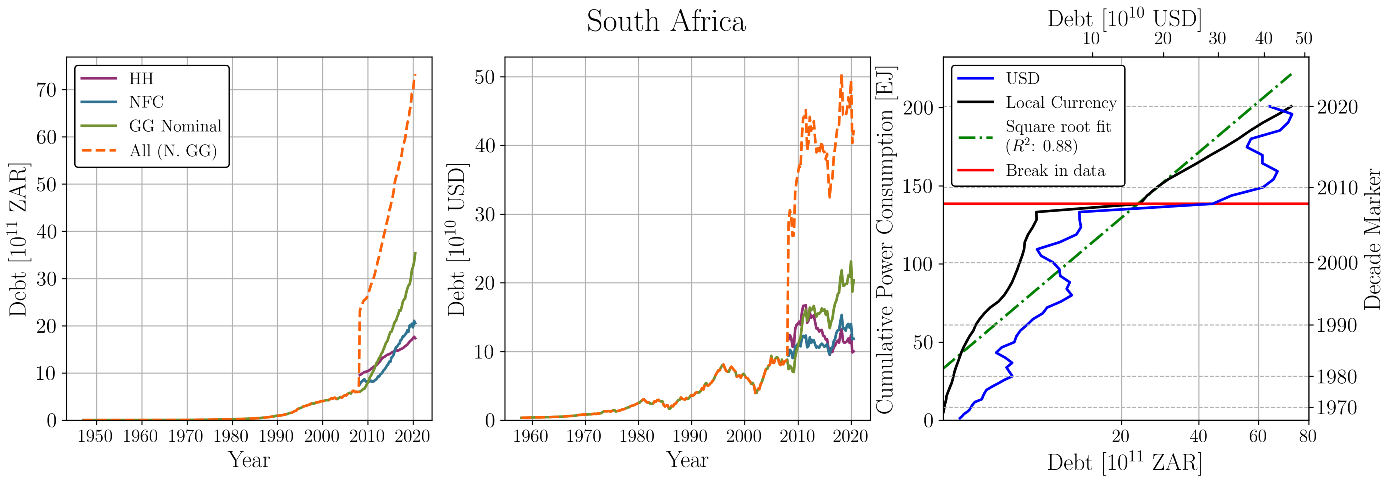

Figure A45. South Africa BIS debt time series and cumulative power consumption vs. debt.

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