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REVIEW

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National electrical energy supply: foundations of a future system

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Abstract

Background Approximately 90% of the global human population have access to a supply of electrical energy. Existing national electrical energy supply systems possess good technical availability but with significant system-inherent risks. The latter show their effects in the systems' operational behaviour, their impact on the national economy and on the global climate. National electrical energy supply systems in their current state can therefore not be considered sustainable. This invites the question, "can there be a national electrical energy supply system that is simultaneously technologically, economically and environmentally sustainable?".

Main text The contents of this article are of a fundamental nature. They start from a newly established axiomatic system for multiple-sustainable electric energy systems. The axioms contain no dependencies on individual users, nation states or technologies. For the transition into a sustainable energy system, core challenges faced by existing systems are synthesized, the fulfillment of which determines the feasibility of future systems. We state that anthropogenically generated electrical energy is a product possessing a cultural-technical significance. In this article, the possibilities arising from the physical fundamentals are considered. In addition, a new control system is developed that integrates user impact, quality assurance and cost developments in order to show a means to multiple-sustainable energy supply systems. An essential component of the control system is a unified view of energy production and energy transport. This also includes a transition from the previous, technology-dominated energy supply system into a new system for which the relevant social concerns are primary. One axiom deals with the economic concerns of management organizations of national electrical energy systems. At first, only the monetary working hypothesis is formulated, whereby organizations within the energy economy must be decoupled from basic business principles. Detailed discussions will be dealt with in a further article.

Conclusions Through the transition from a technology-defined to a user-defined electrical energy supply system, the system-immanent risks in the operational behaviour, the national economy and the climate can be avoided simultaneously in an ideal complementary combination. Building upon the physical solution space, the quality-assured control process, which contains a systematic cost-reversal and a central focus upon the cultural-technical product of electrical energy, ensures such a transition is achievable by means of fulfillment of the core challenges. For these fundamental statements, which refer to the transformation into a future system, detailed explanations of organizational units are not yet necessary since they are not subject to any natural-scientific restrictions. However, they are essential for the post-transformation process.

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Keywords Electrical energy supply, Axiomatic electrical energy supply system, Multiple-sustainable energy supply system, National energy autonomy, Large-area transmission network, Pre-investment behaviour, Natural energy module, User requirements, Cultural-technical product, Physical primary energy

Background

The individual and overall societal benefits resulting from the use of electrical energy have become a central cultural influence. Thus, electrical energy belongs to the group of the most significant anthropogenic products. Because of its importance, the provision of electrical energy is not a 'normal' supply process, but rather one of cultural and technological significance which must be integrated equally.

The existing national electrical energy supply systems[1] (EESS) generally provide their customers with sufficient electrical energy of good quality. Equivalent systems have emerged worldwide that have their roots in a technology that is almost 150 years old. This alone is no reason to change these systems. What has changed, however, are the societal demands on these systems. These demands are heterogeneous nationally, but are generally developing congruently. They concern the maintenance and improvement of technical energy supply, stability of national economies in the face of supply failures and climate neutrality in electrical energy generation.

Globally, the majority of established, national electrical energy supply systems (EESS) have commerce-focussed forms of organization (state or private) as their guiding structure. In this control structure, commercial profits are the primary objective[2][1]. They continue to globalize, structurally, such that national electrical energy autonomy is practically impossible. The existing systems are in a diametrical position to the multiple-sustainable electrical energy supply systems (EESS), discussed herein, which, for example, achieve national electrical energy autonomy early in the transformation process.

Significant for the implementation of a multiple-sustainable electrical energy supply system is the acknowledgement that there are no physical-quantitative primary energy limitations on earth for conversion into electrical energy. This is impressively demonstrated by various DERTEC studies, among others [2]. From this the conclusion can be drawn that there is no physical energy problem on earth, but rather a technology problem for electrical energy generation and supply.

[1] First occurrences of specific terms are italicised to indicate their further description in the accompanying glossary.

[2] Revenues in 2020 (end consumer) in Germany amount to approximately 80 billion Euro.

Main text

Methodical approach

This foundational article focuses on national electrical energy supply systems (EESS) that are multiple-sustainable. The achieved results shall be independent of specifics of the individual states and territories comprising the nation, i.e. shall be universally valid, and, for the individual, there shall be additional design flexibility [3]. In the Appendix, an example electrical energy supply system (EESS) has been designed, which is supposed to support explaining the results with fictitious individual considerations.

The starting point for the system design is the axiomatic system for an EESS given by the authors. The variabilities allowed by Popper K. shall be understood to be analogous to quasi-stationary approximations in physics [4]. This type of approximation means, for the development processes of an EESS, that they are stable in cycles over several years, i.e. the systems can be developed in real terms. In order to specify the statements made, mathematics corresponding to an undergraduate level have been used.

In the present text, the process of electrical energy supply and the product of electrical energy, which are closely interwoven, are directly addressed. For the process of supply, the existing technology of the national EESS is chosen as the initial state and the subsequent evolution quasi-stationarily transforms the initial state into a new target state. For the product applies that the technological generation process of electrical energy is extended, as it now includes additional cultural influences that occur in a multidimensional cultural-technical product.

The user requirements for the national EESS are formulated by the respective national users. Here, a systemic reversal of the user role occurs, from a passive to an active position. The number of national users in systems with a high degree of electrification [5] roughly corresponds to the respective national society. These systems usually contain several million users. They are user-defined and not defined by technologies. User requirements are not laws of nature, i.e. they are subject to change over time. The design of the basic structure of the EESS deliberately ends where the user requirements are described to the maximum, but deliberately ends where no concrete specifications for necessary technologies are yet incorporated.

Introduction

The societal benefits resulting from the development and application of electrical energy are irreversible. The demand for electrical energy used worldwide continues to increase each year [6]. Electrical energy used for anthropogenic purposes is not a natural product and therefore must be produced technologically. The process of electrical energy supply inherently involves energy conversion from a primary energy source to a defined electrical energy source before provision at the user location. The product of this system includes not only the electrical energy as a technical quantity, but also contains social and cultural effects from the national societies, users. The electrical energy is therefore a cultural-technical product. For an electrical energy supply system, the following axiomatic system is created [7].

Axiom I—the electrical energy supply system may use only natural primary energy flows in conjunction with a climate neutral energy conversion process.

Axiom II—the electrical energy supply system must not contain system-inherent risks that could lead to significant product deficit.

Axiom III—the electrical energy supply system must not be managed by an organization that operates primarily on principles for commercial gain, but rather on principles for ecological "zero net loss" [8–11].

Through simultaneous fulfilment of all axioms, a multiple-sustainable electrical energy supply system is created. The focus for the remainder of this article is on Axioms I and II.

The current electrical energy supply system

Worldwide, there are national and international EESSs which supply entire societies and their constituent users simultaneously and sufficiently with electrical energy. This alone confirms any question of technological existence.

Existing EESSs use an internationally similar technology [5]. They consist of the sub-technologies, energy generation and energy transport, technically executed as a symbiotic combination of large-scale energy generation plants and large-area electrical transmission networks[3]. The generation infrastructure, internationally, uses a mix of different primary energy sources [12] in technologically bundled generation plants. The entire supply infrastructure requires a high level of material input as generally every user is connected to every other user and every generation plant via a large-area electrical transmission network. There is no system-relevant electrical energy storage capacity in use, therefore sophisticated power frequency control is required for stable operation.

Multiple-sustainable electrical energy supply system

Are the existing EESSs multiple-sustainable with respect to the established axioms or, if not, do they have the development potential necessary for this? If neither case is true, is it possible to develop a technological system that is multiple-sustainable? In order to arrive at an evaluative analysis, the EESSs are divided into three segments in terms of content: "technology", "national economy", and "climate", which are further described as being beneficial or problematic from the perspective of the user.

Technology The focus is on the technology used to supply the EESS users with electrical energy. The achieved technical availability [13] of the electrical energy is beneficial, partly highly beneficial [14]. The technological system of large-scale generation plants and large-area transmission networks is problematic as it contains the system-inherent risk of significant product outages. Outages are inherent to the system because electrical transmission networks form an electrically interdependent network structure [15]. They can cause national and international blackouts [16] for which the instances and durations are not predictable. This inherent risk also affects the above-mentioned technical availability. In this system, the user is an energy consumer, i.e. they have a passive role.

National economy The economic growth of national economies, measured by gross domestic product (GDP), in which the population is supplied with electrical energy is positively correlated with energy consumption [17]. The use of electrical energy is generally macro-economically beneficial and exceptionally so in systems with high levels of electrification.

The effect of the system-inherent risk of national blackouts is a significant threat to economic growth. The resulting supply failures are problematic [18] and have the potential for dramatic and long-lasting gross domestic product (GDP) collapses. The increasing globalization of energy supply poses further problems. Here, these problems are the internationally connected transmission network with their extended blackout potential, the relocation of generation capacities of a country to a foreign country, and primary energy dependencies for generation plants of the respective domestic and foreign countries.

Climate The generation of electrical energy can only be climatically beneficial in the long-term if it is climate-neutral. This situation does not exist worldwide, since the main primary energy sources continue to be coal and natural gas [12], two fossil fuels whose climate-relevant waste

[3] In Germany, there are approximately 2 million kilometres of transmission lines. (BDEW—Entwicklung Stromnetze in Deutschland; 2023).

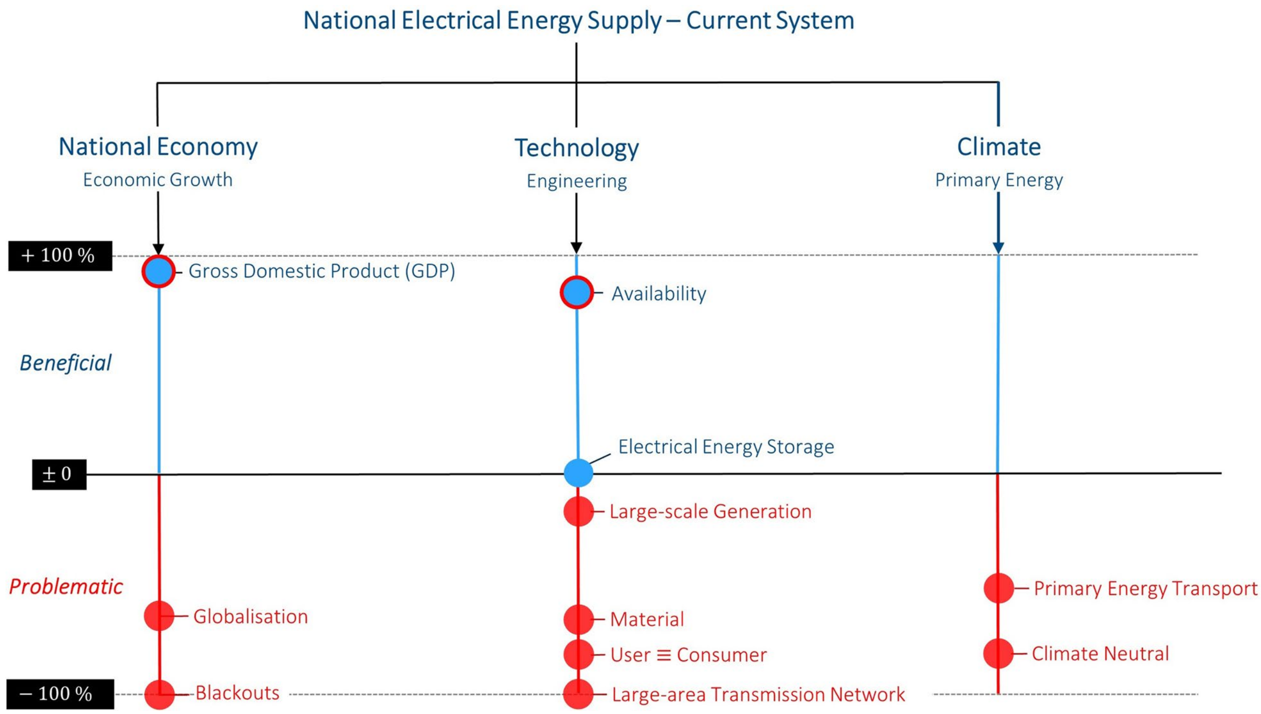

Fig. 1 An overview of a current national EESS and its constituent characteristics scaled from holistically problematic (– 100%) to holistically beneficial (+100%)

product, carbon dioxide, is released into the atmosphere and thus contributes significantly to the anthropogenic greenhouse effect. Thus, the worldwide electrical energy production is to be classified as problematic from a climatic point of view.

Summary evaluation

For the international EESSs, the contents are shown in an overview in Fig. 1. The variables, "blackouts" and "large-area transmission network", have been classified as sources of maximum economic risk. The supply failures are an effect inherent to the use of large-area transmission networks, i.e. the large-area networks are central to the problem of economic risk.

The International Energy Agency's position on electrical transmission networks is described in its 'World Energy Outlook 2022—Outlook for Electricity' [19]. On page 278 it states:

> *"Electricity networks are the backbone of electricity systems, and need to expand and modernize to support energy transitions. ..."*

This statement emphasizes international outlook and intent for future entrenchment of electrical transmission network technology. Assuming that this is also the opinion of all nations with high electrification rates, this is a strong vote for global technological preservation of existing EESSs.

The use of large-scale transmission networks, nationally or internationally connected, can lead to large-scale and sustained electrical power outages [20]. Thus the utilized large-area transmission network approach is in contradiction to Axiom II, i.e. here there is already an exclusion criterion [21] for existing EESSs preventing realization of multiple-sustainability.

If this situation is not socially acceptable for a nation state, is multiple-sustainability possible for a national EESS? Such an EESS of the future must fulfil Axioms I to III. For this purpose, it is necessary to shift the values in the lower half of Fig. 1 to the upper half. The respective values of these variables (0 to + 100%) are determined by national targets and thus form the national degree of fulfilment of a multiple-sustainable EESS.

For the considerations in the present article, an ideal situation with a maximum degree of fulfilment is discussed. From the given axiomatic system for the EESS, concrete working hypotheses (WH) for the system design are given a priori [22].

WH I—The users are transformed from being passive energy consumers into active designers of the EESS.

WH II—Interconnected, large-area electrical transmission networks, as a physical, technological option in an EESS, are not used for supply of electrical energy to users.

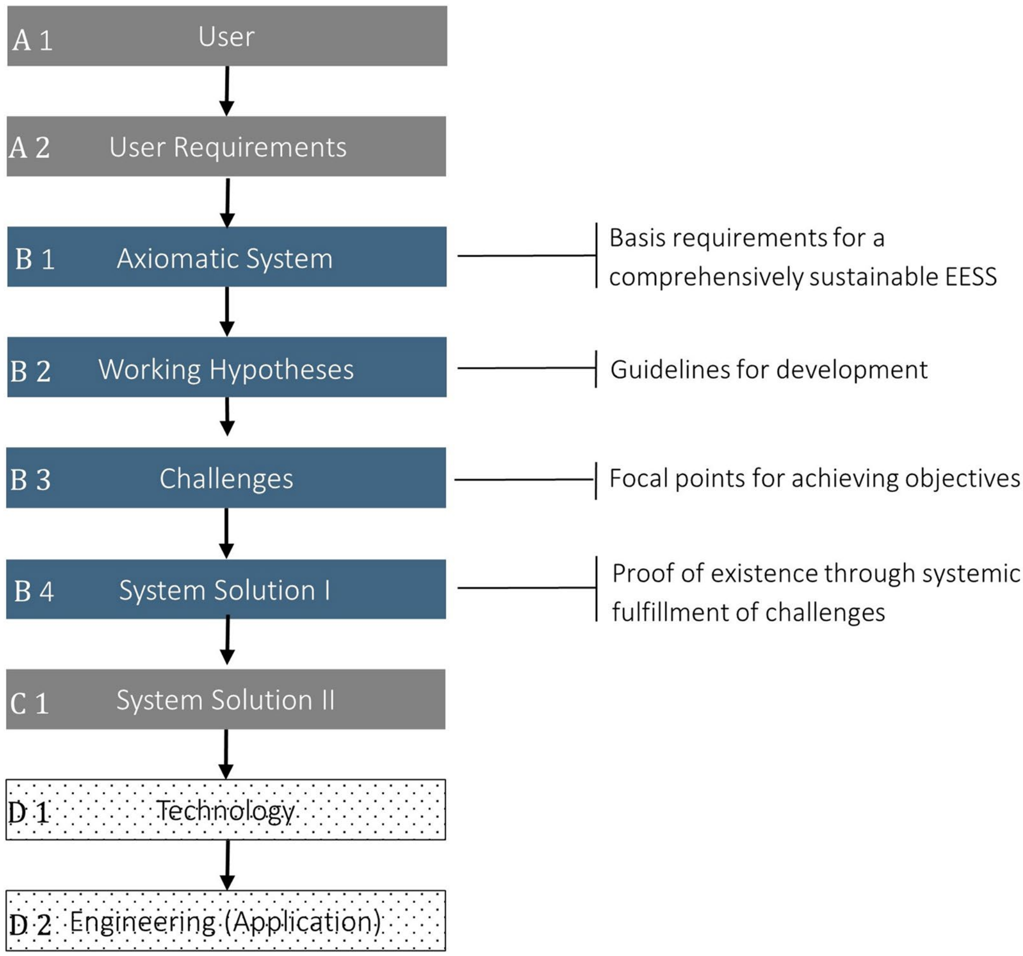

Fig. 2 The guideline process for realization of a multiple-sustainable electrical energy supply system

WH III—In electric energy supply systems of the future, only ubiquitous and cost-free primary energy sources may be used.

WH IV—In the electric power supply system of the future, no commercial economic profits may be achieved.

The above working hypotheses are guidelines for the following design of a multiple-sustainable EESS of the future.

Challenges of a multiple-sustainable EESS

As explained in the introduction, the existing national EESS cannot principally be developed into a multiple-sustainable EESS. To achieve a future-proof EESS, the process shown in Fig. 2 is used as a guideline.

Based on the principle of causality, the users are the cause and the possible technologies/engineering are the effect. This defines the beginning and end of the process. Overall, it is a linear process that can be broken down into individual modules. Part A deals with the new systemic role of the user, manifested as user requirements. This section will be elaborated in a subsequent article. Part B essentially serves the central question: "is there a solution for a multiple-sustainable EESS?" Part C specifies the physical framework of system solutions which will also be elaborated in a subsequent article. Part D is a fundamental engineering article on technological/technical solutions, also presented separately.

Part B is the focus of this article. In the Introduction, the axioms for a multiple-sustainable EESS, based on user requirements, have been identified. Specifically, these have been transformed into working hypotheses that serve as guidelines for the further analyses. These analyses deal with the posed question: "Is a multiple-sustainable national EESS possible?" Analogous to the current EESS, this is a question of whether there is an exclusion criterion [19] against the new proposed EESSs. This essentially touches the scientific foundations and thus Axioms I and II.[4] To find an answer, eight challenges are formulated here and their feasibility is examined. In doing so, they are categorized under "technology", "national economy", and "climate", as previously shown in Fig. 1.

Technology

1. The energy consumption of a natural module is generally increasing to a high level. For the natural energy module, this means that the value determined in a reference year is a minimum (infimum) in the national reconciliation process yet to be presented.
2. Several variables affect the quality of the supply energy; compliance with country-specific standards, e.g., [23], time availability, e.g., [14] and available short-circuit power, S''_{K_N}, at the user location [24].
3. In the case of energy provision costs, the causation principle applies. The user pays the technically determined, individualized and, if necessary, proportionate universal costs of their electrical energy supply. Cost reduction potentials in the current systems are contained in the network structure and the primary energy used. Each user receives a claim for damages (quantitative and non-quantitative) from non-delivered supply energy against the organization that is legally responsible for the electrical energy supply.

National economy

4. A nation's gross domestic product is a major internationally recognized benchmark normalized to the natural module. It can be considered a gauge of the vitality of an economy. Therefore, a national threshold is introduced to establish a limit to the permissible GDP collapse over time due to disruption to the electrical energy supply. The value is to be understood as a lower bound of the function $\mathrm{GDP}(t)$ [25] and is a specific value for the individual natural modules.[5] The value for the national threshold may change over time, e.g., due to technological system changes.
5. The technical aspects of the electrical transmission network structure are also a significant economic variable. For example, electrical transmission network costs in nations with a high degree of electrification are approximately 1% of GDP, annually. [26] Since power transmission network technology is only an engineering choice, its removal presents a significant cost-reduction factor.
6. The energy supply structure is built within self-sufficient energy cells, as their existence inherently reduces the national economic risk. In principle, the smaller an energy cell is, the smaller its economic risk potential is in the event of EESS failure [20]. The national self-sufficient energy cell is a unique case as it creates national electrical energy autonomy. The respective national electrical energy industry is thus no longer a global market participant.

Climate

7. The use of ubiquitous primary energy means, in regard to energy conversion, to make the use of self-sufficient energy cells feasible and to make climate-neutral electrical energy production possible. An example of a ubiquitous and cost-free primary energy source is the electromagnetic radiation emitted from the sun.
8. The use of cost-free primary energy sources for energy conversion refers to the operational costs of energy conversion and thus leads to a further fundamental reduction in energy supply costs. The utilization spectrum of suitable primary energy sources is further restricted with this requirement.

These eight challenges can be reframed as measurable core quantities and set as targets essential to the realization of a multiple-sustainable EESS. The focus is thus on addressing the eight core quantities[6] and their necessary development to design a multiple-sustainable EESS of the future. Let the target level be normalized for all quantities. Qualitatively, the initial situation (see Fig. 1) is reflected in Fig. 3 as exceeding or falling short of the individual values.

Fundamentals of a new regulation system

The instrument for transformation into a multiple-sustainable EESS can be a state regulatory system, with the national regulator as the main agent. It is a form of organization that already works in many nations in the field of transmission network regulation and is near to the requirements of Axiom III. In countries in which there is no central regulation of electrical energy supply, an organization[7] that equally meets the requirements

[4] Axiom III will be handled separately.

[5] $\mathrm{GDP} \geq \mathrm{GDP}$ Threshold.

[6] There are dependencies between the core quantities.

[7] Abbreviated form: Regulator ≡ Regulator or an equally valued organisation.

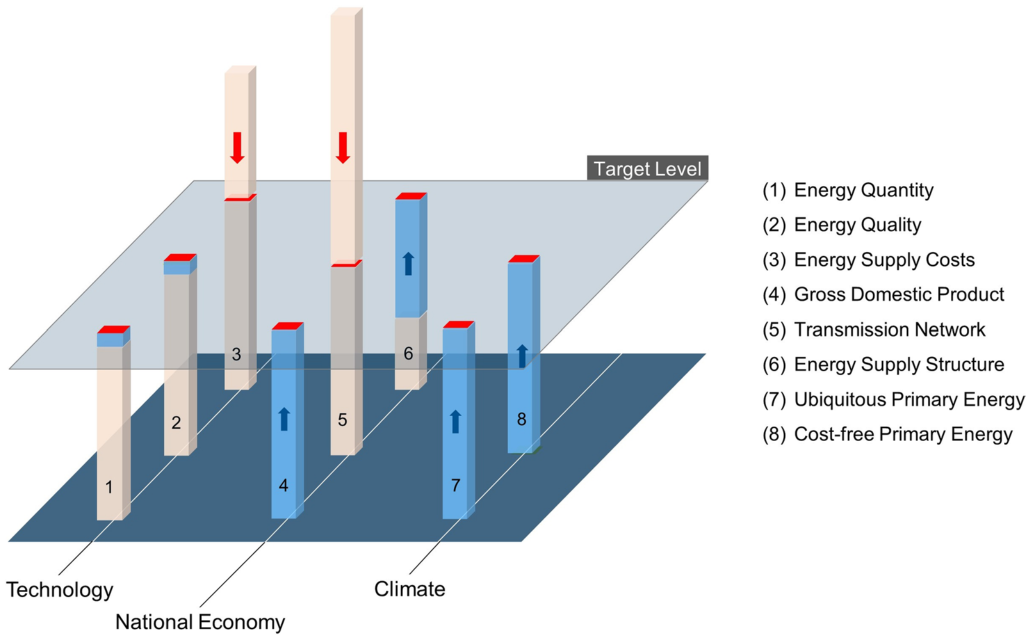

Fig. 3 The eight starting challenges reframed as core quantities and thus forming target levels for a multiple-sustainable EESS

of Axiom III can undertake the task. Due to the high international prevalence of state energy transmission network regulation systems, they are the focus of the following considerations without limitation of generality [27].

Transformation process

In order to arrive at a new EESS, a transformation process is necessary that encompasses the range of technologies required for supplying electrical energy to the users, i.e. generation plants and electrical transmission networks must be the subject of regulation. In this approach, the current infrastructure defines the starting point for the transformation process, from which there is a steady transition from the actual system to the future system. The classic business causality, where the applied technology is the cause and system costs are the effect, is reversed in the transformation process. Under this principle, the system costs are the cause and the technology is the effect.

What are the consequences of this principle?

1. The system costs for the complete supply infrastructure become a significant control variable in the process. Operationally, this means that the regulator sets a time-varying financial framework within which different technologies can evolve. It thus retains complete control of costs and develops the central process. Its basic operation is illustrated in Fig. 4.
2. The reversal of cause and effect creates a fundamental difficulty: A technical plant component results in a unique cost, but a monetary unit does not necessarily result in a unique plant component. This state of affairs corresponds mathematically to a surjective function [28]. But it is precisely this indeterminacy that offers potential for actively shaping national supply infrastructure. No technology/technique is prescribed by regulation for implementation. Instead, the research and development activities of institutions and the competitive market of technology providers are used.
3. The indeterminacy leads to the necessary introduction of an accompanying quality assurance process. This process has, for example, as a target value, the compliance with a given national economic threshold. For quality assurance reasons, this process should not be the responsibility of the regulator.
4. For a transformation process into a new system, another accompanying process is necessary, the auxiliary legislative process, *R*. Here, the respective national legislative organization must be responsible for creating legal certainty.

The approach of the central transformation process and the coupling of the two auxiliary processes is shown in Fig. 5. In the case of a successful transformation, a post-transformation process follows, which is determined by Axiom III.

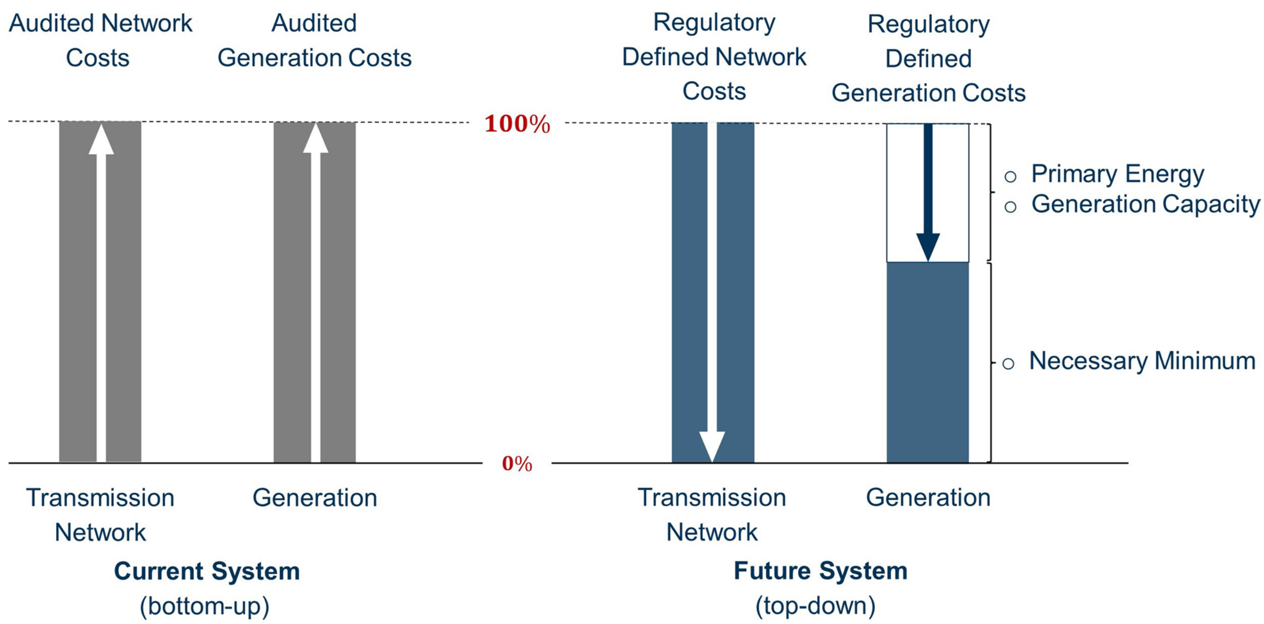

Fig. 4 Causality reversal of system costs from the current regulatory system (left) via transformation into the new regulatory system (right)

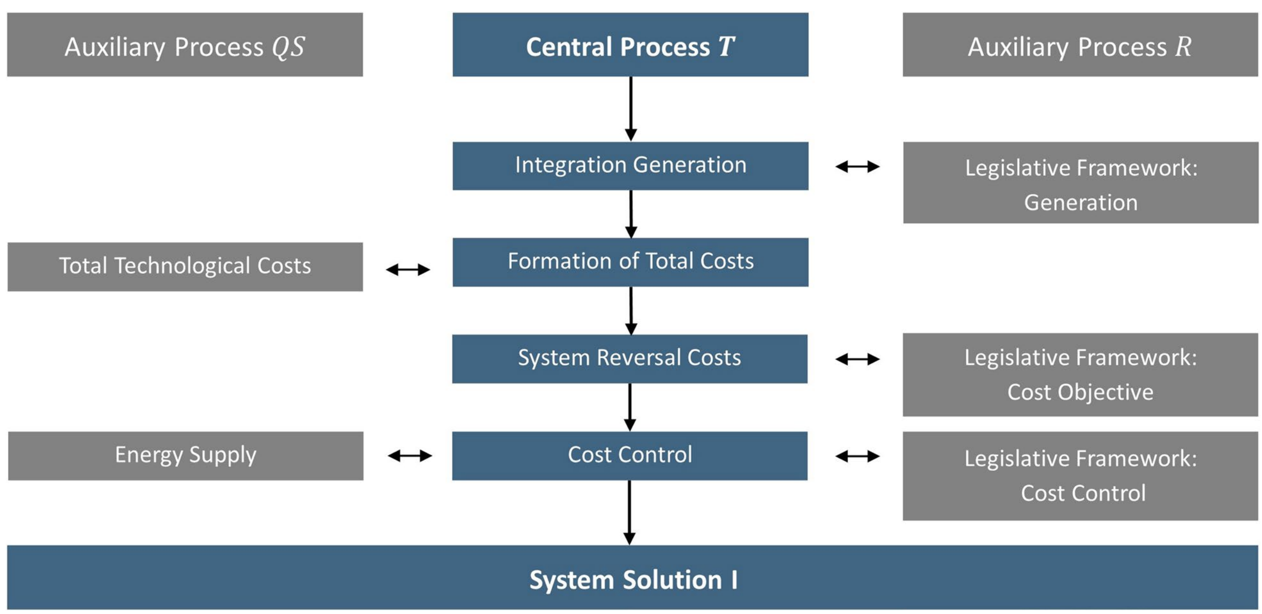

Fig. 5 Complete process overview for the realization of a system solution

Regulatory system control

To achieve the System Solution I, a system architecture as a structural model is introduced. As a system view for an EESS, it includes the total technology used for the electrical energy supply required. It provides the framework for the system control-functions. The user control-function implements into the system architecture the universal and national, individual developments of the all the connected users. The cost control-function is to be understood as a pre-technological regulatory instrument.

System architecture

The system architecture model has the task of describing an arbitrary system state of a national EESS which enables a directed system development process. It uses three quantities for this purpose: structural levels (m), self-sufficient energy cells (k) and number of users (i).

Structure levels: m, $m_{max} \in \mathbb{N}_{>0}$ and $m \leq m_{max}$

In the structural levels, the space is created to allow system states to evolve towards given subordinate goals. This is achieved through changes in the energy cell and user distributions in the individual structural levels. Each structural level always contains within each national system state the total number of all national system users (i_{max}^{nat}). Structural levels have a duration defined by a start (t_S^m) and end (t_E^m). The duration depends on the control-functions and the influence of the auxiliary process, QS. The temporal transitions between the structural levels are without time delay, i.e. $t_E^m = t_S^{m+1}$.

For the following structural levels, there are peculiarities that apply universally[8]:

$m = 1$. This level contains, as a starting point, (t_S^1), an internationally connected electrical transmission network structure[9] consisting of two or more national EESSs. The entire technical system is contained in an international energy cell, which need not be self-sufficient. What is universal is the detachment of the national EESS considered in each case hereafter from this system and the creation of a national self-sufficient energy cell until the time (t_E^1). This procedure creates the national electric energy autonomy.

$m = 2$. Universally, the emergence of at least two self-sufficient national energy cells by time (t_E^2).

$m = m_{max}$. This is the final level in the system architectural model. Its self-sufficient energy cells are called nano-cells. Universal is the emergence of 1:1 nano-cells at the time ($t_E^{m_0}$) as the smallest possible energy-economic unit.

Self-sufficient energy cells: k, $k_{max} \in \mathbb{N}_{>0}$ and $k \leq k_{max}$

The first criterion to distinguish system states in a structural level is the distribution of self-sufficient energy cells. Any cell in an EESS is given by k_m and a system state contains at most k_{max} cells. In a structural level (m), for any given self-sufficient energy cell $(k_m) := (m, k_m)$and for $k = k_{max} := \left(m, k_{max,m}\right)$.

User numbers: *i*, $i_{max} \in N_{>0}$ and $i \leq i_{max}$

The second criterion to distinguish system states in a structural level is the number of users in each self-sufficient energy cell. Each user (i) is contained in exactly one energy cell (k_m) in each system state (m). The label $i^{k,m}$ applies to an arbitrary individual user and the k-cell contains a total of $i_{max}^{k,m}$ users.

A system state can be described by the mathematical triple $(m, k_{max}, i_{max}^{k,m})$ whose variables are usually time dependent. The individual user is also uniquely contained in the system state and has the identifier$(m, k_m, i^{k,m})$. Figure 6 depicts an example of a structural level with different system states. Initial and final states form discrete supporting points in the system. Thus, within a structural level, there are different system states generated by regulation at times (t_S^m) and $\left(t_E^m\right)$. They act as constants in the regulatory process. The transformation within a structural level can take place over different system states and is not necessarily unique.

Each system state has at least one self-sufficient energy cell with the largest number of connected users. Quantitative quality measurement, $Q^{m,k}$, of different system states shall be introduced here for this cell. It is a part of the user control-function, $N(t)$. Let $t \in [t_S^m, t_E^m]$,[10] whereby Eq. (1) and Eq. (2) hold:

$$N(t) := i_{max}^{k,m}, \tag{1}$$

$$Q^{m,k}(t) := (1 - N(t)). \tag{2}$$

The complete system architecture at a glance is shown in Fig. 7 and, in the Appendix, the system architecture of an example EESS is provided for reference.

In the limiting case, the self-sufficient energy cell in the EESS is the 1:1 nano-cell. Thus, applies Eq. (3), and there is no further deviation to the ideal value (Axiom II):

$$Q^{m_0,1}\left(t_E^{m_{max}}\right) := \left(1 - N\left(t_E^{m_{max}}\right)\right) = 0. \tag{3}$$

User control-function

The user control-function, $N(t)$, implements into the system architecture the time evolution of the system states. In a first step, the system states for the discrete nodes $[t_S^m, t_E^m]$ shall be determined. In a structural level, they form the regulatory quality-assured framework for the development of the largest interconnected self-sufficient energy cell (see Eq. (1)) and the necessary time to reach the respective level, $t_S^m \to t_E^m$. The second step is to

[8] "Universally" implies independence from nation states.

[9] E.g., ENTSO—Electrical transmission network in Europe.

[10] $[t_S^m, t_E^m] := \{t_S^1, t_E^1, \ldots, t_S^{m_0}, t_E^{m_0}\}$.

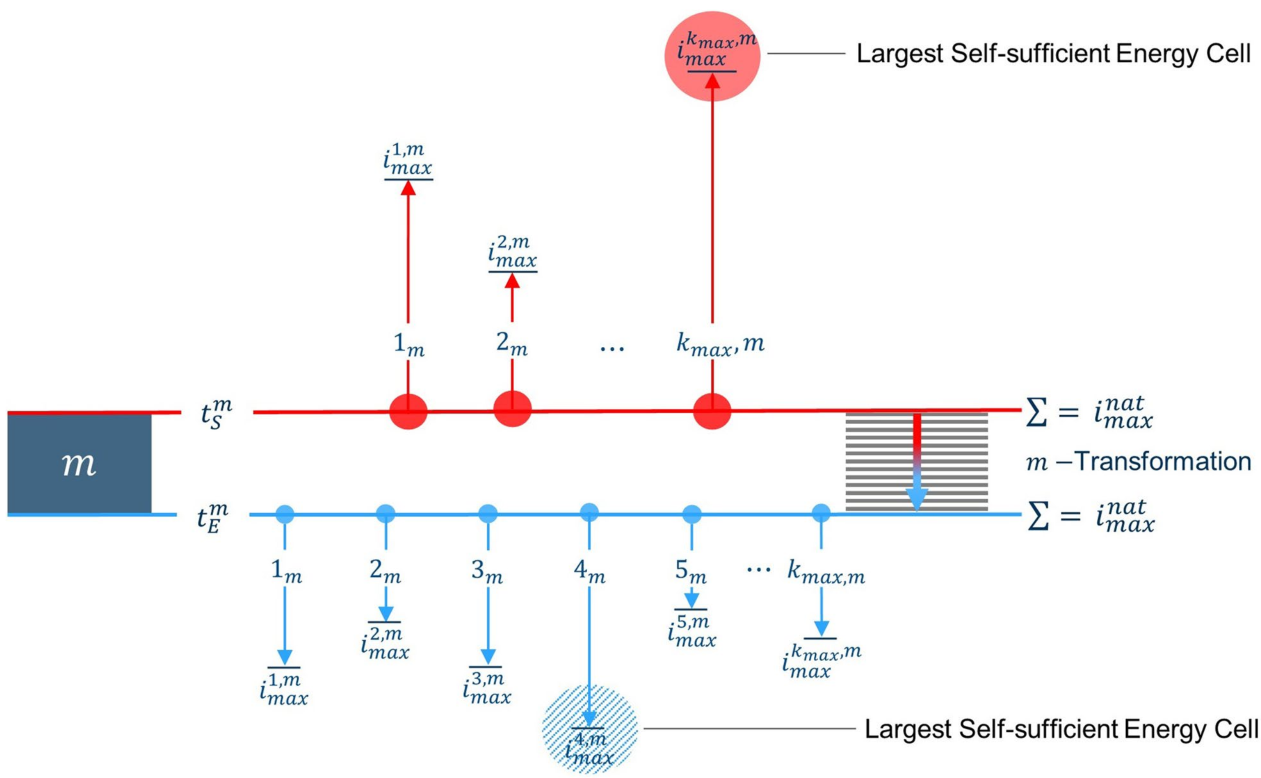

Fig. 6 Example depiction of a structural level, *m*, of an EESS

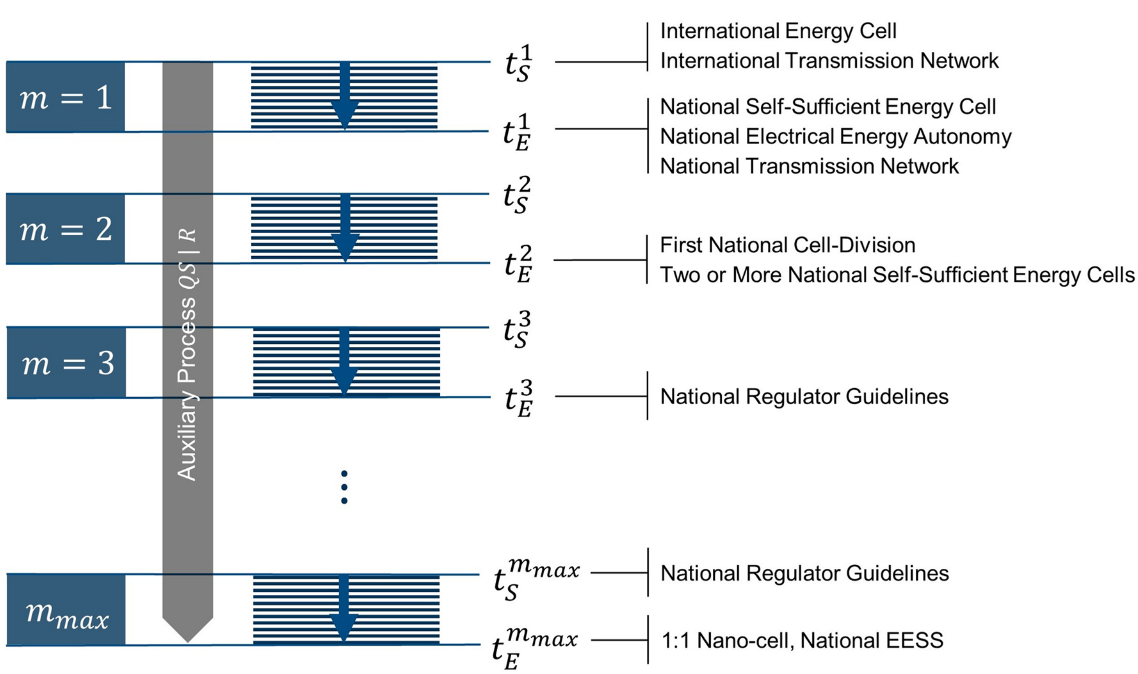

Fig. 7 Overview of the structural system model for a multiple-sustainable EESS

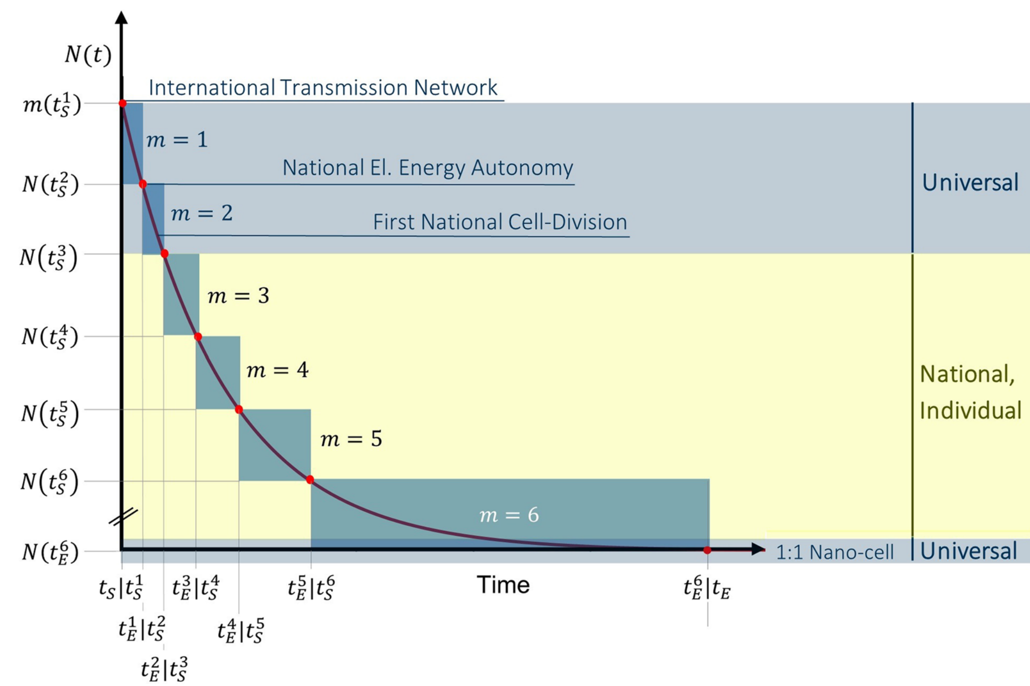

Fig. 8 Behaviour of an example user control-function, Eq. (4)

determine the evolution path of the system states within a structural level, i.e. the overall user function, $N(t)$.

Functional requirements

- The user function must generate self-sufficient energy cells over time, whose number of respective users in the connected network structure within each cell reduces (see Challenge 6 in Fig. 3).
- At the discrete time points $[t_S^m, t_E^m]$, the function values $N(t_S^m)$ and $N(t_E^m)$ correspond to the given largest user cells in the respective system states. The condition $N(t_S^m) > N(t_E^m)$ is valid.
- For the discrete structure levels $m = 1$, $m = 2$ and $m = m_0$ there are universal requirements (see above).

t_S^1	If the national system is integrated into an international system
$t_E^1 = t_S^2$	National self-sufficient energy cell ≡ national electrical energy autonomy
$t_E^2 = t_S^3$	First national cell division in time interval $\Delta t_2 = t_E^2 - t_S^2$
$t_E^{m_0}$	Achievement of 1:1 nano-cell structure in a national EESS.

These requirements apply to all national EESSs and therefore, for regulatory purposes, only the quality-assured time for nationally individual target achievement must be set.

- The number of structural levels in the model, m_0, is a national individual quantity. Thus, the discrete value pairs, $(t, N(t))$, with $t \in [t_S^3, t_E^3, ...t_S^{m_0}]$ are to be set in a regulatory, quality-assured manner.
- The user function, $N(t)$, can be an analytic function in the entire interval, in contiguous subintervals, or section-wise in the structural planes.
- The user function must be continuous and strictly monotonically decreasing in the entire definition interval, and continuously differentiable[11] in the structural levels.
- Within the first structural levels, for example, $m = 1 - 3$, must $\frac{dN(t)}{dt} \ll 0$ be valid, i.e. the user control-function is strongly decreasing.

Example user control-function

A suitable analytical user control-function across the whole definition domain, which fulfils all requirements

[11] Where necessary, a differential quotient.

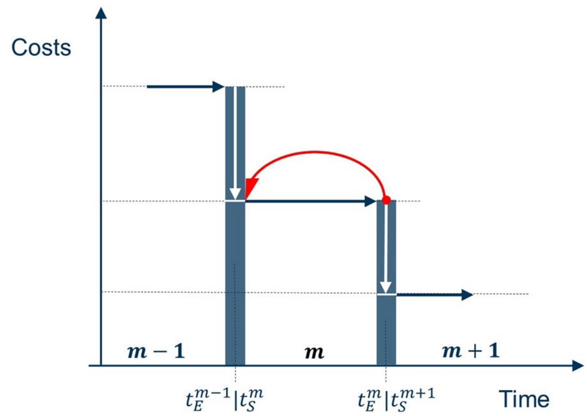

Fig. 9 Regulatory cost evolution step-function within the structural model

and adapts the system architecture of the example EESS (see Appendix), is given by a falling exponential function:

$$N(t) = a \cdot 10^{-t} \text{ where } a \in \mathbb{R}_{>0},\ a = 1,5. \tag{4}$$

The resulting illustration of the example function's progression is given in Fig. 8 in conjunction with universal and national, individual requirements.

Cost control-function

The total regulatory cost, $C_R(t)$, of an EESS consists of the energy generation cost, $C_{RG}(t)$, and the energy transport cost, $C_{RT}(t)$:

$$C_R(t) = C_{RG}(t) + C_{RT}(t). \tag{5}$$

It is primarily a pre-investment regulatory instrument to achieve the goals defined in the user control-function. As a cost control-function, it is a monetary control variable in the sense of regulatory system reversal costs. A step-function is chosen as the function type. The cost determination for a structural level, m, is to be carried out recursively in a regulatory manner. It is determined in advance for the end of the structural level, t_E^m, but takes effect from the beginning, t_S^m, as a constant, lowering the permitted system costs. The function's progression is illustrated in Fig. 9.

This approach has two objectives: to establish the achievability of the regulatory sub-targets and to create a monetary incentive for the relevant operators to reach the target before the deadline.

Energy generation costs

The determination of generation costs has a heterogeneous basis as they often originate from competitive economic markets. In order to obtain nationally homogeneous and internationally comparable costs, they are transferred to the national regulatory system.

The universal 1:1 nano-cell structure is chosen as a basis to determine the necessary plant dimensions and their cost framework. Additionally, the natural power is introduced as a power target for the required user power supply. The following user-related definition applies:

$$P_{\max}^{\text{nat}} := \sum_{i=1}^{i_{\max}^{\text{nat}}} P_{\max}\left(\vec{x}_i\right). \tag{6}$$

This value is technology-independent and defines, if necessary, distances to national generation under- and over-capacities (see national self-sufficient energy cell). The infrastructure cost of a 1:1 nano-cell can be given as the product of the specific system cost, $c_{kW}^G(t)$, [12]and the required maximum power, $P_{\max}\left(\vec{x}_i\right)$.[13] In the system architecture nomenclature, for any given user,$(m, k_m, i^{k,m})$,[14] the 1:1 nano-cell plant costs are thus:[15]

$$c_{m,k,i}^{\text{nano}}(t) \cong c_{G,m,k,i}^{\text{nano}}(t) = c_{kW}^G(t) \cdot P_{m,k,i}^{\max}. \tag{7}$$

Then the regulatory control variable is the universal specific plant cost, c_{kW}^{nano}. In the initial situation, no cost-free primary energy for purposes of calculation is considered. In order to realize the use of the required cost-free primary energy sources, the specific plant costs are adjusted over time by a cost-free primary energy usage parameter, $\gamma_m \in [0,1]$, defined for each structural level (see Appendix for example):[16]

$$c_{kW}^G(t) \to c_{kW}^{G*}(\gamma_m, t). \tag{8}$$

For the 1:1 nano-cell, together with Eq. (7), the individual generation cost is determined by Eq. (9):

$$c_{m,k,i}^{\text{nano}^*}(t) = c_{kW}^{G*}(\gamma_m, t) \cdot P_{m,k,i}^{\max} \tag{9}$$

Thus, for a natural module, as an initial value with the natural power, $P_{\max}^{\text{nat}}$, the generation costs are as described in Eq. (10)[17]:

$$C_{RG}^{\text{nat}}\left(t_S^1\right) = c_{kW}^G\left(t_S^1\right) \cdot P_{\max}^{\text{nat}}. \tag{10}$$

In the central transformation process, T (see Fig. 5), the transition to cost-free primary energy is included and Eq. (11) holds for all$t \in \left[t_S^1, t_E^{m_0}\right]$[18]:

---

[12] $c_{kW}^G(t)$= Specific system costs per Kilowatt (kW).

[13] $\vec{x}_i$ = User location.

[14] Abbreviated form $\equiv (m,k,i)$.

[15] Under the use of a micro-network structure.

[16] c_{kW}^{G*}= specific generation system costs without utilising some degree of ubiquitous primary energy.

[17] P_{max}^{nat} $\equiv$ the natural power.

[18] $C_{RG}^{nat}(t_S^1) \equiv C_m^{RG^*}(t_S^1)$, see Appendix—Example EESS System Architecture.

$$C_m^{RG^*}(t) = \sum_{k=1}^{k_{\max}} \sum_{i=1}^{i_{\max}^k} c_{m,k,i}^{\text{nano}^*}(t) \widehat{=} C_{RG^*}^{\text{nat}}(t). \quad (11)$$

The system architecture, together with the step-function (see Fig. 9), leads to values $z_m \in R$ with $m = 1, ..., m = m_0$, so that, for the constant generation cost function of a structural level, Eq. (12) is valid.

$$C_m^{RG^*}(t) = z_m\left(t_E^m\right) \text{ for } t \in \left(t_S^m, t_E^m\right) \quad (12)$$

For the time period holds: $z_{m=1} > \cdots z_m \cdots \geq z_{m_0}$, i.e. the step-function is monotonically decreasing. The reasons for this are the natural power approach, falling primary energy costs due to the increase in utilization of cost-free primary energy and the higher economic efficiencies of the new generation facilities. The is based in particular on cost-advantages anticipated from large volumes in manufacturing.

The function has a non-zero base-value, which represents the necessary anthropogenic electric energy supply. That is, starting at a structural level, $m\prime$, with $m\prime \leq m_0$, the required generation costs are constant. The effect of any subsidies to develop suitable technologies for the EESS are not considered here.

Energy transport costs

Infrastructure costs for energy transport in transmission network regulated nations have a regulatory defined history. The regulator usually has audited data from a past base year, t_0, that precedes the start of the process and can set the baseline for national energy transport costs, i.e. $C_{RT}^{\text{nat}}(t_0)$. Whether or not the national interconnected transmission network is integrated into an international system at the time is not important from an electrical engineering point of view. The national total costs enter the regulatory system. The user control-function at the start time, t_S^m, and the end time, t_E^m, of a structural level defines the largest number of connected users and thus also their reduction in this level. These values have a reducing effect on the initial value of the total cost, $C_{RT}^{\text{nat}}(t_0)$. The step-function logic shown in Fig. 9 gives an $\alpha_m \in R_{\leq 0}$ for each structural level. Thus, the regulatory cost for the duration of the corresponding level, m, is given by Eq. (13):

$$C_{RT}^m(t) := \alpha_m\left(\delta N\left(t_S^m, t_E^m\right), N\left(t_E^m\right)\right) \cdot C_{RT}^{\text{nat}}(t_0) = \text{const.} \quad (13)$$

Analogous to Eq. (12), $\tau_m \in R_{\geq 0}$ with $m = 1, ..., m = m_0$ in Eq. (14) defines the total energy transport costs for the structural level:

$$C_m^{RT}(t) = \tau_m\left(t_E^m\right) \text{ for } t \in \left(t_S^m, t_E^m\right). \quad (14)$$

Over time, $\tau_{m=1} > \cdots \tau_m \cdots > \tau_{m_0}$, which satisfies the requirement of strictly monotonically decreasing values for the power transmission network costs and the associated number of connected users. In the range of 1:1 nano-cells, the function values vanish, i.e. $\tau_m\left(t_E^{m_0}\right) = 0$.

Total cost function

The total cost of the national EESS infrastructure is the sum of the necessary generation and transportation costs. These constituent costs are specified by the regulator in the new system, top-down, as shown in Eq. (15). For the limiting case of the 1:1 nano-cell Eq. (16) is valid, i.e. there are no longer any national transmission network costs:

$$C_R^{\text{nat}}(t) = C_m^{RG^*}(t) + C_m^{RT}(t) = z_m\left(t_E^m\right) + \tau_m\left(t_E^m\right) \quad (15)$$

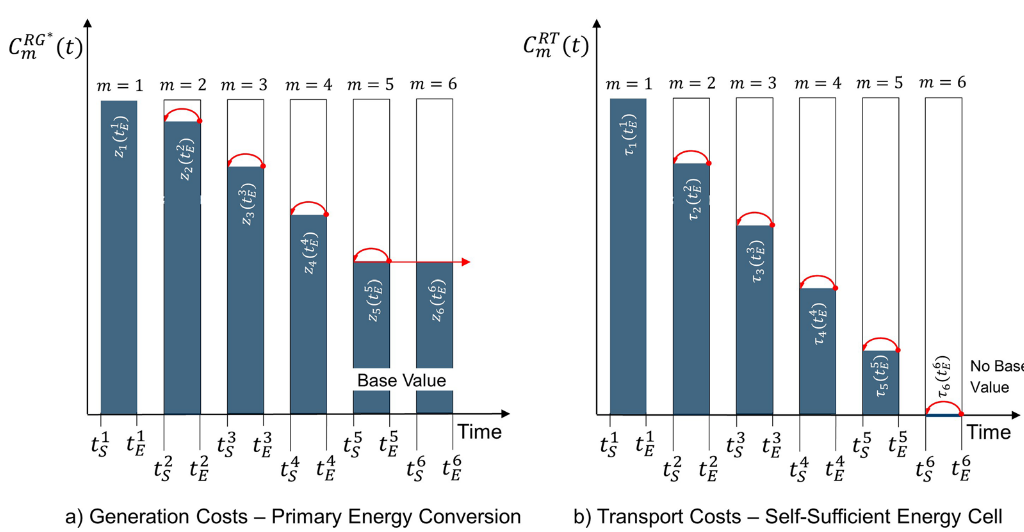

Fig. 10 National regulatory cost control-functions' effect on energy generation and transport costs

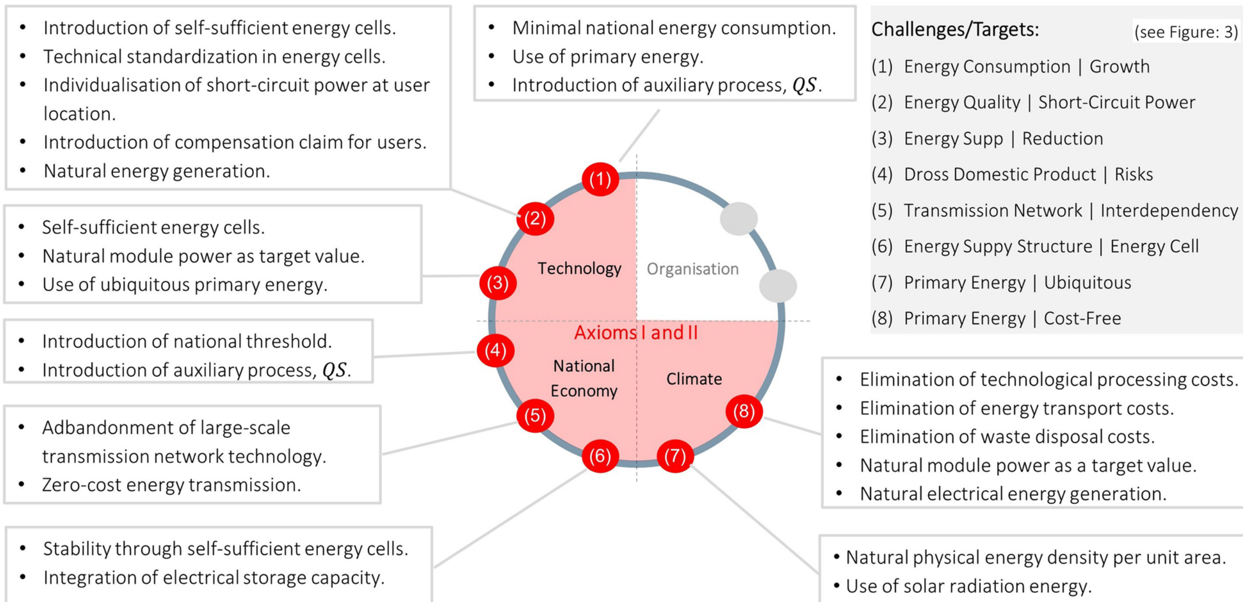

Fig. 11 Achieving the eight challenges/targets derived from Axioms I and II for a multiple-sustainable EESS

$$C_R^{\text{nat}}\left(t_E^{m_0}\right) = C_{m_0}^{RG^*}\left(t_E^{m_0}\right) = z_{m_0}\left(t_E^{m_0}\right) > 0. \quad (16)$$

Example total cost function

Based on the example user control-function (see Fig. 8), the temporal developments of the cost control-functions for energy generation, C_{RG}, and energy transport, C_{RT}, are shown in Fig. 10. The durations of the structural levels are normalized to 1 (one). The illustration in Fig. 10 focuses on climatic and economic effects.

The elimination of possible national over- or under-capacities with respect to generation have a positive or negative effect on users, depending on the individual national situation, i.e. they generally do not have a uniform effect and are therefore not included in the considerations. Likewise, no cost developments for innovations of new generation plant technologies are included. What remains, however, is a cost base that is always greater than zero, since usable electrical energy must always be generated from a primary energy.

The development of energy transport costs depends on the development of self-sufficient national energy cells. The user control-function selected in each case determines the maximum number of users connected via a coherent transmission network and thus reduces the network costs over time.

The possible cost-reduction potential is estimated by the following example for the European Union. The gross domestic product in the EU in 2020 was approximately 14.5 trillion euros. [29] Assuming a share of 1% for the transmission network costs (see challenges (5)), this results in a cost potential of 150 billion euros, which has a positive effect on the consumer surplus of the users.

Conclusions

The question of achievability of a multiple-sustainable national EESS was posed in the introduction of this article. Provided an EESS suits the prescribed axiomatic system, this question can be positively answered.

In the present article, the focus is first on Axioms I and II. They determine the Climate-National Economy-Technology trinity for the EESS, which further produces, if necessary, insurmountable scientific hurdles.[19] For this purpose, eight challenges were formulated and reformulated into measurable targets, the fulfilment of which is equated here with the fulfilment of the first two axioms. The results of the investigations are shown in Fig. 11.

The achievability of natural energy production comprising targets 2 and 8, is the subject of separate considerations in System Solutions II, i.e. this process is not considered in this article (see Outlook). With the mechanisms and instruments shown, Axioms I and II can be sufficiently fulfilled, i.e. there are no insurmountable scientific hurdles. This is not yet sufficient for the multiple-sustainable EESS, since no differentiated statements were made here about Axiom III. For the overall system, the fulfilment of Axioms I and II can only be classified as necessary.

[19] See exclusion criterion.

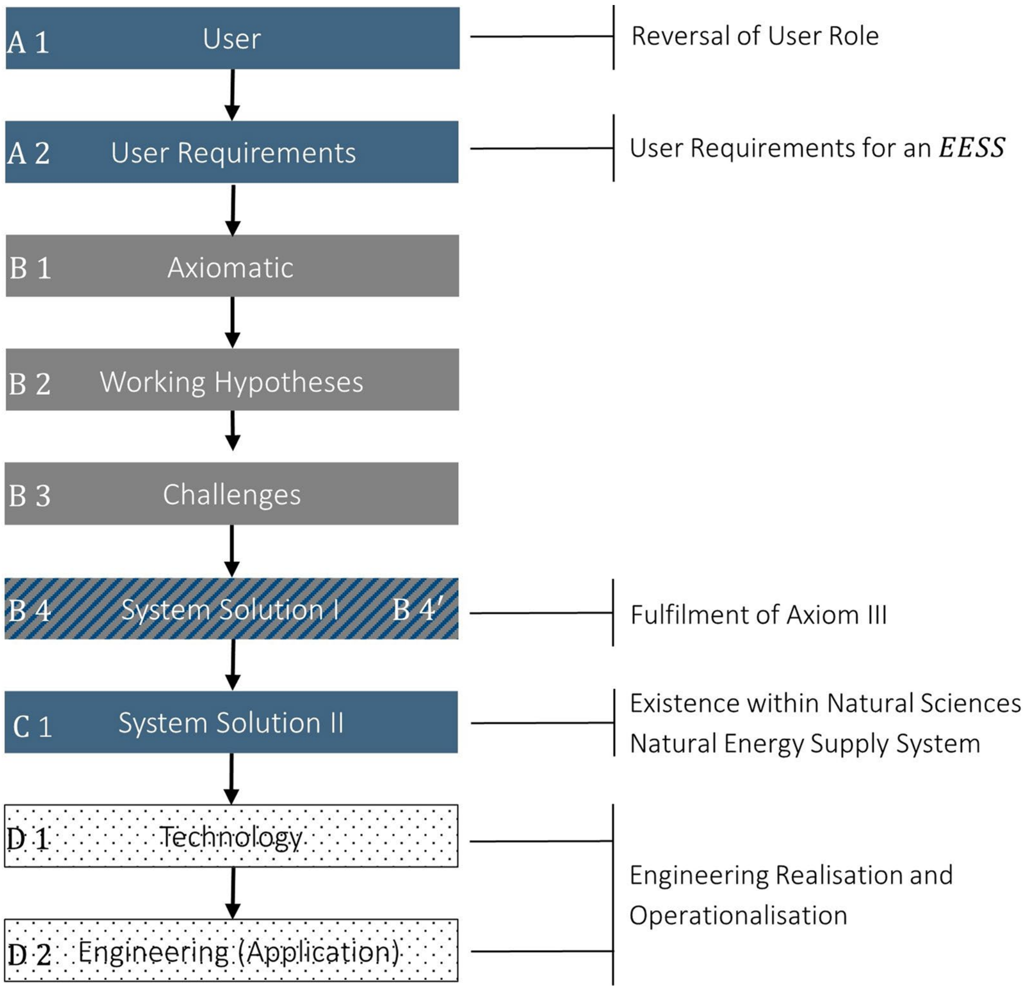

Fig. 12 The subsequent tasks for realization of a multiple-sustainable EESS, expanding upon Fig. 2

Outlook

From the above analysis, the following subsequent tasks arise:

A—Description of the change to the user role from a passive energy consumer to an active designer of electric EESS. Its formulations, of universal and individual user requirements, are prioritized for the entire design process. This eliminates, among other things, the technology dominance that is usually contained in current systems.

B4'—Fulfilment of the requirements of Axiom III, thus providing sufficient design criteria for multiple-sustainable EESSs.

C—Demonstrate solutions for EESSs. Such a system defines the evolution of energy quality (entropy) throughout the whole process, i.e. from the primary energy through to ultimate conversion to dissipated thermal energy.

D—If the fundamental elements for the design of multiple-sustainable EESSs are available, the engineering tasks within the overall process can start (see Fig. 5).

The subsequent tasks necessary to reach a multiple-sustainable EESS, building upon those detailed in Fig. 2, are depicted in Fig. 12.

In addition to the above tasks, below are topics for further scientific investigation:

A national communication strategy for the introduction of a self-sufficient energy cell system for electrical energy supply.

Social user behaviour in the use of ubiquitous and cost-free primary energy, whose generation process to electrical energy is climate neutral.

Optimal economic distributions of self-sufficient electric energy cells in national electric energy supply systems.

Optimal mathematical, physical distributions for national energy flows in self-sufficient electrical energy cells for national electrical energy supply systems.

Development of legal bases for the introduction of self-sufficient electrical energy cells.

Development of legal bases for the primary use of ubiquitous and free primary energy in the generation process of electrical energy.

Appendix

Example EESS system architecture

In order to clarify the functions of the system architecture in the example EESS, the following procedure is chosen. The following exemplary assumptions in the given system architecture are made:

- The number of users refers to the largest connected self-sufficient energy cell of a system state.
- For the energy transport costs, a uniform relative reduction has been made in relation to the actual initial value.
- In the case of energy production costs, the focus is on the use of ubiquitous and cost-free primary energy.

Structural level	Time	Number of self-sufficient energy cells	Number of users	Costs	
				Transport	Generation
	Start (S)	$k_{max}(t_S^m)$	$i_{max}^{k_{max},m}(t_S^m)$	Existing transmission network $C_{RT}^{nat}(t_0)$	Primary energy
	End (E)	$k_{max}(t_E^m)$	$i_{max}^{k_{max},m}(t_E^m)$		
$m=1$ (International)	t_S^1	(1)	10^8	100%	0%
	↓	↓	↓		
	t_E^1	1	10^7	100%	0%
$m=2$ (National)	t_S^2	1	10^7	100%	0%
	↓	↓	↓	– 20%	+10%
	t_E^2	10	10^6	80%	10%
$m=3$ (Regional)	t_S^3	10	10^6	80%	10%
	↓	↓	↓	– 20%	+30%
	t_E^3	10 0	10^5	60%	40%
$m=4$ (Decentral)	t_S^4	100	10^5	60%	40%
	↓	↓	↓	– 20%	+30%
	t_E^4	1000	10^4	40%	70%
$m=5$ (Local)	t_S^5	1000	10^4	40%	70%
	↓	↓	↓	– 20%	+30%
	t_E^5	10000	10^3	20%	100%
$m=6$ (Nano-cell)	t_S^6	10000	10^3	20%	100%
	↓	↓	↓	– 20%	
	t_E^6	$i_{max}^{nat}=10^7$	1	0%	100%

Example EESS explanation	
- The cell-divisions always lead to equally sized number of users in the subsequent self-sufficient energy cells	
- All national users are contained within each structural level	
Initial state	At the beginning, t_S^1, the first structural level is an internationally connected transmission network consisting of two or more island transmission networks. The Island-networks contain 10^8 interdependent users
$m=1$	*Key characteristics:* - Conversion of sample EESS into a system state equal to a nationally self-sufficient energy cell - Reduction of economic risk - No climate neutrality required
	At the end of the first structural level, t_E^1, the example EESS is no longer a component of the international transmission network. The EESS contains now 10^7 national users in a national transmission network
Transition	*Key characteristics:* - Reaching the limit of national electrical energy autonomy - Universal criterion, i.e. nationally independent
$m=2$	At the beginning of t_S^2 the second structural level consists of exactly one self-sufficient energy cell with 10^7 interconnected national users
	Key characteristics: - Achievement of the first national cell division into two self-sufficient energy cells - Reduction of economic risk - Start of the process: Introduction of the use of ubiquitous and cost-free primary energy
	At the end of the second structural level, t_E^2, the example EESS is, at a minimum, divided into two self-sufficient energy cells. Each system contains exactly the same order of magnitude of interconnected national users, 10^6
Transition	*Key characteristics:* - The national interconnected transmission network breaks down into at least two self-sufficient energy cells: A universal criterion, i.e. nationally independent

Example EESS explanation	
$m = 3$ to $m = 5$	In each subsequent structural level, the number of self-sufficient energy cells increases by a factor of 10
	Key characteristics: - The number of interconnected national users per energy cell continues to reduce consequently also by a factor of 10 and, with this, also the economic risk - The use of ubiquitous and cost-free primary energy increases to 100%
Transition(s)	National individual, i.e. the limiting case is to be determined by the nation state
$m = 6$	At the beginning of the sixth structural level, t_S^6, (the final level) the system state consists of 10,000 self-sufficient energy cells, each containing 1,000 interconnected users
	Key characteristics: - The transmission network is reduced down to a micro-network structure - The degree of individualization for the users is at a maximum - There is a 100% implementation of ubiquitous, cost-free primary energy - The generated power corresponds to the natural power
Final state	In the final system state, t_E^6, in the sixth structural level, a nano-cellular structure is achieved. This is a universal criterion and therefore is independent of the nation state

Abbreviations

EESS Electrical energy supply system
GDP Gross domestic product
WH Working hypothesis

Glossary

Axiomatic system — 'A theoretical system is axiomatic when a number of propositions, axioms, 20 are established which satisfy the following four basic conditions: The system of axioms must, considered by itself, (1) be free from contradiction, which is equivalent to the requirement that not any proposition should be derivable from the axiomatic system; (2) the system must be independent, i.e. not contain any proposition derivable from the other axioms ('axiom' is to mean only a principle not derivable within the system). As far as their logical relations to the other propositions of the axiomatic system are concerned, (3) the axioms should moreover be sufficient for the deduction of all propositions of this domain, and (4) contain no superfluous components.' [7].

Blackout — 'A blackout is an uncontrolled and unforeseen failure of electrical transmission network elements. This causes larger parts of the interconnected transmission network or the entire network to fail, known as a " blackout ". Such an event could occur, for example, if severe faults also occur at nodal points in the transmission network in a tense load and generation situation. A blackout is therefore fundamentally not an event triggered by an undersupply of energy, but rather caused by faults in network operation.' [16]. The duration of a blackout depends on the individual case: it cannot be assumed that they are short-term events [30].

Causation principle — Analogous to the basic causality principle, the user of electrical energy pays the costs for its production and supply.

Claim for damages — Quantitative damages are measurable quantities, such as loss of production. Non-quantitative damages are non-measurable quantities, such as personal injury.

Climate neutral — An energetic process is climate neutral if the time function of entropy is monotonically increasing [36].

Multiple-sustainability — An electrical energy supply system is multiple-sustainable if it satisfies Axioms I–III.

Primary energy (cost-free) — Primary energy which may be converted to useable electrical energy without anthropogenic processing or transport. Such primary energy is therefore free of costs before conversion to useful electrical energy. An example of cost-free primary energy is solar electromagnetic radiation.

Electrical energy supply — The process of supplying electrical energy to the users at their locations.

Electrical Energy Supply System (EESS) — A technological/engineered system that forms the basis for the product of energy supply.

Energy cell (Electrical, Self-Sufficient) — An electrical energy cell is a clearly defined spatial structure. It contains a defined supply energy which is the summed utility energy of all contained users. A

	self-sufficient electrical energy cell is an energy cell over whose boundaries no anthropogenic energy transport, as primary energy flow or as electric energy itself, takes place. The difference between the terms self-sufficient energy cells and island transmission networks lies in their origin: energy cells are based on a physical view of energy or energy flows, while island transmission networks are based on a technical view of power frequency control [31]. This can lead to both terms describing the same subject. For example, national island transmission networks can also be self-sufficient energy cells.
Energy generation plant (large-scale)	A technological plant for the conversion of primary energy into usable supply energy. A large-scale generation plant performs the task of many generation plants. In the plant design, the physical bundling option of electrical energy sources is used [24]. This technical form of operation requires a connecting electrical transmission network.
Electrical transmission network (large-scale)	An electrical transmission network (transmission network) is a physically interconnected line structure linking electrical energy sources and sinks in an electrical energy supply system. The network structure is mathematically based on the French train network and is path dependent. [33–35] The ideal value of the system transfer function is 1 (one). The technical dimensioning of an electrical transmission network depends on the electrical energy to be transferred, but not on the primary energy used in the energy conversion plants. A large-area electrical transmission network is an energy network that electrically connects a large number of users over large geographic distances with a few large generation plants. In technical design, nationally/internationally interconnected transmission networks are a characteristic feature.

Nano-cell	A nano-cell is a self-sufficient electrical energy cell that contains very few users and connects the necessary infrastructure. A 1:1 nano-cell is a self-sufficient electrical energy cell that contains exactly one user as well as the necessary infrastructure.
National electrical energy autonomy	All electrical energy consumed within the nation state is also generated within the nation state. The national self-sufficient energy cell directly enables national electrical energy autonomy (see electrical energy cell).
National threshold	The national threshold is a quantity related to gross domestic product (GDP). It provides a lower bound for impacts of electrical energy on a given economy. The lower bound is defined as a measure of GDP reduction.
Natural energy module	The sum of the user-determined electrical energy supply/utility energy of a Natural Module in a calendar year. This amount of energy is fundamentally not determined by technology.
Natural energy production	Natural energy generation is understood to be an energy generation process that converts a natural primary energy into electrical energy in a qualitatively equivalent manner (see climate-neutral).
Natural module	Nation states are a given structure from which the entire community of states can be described in a modular way. They are referred to here as natural modules. In particular, it is true that every user worldwide can be assigned to exactly one natural module.
Natural module power	The concept of power is defined in macroscopic electromagnetism in [37]. The natural module power is electrical power related to the supplied energy at the user location. Its peak value is determined by the maximum power required by a natural module.
Natural primary energy flow	An anthropogenic primary energy flow (primary energy transport) is necessary if the locations of origin and utilization of the primary energy

	are geographically different. A natural primary energy flow (natural primary energy transport) is given if the primary energy transport to the generation plant occurs naturally, i.e., anthropogenic involvement is not necessary.
Non-profit Organization (NPO)	The electrical energy supply is a cultural-technological product with special meaning for the national societies. This becomes strikingly understandable when electrical energy is not available. The resulting consequences range from short and local events to the disablement of entire national economies. For such a system, commercial profits as a return on investment is usually not an acceptable overall objective for the users, thus a non-profit organisation is required.
Pre-technological	A control variable for a national electrical energy system that acts in time before a particular technology isrealized.
Quality-measurement	The distance from the largest self-sufficient energy cell, i.e., the number of connected users, of a structural level and the 1:1 nano-cell (ideal value).
Supply energy	The technically-defined energy at the location of the user.
System architecture	A structural-model description of a national electrical energy supply system via system states that do not incorporate technological/engineering requirements.
System state	Electrical energy supply systems are described by time-varying system states. The individual states have the quality of macroscopic systems in physics, such as temperature in thermodynamics. The quality characteristic of a state is the largest contained self-sufficient energy cell (number of users).
Ubiquitous	Latin 'ubique', for omnipresent, omnipresent, world-embracing [38]. A ubiquitous primary energy is spatially available everywhere on earth. Temporal availability is not considered here.
Usable electrical energy	The supplied electrical energy used by the user.
Users	Users are the consumers of the product of electrical energy. They can be individual people or organizations.
User requirements	User requirements are social requirements for the design of electrical energy supply systems that do not violate scientific laws.

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Author contributions
MB conceptualized and designed the fundamental thesis of the submission. MB conducted the mathematical analysis through which the solution method was developed and the example case extrapolated. MB authored the original thesis in German. MB conceptualized and designed all figures presented within the body of the submission. LG aided in development, interpretation and refinement of the thesis of the submission. LG revised and refined the figures presented within the body of the text. LG revised and structured the thesis into its current form for submission. LG translated the original text from German to English. MB and LG have approved the submitted version prior to submission. MB and LG have agreed to both be personally accountable for their respective contributions and ensure that questions related to the accuracy and integrity of their combined contributions to the submission, even those in which either author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature.

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