Modeling the Power Sector of Wonderland: an integrated system dynamics model to assess a sustainable regional development

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***Abstract*—In a modern world, energy poverty limits opportunities and widens the gap between the rich and the poor. Thus, a broad understanding of the underlying mechanisms that relate to the lack of energy access to the regional economy, demography, and environment is crucial for the deployment of interventions aimed to eradicate extreme poverty. Some mathematical models have been proposed to analyze the power sector's response to the growing energy demand and the increase in the number of distributed renewable energy generation units. However, they fail in assessing the impacts of such changes in a wider field of view, including the interactions between (a reliable) energy access and population growth, economic output, income, and the quality level of the environment. This work proposes a system dynamics model combining both perspectives that, by extending the Wonderland model and based on its equations and dynamics, permits the visual simulation of multiple regions and public policies or interventions. The proposed model is tested in a multi-country case study. In simulations, large time-scales were used to portray the effects of changes upon future generations.**

***Index Terms*—System dynamics, nonlinear systems, energy poverty, sustainable development, systems engineering**

I. Introduction

Energy poverty is a challenge often associated with the underdeveloped and developing regions of the world. Although the specific demographic, economic, and environmental conditions vary from country to country, the understanding of the main dynamics of this phenomena is key to drive endangered communities out of extreme poverty, once electricity is an important provision that enables public health, educational, commerce, agricultural, and industrial activities [1].

According to reference [2], there are over 1.3 billion people without electricity access globally, and there is strong evidence that some policies may contribute to alleviate this problem and improve energy access in outlying and mountainous regions [3]. These mainly consist of special motives given for applying energy-saving and energy-efficiency improvements [4]; a redesign of the allowance policy for heating oil in colder areas [5], and; incentives for the introduction of affordable distributed renewable energy generation and storage units [6].

Despite the existing efforts, a great portion of the energized households is still supplied by polluting energy sources, such as fossil fuels, which are limited and exhaustible. Fossil fuel depletion, global warming, and pollutant emissions are also relevant factors for sustainable development regarding energy systems. In this sense, the management of finite resources, including fossil fuels, should not be extracted at a faster rate than they can be redeposited by the environment [7].

Based on historical data and information available worldwide, the study of energy poverty and sustainable regional development has merited great attention recently, searching for solutions in the form of public policies and interventions. Some mathematical models have been proposed [8]–[10].

Reference [8] proposes a system dynamics model to project the energy supply facilities' response to growing energy demand, while [9] takes a similar approach to evaluate the impacts of integration of renewable energy sources on the operational efficiency of power systems. Reference [10] discusses a complex system dynamics analysis of the regional energy development in Australia, focused on solving the high oil dependency problem.

It is essential, though, to realize that these models are limited to the context of the power sector and fail to assess the impacts of energy poverty, growing demand, and the introduction of distributed renewable energy sources in a wider field of view, including some economic, demographic and environmental interactions.

Continuing the applications of system dynamics approaches in modeling real-world phenomena, some established models reflect on the interactions between economic, demographic, and environmental aspects: the World3 model of [11], and the Wonderland model of [12]. Both models can serve as a solid basis to start modeling energy poverty. The Wonderland of Sanderson et al. is a prominent one due to its small number of parameters and equations and relatively easy implementation and adaptability [13].

This document reports the combination of both aforementioned system dynamics approaches: the introduction of key energy poverty and energy sustainability concepts to the Wonderland model, constituting a didactic tool for the qualitative assessment of sustainable regional development. The proposed simulation framework permits the visual interpretation of the effects of several energy policies, such as investments in energy efficiency, distributed renewable sources, energy storage,

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and so on. Given the exposed context, the main contributions of this paper are now highlighted:

- the proposal of a didactic tool for a qualitative assessment of the sustainable regional development, considering some relevant aspects associated with the local economy, population, environment, and the power sector;
- the proposal of an extension to the existing Wonderland model;
- the possibility of visualizing the effects of several public policies or interventions and their respective impacts in a wider perspective;
- the use of larger time-scales to visualize the impacts of changes in future generations;

The remainder of this paper is organized as follows. Section II describe the original Wonderland model as well as some relevant extensions that have been published. The main assumptions and variables of the proposed model are summarized in Section III. Section IV details the simulation framework, study cases and describe the results, while Section V concludes the paper.

II. Wonderland Model

The original Wonderland model was first published by W. Sanderson in 1992 [12] as part of a study to propose and compare dynamical systems models of development, population, and the environment. It consists of a system of low-order differential equations with particular emphasis on economic growth and the stock of natural capital.

Originally, it was proposed in discrete time, but to investigate the dynamic stability of economic growth, the author later reformulated it to use continuous-time signals in [14]. Despite this change, the model behavior was kept similar to the original. The dynamic of Wonderland is characterized by four state variables:

$x(t)$: population;
$y(t)$: per capita economic output;
$z(t)$: stock of natural capital;
$p(t)$: pollution per unit of output;

For notational convenience, the arguments of x, y, z, and p are hereon omitted. The population and economic output variables can assume all non-negative real values ($x, y \in [0, \infty)$), while the stock of natural capital and the pollution per unit of output are confined to the unit interval ($z, p \in [0, 1]$).

The stock of natural capital z is also referred to as the quality of the environment. If the environment is not polluted at all, it approaches the unity value. It approaches zero as the environment gets polluted, threatening the population's health and the economy. Complimentarily, $p \approx 1$ represents the situation when there is maximum pollution per unit of output, and $p \approx 0$ implies no pollution per unit of output.

These four state variables evolve according to the following set of differential equations:

$$\frac{dx}{dt} = xn(y, z) \tag{1}$$

$$\frac{dy}{dt} = y\left[\gamma - (\gamma + \eta)(1 - z)^{\lambda}\right] \tag{2}$$

$$\frac{dz}{dt} = \nu z(1 - z)\left[-\frac{\omega f(x, y, z, p) - \delta z^{\rho}}{1 + \omega f(x, y, z, p) - \delta z^{\rho}}\right] \tag{3}$$

$$\frac{dp}{dt} = -\chi p \tag{4}$$

Finally, the model is complemented by the following set of algebraic equations.

$$n(y, z) = b(y, z) - d(y, z) \tag{5}$$

$$b(y, z) = \beta_1\left[\beta_2 - \frac{1}{2}\left(\frac{\beta i(y, z)}{1 + \beta i(y, z)}\right)\right] \tag{6}$$

$$d(y, z) = \alpha_1\left[\alpha_2 - \frac{1}{2}\left(\frac{\alpha i(y, z)}{1 + \alpha i(y, z)}\right)\right](1 + \alpha_3(1 - z)^{\upsilon}) \tag{7}$$

$$c(y, z) = \phi(1 - z)^{\mu} y \tag{8}$$

$$i(y, z) = y - c(y, z) \tag{9}$$

$$f(x, y, z, p) = pxy - \frac{\kappa}{2}\frac{\sigma c(y, z)x}{1 + \sigma c(y, z)x} \tag{10}$$

Equation (5) defines the population growth n as the difference between the crude birth and death rates (the ratio of births and deaths to 1.000 of population, respectively). As seen in eqs. (6) and (7), both crude birth and death rates decrease when the net per capita output i increases. The death rate also rises as the level of natural capital is diminished.

The net per capita output in eq. (9) is given by the subtraction of the government expenditure on pollution abatement c from the per capita economic output. This expenditure, as seen in eq (8), is determined by the level of natural capital and the per capita economic output.

The flow of pollutants f is the result of the impacts of economic activities, population size, and the state of the environment. The term pxy in eq. (10) corresponds to the I-PAT identity (see [15]), which states that the impact on natural resources and the environment is related to the size of the population, per capita output, and technologic level of the region, which refers to pollution generated per unit of output.

A special feature of wonderland is the fact that not all system variables evolve with the same velocity. Even with no stochastic, external shocks, the structure of the model is a mixture of slow and fast dynamics that can lead to unpredictable outcomes [16]. The environment variable z evolves much faster than x and y, and the rate of change is determined by the parameters ν for the variable z; β_1 and α_1 for the variable x and γ and η for the variable y.

All of the twenty parameters of this model in the continuous-time formulation can be subdivided into three sections:

- Population: $\beta_1, \beta_2, \beta, \alpha_1, \alpha_2, \alpha_3, \alpha, \nu$;
- Economy: γ, η, λ;
- Environment: $\kappa, \sigma, \delta, \rho, \omega, \upsilon, \phi, \mu, \chi$.

A. Environmental policy

The Wonderland model was further extended by [17] to include effects of environmental taxes that penalize the emission of pollutants. These taxes promote a decline in pollution per unit of output p, but also a negative effect on the economy as firms may invest their resources in technologies to reduce pollution. Mathematically, equations (2) and (4) become

$$\frac{dy}{dt} = y\left[\gamma - (\gamma+\eta)(1-z)^{\lambda} - \frac{\gamma_0 \tau}{1-\tau}\right] \tag{11}$$

and

$$\frac{dp}{dt} = -(1-\tau)\chi p \tag{12}$$

where τ is the rate of environmental taxes and γ_0 is the scale factor of the effect of taxes on per capita economic output.

B. A multi-country model

The original model considers the visualization of only one region of Wonderland at a time. Consider two separate regions A and B. The economic and environmental changes that may occur in them can be slowed or accelerated by their individual economic and environmental policies and their neighbors' simultaneously. Considering the inclusion of environmental taxes, eq. (2) referred to region A can be rewritten as

$$\frac{dy_A}{dt} = y_A\left[\gamma_A - \gamma_A^{adj} + \phi_{adj}\left(\gamma_B - \gamma_B^{adj}\right)\right] \tag{13}$$

with

$$\gamma_A^{adj} = (\gamma_A + \eta_A)(1-z_A)^{\lambda_A} - \frac{\gamma_{0A}\tau_A}{1-\tau_A}$$

where ϕ_{adj} ($0 \leq \phi_{adj} \leq 1$) characterizes the adjusted economic linkages between both regions. Equation (13) repeat its structure for region B.

Reference [18] also discusses the linkage between the environments of regions A and B, where an equation with similar structure to eq. (13) is proposed.

In this work, however, it is considered that both regions are geographically close to each other, and thus, share the same environment. In other words, the collapse of the environment may negatively affect all economies, population, and development, simultaneously.

The main benefit of a shared environment is the fact that it permits a balance between the activities of all regions, i.e., even if A is more pollutant than B, it is possible to maintain a high-quality level of the environment if B leads the efforts in promoting pollution abatement tecnologies and/or imposing environmental taxes to polluting business.

III. Overview of the Proposed Model

In this section, the system dynamics, equations, and the main assumptions of the model are presented. It is subdivided into four main parts, which are: (1) Economy, (2) Demography, (3) Environment, and the (4) Power Sector.

The Power sector of Wonderland aggregates information related to the region's capacity to satisfying the customer's electricity demand by producing energy from renewable and non-renewable sources. Some aspects related to the costs of energy production, system resiliency, efficiency, energy trade, and policies are also considered.

The Economy, Demography, and Environment sections are constituted by equations similar to the original ones in the Wonderland of reference [14].

Some specific changes to the mathematical equations are described in the next section, but the main assumptions of the proposed model can be summarized into two main topics: the effects of electricity access on population growth, and the importance of energy security for economic development and pollution abatement.

- *Demographic effects of energy access*

Fertility is declining at different speeds across almost all developing countries. The debate about the causes of that heterogeneity is typically a debate about whether family planning or economic development is more effective in triggering the fertility transition [19].

According to [20], the electrification of urban areas may play a role for both, since it opens access to television and other modern media, which may improve the access to information about contraception and diffuse new norms and role models. On the other hand, because electrification is a driver of economic development, it can affect the direct and indirect costs of having children and therefore also can affect fertility choices.

Reference [20] also stresses that there could be different results between the electrification of rural and urban areas. The authors reported a positive correlation between fertility and electricity access in rural regions of Ghana, starting in 1992. Thus, the share of the population living in urban areas is an important parameter to evaluate the effects of energy access in population growth.

Regarding mortality rates, reference [21] suggests that the infant, under-5 years, and the overall population mortality rates are negatively and significantly related to the energy consumption in the region. The study was conducted using data from twenty-three African countries, from 1999 to 2014.

Finally, it is expected that the energy demand may vary as a function of the size of the population and the region's level of economic development. Reference [22] reported that in a developed urban region in China, the growth in energy consumption was proportional to double the population growth rate. Again, the differentiation between rural and urban areas may be an important factor to be considered in the model.

- *Economic and environmental effects of energy access*

While electricity access is likely, not sufficient for economic growth, some references show that electricity use and a country's gross domestic product tend to go hand-in-hand [23], [24]. Reference [24] summarizes the results for the electrification rate of several countries with relatively low per capita income in 1971 and their evolution until 2014, under a macroeconomic perspective. The majority of study cases showed a positive correlation between energy use and economic growth.

Reference [23] also suggests that electricity access is likely to be an important enabler of economic growth. However, the unreliability of the electricity supply is frequently cited as a constraint to economic growth. In this work, an energy security index – a function of the region's surplus of energy available, level of economic development, and investment in the power sector – is going to be used to represent the unreliability of energy supply.

Regarding the environment, renewable energy resources appear to be one of the most efficient and effective solutions for clean and sustainable energy development worldwide. Reference [25] strengthens this argument by stating that the dependency on expensive, imported energy resources and the usage of biomass, oil, and coal, mainly for heating, have led to a big burden on the economy, air pollution, and deforestation in Turkey.

The proposed model takes into consideration the energy generation from dispatchable and non-dispatchable sources, as well as the pollution output of both options during operation. These may affect the quality level of the environment depending on the amount of energy generated from polluting sources. Also, where there is a lack of energy in the region, the model considers the negative effect on the pollution abatement efforts, representing the regions' inability of processing garbage or remanufacturing older products.

A. Equations

In total, the proposed model is constituted by seventeen equations. We shall deal with each one of the model sections in turn. All the variables are described in Table I.

TABLE I
MODEL VARIABLES, BY SECTION

Var	Description	Section
x	size of the population	Demography
n	net population change rate	Demography
b	crude birth rate	Demography
d	crude death rate	Demography
y	per capita economic output	Economy
i	net per capita income	Economy
c	govt. expenditure on pollution abatement	Economy
eb	energy bill	Economy
z	stock of natural capital	Environment
p	pollution per unit output	Environment
f	flow of pollutants	Environment
ed	energy demand	Power Sector
pc	energy effectively being consumed	Power Sector
ndg	non-dispatchable (non-polluting) generation	Power Sector
dgc	installed capacity for dispatchable generation	Power Sector
dg	dispatchable (polluting) generation	Power Sector
pg	total power being generated	Power Sector
et	energy trade between regions	Power Sector
es	energy security index	Power Sector

1) Population:

$$\frac{dx}{dt} = xn \tag{14}$$

$$n = b - d \tag{15}$$

$$b = \beta_1 \left[\beta_2 - \frac{1}{2}\left(\frac{\beta i + \beta_e es}{1 + \beta i + \beta_e es}\right)\right] \tag{16}$$

$$d = \alpha_1 \left[\alpha_2 - \frac{1}{2}\left(\frac{\alpha i + \alpha_e es}{1 + \alpha i + \alpha_e es}\right)\right] \times \left(1 + \alpha_3 (1-z)^{\upsilon}\right)\left(1 + \alpha_4)(1 - es)^{\upsilon_e}\right) \tag{17}$$

Equations (14) and (15) kept their structure from the original model, where the difference between the crude birth and death rates dictate the population growth. Equations (16) and (17), however, have an energy security term being added in the main fraction to represent the reduction in both fertility and mortality rates as electricity is more available to the population.

Equation (17) has also a term being multiplied, proportional to α_4, representing an increase in mortality when there is no energy available ($es = 0$). This therm produces no effect when the electrification has achieved the whole population ($es = 1$).

TABLE II
PARAMETER VALUES IN DEMOGRAPHY (DREAM SCENARIO)

Parameter	Value	Parameter	Value
β_1	0.04	α_3	4.0
β_2	1.375	α_4	0.5
β	0.07	α	0.03
α_1	0.01	υ	3
α_2	2.5	υ_e	0.03

Not all parameters shown in Tables II to V represent objective data. However, with enough historical information it is possible to estimate their values. In case it is not possible to make this inference, a trial-and-error callibration of parameters was employed in order to produce a coherent behaviour. Whenever possible, parameter values were kept unchanged from the original Wonderland model.

2) Economy:

$$\frac{dy}{dt} = y\left[\gamma - (\gamma + \eta)\left((1-z)^{\lambda} + (1-es)^{\upsilon_y}\right) - \frac{\gamma_0 \tau}{1-\tau}\right] \tag{18}$$

$$i = y - c - eb \tag{19}$$

$$c = \phi(1-z)^{\mu} y \tag{20}$$

$$eb = \phi_e pc \tag{21}$$

Equations (18) and (20) kept the same structure of the original model with environmental taxes. In the per capita economic output dy/dt, the new term $(1 - es)^{\upsilon_y}$ translate the negative effects of the lack of power in the economy while $es \to 0$.

In eq. (19) another term is being subtracted, representing the energy bill – the amount of income that is destined to compensate the energy that is being consumed by the customers plus the energy that is lost during transmission and distribution. The energy bill is given in eq. (21), as a constant multiplication of the amount of energy consumed pc.

3) Environment:

$$\frac{dz}{dt} = \nu z(1-z)\left[-\frac{\omega f - \delta z^{\rho}}{1 + \omega f - \delta z^{\rho}}\right] \tag{22}$$

$$\frac{dp}{dt} = -\chi(1-\tau) es^{\upsilon_p} p \tag{23}$$

$$f = \frac{pxy}{1 + e^{-dg}} - \frac{\kappa}{2}\frac{\sigma cx}{1 + \sigma cx} \tag{24}$$

TABLE III
PARAMETER VALUES IN ECONOMY (DREAM SCENARIO)

Parameter	Value	Parameter	Value
γ	0.025	τ	0.0
η	0.1	ϕ	0.5
λ	2	μ	2
υ_y	0.01	ϕ_e	0.001
γ_0	0.0	-	-

The stock of natural capital in eq. (22) remains unchanged. The pollution per unit of output in (23) presents the same exponential decay of the original model, however, in case of a deficient energy balance ($es < 1$) the rate of reduction of pollution output is slowed proportionally to the amount of needed energy and.

Equation (24) deals with the flow of pollutants. The main difference between the original equation is the inclusion of the $1 + e^{-dg}$ denominator, which represents the flow of pollution originated by energy generated from dispatchable (polluting) sources dg.

TABLE IV
PARAMETER VALUES IN ENVIRONMENT (DREAM SCENARIO)

Parameter	Value	Parameter	Value
ν	5	χ	0.03
δ	0.2	υ_p	0.05
ω	0.2	κ	2
ρ	3	σ	0.01

4) Power Sector:

$$ed = \phi_d x \left(1 + \frac{e^{\omega_d y}}{1 + e^{\omega_d y}}\right)(1 - \tau_f) \tag{25}$$

$$pc = ed(1 + \sigma_e) \tag{26}$$

$$dgc = \phi_{dg} z \tag{27}$$

$$dg = \begin{cases} s_{ndg} & \text{if } s_{ndg} > 0 \text{ and } s_{ndg} < dgc \\ dgc & \text{if } s_{ndg} > 0 \text{ and } s_{ndg} >= dgc \\ 0 & \text{if } dgc \leq 0 \end{cases} \tag{28}$$

$$pg = ngc + dg + et \tag{29}$$

$$es = \frac{\nu_e}{1 + e^{-\rho_e (pg - pc)}} \tag{30}$$

Equation (25) describes the energy demand proportionally to the size of population x and economic output. As the economy evolves, i.e., y assumes higher values, the fraction assumes value of 2. This is in accordance with reference [22]. Parameters ϕ_d and τ_f correspond to the initial share of population with electricity access and the reduction of consumed power through energy-efficiency incentives.

The power that is effectively consumed as seen from the network perspective (eq. 26) corresponds to the sum of the customers' energy demand and electric power losses, considered to be a constant fraction (given in %) of the overall consumption.

Equations (27) and (28) set out the installed capacity and the actual generation from non-renewable (dispatchable) generation units, respectively. The former is also a function of the stock of natural capital, representing the availability of energy resources as long as there is a high-quality level of the environment. The latter sets out the amount generated from dispatchable sources as a function of the difference between the consumed power pc and the amount being generated from non-dispatchable sources ndg.

The non-dispatchable generation ndg is an input variable of the system and thus can assume any form to better adequate to the variability of renewable energy resources, such as solar radiation and wind speed.

The total amount of power being generated in eq. (29) is given as the sum of the generation from dispatchable and non-dispatchable sources, as well as the amount of energy being traded between two neighboring regions. The algorithm that sets the energy trade is described in a further section of this paper.

Finally, the energy security index is given in eq. (30). It is a function of surplus (or deficiency) of energy in the region. As long as customers' energy demand is being satisfied, this index assumes the unity value. It tends to zero otherwise. This index represents the power system capable of continually supplying all customers. If it is less than unity, it can be inferred that not all households, commerce, or industries are being energized, and thus the economy may be affected.

TABLE V
PARAMETER VALUES IN POWER SECTOR (DREAM SCENARIO)

Variable	Value	Variable	Value
ϕ_d	1	ϕ_{dg}	8
ω_d	0.01	ν_e	1
τ_f	0.0	ρ_e	50
σ_e	0.03	-	-

B. Representations

Although it is possible to subdivide the model variables and parameters into these four sections, there is a strong interdependency between all equations and the main system state variables. Their relationship can be better visualized in a causal loop diagram, as shown in Fig. 1.

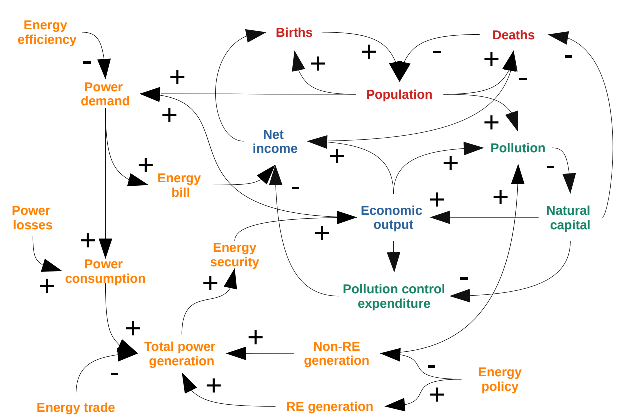

Fig. 1. Causal loop diagram of the proposed model. Sections are highlighted in different colors: in red, the demographic section; blue, economic; green, environmental, and; orange, the power sector.

C. Development scenarios

Depending on how the initial conditions and certain parameters vary, the model evolves into different paths. At least three types of developing scenarios, each starting with an almost unpolluted environment can be considered: Dream, Horror, and Escape.

The Dream scenario is the best possible outcome, in which the economy grows exponentially, and the size of the population stabilizes after a while. There are no rapid changes in natural capital and pollution decays exponentially. Also, the amount of energy generated is sufficient to keep customers satisfied.

Figure 2 shows the development of the Wonderland model for the Dream scenario. Units are given in the per-unit system. Note that the values of parameters used here can be found in Tables II through V.

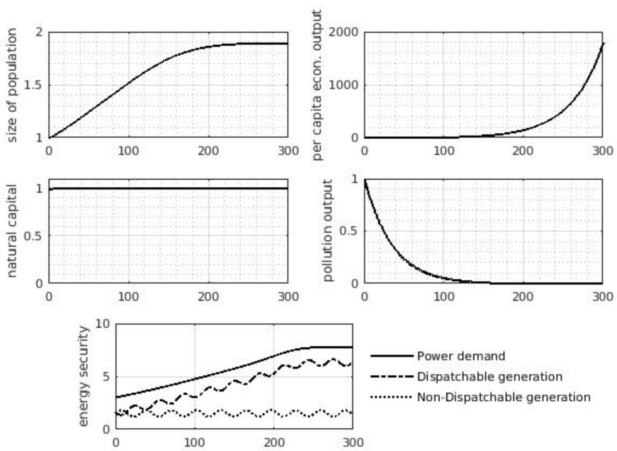

Fig. 2. Development of the proposed model for the Dream scenario. For this simulation, the input for the renewable generation was: $ndg = 1.5 + 0.3sin(t/5)$, with t being time, in years.

The Horror scenario is where sustainable development gives way to a catastrophic collapse of the economy, population, and environment. Two Horror scenarios and their respective Escape are discussed in this paper. Escape scenarios are the ones at which control actions are taken to avoid the implications of the region collapse.

In the environmental collapse scenario, the decay on pollution per unit output χ is set to fall 1% per year ($\chi = 0.01$). This drives the environment incapable of regenerating itself, which leads to the abrupt collapse of nature around year 50, as depicted in Fig. 3. This reduction in the quality level of the environment leads to an increase in mortality rates and a decrease in the per capita economic output (see Eqs. (17) and (18), respectively).

The escape from this scenario is possible through the introduction of environmental taxes, as proposed by [17]. With $\tau = 0.03$ and $\gamma_0 = 0.05$, Wonderland is capable of sustaining a higher stock of natural capital and behavior similar to the Dream scenario, however, with increased population and lower per capita economic output during the period.

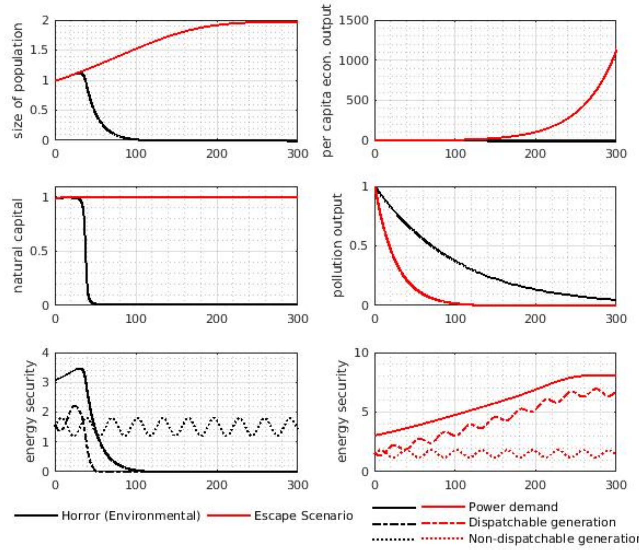

Fig. 3. Development of the model during the environmental collapse and escape scenarios.

In the energy depletion horror scenario, there is no generation from renewable (non-dispatchable) sources, and the installed capacity of dispatchable generation is halved (from 8 p.u.). This condition is sufficient to supply the energy demand for the initial 80 years, however, with still increasing population and economic output, the power system is unable to maintain the energy balance of the system. This is depicted in Fig. 4.

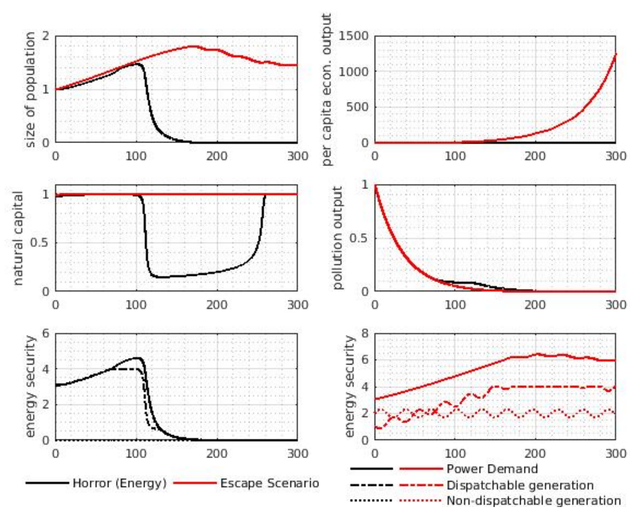

Fig. 4. Development of the model during the energy depletion horror and escape scenarios.

During the energy depletion period, not all the Wonderland population and businesses are energized and there is an increase in mortality rates and a decrease in economic output. All pollution abatement measures are also slowed. Note that the stabilization of the size of the population depends on the total installed generation capacity from both dispatchable and non-dispatchable units.

D. Energy trade between regions

When multiple regions are considered, the energy trade between them is possible once there is an energy surplus on one side, and demand not satisfied on the other.

Consider two regions A and B. In this example, region A lacks the energy to maintain the balance of the system, while B has surplus energy that can be traded. The algorithm that summarizes the trade procedure is as follows.

Algorithm 1: Trade from Region B to Region A

```
Result: direction and magnitude of traded energy.
initialization: consider regions A and B; calculate the
  energy demand pc; the total power being generated
  pg; estimate the energy surplus sA and sB, if any is
  available.
if sB > 0 then
    if sA ≥ 0 then
        trade = 0;
    else
        if sA < 0 & | sB | > | sA | then
            trade = sA;
        end
        if sA < 0 & | sB | < | sA | then
            trade = sB;
        end
    end
else
    trade = 0;
end
```

Figure 5 depicts the model development in this scenario. Note that while region B has sufficient energy to supply the extra demand from A, there is sustainable development in both regions. However, the size of the population in A depends on the amount of energy available, and thus it stabilizes in a lower value at the end of the simulation.

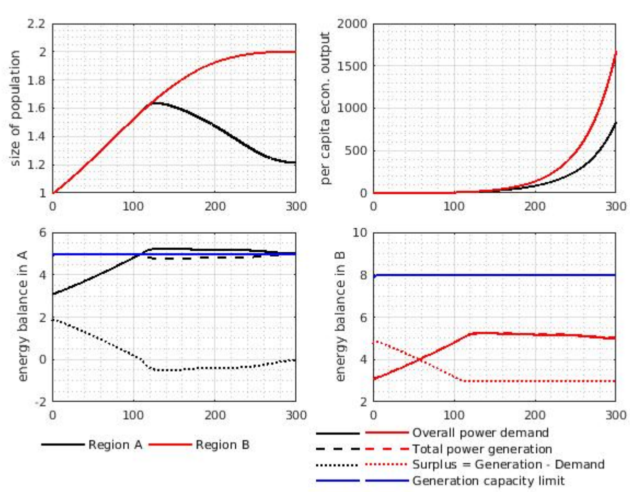

Fig. 5. Model deployment in the energy trade example.

IV. Results and Analysis

In this section, we analyze the proposed model when applied to a case study representing two different regions with distinct economical and demographical behaviors in a shared environment.

These regions can be characterized as follows. Region A leads in economical and population size with increased generation capacity (mainly with non-polluting energy sources). Region B is the poorer region, with low economic development and increased population size. This region has also a limited generation capacity with mainly polluting energy resources. Figure 6 depicts the interactions between both regions.

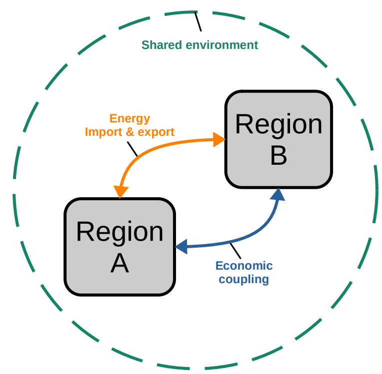

Fig. 6. A multi-country example with economic coupling in a shared environment.

Table VI sets out the initial conditions of the system dynamics' state variables. It is assumed that the environment is shared amongst the regions, so an unsustainable development in one end can lead the entire region to a collapse.

TABLE VI
Set of initial conditions of the case study

	State variable			
Region	x	y	z	p
Region A	0.50	1.00	0.98	1.00
Region B	2.00	0.50		1.00

In these terms, Region B has a population four times larger than Region A, while the latter has a doubled per capita economic output. The initial pollution per unit output p was considered to be the same, as well as the capital natural, due to the shared environment. Figure 7 shows the economic and demographic results for both regions.

Note that the most populous region remains as is during the entire simulation. A peak of 4 p.u. in the population size for Region B is achieved around year 160, and starts decreasing due to the region's inability to produce energy to address the populational increase (energy depletion horror scenario).

Meanwhile, Region A prospers with exponential growth in economic development in a stable size of population (dream scenario). Thus, the economic inequality between both regions increases continuously.

Two options can be considered to solve Region B's energy depletion scenario: an increase in local energy generation capacity, and the energy trade between both regions, since

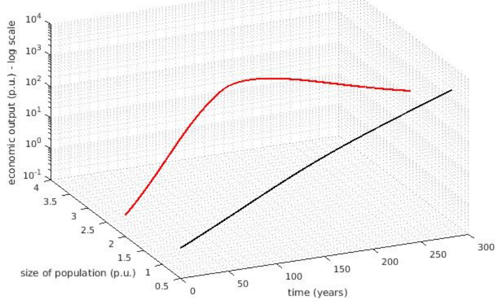

Fig. 7. Economic and demographic development for A (in black) and B (in red).

there is surplus energy in A. Figure 8 shows the results with these actions are taken one at a time.

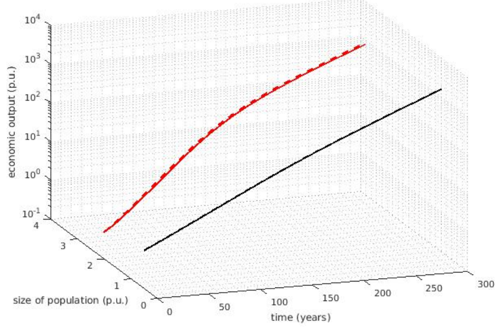

Fig. 8. Economic and demographic development for A (in black) and B (in red), after interventions. Solid lines: energy trade. Dashed lines: increased generation capacity in B.

During both executions, Region B was driven out of the energy depletion horror scenario with negligible effects on the development of A. Population in B is kept higher than A's at all times, but it stabilizes after the energy crisis is solved, around year 160. After this event, there is an exponential growth of the per capita economic output in B but in a lower state of development than in A.

This example shows that reliable energy availability is an enabler of the regional economy. If energy is always available to households and businesses, the region can develop the economy to its maximum potential.

V. Conclusion

This paper proposed a mathematical framework to qualitatively assess regional development, considering economic, demographic, and environmental aspects. The introduction of the power sector in Wonderland is its main contribution. Results allowed the visual interpretation and validation of some concepts described in the literature.

Further work will entail a more detailed evaluation of the model to consider the need for adjustments.

Finally, it is important to state that computational models, even differential equation-based models, are simplifications of the real world/phenomena. However, only when a model can teach a concept, inspire scientific research, and stimulate the creative process, it has achieved its duty.

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