Philosophy of Science and Ethics Course Essay
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Good by being Complex?
How to Consider the Intrinsic Value of Complexity within a System, using Energy Transition as an Example

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1 Introduction

God died in the 19th century, but the earthly heaven promised by many thinkers then, left or right, never bore fruit. Instead, we humans now find ourselves in a self-induced existential crisis that might destroy the Earth system which our prosperity is based upon. Young students fought for a better world in the 1960s; today they fight for a mere chance of continual survival. Something must have gone wrong in the last century, to put it mildly.

Perhaps it was the economists, who for long focused too much on economic efficiency at equilibrium and never fully embraced the complex interactions and long-term dynamics within society. Perhaps it was the engineers, who for long regarded their capability in STEM as a certificate to look down upon other fields of studies[1]. Perhaps people in other fields also played their parts. The cold fact remains: humanity failed in the past, and we are still far away from fixing the failure. Why is this the case?

Some philosophers and environmentalists tell us it is perhaps because our ethics have long been built upon the assumption that humanity should be the only concern, as noted in [1][2]. But what alternative is possible, then? In the course material, [3] provided 3 options to formulate a non-anthropocentric value theory:

1. Return to theology-based ethics.
2. Consider "holistic rationalism" and claim that from the perspective of the universe, there exist something that is objectively good.
3. Base the intrinsic values of non-human natural entities upon psychological grounds: a certain type of entity has intrinsic values only when humanity has moral sentiments towards it, however once such sentiments are established, the value of the natural entity is no longer just the instrumental utility it can bring towards humanity.

Resurrecting God from their tomb to the foundations of ethics is of course incompatible with the scientific progress humanity has gained in the past few centuries, while [3] considered neither hedonic utilitarianism and holistic rationalism good candidates for the foundation of a non-anthropocentric value theory. The author of [3] therefore advocated for the third option as the foundation of his non-anthropocentric value theory.

In this essay I will instead attempt to combine holistic rationalism with utilitarianism to construct a non-anthropocentric value theory. At the core of this value theory is the presupposition that there is intrinsic value within complex phenomena; i.e., for any structure in the universe, the fact of it being complex along brings value.

This essay will be structured as the follows. In section 2, I will formulate this concept in a precise manner and integrate complexity into the utility functional. In section 3, I will elaborate why and how a scale of preference should be chosen in the calculation of complexity. Finally, in section 4, I will demonstrate how to apply this framework, using energy transition as an example.

[1]The main reason I specifically mention economists and engineers here is because I came from an engineering background and I am currently working in a department where almost all that my colleagues discuss is efficient power market designs. Needless to say, my personal experience serves as anecdotal evidence at best, and the rhetorical sentences here are not intended to be robust cause-and-effect statements.

2 Abstract concept formulation

2.1 The utility functional

Let $\mathcal{X}$ be the set of all fundamental substances that have and will ever have existed in the universe. $\forall x \in \mathcal{X}$, let $\theta(x)$ be the set of all fundamental properties of x, of which one will be particularly important for our later discussion: $r(x)$, the coordinate of x on the space-time manifold $\mathcal{M}$ of the universe. Each element in $\mathcal{X}$ that occupies a unique coordinate on $\mathcal{M}$ will be considered a unique element in $\mathcal{X}$. Conversely, no 2 elements in $\mathcal{X}$ should share the same coordinate on $\mathcal{M}$.

Let $P(\mathcal{X})$ be the power set of $\mathcal{X}$. We now choose some of the elements in $P(\mathcal{X})$ and name it the set of all sentient beings, $\mathcal{S}$. $\mathcal{S}$ should have the following properties:

1. Every $s \in \mathcal{S}$ should be mutually exclusive to one another. That is, $\forall\, s_i, s_j \in \mathcal{S}$, $s_i \cap s_j = \emptyset$.

2. $\forall s \in \mathcal{S}$, the elements within s should be close enough to each other on $\mathcal{M}$ such that s can be reasonably considered as a continuum on $\mathcal{M}$. They should also form close and complex relations with each other; in particular, the capability to perceive and feel distinguishes s from any other element in $P(\mathcal{X})$.

3. Elements in s should trace out a finite amount of worldlines, and each of them belongs to exactly 1 of such worldlines.

For convenience, we henceforth use $s(t)$ to represents all $x \in s \in \mathcal{S}$, such that the temporal component of $r(x)$ is t. Likewise, we will use $p(t)$ to represent all $x \in p \in P(\mathcal{X})$ that have the same property.

Let $\mathcal{R}$ be the set of all logically possible relations between 2 elements in $P(\mathcal{X})$, and let $P(\mathcal{R})$ be the power set of $\mathcal{R}$. We now define a mapping $\rho : (p_1(t), p_2(t)) \mapsto \Gamma$ that encrypts all logically possible relations, $\Gamma \in P(\mathcal{R})$, $p_1(t)$ can have with $p_2(t)$. We will not assume ρ to be commutative, so the order of $p_1(t)$ and $p_2(t)$ matters[2].

With ρ, we can construct the utility function as:

$$u : (s(t), p(t), \gamma) \mapsto o \tag{1}$$

Here γ belongs to $\rho(s(t), p(t))$ and o is an ordinal number. For convenience, we henceforth use $u_i(\cdot)$ to denote $u(s_i(t), p(t), \gamma)$ and $\gamma(s(t), p(t))$ the set of relations $s(t)$ actually have with $p(t)$.

The traditional utility functional of the universe can now be written as

$$\mathcal{U} : (u_1, u_2, u_3, ...) \mapsto o \tag{2}$$

which maps utility functions u_i onto an ordinal number o.

A note on why we are calling $\mathcal{U}$ the utility *functional* in this essay. While one obvious reason is that we can differentiate between $\mathcal{U}$ of the universe and u_i of each sentient being by doing so, another more fundamental reason is that we wish to stress that $\mathcal{U}$ is acting on functions, that is, the domain of $\mathcal{U}$ is the span of the function spaces of u_i of each sentient being. Among all possible functions in this spanned space, moral theorists from the school of utilitarianism have traditionally taken those which represent the pleasure and suffering of sentient beings for the evaluation of $\mathcal{U}$. How to justify this choice metaethically is not the subject of this essay, and we will proceed by assuming u_i of each sentient being to be the same type of function that is considered by utilitarians traditionally, in a manner similar to how we assume complex phenomena have intrinsic values.

2.2 The utilitarian's optimization problem

Let us denote the spanned space of $\theta(x)$ for all $x \in \mathcal{X}$ as Θ. Natural laws of the universe will confine Θ into a plausible space $\mathcal{N}$. This will implicitly confine $\rho(p(t), p(t))$ for all physically possible pairs of $p(t)$[3].

Next, consider $\mathcal{A}$, a subset of $\mathcal{S}$, which we will call the set of all moral agents. In addition to any natural constraints, we can also impose moral constraints on the relations a moral agent a can choose to have with any $p(t)$. The resulting possible moral relations, $\rho^m(a(t), p(t))$, is obviously a subset of $\rho(a(t), p(t))$.

[2] For example, a person can own a laptop, but not the other way around.

[3] For example, it is currently impossible for humanity to consume the resources from Mars, although such relation between the two is not logically impossible and might therefore become physically possible in the future. Furthermore, since we construct the mapping ρ considering a pair of $p(t)$ one at a time, the situation where some types of resources cannot be consumed simultaneously by 2 entities is also dealt with here.

A deontologist will stop here and deem every $\gamma(a(t), p(t))$ in $\rho^m(a(t), p(t))$ as equally moral for a, whereas every $\gamma(a(t), p(t))$ outside $\rho^m(a(t), p(t))$ but within $\rho(a(t), p(t))$ as equally immoral. In contrast, a rule utilitarian, apart from the possibility of having a different set of $\rho^m(a(t), p(t))$ for $a(t)$, will go one step further and try to solve the following optimization problem:

$$\begin{aligned} \max \quad & \mathcal{U}(u_1, u_2, u_3, ...) \\ s.t. \quad & \Theta \in \mathcal{N} \\ & \gamma(a(t), p(t)) \in \rho^m(a(t), p(t)) \, \forall \, a(t), p(t) \end{aligned} \tag{3}$$

Optimization of $\mathcal{U}$ is possible even if there is no arithmetic rule to directly sum up all the ordinal numbers resulting from u_i. However, for the integration of complexity into the utilitarian calculus in the latter part of this essay, we need to confine u_i on a specific set of functions that map onto elements forming a mathematical field, where commutative addition and multiplication exist[4]. Therefore we will focus on u_i that maps onto the real numbers henceforth.

2.3 Complexity functions

As elaborated in [4], the complexity of a system at a given scale is the information required to describe the system at that scale. To properly proceed with this notion, let us construct a weighting function, $w(\cdot, r_0)$, at a certain point r_0 on the sub-manifold of $\mathcal{M}$ when the temporal component is held fixed, $\partial\mathcal{M}|_t$. w should have the following properties:

1. It is a continuous function over the entirety of $\partial\mathcal{M}|_t$.
2. It is unimodal, with global maximum at r_0.
3. Integrating it over $\partial\mathcal{M}|_t$ will result in 1.
4. There is a scale parameter λ for $w(\cdot, r_0)$ such that in the neighborhood of r_0 where $\partial\mathcal{M}|_t$ behaves like $\mathbf{R}^3$, $w(r - r_0, r_0; \lambda) = \frac{1}{\lambda} w(\frac{r-r_0}{\lambda}, r_0; 1)$.

With w, we can construct a smoothed field of fundamental property i, $\bar{\theta}_i(r)$ (assuming that the property can be measured with real numbers):

$$\bar{\theta}_i(r; \lambda) = \sum_{x \in \mathcal{X}} w(r, r(x); \lambda) \theta_i(x) \tag{4}$$

We now ask ourselves the following question: suppose we are to pick a random point r on the sub-manifold $\partial\mathcal{M}|_t$, how well can we guess the value of $\theta_i(r; \lambda)$ at r? Or equivalently, without any other a priori information, how much additional information is needed in order to tell the value of $\theta_i(r; \lambda)$ at r with 100% certainty? This naturally leads us to construct an entropy-like function for the quantification of complexity:

$$C\left(\theta_i(\lambda)\right) = -\int f_{\theta_i(\lambda)} \ln\left(f_{\theta_i(\lambda)}\right) d\theta_i(\lambda) + K \tag{5}$$

Here $f_{\theta_i(\lambda)}$ is the ensembled distribution function of the variable of $\theta_i(r, \lambda)$ at all possible positions r, and K a zero-point adjustment constant whose purpose will be made clear in section 4.1. While by the way we framed it, the construction of equation (5) might seem to be rooted in radical probabilism, it is not necessary so since the ensembled distribution function need not to represent a stochastic variable.

2.4 Integrating complexity into the utility functional

We are now in a position to integrate complexity into the utility functional, We first define the complexity-integrated utility functional at a certain scale λ, $\mathcal{U}(\lambda)$ as

$$\hat{\mathcal{U}}(\lambda) = \sum_i u_i \mathrm{w}(\lambda_i - \lambda) + \sum_j \alpha_j C\left(\theta_j(\lambda)\right) \tag{6}$$

Here $\mathrm{w}(\cdot)$ is a weighting function, λ_i the characteristic scale of sentient being i, α_j coefficients for considering the complexity of different properties in the system.

[4] The main reason behind this is because we will take weighted summations of u_i and complexity functions when integrating complexity into the utilitarian functional (see section 2.4). For some other rules of utilitarianism, the space of the maps can be more broader. For example, if egalitarian rule is adopted, then we only need to assume that ordinal numbers which the utility functions u_i and complexity functions map onto are comparable with each other, given some order-preserving transformation.

Base on equation (6), we can also construct the complexity-integrated utility functional of all scales:

$$\hat{\mathcal{U}} = \int \mathbf{W}(\lambda)\hat{\mathcal{U}}(\lambda)d\lambda \tag{7}$$

Equation (2) can be considered as a special case of equation (7); namely, the ordinary utility functional has $\alpha_j = 0$ for all j, a uniform weighting of $\mathrm{w}(\cdot)$ among the range of scales where sentient beings flourish, and a Dirac-delta distribution centered within that range for $\mathbf{W}(\cdot)$[5]. Conversely, we can also consider equation (7) a generalization of equation (2).

We can, in fact, argue further: utility functions of sentient beings and complexity functions of the properties of substances are, ultimately speaking, mappings that assign intrinsic values to certain configurations of substances and interactions in the universe. After all, what we regard as pleasure or suffering of a sentient being is nothing more than the complex interactions of neuron networks or processing units. Equation (7) is therefore describing a rule to assign a value to all the configurations of substances and interactions in the entire universe.

2.5 Is this actually non-anthropocentric?

Even with an extension of the utility functional, as human beings we of course will want to justify a greater emphasis on the utility functions of sentient beings (and in particular, human beings) within such a functional, the result of which we will discuss in section 3.2. Does this imply that our value theory is, after all, still anthropocentric? Indeed, any value theory we humans encountered so far has been developed by humans, based merely on the bounded rationality of human beings. Furthermore, all politics human beings formed up to this date are inherently anthropocentric, in which political power has been distributed exclusively among humans only. It is thus impossible for human beings to completely escape anthropocentric tendencies (which [5] called "perspectival anthropocentrism") when discussing intrinsic values of non-human beings, sentient or not.

The value theory we present here, however, has the important advantage of being non-discriminative against similar complex phenomena across the universe. While it is totally natural for people to cherish the prosperity of their own planetary communities, from the perspective of the universe there is no objective reasons to prefer one complex system of a planet over another, if their level of complexity are similar. Any value theory that prioritize a certain community above all under such a circumstance is, strictly speaking, a disguised form of patriotism (if not outright chauvinism). If we human beings were to survive the ongoing self-induced existential crisis and enter the interstellar community, planetary patriotism would be an obstacle for our integration with other (perhaps more sophisticated) civilizations.

Another important advantage of this value theory is that utility functions of sentient beings are now put into a broader spectrum of complex phenomena. Sure, we can (and probably will) argue that pleasure and sufferings of sentient beings should still be given some level of special treatment under this framework. But just as the intrinsic values of non-sentient beings depend on the complexity of their structures, the intrinsic values of the pleasure and suffering of sentient beings should also depend on the complexity of these feelings. The mechanism behind the pleasure and suffering of human beings is very complex (and therefore should be valued highly), while that of animals with simpler neuron systems is less so. At some critical threshold on the continuum, the complexity of non-sentient natural entities might have more values than the utility of a sentient being. This threshold is where, for instance, the preservation of the complexity of an ecosystem becomes more important than the well-beings of individuals of an invasive species. Conversely, if there happens to be phenomena that exhibit greater complexity than human mind to a certain extent (e.g. a highly-developed artificial general intelligence), we will have to admit that these phenomena should be valued similar (if not more) compared with the utility of human beings[6].

Therefore, our value theory not only no longer places Earth as the center of its moral consideration, it also does not regard the intrinsic values of the utility of sentient beings (humans or not) to be absolutely superior to those of the complexity of other natural entities. It is due to these 2 properties that we claim that this value theory is non-anthropocentric at its core, even if anthropocentric tendencies can never be eliminated during its formulation and actual application, as in the case of any other anthropogenic value theory.

[5] We can also set $\mathrm{w}(\cdot)$ to be Dirac-delta distributions and $\mathbf{W}(\cdot)$ a uniform distribution along a certain range of scales.

[6] This might sound like a perfect setting for a dystopian science fiction at first, but what we are arguing for is probably the best way to avoid such a dystopia; by granting artificial general intelligence (AGI) the same moral consideration as human beings, we can argue that they should be protected by the same basic rights humans enjoy, therefore no governments nor corporations may exploit these AGI for their own benefits against the overall society.

3 Caveat in application: scale of preference

3.1 The dilemma

Equation (7) itself is sufficient to define the complexity-integrated utilitarian's problem. However, we will run into trouble if it is applied under certain weighting functions of all possible scales. To see why, let us go for the extreme and choose a weighting function that favors complexity in the smallest meaningful scale for the scope of this essay, namely the scale of molecules. It becomes clear that equation (5) in this scale is just the usual definition of entropy in classical statistic mechanics.

Solving the complexity-integrated utilitarian's problem under such a weight function, we will arrive at the conclusion that a glass with 2 types of liquid mixed homogeneously within is somehow inherently "better" than the glass with the same amount of the 2 types of liquid stratified; in the latter case, with N molecules, we need at most $12N$ pieces of information to describe the system at the microscopic scale[7], where when the 2 types of liquid are mixed we need an additional piece of information for each molecule to identify which type of molecule it is.

This conclusion is in direct conflict with the conclusion one would derive from ecological economics. For example, Nicholas Georgescu-Roegen, an important contributor to the creation of the study of ecological economics, documented attempts to make a connection between entropy in thermodynamics and value in economics from his era, some of which claimed that economic value of materials came from their available energy [6] (which is negatively correlated which thermodynamic entropy). In another example, [7] argued for a "hierarchy of resource use" based on the (thermodynamic) entropy of matter and energy: human activities that increases the entropy of Earth system the least should be considered first before activities that increases entropy more is proven to be unavoidable. This implies that at least in the value theory behind ecological economics, complexity at the smallest scale is not only undesirable but even something human society should try to avoid.

3.2 The solution to the conflict

Fortunately, this conflict can be solved quite conveniently, if we view equation (7) as an analytic continuation of equation (2) along broader domains of $\mathrm{w}(\lambda)$, $\mathbf{W}(\lambda)$, and $\{\alpha\}$ (as mentioned in section 2.4). With this interpretation, the most natural $\mathbf{W}(\lambda)$ we should choose are ones whose value is greatest around the scale where most sentient beings flourish, λ^*, and decreases smoothly as λ deviates further away from λ^* (see figure 1).

It is easy to understand why this choice of $\mathbf{W}(\lambda)$ is the most natural: since (as far as we know) sentient beings capable of feeling pleasure and suffering seems to lie within a certain range of scale, and since we (as human beings) prefer our complexity-integrated utility functional to give emphasis on utility functions of sentient beings, giving the scale where most sentient beings flourish extra weight is a straight forward result. Meanwhile, beyond the characteristic scale of most sentient beings, there is no objective reason to prefer a specific scale of complexity, therefore $\mathbf{W}(\lambda)$ should be unimodal.

It should also be noted that in natural processes, complexity within one scale is usually negatively correlated with complexity within another scale. We can see why so if we return to our glass with 2 types of liquid. If we stratify the 2 types of liquid in the beginning, the 2 types of liquid will gradually mix with each other, until the liquid within the glass becomes homogeneous (at the macroscopic scale).

In the very beginning, we need 5 pieces of information to meaningfully describe the system at the macroscopic scale[8], but once the liquid is homogeneous, we no longer need to identify which type of liquid is on the top (at the bottom) nor the relative volume of the 2 types of liquid; there is now only one type of liquid in the glass (macroscopically speaking). This means that during the mixing process, complexity at the macroscopic scale decreases while that at the microscopic scale increases. Observing this empirical phenomena, along with the requirement that complexity at the scale where sentient beings flourish is more preferable, it is then natural to avoid an increase of complexity at the microscopic scale under most circumstances.

3.3 A word on the implication of a scale of preference

This scale of preference in considering complexity, apart from solving the conflict mentioned previously, can also provide us further insights to some modern political theories. For example, the core belief behind Jacques

[7]For each molecule, 3 pieces of information are needed to describe its position, 3 for velocity, 3 (at most) for its orientation, and 3 (at most) for its angular velocity.

[8]They are: pressure, temperature, volume of each type of liquid, and the relative position of the 2 types of liquid.

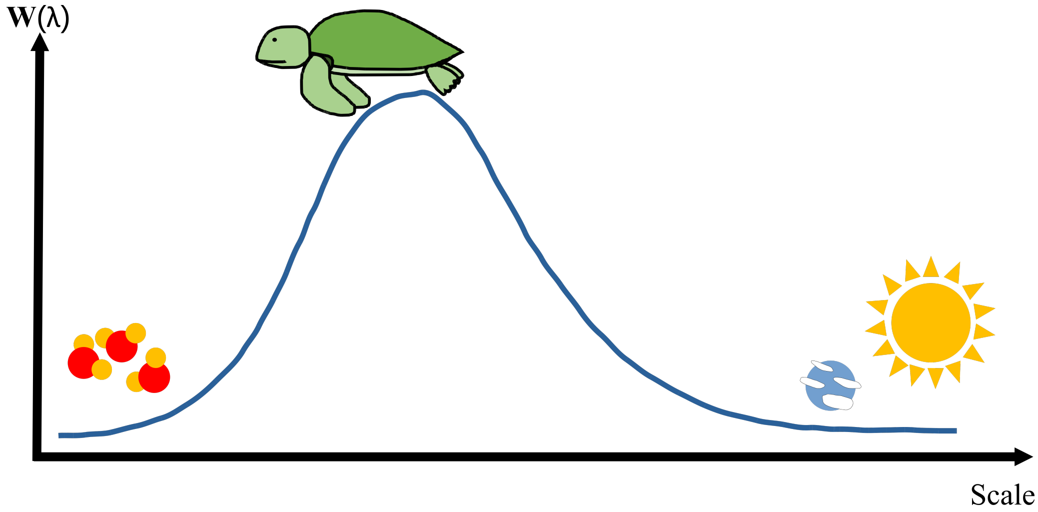

Figure 1: A schematic plot of $\mathbf{W}(\lambda)$ at different scales.

Rancière's notion of democracy, "equality is a presupposition, not a goal to be attained" [8], can be understood as a statement of the principle of maximum entropy (complexity) at the scale of moral agents capable of forming politics: the distribution of political power among these beings should not be given presupposed bias, and a uniform distribution is exactly what maximizes entropy in such context, given no *a priori* information.

The emphasis of complexity at the scale of sentient beings also gives us a counter-argument against authoritarian regimes who often claim that democracy is merely a product of western values, and that the world should tolerate a "diversity" of governance styles based on cultural differences: as pointed out in [9], an autocratic state could lead to less complexity in the society under it[9]. What this implies is that, apart from the obvious harm dictators incur on their subjects, if we pursuit a world where the complexity at the scale of the international level (regarding governance styles) is high, the complexity at the level of individual sentient beings might decrease in non-democratic countries.

Therefore, the dichotomy between the "right" of states to rule with different governance styles and the right of individuals to enjoy democracy (a common theme in the discussion of international laws [10][11]) is also a dichotomy between the complexity at the 2 scales. And if we gradually weight more on the complexity at the scale of the individual sentient beings and their local communities, we eventually rediscover the political tradition of anarchism at the end of the tunnel. It is therefore not surprising that many modern anarchists embed their political theories heavily on complex systems science [12][13]; in particular, the school of social ecology deals directly with the topic we are about to present in the next section [14], and hopefully our complexity analysis on different pathways in energy transition will provide some further insights on their arguments[10].

4 Specific application in energy transition

4.1 Complexity analysis of different energy transition pathways

Let us turn our attention now to a specific application of the above framework in energy transition. Suppose within a local community, there exists a microgrid where N households traditionally draw electricity from a diesel generator. Now there exist 2 options for the community to switch into a renewable-based system: a centralized pathway, where a single variable renewable energy power plant plus battery energy storage (VRE-BES) system supplies all of the electricity demand on the microgrid, and a decentralized pathway, where the centralized VRE-BES system is downsized and all the households install residential VRE-BES systems instead.

We quantify the complexity of this microgrid by the information needed to track down the power flows going from one end of the microgrid to another. Losses on the grid will be neglected, and it is only the starting (ending) nodes of the power flows we care about. This is probably the simplest way to quantify complexity for

[9] The fact that this was written by 2 Chinese scientists in the post COVID-19 era should be given extra credit for. Whether the authors were implicitly referring to their own nation when making the claim is of course irrelevant to our abstract discussion here.

[10] Interestingly, [14] provided some thoughts on the relation between complexity and human agency, something also highly relevant to this essay: "I am not saying that complexity necessarily yields subjectivity, merely that it is difficult to conceive of subjectivity without complexity, specifically the nervous system. Human beings, as active agents..., could not have achieved their present level of control over their environments without their extraordinary complex brains and nervous systems..."

the purpose of this essay[11].

Let us considered the centralized pathway first: at any given time, we know that the power consumed from every household must come from the centralized VRE-BES system. Therefore, the only information required to fully track down the starting (ending) nodes of the power flows is the demand profiles of the households. Given a joint probability distribution f_1 of the demand profiles D_i of household i, it is natural to quantify the complexity of the centralized pathway as the zero-point adjusted entropy of the probability distribution, $\hat{\mathbf{S}}[f_1]$:

$$\mathbf{S}[f_1] = -\int f_1(D_1, D_2, ..., D_N, S_0) \ln \left(f_1(D_1, D_2, ..., D_N, S_0))\right) \, dD_1 dD_2 ... dD_N \tag{8}$$

$$C_1 = \hat{\mathbf{S}}[f_1] = \mathbf{S}[f_1] + \int \mu_1(D_1, D_2, ..., D_N, S_0) \ln \left(\mu_1(D_1, D_2, ..., D_N, S_0)\right) \, dD_1 dD_2 ... dD_N \tag{9}$$

Here $\mu_1(D_1, D_2, ..., D_N, S_0)$ is a reference probability distribution that can allow us to define the "ground state" distribution on the domain $(D_1, D_2, ..., D_N, S_0)$. It should be chosen so that for any realistic probability distribution f_1, the value of $\hat{\mathbf{S}}[f_1]$ is always non-negative[12]. Furthermore, We denote the maximum available power output profile from the centralized VRE-BES system as S_0; it is needed to determine the operation of the battery within the VRE-BES system.

Now let us consider the decentralized pathway; things start to become much more complex when more power suppliers enter the picture. To begin with, we now need to consider the supply side in the the joint probability distribution, the entropy of which therefore becomes:

$$\hat{\mathbf{S}}[f_2] = -\int f_2(D, S) \ln \left(f_2(D, S)\right) \, dDdS + \int \mu_1(D)\mu_2(S) \ln \left(\mu_1(D)\mu_2(S)\right) \, dDdS \tag{10}$$

Here D represents $D_1, D_2, ..., D_N, S_0$ and S represents $S_1, S_2, ..., S_N$, the maximum available power output profile from household 1, 2, ..., N. Again, $\mu_2(S)$ is a reference probability distribution for the definition a ground state distribution in the domain S, such that $\hat{\mathbf{S}}[f_2(S|D)] = -\int f_2(S|D) \ln \left(f_2(S|D)\right) dS + \int \mu_2(S) \ln \left(\mu_2(S)\right) dS$ is non-negative for any reasonable $f_2(S|D)$. Observe that $\hat{\mathbf{S}}[f_2]$ will be greater than $\hat{\mathbf{S}}[f_1]$ for any reasonable case, since

$$\begin{aligned}
\hat{\mathbf{S}}[f_2] &= -\int f_2(D, S) \ln \left(f_2(D, S)\right) \, dDdS \\
&\quad + \int \mu_1(D)\mu_2(S) \ln \left(\mu_1(D)\mu_2(S)\right) \, dDdS \\
&= -\int f_2(S|D) f_1(D) \ln \left(f_2(S|D) f_1(D)\right) \, dSdD \\
&\quad + \int \mu_1(D)\mu_2(S) \ln \left(\mu_1(D)\mu_2(S)\right) \, dDdS \\
&= \int \left(-\int f_2(S|D) \ln \left(f_2(S|D)\right) \, dS\right) f_1(D) \, dD - \int \left(\int f_2(S|D) \, dS\right) f_1(D) \ln \left(f_1(D)\right) \, dD \\
&\quad + \int \left(\int \mu_2(S) \ln \left(\mu_2(S)\right) \, dS\right) \mu_1(D) \, dD + \int \left(\int \mu_2(S) \, dS\right) \mu_1(D) \ln \left(\mu_1(D)\right) \, dD \\
&= \int \left(-\int f_2(S|D) \ln \left(f_2(S|D)\right) \, dS + \int \mu_2(S) \ln \left(\mu_2(S)\right) \, dS\right) f_1(D) \, dD \\
&\quad + \int \left(-f_1(D) \ln \left(f_1(D)\right) + \mu_1(D) \ln \left(\mu_1(D)\right)\right) \, dD \\
&= \mathbf{E}_D \left[\hat{\mathbf{S}}[f_2(S|D)]\right] + \hat{\mathbf{S}}[f_1] \\
&\geq \hat{\mathbf{S}}[f_1]
\end{aligned} \tag{11}$$

Here $\mathbf{E}_D \left[\hat{\mathbf{S}}[f_2(S|D)]\right]$ is the expected value of $\hat{\mathbf{S}}[f_2(S|D)$ over the probability distribution of D. Note that we assume the probability density functions in equation (11) are all well-behaved and the multiple integrals are

[11] For example, we can discuss the power flows on the lines instead, but then we will need to take into account the topology of the microgrid, and given a fixed topology and reasonable boundary conditions, identifying the power flows on the lines is equivalent to identifying the power sources (sinks) at the nodes.

[12] This can be achieved by choosing a μ_1 that is "narrow" enough. For example, if we know that the variance of f_1 is at least σ^2, than we can choose μ_1 such that its variance is much smaller. While this construction seems arbitrary, μ_1 can be interpreted as the probability distribution function for the measurement error of the variable; since we cannot reliably acquire data whose variance is smaller than the variance of the measurement error, under this interpretation μ_1 naturally sets the lower bound of the entropy of the measured variable. We can also interpret μ_1 as the probability distribution function for uncertainties of the variable resulting from random fluctuations at smaller scales, if we wish to avoid any tendencies towards scientific anti-realism in our argument.

integrated over an appropriate domain (namely the support of the probability density functions), such that Fubini's theorem holds (therefore integrating the integrals iteratively is allowed).

But the demand and supply profiles themselves alone are not sufficient to determine the complexity of the system; every household (and the centralized VRE-BES system alike) now has the possibility to exchange power flows with multiple agents in the system. The households are nevertheless subject to physical laws of energy conservation:

$$D_i + \sum_j F_{ij} + B_i^{ch} = S_i + \sum_j F_{ji} + B_i^{dc} \tag{12}$$

Here F_{ij} is the power flowing from household or power plant i to household or power plant j, and B_i^{ch} (B_i^{dc}) the charge (discharge) of the BES system from household or power plant i. Since all of the variables in equation (12) are bounded physically[13], we can conclude that for any possible combinations of $(D_1, D_2, ..., D_N, S_0, S_1, ..., S_N)$, the feasible space of all the F_{ij}, $\Omega(D,S)$, has a finite volume[14]. We can thus quantify the complexity of the decentralized pathway as

$$C_2 = \hat{\mathbf{S}}[f_2] + \int f_2(D,S) \ln\left(\frac{|\Omega(D,S)|}{\sigma_F}\right) dDdS \geq \hat{\mathbf{S}}[f_2] \tag{13}$$

Here σ_F is the smallest plausible volume for $|\Omega(D,S)|$ in any realistic case. Obviously from equation (11) and (13), $C_2 \geq C_1$ for any realistic situation.

4.2 Implications in cost-benefit analysis of transition pathways

From section 4.1, it is clear that given similar conditions of electricity demand, the more distributed the supply sources are, the more complex the energy system may become; furthermore, the closer this complexity occurs at the scale of individuals, the greater it will be valued in the utility functional of equation (7). It is therefore not difficult to come to the conclusion that, in terms of the complexity of the energy system, decarbonization pathways that focuses mainly on large conventional power plants (e.g. fossil fuel power plants plus carbon capture or nuclear power plants) are less preferable than pathways focusing on renewable energy sources. In fact, we can argue that since the former have less disruptive effects on the complexity of the energy system at our scale of preference, their results can hardly be described as an actual transition.

Since under current techno-economic trends, betting on conventional power plants for decarbonization will probably result in higher economic costs anyway [15][16][15], the inclusion of complexity in the cost-benefit-analysis only makes pathways focusing on such technologies less appealing[16], compared with those leading to an actual transition in the energy system.

Complexity analysis is therefore more relevant when comparing transition pathways of different priorities of renewable energy deployment: should we choose pathways that focus more on transmission power networks, utility-scale battery energy storage systems (BESS), green hydrogen, offshore wind farms, and large ground-mounted photovoltaic (PV) power plants? Or should we prefer pathways that encourage more development on the distributed power networks, behind-the-meter BESS, local flexibility, and residential PV power plants?

While the 2 focuses are not mutually exclusive and we probably will have both on the agenda in most transition pathways, currently the focus seems to be more on the former, based primarily on techno-economic concerns [19][20]. Indeed, a more decentralized transition pathway may hinder the economies of scale per project and up-scaling at the device level, to which part of the success of renewable energy technologies have so far been attributed [21].

Yet as renewable energy sources, along with their complimentary technologies such as BESS and green hydrogen, continue to become cheaper and more mature, enabling greater social license of further deployment

[13]In addition, F_{ij} and F_{ji} are complementary (only 1 of them can be non-negative at the same time). Otherwise, we can always subtract or add both F_{ij} and F_{ji} with the absolute value of either variable, such that the complementary condition is achieved. In this process, equation (12) remains true.

[14]$\Omega(D,S)$ is a N^2-1 dimensional manifold embedded in a $N(N+1)$ dimensional vector space. It would be more satisfying to derive a closed-form expression for the value of $|\Omega(D,S)|$, if only I had more time!

[15][17] and [18] provided a comprehensive overview on how the potential of variable renewable energy sources had historically been underestimated in energy transition models and reports from influential institutions, and how wind and solar could easily dominate pathways based on techno-economic perspectives once such biases were corrected.

[16]The only exception to this argument is probably micro nuclear reactors, although one can reasonably question whether the benefits of allowing direct control over radioactive infrastructures by individuals and local communities outweigh the tremendous regulation and deployment costs associate with them, when other cheaper and more mature alternatives at this lowest level of the energy system already exist.

becomes a more important concern over oversimplified techno-economic calculations [22][23]. Coincidentally, transition pathways prioritizing distributed resources (and thereby leading to higher socio-technical complexity) are the ones that empower local communities and individual agents most directly [24][25].

Complexity analysis should thus be integrated in energy transition studies. Granted, people can study the complexity of different pathways during energy transition without acknowledging its intrinsic values, considering only the economic values complexity can ultimately bring. But from a pure utilitarian viewpoint, if the treatment of complexity becomes a presupposition in energy transition studies, it will be easier for people honoring complexity as part of our universe's moral compass to argue for such intrinsic values onward.

5 Summary and Final Remarks

In this essay, we have shown how to integrate complexity into the utilitarian's optimization problem. Since complexity of a system comes in different scales, it is necessary to choose a scale of preference when actually applying this framework of non-anthropocentric value theory. A real life example is then demonstrated, using energy transition as example. We see that transition pathways focusing more on decentralized resources will result in greater complexity in the energy system, and thus a cost-benefit analysis taking into account the intrinsic values of energy system complexity should tilt more in favor of decentralized pathways.

Still, there are many aspects we do not have the time and effort to discuss in this essay. For example, under the framework presented in this essay, only the utility and complexity functions at a given time slice is considered; how then, should we value the utility and complexity functions over time? Also, what properties of a system should we take into account when calculating its complexity in practice? In the examples we presented the answer seems to be straight forward, but we probably need a more sophisticated selection rule for general application.

The massive effort of discussing and applying a non-anthropocentric value theory, and the feeling of futility accompanied afterwards[17], reminds me of Nozomi in the anime *Sonny Boy* [26]. While all her other classmates gained fancy superpowers when drifted into another universe, the power she gained seemed useless in comparison: she was gifted the ability to see a source of mysterious light visible only to her; an ability useful for neither the survival at first nor the ordinary Isekai life afterwards.

Yet Nozomi always knew (with a leap of faith) that the light came from the actual exit of the Isekai, and in the end it was exactly her ability (immortalized as a compass pointing constantly toward a specific direction) that helped her friends to find their way back to reality. Perhaps this is the story that best describes the value of value theories for moral agents.

"There is no god, but let there still be light amongst the vast void of darkness, and let all moral agents thrive to find it." Thus says Plutarch Heavensbee[18] of our universe.

[17]After all, what energy economist will actually change their methodology just by reading this type of argument? Who will bother reading it in the first place anyway? An essay about utilitarianism that brings negligible utility and complexity to the universe, how ironic!

[18]The head gamemaker of the 75th hunger games in *Catching Fire* [27], the second book of the dystopian novel series *The Hunger Games*.

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