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Research article

From a few security indices to the FEW Security Index: Consistency in global food, energy and water security assessment

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ABSTRACT

Following intense debates about a new global development agenda, in 2015 the Sustainable Development Goals (SDGs) were introduced based on the commitment for international collaboration to promote sustained and inclusive economic growth, social development, and environmental protection. In accordance with these objectives, the 'food–energy–water' (FEW) nexus developed as an integrative concept to optimize the interdependent uses of the different nexus resources in order to achieve a sustainable, fair allocation of these resources while enabling economic growth. Addressing this challenge, various FEW nexus indices have been published to allow the global comparison of countries' nexus statuses. Given the complexity of nexus thinking, measuring the state of the nexus is a challenging task in need of a clear methodology. Based on the comparative analysis of selected nexus indices – including our own nexus index (the STE FEW Security Index) – and their underlying methodical approaches, in this paper we discuss the consistency and inconsistencies among these indices as well as their resulting implications.

1. Introduction

The Sustainable Development Goals (SDGs) introduced in 2015 have spurred the debate about implementing the global development agenda. In contrast to its predecessor, the Millennium Development Goals (MDGs), the post-2015-agenda encompasses a much broader spectrum of objectives and also holds industrialized countries accountable (EEA, 2013; United Nations, 2012; Brandi et al., 2013; Weitz et al., 2014). The SDGs are based on a commitment to "work together to promote sustained and inclusive economic growth, social development, environmental production and thereby to benefit all" (UN General Assembly, 2014). The agenda's SDGs are embedded in an interconnected network of targets (Le Blanc, 2015; Lusseau and Mancini, 2019; Pradhan, 2019). It is this interdependence, which draws the direct link between the sustainable development agenda and the concept of the food–energy–water (FEW)[1] nexus. A core element of both is the integrated sustainable governance of natural resources, such as, e.g., "zero hunger" (SDG 2), "clean water and sanitation" (SDG 6), and "affordable and clean energy" (SDG 7) (UN General Assembly, 2015). The consumption of food, energy and water contributes most strongly to the human environmental footprint (Sherwood et al., 2017). Moreover, global population and economic growth trends drive demand for these resources, while climate change negatively affects their availability and quality. A rapid transformation is needed to satisfy the growing demand without transgressing environmental limits (ODI et al., 2012), requiring faster and more profound interventions by public and private decision-makers (WBGU, 2016). Monitoring the efficiency and respectively the environmental impact especially of the water, energy and food provisioning system thus becomes increasingly important (Sherwood et al., 2017).

Within this sustainability discourse, the FEW nexus emerged as an integrative concept to optimize the interdependent uses of the different nexus resources in order to achieve a sustainable, fair allocation of these resources while enabling economic growth (Weitz et al., 2014; Hoff, 2011). It is often applied to trans-sectoral challenges such as, e.g., the food vs. fuel dilemma in biomass production, or the conflict between the water demands of agriculture, energy production, and ecosystems (Hoff, 2011). Although the concept has played a significant role in much of the political sustainability debate since its emergence (Hoff, 2011; WEF, 2011; SEI, 2014; FAO, 2014a), it is increasingly criticized for its conceptual character and lack of unified measurability (Benson and Gain, 2015; Biggs et al., 2015). However, in order to systematically understand and manage the challenges related to the

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[1] Although the resource nexus is most commonly referred to as the FEW (or WEF) nexus, other authors include further or alternate resources, e.g., land, climate, or waste (for an in-depth discussion, see also (Venghaus and Hake, 2018). Since we address resource security assessments in pursuit of the goal of sustainable development in this paper, the more human needs-centered and common WEF nexus concept was chosen.

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interdependencies among the food, energy and water systems, a consistent approach for measuring the state of the nexus is a critical precondition.

To address this challenge, various measures of resource security have been proposed. 'Security' is an anthropocentric concept, which – in the more traditional conception as 'negative security' – regards external threats to human life and well-being (Wolfers, 1962; Gjørv, 2012). The concepts of food security, energy security and water security refer to threats either through physical or social access to these resources and/or to harmful environmental conditions such as pollution or natural disasters (cf. Section 2.1). Especially in recent years, a number of nexus-relevant (security) indices have been developed to estimate national nexus security.

In this paper we comparatively analyze the methodology of nexus security indices and their effects and relevance. The remainder of this paper is thus structured as follows. Section 2 serves to introduce the conceptual foundations by providing an overview of the different nexus-relevant security concepts and indices. In Section 3 we derive the calculation of the STE FEW Security Index[2] based on a multi-centric perspective on food, energy and water security as a means to allow a global comparison of countries' statuses. In the subsequent Section 4, the results of this index calculation are first presented (4.1), and then comparatively analyzed with other existing nexus indices (4.2). The methodological (in-)consistencies of calculating nexus security indices are discussed in Section 5. Finally, the paper concludes with a discussion of the research limitations and a research outlook.

2. Background

Global indicators for the comparison of countries' statuses have been developed for a variety of issues — most notably, perhaps, the Human Development Index (HDI) (UNDP, 2015). Regarding the status of sustainable development, several dedicated models exist, for example, to analyze the impact of resource use (e.g., the Index of Sustainable Economic Welfare (ISEW) (Cobb and Cobb, 1994; Menegaki and Tugcu, 2018)) or the sustainability of more specific industries or sub-sectors (e.g., organic food consumption (Azzurra et al., 2019), furniture industries (Feil et al., 2015)). Likewise, various indices also exist, which directly provide information on the status of resource security for the FEW-nexus resources, e.g., the FAO Food Price Index (FAO, 2019), the WEC Energy Trilemma Index (WEC, 2019), or the Water Exploitation Index Plus (EEA, 2018).

These indicators differ significantly with respect to their reference objects and spatial scales. The reason for this broad spectrum of differing measuring approaches is based in the multidimensionality of the sustainability concept itself — including its economic, ecological and social perspective, from individual- to industry-level, or from local to national or global scale (Darton and Guenther, 2019). Often indicators focus on a specific type of resource, e.g., energy (Grubler et al., 2012), or water (Paterson et al., 2015; Hoekstra et al., 2011; Van Leeuwen, 2013; Vanham and Bidoglio, 2014). Especially recently, however, a number of broader composite indicators have been developed addressing all three of the FEW nexus components (Al-Ansari et al., 2014; Karnib, 2017; Gondhalekar and Ramsauer, 2016; Ramaswami et al., 2017; Sherwood et al., 2017). Moreover, some of those indicators focus on smaller geographic scales to quantify the state of the FEW nexus in specific river basins (e.g., Giupponi and Gain, 2016), or to compare the state of cities across world regions (e.g., Schlör et al., 2018).

Because most composite indicators are based on sectoral resource indicators, the concept of resource security is briefly discussed below, before both the available, nexus-relevant sectoral resource indices as well as the two most widely used composite nexus indices are introduced.

2.1. Security in the context of the FEW nexus

The concept of resource security has often been employed as a way to 'measure' the nexus. Since the end of the Cold War, the concept of security has broadened from its traditional understanding of threats to the nation state to include broader and more ambiguous threats. It now captures individual-level (human) security as well as risks emanating from the economic and ecological spheres (environmental security) (Daase, 2010). Especially since the early 2000s, the growing awareness of climate change and environmental degradation as well as the interrelations between different natural resource systems has led to concerns about scarcity and the potential for conflict (Allouche et al., 2015). Along this line of thinking, challenges of resource management have increasingly been framed in terms of security (e.g. Obama, 2015). Security can thus be understood as a normative term that reflects the absence of threats towards societal values (Wolfers, 1962), from physical safety to protection against poverty and environmental degradation. This constructedness of the security term becomes apparent in the many diverging definitions of energy, water and food security, depending, e.g., on the national and disciplinary context (Pahl-Wostl et al., 2016; Sovacool, 2016). Thus, security is in itself an ambivalent term, and measuring security requires clear definitions.

In the context of the FEW nexus, security largely refers to challenges of access. In the World Economic Forum's (WEF) 2011 "Global Risks" report, water, energy and food supply are identified to be among the most significant future risks (WEF, 2011). Similarly, growth in demand for the nexus resources is characterized as a future security challenge in the U.S. National Intelligence Council's report (US NIC, 2012). However, security in the FEW nexus context also includes the negative environmental effects of the production and use of the nexus resources, especially in terms of climate change and health risks. In the 2019 "Global Risks" report half of the top 10 risks – both in terms of likelihood and impact – are environmental threats such as the failure of climate-change mitigation and adaptation, man-made environmental disasters and ecosystem collapse (WEF, 2019). Consequently, nexus security should be framed as the absence of threats to human well-being and to ecosystems that are linked to the production and use of food, energy and water in consideration of their mutual interdependence. Thus, measuring nexus security allows for conceptualizing and evaluating the state of global sustainable development. The nexus security concept builds upon the sector-level concepts food security, energy security, and water security.

2.2. Food security and its indices

Food security has long been recognized as one of the most fundamental prerequisites of human well-being and development. Already in the 18th century, economist Thomas Malthus introduced the thought of food availability as a limit to population and therefore economic growth (Malthus, 1998). Food security has since been recognized as a human right by the United Nations (UN) (Human Rights Council, 2010). Building on its decades-long work on analyzing the state of food systems worldwide, the UN's Food and Agriculture Organization (FAO) states that food security

[2] STE refers to the department at which the index was developed — namely the Department of Systems Analysis and Technology Evaluation (STE) at the Institute of Energy and Climate Research, Research Center Juelich.

exists when “all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life” (FAO, 1996). Based on this early and still widely accepted definition, food security is considered to consist of the four dimensions food availability, access, stability of supply, and utilization (FAO, 2014b). More recent studies connect food security to the state of nutrition by taking into account nutrient deficiencies such as iron deficiency anemia, or the simultaneous existence of child stunting and adult obesity (FAO et al., 2018). The food sector is comparatively experienced in estimating and monitoring the risks of supply shortages.

There are various indicators for the estimation of aspects of food security in any given region or country. Most of those have been developed for incidences of famine in order to be able to provide adequate supporting measures quickly. Thus, the majority of food security indicators refers to access to and the utilization of food (Jones et al., 2013), e.g., the Global Hunger Index (GHI) or the Food Consumption Score (FCS). However, it has been argued that especially considerations of food availability as well as political and economic stability are further aspects, which are often neglected in index calculations, despite the fact that according to the FAO’s definition they are important prerequisites of food security (FAO, 1996). Furthermore, many indicators are ascertained only for countries with rather low food security and, thus, are not available for industrialized countries.

Of the various available indicators, the Global Food Security Index (GFSI) of the Economist Intelligence Unit (EIU) (EIU, 2018) is the only one, which encompasses all dimensions of food security as discussed above, and which is globally available also for industrialized countries. Its objective is to provide information on which countries are most or least vulnerable to food insecurity. The GFSI is a dynamic qualitative and quantitative benchmarking model, constructed from 28 unique indicators, measuring drivers of food security across 113 countries. It is based on and includes the four categories of Affordability, Availability, Quality & Safety, and Natural Resources & Resilience. Each of those categories consists of several quantitative and qualitative indicators. The category scores are calculated from the weighted mean of underlying indicators and are scaled from 0 to 100, where 100 refers to the most favorable performance. The overall score of the GFSI is calculated as the simple weighted mean of the first three category scores, with the fourth category serving as an adjustment factor. Additional background variables like the prevalence of undernourishment or the HDI are also included in the GFSI model as it is provided online by the EIU, but they are not included in the index calculation. Instead, they serve as values for comparison and better understanding of the situation in a certain country. Data is drawn from national and international statistical sources as well as from indicators and estimates created by the EIU based on a range of sources — primarily the World Bank, the International Monetary Fund (IMF), FAO, and the UN Development Programme (UNDP) (EIU, 2018).

2.3. Energy security and its indices

Energy security periodically receives specific attention in the context of international political and economic relations, most strongly following the oil crises in the 1970s and, more recently, in the light of unreliable trade relations, shifting regional demands, and the integration of renewable energy sources into existing systems (Yergin, 2006). Although the different nexus sectors are closely interrelated, energy differs from the other nexus sectors in one important aspect: energy is generated by utilizing different natural resources such as fossil fuels or solar light. So instead of measuring the availability of energy as a natural resource itself, energy security is determined by the availability of other natural resources (European Commission, 2012).

According to the International Energy Agency (IEA) energy security is defined as “uninterrupted physical availability of energy at a price which is affordable, while respecting environment concerns” (IEA, 2014). Following this line of thought, energy security definitions often revolve around trade relations, specifically consumer countries’ concerns about being dependent on a small number of supplier countries (Goldthau, 2012; Herbstreuth, 2014). The UN’s definition focuses more strongly on the individual energy user, i.e. “access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses” (UN AGECC, 2010). Building on these definitions, energy security consists of the dimensions availability, affordability, efficiency, sustainability, and governance (Sovacool, 2013). The energy sector is experienced in estimating and monitoring risks for specific globally traded resources, such as oil and coal, as well as the performance of energy infrastructures (e.g., the long-running monitoring reports by the IEA, or the WEF’s Global Energy Architecture Performance Index).

There are several indicators for estimating aspects of energy security, most of them developed for supply-side risks such as emergency supply disruptions, price shocks or technical and economic system optimization potentials (Löschel et al., 2010). The IEA, for example, measures energy production, energy self-sufficiency, overall energy intensity and energy consumption (IEA, 2019). The World Energy Council’s (WEC) Energy Trilemma Index attempts to account for the lack of political and ecological aspects by pairing energy security in the sense of supply security with the two additional dimensions energy equity and environmental sustainability (WEC, 2018). Moreover, energy security indicators are mostly calculated for the largest consuming countries, but are often not available for developing countries of less relevance for global trade.

A comprehensive and globally available index for energy security is the International Index of Energy Security Risk (Global Energy Institute, 2018). It was introduced in 2012 by the Global Energy Institute of the U.S. Chamber of Commerce as a companion to its U.S. Energy Security Risk Index. Its objective is to estimate global energy security risks in order to further understanding of their relevance for US energy security. The International Index of Energy Security Risk is a qualitative and quantitative benchmarking model that measures energy security risks across countries and across time. In its report, the index is applied to the 25 top energy consumers globally, and in its online tool, data is available for the top 75 energy consumers. The time frame considers ranges from 1980 to the year prior to publication. The index is currently constructed from 29 indicators which are organized in eight broad categories with a minimum of two indicators per category. The scores for each country are calculated in absolute terms and in relation to a baseline average of member countries of the Organisation for Economic Co-operation and Development (OECD). For each country and each indicator, there is a time series value that is normalized into a risk measure with the OECD 1980 value set to 1000 (Global Energy Institute, 2018). The indicators’ weighting is replicated from the U.S. Index, consisting of a fixed value based on analysis and expert judgement (Global Energy Institute, 2017). The International Index of Energy Security Risk relies primarily on data from the U.S. Energy Information Administration (EIA) and IEA as well as additional data from international organizations such as the World Bank and commercial providers such as BP (Global Energy Institute, 2018).

2.4. Water security and its indices

Water is often considered at the heart of nexus thinking (UNEP, 2012). It is discussed in relation to food security (Bogardi et al., 2012; UN, 2011; Venghaus and Hake, 2018), and increasingly in relation to energy security (IEA, 2016). The reason may be that water constitutes both a natural resource as well as – in the form of drinking water – a life-enabling ecosystem service. Water is an essential resource for all biomass growth and thus fundamental for all ecosystem services (Hoff, 2011). As such it is considered non-substitutable (Bogardi et al., 2012).

Concerns for water security have been central to development agendas since the 1990s (Cook and Bakker, 2013). For example, the MDG for environmental sustainability aimed at securing "sustainable access to safe drinking water and basic sanitation" (UN, 2019), later mirrored in SDG 6 "clean water and sanitation" (UN General Assembly, 2015). Both aspects have become a human right in 2010 (UN General Assembly, 2010). Against the backdrop of emerging nexus thinking, the Second World Water Forum in 2000 was influential in developing a broader and more comprehensive definition of water security (Cook and Bakker, 2013, 2016). According to its Ministerial Declaration, achieving water security consists in "[m]eeting basic needs", "[s]ecuring the food supply", "[p]rotecting ecosystems", "[s]haring water resources", "[m]anaging risks [i.e. water-related hazards]", "[v]aluing water", and "[g]overning water wisely" (WWC, 2000) This broadened definition has still registered criticism for not adequately taking water into account as a binding force between nature and society, e.g., with regard to the interrelations between food, energy and water sectors (Bogardi et al., 2012; Joseph et al., 2008). Nonetheless, the emphasis of water security definitions shifted from "the provisioning, treatment and management of water for human use" to "the availability of and access to water for all human and ecosystem uses" (Hoff and Kasparek, 2016). Scientific use of the term water security has been noticeably increasing since the 2000s and is dominated by the four themes water availability, human vulnerability to hazard, human needs (e.g., food security), and sustainability (Cook and Bakker, 2013), as well as growing attention to issues of power and equity (Cook and Bakker, 2016).

Multiple approaches exist for deriving indices related to water security, e.g., the Water Poverty Index (Sullivan et al., 2003), the Water Risk Security Index (Maplecroft, 2016), or the Water Risk Framework (WRI, 2016). From the outset, many indices have focused on aspects of physical availability, often estimating national water resources. One such index is the widely used Water Stress Index which was developed in the context of food security to measure the availability of renewable fresh water resources to the population by the proxy of mean annual river run-off (Falkenmark, 1989). However, such approaches of water security are often not capable of accounting for the dynamics and variations that exist within a country and between seasons. Therefore, more holistic approaches have emerged that include society's adaptive capacities and environmental demands, both of which can entail also water quality characteristics (Damkjaer and Taylor, 2017). The Water Poverty Index evaluates water availability, access, management capacities, human demands, and environmental demands, determining water demand by household-level data (Sullivan, 2002; Lawrence et al., 2002). Also, against the backdrop of global urbanization trends, there are a number of approaches measuring water security at city level (e.g. Srinivasan et al., 2013; Jensen and Wu, 2018). Due to the varying and broad understandings of the term, approaches to quantify water security vary considerably in framing, methods, and scale (Cook and Bakker, 2013).

The Water Risk framework was introduced by the World Resources Institute for the "Aqueduct Water Risk Atlas" in 2013 (Reig et al., 2013). It builds on existing water-related indices and indicators and is a benchmarking model of global scope derived from the twelve indicators of the Water Risk Atlas, which are aggregated into the three risk dimensions Physical Risk Quantity, Physical Risk Quality, and Regulatory and Reputational Risk, as well as in a composite index. Twelve indicators are grouped in these three dimensions, six of which were developed specifically for this framework, whereas the others are adapted from existing publications. Scores are aggregated by mapping indicator values to thresholds and normalizing them to a score between 0–5 (with 0–1 being the lowest category). Weighting of indicators can be determined by users or chosen according to industry sector weighting profiles such as agriculture or mining, allowing for personalized risk maps. Spatial comparison is possible across regions, countries and continents. Data is acquired from publicly available global data sources that were selected based on literature review and in consultation with external experts, both global data bases produced by research projects as well as data from international organizations such as the National Aeronautics and Space Administration (NASA) and FAO (Reig et al., 2013; Gassert et al., 2015, 2014).

These sector-level indices serve to estimate the state of food, energy and water security respectively, and are employed to this purpose regularly. Each of them largely measures comparable dimensions: resource quantity, quality, accessibility and availability. As briefly alluded to in the introduction, however, specific to the FEW-nexus approach is its holistic, multi-centric perspective on integrated resource management in order to capture the sectors' interdependencies and their effects (Benson and Gain, 2015). To account for these, a number of further indices have been developed which build upon sectoral estimates but aim to provide valuable further insight on integrated nexus security.

2.5. Nexus security indices

Developing and using an integrated nexus index, however, inheres its own methodological challenges, which – depending on the underlying assumptions – may significantly influence the results. Composite indices are often used in policy analysis and public communication (OECD, 2008). There is an ongoing debate on the usefulness of aggregated indices which centers on balancing two demands: making complex developments and large datasets accessible for informing decision-makers on the one hand, and providing the details and interrelations of partial aspects and variables in order to not potentially prompt incorrect conclusions on the other hand (Jollands et al., 2003; OECD, 2008). In the case of measuring the nexus, indices as descriptive statistic serve the valuable purpose of rendering the nexus' complexity tangible. However, given the potential for misrepresentation, an adequate nexus index requires conceptual consistency. Composite indices' central methodological challenges have been identified as the selection of sub-indices, an appropriate aggregation function, and the weighting scheme (Jollands et al., 2003).

A number of nexus related indices exist. Among the most widely used are the RAND Food–Energy–Water Security Index and the SDG Index. The RAND Food–Energy–Water Security Index mirrors the concept of a nexus comprised of the three sectors food, energy and water and relies on the respective sector-level indicators. In contrast, the SDG Index is a broader index with considerations that go well beyond measuring the three FEW sectors. However, as described in the introduction, the basic resources food, energy and water are core elements of sustainable development and thus constitute crucial factors for achieving the broader, but closely intertwined more socio-economic SDGs. For this reason, both the RAND Food–Energy–Water Security Index and the SDG Index and their methodological differences are included in the consecutive analysis (Section 4).

The RAND Food–Energy–Water Security Index was developed by the RAND Corporation in order to inform development agencies concerned with the nexus resources (Willis et al., 2016). The RAND FEW Index is a quantitative benchmarking model, calculated from three sub-indices which in turn comprise at least two indicators. The index is calculated for every country, though data availability varies. Indicators reflect two categories, Availability and Accessibility. Indicators are normalized by selecting the logical minimum and maximum values, with minimum = 0 and maximum being the maximum possible value. The overall index score and the sub-indices are calculated from the unweighted geometric mean of the indicators respectively, and are scaled from 0 to 1, where 1 = most favorable. In the accompanying technical report, the RAND FEW Index is related to the HDI, this consideration, however, is not included in the index calculation. Data is acquired from publicly available sources of global scope, primarily from the FAO as well as the World Bank, the UN's MDG indicators, the EIA, and a monitoring program by the World Health Organization (WHO), and the UN's Children's Fund (UNICEF) (Willis et al., 2016).

The SDG Index was introduced by the Sustainable Development Solutions Network and the Bertelsmann Stiftung in 2016 in order to track all 193 member countries' performance on the SGD goals, although only 156 are included in the ranking due to data availability (Lafortune et al., 2018). The SDG Index is a quantitative benchmarking model, constructed from official SDG indicators endorsed by the UN Statistical Commission that reflect the overarching conceptual framework of the 17 SGDs. Where data is unavailable, gaps are closed by including metrics by other providers. In the 2018 edition, 86 indicators are included. They measure absolute country performance and are normalized from 0 to 100, where 100 corresponds to the "technical optimum", i.e. sustainability. Equal weighting is used at the goal and indicator level. Individual SDG scores and the overall index score are calculated using the arithmetic mean. Methodology and indicators are revised annually. Data is mainly acquired from publicly available, but also additional non-official data, which is provided e.g. by research institutions. Official data sources are primarily OECD, WHO, UNICEF and World Bank as well as several other UN organizations (Lafortune et al., 2018).

The variety of actors and approaches involved in measuring food, energy and water security only hint at the challenges of devising an appropriate nexus security index. Most fundamentally, both indices propose equal weighting of the three nexus resources, which arguably reflects that the nexus is thought of as triangle-shaped complex (Hoff, 2011). However, with regard to the aggregation function and the selection of sub-indices they differ greatly resulting in different rankings of national nexus securities. Thus, a thorough analysis of their methodology is important. In order to conduct such an analysis, we employ the SDG Index and the RAND FEW Security Index as a foil for developing and comparing our STE FEW Security Index. This approach allows us to analyze potential methodological inconsistencies and their effects in a consecutive step by step process (Sections 3 and 4).

3. Method

The first element of our analysis was the development and calculation of the STE FEW Security Index. By doing so we were able to directly identify and explain potential methodological inconsistencies. We developed the FEW Security Index based on the comprehensive and well-established sector indices introduced in Section 2 – the International Index of Energy Security Risk (Global Energy Institute, 2018), the Global Food Security Index (EIU, 2018), and the Aqueduct Water Risk Framework (WRI, 2016). In this section, the basic conceptual and structural requirements for developing and comparing indices were systematically established.

3.1. Data selection and comparability

In a first step, data was carefully selected and prepared for index development and comparison. Based on the screening of the existing sector indices, only countries were included for which full data for all three sector indices and both nexus indices were available.[3]

In order to ensure comparability of the data, all indices were normalized. Since both considered nexus indices are security indices (i.e., the higher the value the higher the level of security), but two of the sector-level indices used as sub-indices are risk indices (i.e., the higher the value, the lower the level of security), the inverse was calculated for the respective risk indices. Furthermore, because the spread between the maximum value and the minimum value ranged from 0.370 for the SDG Index to 0.881 for the Water Stress Indicator in the Water Risk Framework, in a next step all values were normalized. For this purpose, indicators were transformed linearly to a scale between 0 to 1 using the following rescaling formula: $x' = (x - \min(x))/(\max(x) - \min(x))$, where x is the raw data value, max(x) and min(x) denote the bounds for best and worst performance respectively, and x' is the normalized value after rescaling. This fully normalized dataset served as the data basis for the analysis.

3.2. Aggregation of sub-indices

Given that our calculation builds on existing sector-level indices, the next critical step in devising the STE FEW Security Index was the choice of the aggregation method. Fundamentally, this choice entails an assumption about how the individual variables – here, the nexus resources food, energy and water – relate to each other. More precisely, this represents the degree to which changes in one variable affect another. In composite indices, these relations can be described by the standard constant-elasticity-of-substitution (CES) function (e.g., Lafortune et al., 2018; Arrow et al., 1961; OECD, 2008). This function describes the level of substitutability among the variables. Since the premise of nexus thinking is that the nexus resources are interrelated, as presented in the introductory and background sections, the CES function is especially suitable for devising a nexus index. Only the SDG Index employs the CES function explicitly (Lafortune et al., 2018), whereas the RAND FEW Security Index directly opts for an unweighted geometric mean in order to improve transparency and supposedly greater understanding (Willis et al., 2016). However, in order to explore the effects of different assumption about substitutability and to allow for maximum flexibility in the aggregated data, we use the CES function to generate the STE FEW Security Index I_{ij} for index j and country i. I_{ijk} is the score of indicator k, and N the number of indicators. ρ describes the substitutability of the index components with a range of $-1 \leq \rho \leq \infty$. σ describes the elasticity of substitution with a range of $0 \leq \sigma \leq \infty$, where $\rho = \frac{1-\sigma}{\sigma}$.

Thus, as basic formula for the STE FEW Security Index we presume:

$$I_{ij}\left(N_{ij}, I_{ijk}, \rho\right) = \frac{1}{N_{ij}}\left[\sum_{k=1}^{N_{ij}} I_{ijk}^{-\rho}\right]^{-\frac{1}{\rho}}$$

[3] A complete list of the 40 countries included is provided in the Appendix.

3.3. Substitutability assumptions

To explore the effects of different substitutability assumptions, we revert to three special cases of the CES function: perfect substitution, no substitution, and non-linear substitution (OECD, 2008; Lafortune et al., 2018). In the case of the FEW nexus, these cases have the following implications:

Nexus thinking assumes complex relations between food, energy and water, which can take any form from synergies to trade-offs. For example, energy and water demand are intrinsically linked by the water provisioning system. Energy and food can be bound by a diametrically opposed relation. The land to produce biomass is limited, so in order to grow more energy crops, the space for food production would have to be compromised. Such links and trade-offs between nexus resources are not easily definable and neither is the degree of their substitutability.

A key concern of the nexus approach is to optimize the sustainable use of nexus resources by explicitly considering the interdependent links between them. Sustainability is generally understood as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). There is an ongoing theoretical debate rooted in economic growth theory about the relation between sustainability and substitutability of natural resources.

On the one hand, there is a line of thought based on neoclassical economics which assumes that inputs into the production and exchange of goods and services are independent from each other, so that they can perfectly substitute each other. Consequently, natural capital is thought to be replaceable by human capital, e.g. consumed or degraded natural resources can be balanced out by technological change. This is referred to as 'weak sustainability' (e.g., Solow, 1995; Neumayer, 1999, 2012; Ayres et al., 1996).

A second line of thought based in the field of ecological economics, in contrast, criticizes those assumptions, arguing instead with the significant – and non-substitutable – role of ecosystem services. It is argued that natural capital is multi-functional and complementary to – thus not substitutable with – human capital, referring to this case as 'strong sustainability' (e.g., Ekins et al., 2003; Brand, 2009; Ayres et al., 1996).

These co-existing lines of argumentation can be directly translated to the FEW nexus. One option is to achieve sustainability on the nexus level by accounting for and exploiting the synergies and trade-offs between the individual resources food, energy and water. This correlates to the assumptions of weak sustainability. However, each of these resources can also be conceived of as fundamental to sustainability in their own right: each of these resources provides services that cannot be fully compensated for by other resources. Referring to the earlier discussion of sustainability, this line of thought would argue that a more sustainable energy system cannot compensate for services provided by less sustainable food and water systems, since unsustainable practices in one sector already render the overall nexus unsustainable. Instead, it would require sustainable food, energy and water systems at the same time, leading to the conclusion that nexus resources cannot or only to a very limited degree be substituted for each other. In terms of the sustainability debate, this correlates to strong sustainability.

Yet, considering no substitutability between the nexus resources seems counterintuitive. Not only is substitutability among natural resources assumed in economic theory, but the whole concept of nexus thinking rests on the idea of holistic and integrated resource management. It assumes trade-offs and synergies between the nexus resources (Hoff, 2011). There are, however, two major limiting factors to substitution: complementarity (as discussed above) and scarcity. Especially under conditions of scarcity, substitution may not be feasible. It is important to note that scarcity does not necessarily refer to physical nature. Also political tensions, social inequality, economic constraints, international trade relations, or even sustainability thresholds can limit the ability to substitute one nexus resource for another. As this discussion shows, there are varying assumptions about substitutability, ranging from no substitutability, to perfect substitutability, or limited substitutability, which should be considered in the analysis.

3.4. Aggregation cases

These three cases of substitutability can mathematically be well represented using the CES function. As derived above, for the case of the STE FEW Security Index we will refer to them as the cases of weak sustainability, strong sustainability, as well as a third case of intermediate sustainability:

(1) We presume a case in which the nexus resources are *perfectly substitutable*, where $\sigma = \infty$ and $\rho = -1$. Here, the function mathematically converges into the arithmetic mean of the index components: $I_{ij} = \frac{1}{N_{ij}}\left[\sum_{k=1}^{N_{ij}} I_{ijk}\right]$. This case corresponds to the assumptions of weak sustainability.
(2) We further presume a case in which there is *non-linear substitutability* with $\sigma = 1$ and $\rho = 0$. In this case the function mathematically converges into the geometric mean: $I_{ij}\left(N_{ij}, I_{ijk}\right) = \prod_{k=1}^{N_{ij}} \sqrt[N_{ij}]{I_{ijk}}$. This corresponds to an intermediate case of sustainability.
(3) In the last case we assume *no substitutability*, with $\sigma = 0$ and $\rho = \infty$. This case corresponds to a Leontief production function, where in the lowest indicator value (i.e., the lowest security) defines the index score: $I_{ij}\left(I_{ijk}\right) = Min\left\{I_{ijk}\right\}$. This case corresponds to the assumptions of strong sustainability.

The SDG Index uses the arithmetic mean due to simpler interpretation and similarity of results compared to using the geometric mean (Lafortune et al., 2018). However, as discussed, this approach assumes perfect substitutability between all variables, which may not be applicable to the nexus resources under all circumstances. The RAND FEW Security Index, in contrast, applies the geometric mean in order to account for more heterogeneous variables (Willis et al., 2016). As discussed, this approach incorporates the idea of limited substitutability between nexus resources, however calculating the geometric mean enhances the impact of a low variable value on the overall score. The implications of the choice of aggregation method are pronounced in some of the resulting country scores. For a deeper understanding of these effects, the results of the RAND FEW Security Index and the SDG Index are analyzed in the consecutive section in comparison to the STE FEW Security Index.

We pursued the STE FEW Security Index calculation based on a weighted multi-centric perspective on food, energy and water security with the three introduced variations on the assumed degree of substitutability — perfect, non-linear, and no substitutability. We then proceeded to calculate country scores in order to comparatively analyze the index outcomes. Data was acquired for a comparable time span; namely from the 2015 projection of Water Stress (business-as-usual) in 2020, the 2016 Energy Security Risk Index, the 2012 Global Food Security Index, the 2016 RAND FEW Security Index, and the 2017 SDG Index.

Table 1
STE FEW Security Index' sub-index scores for Mexico.

Mexico	Food sub-index	Energy sub-index[a]	Water sub-index[a]
STE FEW Security Index	0,625	0,973	0,221

[a]Inverse and normalized (cf. Section 3).

Table 2
Comparison of RAND FEW Security Index and STE FEW Security Index subindex values for Kazakhstan.

Kazakhstan	FEW Index (norm. [0;1])	Food sub-index	Energy sub-index	Water sub-index
RAND FEW Security Index	0,778	0,730	0,860	0,870
STE FEW Security Index (non-linear substitutability)	0,000	0,533	0,872[a]	0,068[a]

The table displays original data in case of the RAND FEW Security Index' sub-indices, and data normalized to a 0–1 range for the STE FEW Security Index' sub-indices, respectively.
[a]Inverse (cf. Section 3).

4. Results

In order to analyze consistency, and thus the robustness of results, among nexus indices, the discussion of the results is separated into two sections. First, we comparatively discuss the results of our STE FEW Security Index calculation for the three different aggregation methods described above and for all selected countries (Section 4.1). In Section 4.2, we present the results of the comparative analysis of our own STE FEW Security Index with two widely used nexus indices, the RAND FEW Security Index and the SDG Index.[4]

4.1. Country comparison according to different aggregation methods

Fig. 1 provides the results of the STE FEW Security Index calculation based on the assumption of perfect substitutability (weak sustainability) for the selected countries using the arithmetic mean of the three sub-indices.

It shows that for this case, the STE FEW Security Index provides plausible results with countries such as Denmark and Norway performing best on nexus security, and countries such as Kazakhstan, Morocco or Ukraine showing a low security level.

In a next step, we compared the countries' STE FEW Security Index values for the three special cases of perfect, non-linear and no substitutability. As displayed in Fig. 2, for the high security and low security spectrum the results show a general level of consistency, although among the different cases the country ranking differs.

Overall, in the case of no substitutability (strong sustainability) countries' security scores are noticeably lower, whereas in the case of perfect substitutability (weak sustainability) security scores tend to be relatively higher. These results are in line with general expectations that no substitutability of nexus resources signifies lower nexus security. Methodologically, the results can be explained by the high impact of a single low value variable on the aggregated score when calculating a Leontief production function in comparison to calculating the arithmetic mean. The case of Mexico well exemplifies this effect (Table 1).

Whereas the sub-index for energy security is very high, there is a moderate value for food security and a low value for water security. In this case, the mathematical translation of perfect substitutability into the arithmetic mean leads to a moderate overall FEW nexus security. In the case of no substitutability, instead, the low level of water security defines the overall security, thus implying also a low overall FEW nexus security score.

4 For illustration purposes, the respective figures show different selections of indices. A figure showing the results of all indices has been added to the Appendix.

Such effects show especially in the middle sector of moderate FEW nexus security, in which results vary much more strongly. For several countries in this category, the non-linear substitutability case results in significantly higher security scores than for either no or perfect substitutability. Conceptually this reflects the assumption that high security in one resource sector can compensate for moderate deficiencies in other resource sectors.

As this discussion shows, differences in aggregation methods can strongly determine overall scores for FEW security, especially for the majority of countries, which score neither evenly high nor evenly low in all three resource sectors. The implications will be discussed in Section 5.

4.2. Comparison across different indices

In addition to the above comparison of different substitutability assumptions and their effects on the STE FEW Security Index, in the following the results will further be analyzed with respect to differences and inconsistencies when compared to the RAND FEW Security Index (Fig. 3) as well as the SDG Index (Fig. 4).

As Fig. 3 shows, for certain countries the security values diverge considerably. Reverting again to exemplary cases, the country of Kazakhstan provides interesting results. Its RAND FEW Index value is much higher than the comparable non-linear substitutability case value of the STE FEW Security Index. The intermediate case was chosen since both index calculations are based on the geometric mean. The reason for this significant difference between the two nexus indices primarily lies in the respective sectoral sub-index values for water security (Table 2). The RAND FEW Security Index mostly builds on data from the FAO for water security (Willis et al., 2016), whereas the STE FEW Security Index builds on the Water Risk framework which draws on datasets by multiple international research organizations with FAO being only one source (Gassert et al., 2014). Although these data sets overlap, the choice of data sources and variables, and the subsequent calculations differ between the STE FEW Security Index and the RAND FEW Security Index. For the values of the other two sub-indices, these differences are similar, but not as pronounced (Table 2).

In turn, we also found cases in which we calculated much higher security levels than those of the RAND FEW Index. To understand the reasons, we further investigated the underlying values (specifically the indicators used to calculate the sub-indices). Whereas the STE FEW Security Index aggregates sub-indices on the sector level, the RAND FEW Index aggregates on the indicator level. This methodical difference produces notable effects. Similar to the effects that became apparent when calculating the geometric mean for countries with one extreme value in a sub-index, we found that very high or low security values in one of the sub-indices' indicators decisively influences the overall score.

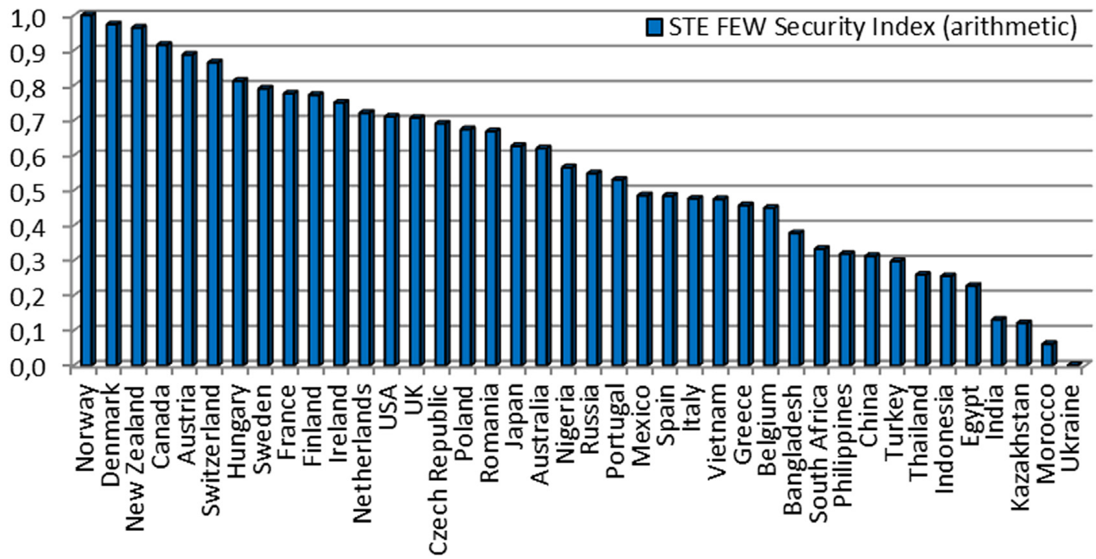

Fig. 1. STE FEW Security Index scores for the case of perfect substitutability (arithmetic mean).

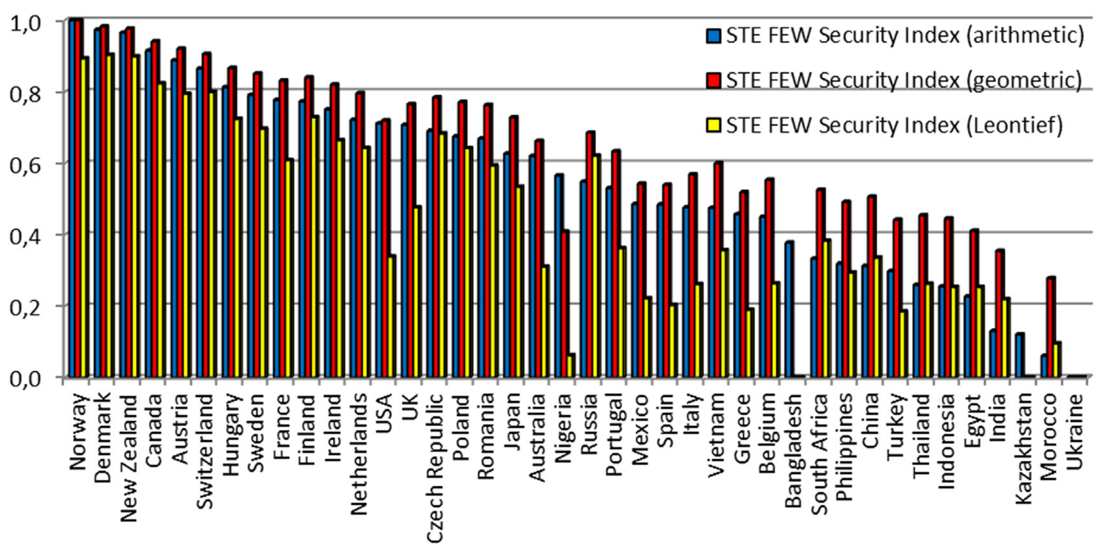

Fig. 2. Comparison of STE FEW Security Index scores for the three aggregation cases perfect substitutability (arithmetic mean), non-linear substitutability (geometric mean), and no substitutability (Leontief production function).

In this case, the results for Denmark differ considerably (Tables 3a and 3b). Denmark is conventionally known to have high security levels for its food, energy and water systems, and, unsurprisingly, we calculated a very high score for Denmark. However, the RAND FEW Index proposes a significantly lower security score. Looking into its indicators we found high security values for all except one: water adaptive capacity (Table 3a). This indicator refers to the "availability of water resources to meet new needs or compensate for declines in existing sources" (Willis et al., 2016). Even though every other aspect of Denmark's food, energy and water systems is rated very positively, and the chance of sudden changes to Denmark's water demand and supply is low, calculating the geometric mean from the indicators results in an overall lower nexus security score. Therefore, in this case, the differences in the level of aggregation result in diverging scores. Moreover, including this specific additional indicator has an impact on the scores.

Examining individual indicators' role in the overall index is especially relevant with regard to aspects of accessibility, i.e. resources' distribution across society (Willis et al., 2016). Sustainability as the overall normative frame of the nexus suggests intra-generational justice for the allocation of resources. Taking into account socioeconomic conditions such as equity in index calculations (e.g., Schlör et al., 2018) may provide further valuable insight when measuring the nexus. Rather than considering merely the aspect of accessibility, some indices (e.g., the RAND FEW Index and the Global Food Security Index) reflect their results against the HDI (see Sections 2.2 and 2.5 respectively). The SDG Index much more explicitly integrates the social dimension by including further indicators reflecting the status of health, education or inequality in a country.

When comparing the results of the RAND FEW Index, the SGD Index and the STE FEW Security Index, we found that the SDG Index results for developed countries' nexus security tend to be more adequate than the other indices' (Fig. 4). For example, for Denmark, while the RAND FEW Index highlights the

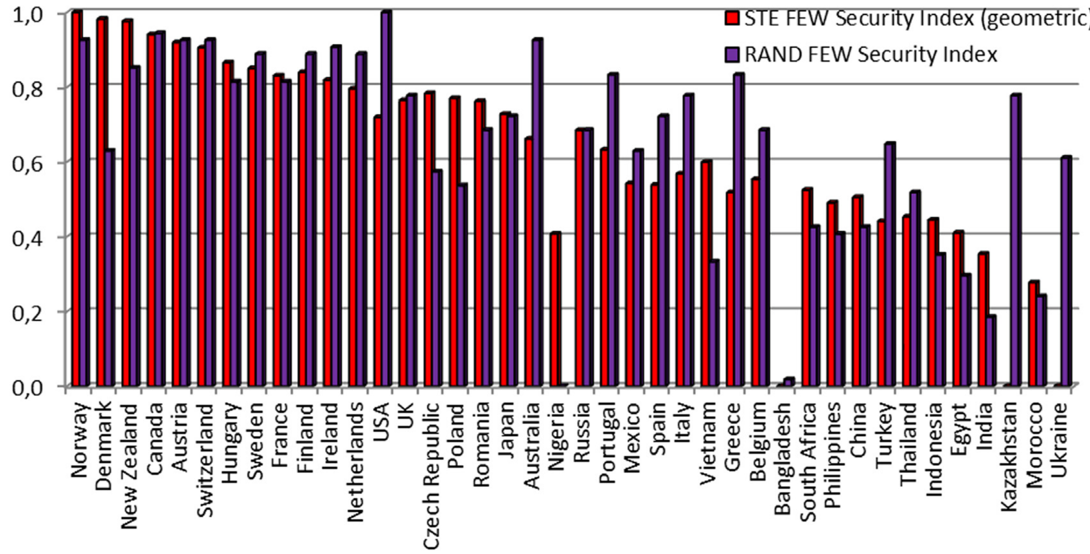

Fig. 3. Comparison of STE FEW Security Index non-linear substitutability case (geometric mean) and RAND FEW Security Index.

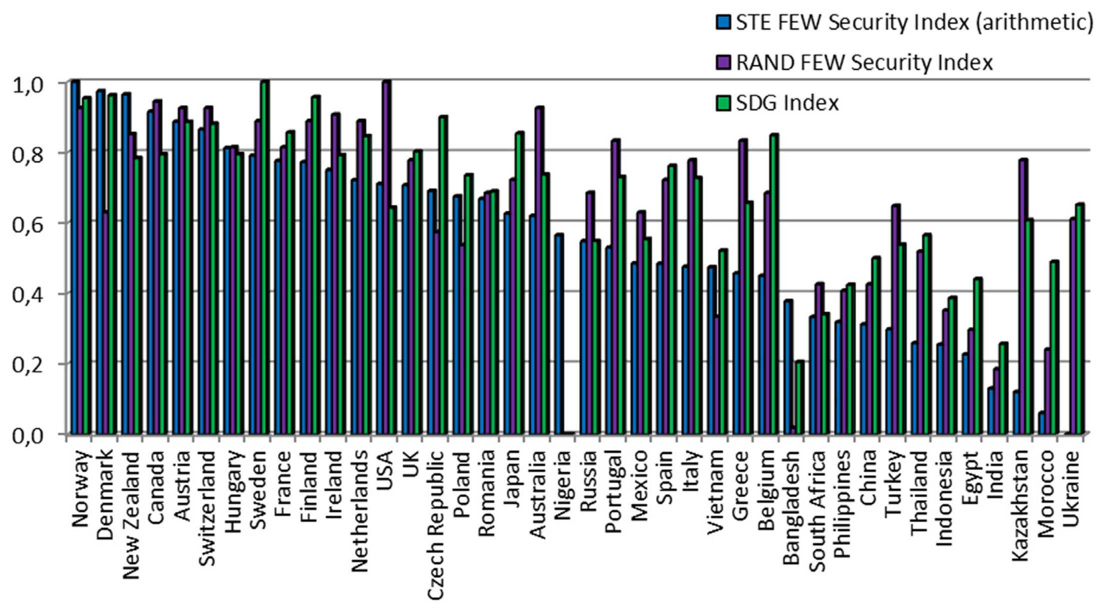

Fig. 4. Comparison of STE FEW Security Index perfect substitutability case (arithmetic mean), RAND FEW Security Index, and SDG Index.

water insecurities and results in mid-level overall performance, the SDG Index results in one of the best overall performances, given the strong social characteristics of the country. By including the social dimension, the SDG Index demonstrates how socially strong countries are able to compensate for weaknesses in single aspects of the nexus. In turn, for developing countries SDG Index values tend to be lower than the STE FEW Security Index values, e.g., especially for Nigeria. Thus, the scope of indicators included in nexus indices impacts on countries' scores, even more so for socioeconomic indicators.

5. Discussion

The results of the STE FEW Security Index and the comparative analysis of three nexus indices reveal significant inconsistencies in measuring the nexus that require further explanation. The calculation of our STE FEW Security Index for the three different substitutability assumptions in the sustainability concept revealed unexpected outliers especially for calculating strong and intermediate sustainability cases. In the first case, low values of security in one sector result in an overall low security score. In the second case, however, high security values in one sector are responsible for an overall high security score. Since we inverted two sub-indices from a risk index to a security index, calculating risk rather than security in all cases would have the exact opposite effect. In general, this means that extreme values in one sub-index highly impact the overall score. More fundamentally, however, these results highlight that underlying, potentially implicit assumptions about the substitutability of food, energy and water resources, and about overall sustainability play a significant role for estimating countries' nexus security. These assumptions are especially consequential in the nexus context, since they rest on the very understanding of the trade-offs and synergies which link the individual nexus resources.

A further aspect of major consequence is the choice of data. The RAND FEW Security Index mostly builds on data from the FAO (food, water), and the EIA and World Bank (energy), whereas the STE FEW Security Index builds on the established sectoral indices

Table 3a
RAND FEW Security Index' sub-index and indicator values for Denmark.

RAND FEW Security Index			Denmark							
FEW Index	Food sub-index	Food accessibility	Food availability	Energy sub-index	Energy accessibility	Energy availability	Water sub-index	Water accessibility	Water availability	Water adaptive capacity
0,630	0,800	0,740	0,860	0,880	0,970	0,800	0,570	1,000	0,870	0,210

The table displays data normalized to a 0–1 range.

Table 3b
STE FEW Security Index' sub-index values of non-linear substitutability (geometric mean) case for Denmark.

STE FEW Security Index (non-linear substitutability)			Denmark
FEW Index	Food sub-index	Energy sub-index	Water sub-index
0,982	0,903	0,923	0,957

The table displays data normalized to a 0–1 range, and in case of the energy and water sub-indices the inverse (cf. Section 3).

as discussed in Section 2. Comparing both indices' nexus security values revealed differences in data sources which were amplified by the methodological choices. An in-depth evaluation of the respective data collections is beyond the scope of this paper. However the results of our analysis show that the effects of data choices can be significant and are often motivated by the index developer's intent. Each institution has its unique perspectives and objectives which are reflected in the data they provide. For the above example of water security (Section 4.2), the Aqueduct dataset, on which the STE FEW Security Index water sub-index rests, comprises multiple datasets on very specific issues such as flood occurrence by specialized institutions, whereas the FAO's AQUASTAT database primarily used in the RAND FEW Security Index offers extensive data on national water resources with a focus on irrigated agriculture in developing countries. These slight variations are enhanced by the fact that only few variables are ultimately selected from the databases for the sub-indices.

We also delved more deeply into the various nexus indices' underlying indicators. Comparing the values for food security, energy security and water security across the three nexus indices revealed two major inconsistencies. Firstly, the level at which aggregation occurs – e.g., across sub-indices or on the level of indicators – proved to have considerable impact on the overall nexus security score. This holds true especially for countries with very high or very low values in any one of the subcategories — regardless of how significant this single aspect actually is in the respective case. Secondly, including further aspects into nexus estimations such as the social dimension, significantly changes outcomes, e.g., correcting for differences between developing and developed countries. Both inconsistencies concern the scope of chosen indicators.

The relevance and consequences of including socioeconomic aspects is especially noteworthy. Nexus indices mostly portray the sustainability of natural resource systems at the level of the nation state. Though politically useful, choosing this scale has a significant limitation: issues of inequality are concealed (Ayres et al., 1996). As mentioned in the analysis, domestic socioeconomic structures determine risks to the availability of national resources for households and individuals, which can differ significantly from the national-level estimates (e.g., Schlör et al., 2018). Furthermore, countries increasingly engage in the trade of natural resources in order to balance out local resource risks or shortages. The effects of these trade dynamics, however, occur on the resource rather than the nexus level, so that these effects are or should be considered on the sectoral sub-index level.

All in all, our analysis demonstrated that basic methodological choices with regard to data sources, level of aggregation, and scope of indicators fundamentally shape nexus security indices' outcomes. These inconsistencies are problematic for adequately measuring the nexus in pursuit of sustainability. Regarding aggregate indices of energy security, Narula and Reddy (2015) note that the large variation in some scores implies individual countries' greater sensitivity to methodological choices. We can confirm this observation for nexus indices, which are aggregated on an even higher level. The scores of countries characterized by less 'extreme' nexus security performance, i.e. neither overwhelmingly positive nor negative, as well as an 'extreme' performance in a single aspect of national nexus security, are greatly determined by methodology. This potential for misinformation raises fundamental questions about the appropriateness and sufficiency of existing nexus indices. It also calls to critically reflect upon and put into context nexus index scores and rankings — especially, since methodological choices are often not sufficiently communicated to their major target group, the decision-makers.

Moreover, certain characteristics of nexus security indices fail to capture the fundamentals of nexus thinking. In a review of the nexus literature, Albrecht et al. (2018) termed this a considerable "disjuncture" between the nexus concept and nexus operationalization. For example, simply adding up sector security values disregards the complex relations and feedbacks between the nexus resources food, energy and water, and instead assumes static relations. A useful contribution to this gap is provided by Pradhan et al.'s (2017) quantification of SDG interactions, which addresses both positive and negative correlation between individual goals by measuring associations between variables. This approach allows a quantitative approximation of dynamics between food, energy and water, which has so far been disregarded in composite nexus indices. However, prior to doing so, several fundamental challenges of measuring a dynamic nexus must be resolved: the choice of aggregation method, variables and data, especially with regard to scale, measuring complex interactions between the three variables, and integrating sector-level values and correlation values into a coherent composite index value. However, to adequately account for all of these, a complex simulation model may be the most suitable approach for estimating a dynamic nexus given the complexity of interdependent nexus resources and effects.

Furthermore, given its origin in sustainability discourse, a major challenge for nexus research is "how nexus thinking can facilitate empowering food–water–energy designs that decentralize, democratize, and facilitate social and environmental justice" (Allouche et al., 2015). This claim to include political and social aspects of natural resource management also applies to measuring the nexus through indices. Our results suggest that when estimating the state of the nexus, the complexity of the individual resources and their mutual relations as well as their interaction with other societal systems need to be taken much stronger into account in future research.

6. Conclusions

Following the adoption of the SDGs, the food–energy–water nexus concept was employed as an approach to optimize the interdependent uses of the different natural resources. However, the concept has been criticized for its lack of operationalization. Since then, numerous indices have been developed to measure and internationally compare the state of the nexus. Given the significance of moving towards more sustainable development and the complexity of its underlying challenges, accurately estimating the state of the nexus is essential. Therefore, we analyzed the effects and inconsistencies of various indexing approaches as well as their underlying assumptions in two steps. First, we developed the STE FEW Security Index in order to scrutinize the effects of different conceptual and methodological choices. Then, we comparatively analyzed countries' scores across the RAND FEW Security Index, the SDG Index as well as the STE FEW Security Index. The development and comparison of a new nexus index served the purpose of identifying the implications of existing indices' methodological choices step by step.

The analysis revealed that assumptions about the substitutability of nexus resources, the scope of nexus aspects, as well as

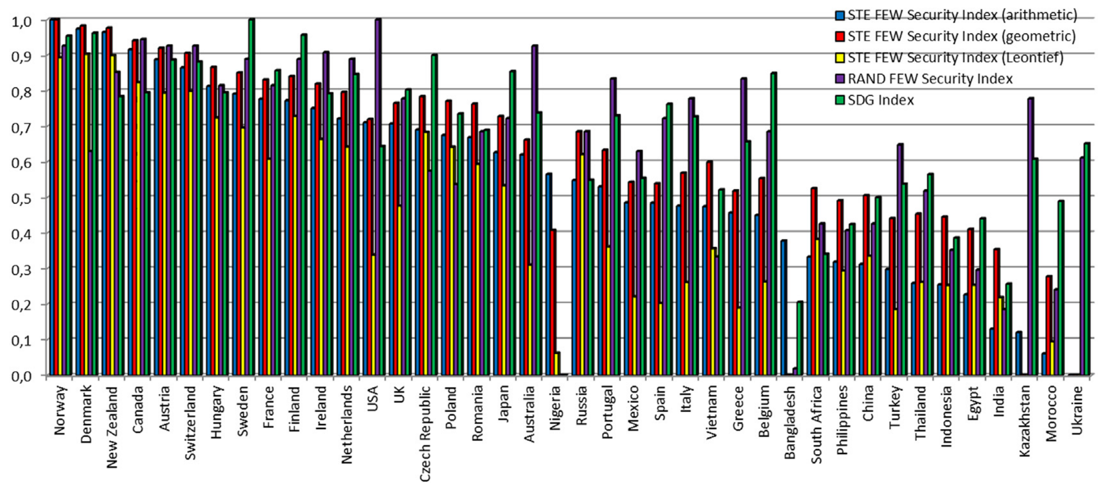

Fig. A.1. Comparison of the three aggregation cases of the STE FEW Security Index, perfect substitutability (arithmetic mean), non-linear substitutability (geometric mean) and no substitutability (Leontief production function), as well as the RAND FEW Security Index and the SDG Index.

Table A.1
List of countries included in the index analysis (Section 4) in alphabetical order.

Countries included in analysis	
Australia	Morocco
Austria	Netherlands
Bangladesh	New Zealand
Belgium	Nigeria
Canada	Norway
China	Philippines
Czech Republic	Poland
Denmark	Portugal
Egypt	Romania
Finland	Russia
France	South Africa
Greece	Spain
Hungary	Sweden
India	Switzerland
Indonesia	Thailand
Ireland	Turkey
Italy	Ukraine
Japan	United Kingdom
Kazakhstan	United States of America
Mexico	Vietnam

the underlying data on food, energy and water systems are of decisive effect for nexus index scores. Especially with regard to 'middle-scoring' countries, we found numerous inconsistencies. We conclude that the calculation of nexus indices is influenced on the level of the indicators by data sources and the scope of indicators, and on the level of sub-indices and the overall system by weighting and aggregation methods, specifically assumptions about substitutability. These results demonstrate the necessity to critically reflect on the methodological decisions when using highly aggregated indices to measure the interrelated nexus challenges. Even more so, since estimates of the nexus' state often form the basis of policies on sustainable development. As Jollands et al. (2003) point out, such highly aggregated indices are "necessary but not sufficient" for improving decision-making.

Finally, this analysis highlights the crucial importance of developing indices and models capable of appropriately reflecting nexus thinking, i.e., the interrelated nature of the resources food, energy and water. The results have shown that static nexus indices must be carefully interpreted, because their capacity to represent the complexity of the interdependent food, energy and water systems is limited. Instead of assuming static relations between the nexus resources, we propose further research on the dynamic relations among the nexus resources in order to account for the fact that the nexus is more than the sum of its parts. However, such complex models are more difficult to operationalize. Further research on nexus estimates needs to find a balance between measurability and adequate representation which is both true to nexus thinking, and transparent to decision-makers with regard to its explanatory power.

Appendix

See Table A.1 and Fig. A.1.

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